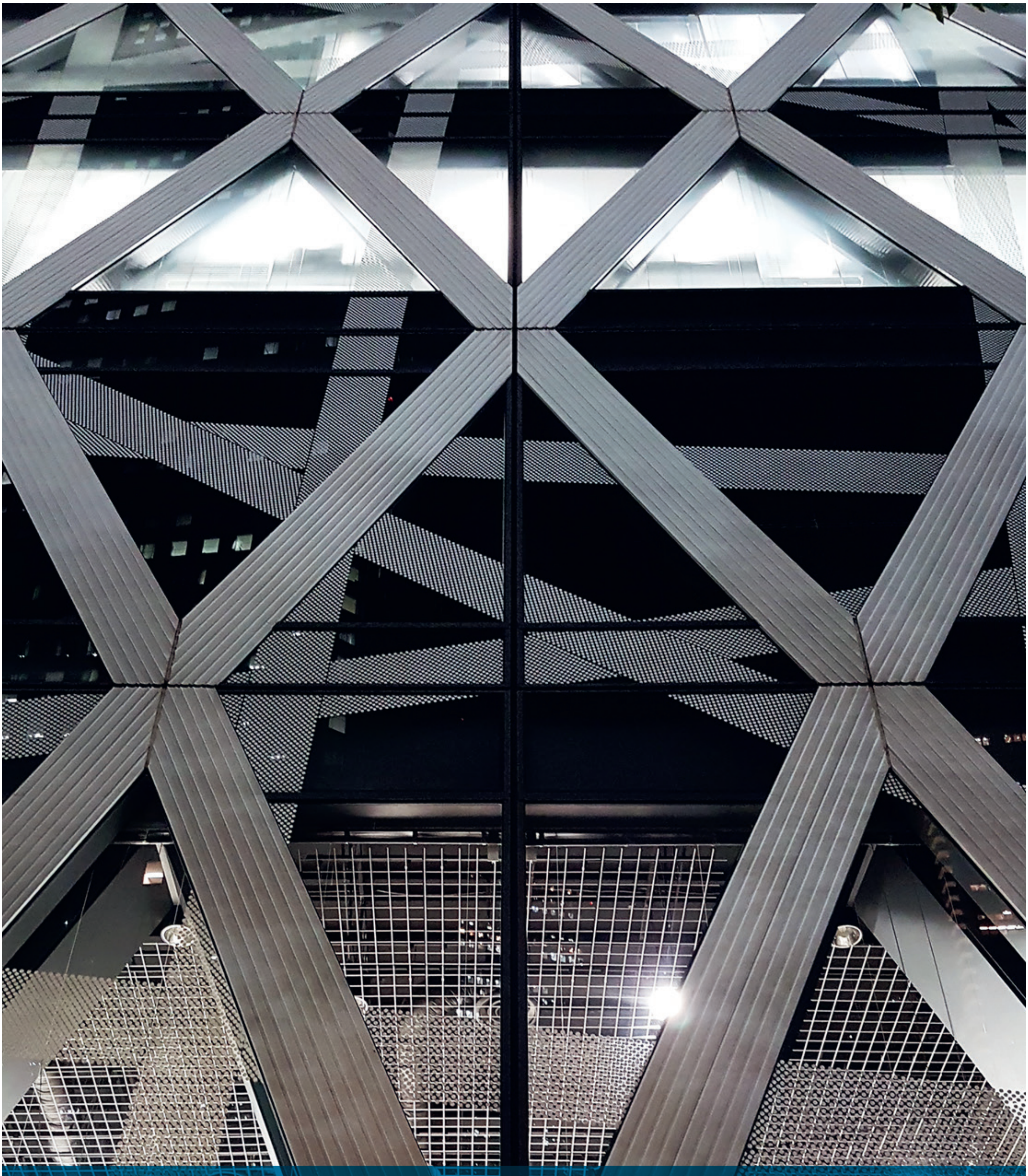

VOL. 11, NO. 2 (2025)

CONSTRUCTION AND ITS INTERCONNECTIONS

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
DOI: 10.30682/tema1102

Cover illustration: Mode Gakuen Cocoon Tower in the Nishi-Shinjuku district (Tokyo, Japan) by Kenzō Tange, external view. © Riccardo Gulli, 2018

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
ISBN online 979-12-5477-692-6
DOI: 10.30682/tema1102
Vol. 11, No. 2 (2025)
Year 2025 (Issues per year: 2)

Publisher:
Ar.Tec. Associazione Scientifica per la Promozione dei Rapporti tra Architettura e Tecniche per l'Edilizia
c/o DICATECH - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica - Politecnico di Bari
Via Edoardo Orabona, 4
70125 Bari - Italy
Phone: +39 080 5963564
E-mail: info@artecweb.org - tema@artecweb.org

Publisher Partner:
Fondazione Bologna University Press
Via Saragozza 10
40123 Bologna - Italy
Phone: +39 051 232882
www.buponline.com

TEMA: Technologies Engineering Materials Architecture
Vol. 11, No. 2 (2025)
e-ISSN 2421-4574

THE USE OF WPC COMPONENTS IN BUILDINGS: A CIRCULARITY PERSPECTIVE

TEMA
Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 11, No. 2 - (2025)

Sara Lanzoni, Luca Guardigli

DOI: 10.30682/tema110022

Abstract

Over 20 years of theoretical studies and practical applications have enabled some Wood Plastic Composites (WPCs) to achieve outstanding durability, stability, and performance. Originated from secondary raw materials, such as selected wood and plastic scraps, WPCs contribute to resource conservation by reducing the demand for virgin materials and facilitating the recovery of plastic and wood waste, offering significant environmental benefits. At the end of their service life, WPCs can be milled and extruded multiple times to form new profiles with the same properties as the originals. This complete recyclability and renewability make WPCs an exemplary model of circularity. This study proposes new approaches to optimize the use of WPC components in buildings, with the dual objective of improving environmental performance and reducing life cycle costs.

Environmental data for WPC components were obtained from environmental product declarations (EPDs) and from an Italian company that controls the process of production, design and installation of WPC elements and façade components. A specific case study focuses on replacing WPC facade cladding with new components, recycling the material from the dismantled elements and reintroducing it into production for reuse in other facades. The dismantled components are sent to the factory to be shredded and extruded into new profiles. A production waste collection system is also introduced as part of the strategy, promoting a closed cycle of material before and during construction. The eco-design approach is examined with reference to façade and floor panel systems made with WPC elements. The results indicate that the proposed strategies enable greater cost savings and a lower environmental impact compared to conventional WPC recycling practices.

Keywords

Wood Plastic Composite, Circular economy, Recycling, Sustainability, Life Cycle Assessment.

Sara Lanzoni*
DA - Dipartimento di Architettura, Università di Bologna, Bologna (Italy)

Luca Guardigli
DA - Dipartimento di Architettura, Università di Bologna, Bologna (Italy)

** Corresponding author: e-mail: sara.lanzoni@unibo.it*

1. INTRODUCTION: MAIN PROPERTIES OF WOOD PLASTIC COMPOSITES

The Wood Plastic Composite (WPC) is a material made by blending wood fibers or wood flour with a plastic matrix. The wood components in WPCs typically come from by-products of the mechanical wood processing industry, sourced from conifers, hardwoods or other cellulose-based fiber fillers. The plastic or polymer used in WPC is often recycled or waste material, which can be thermoplastic, such as polypropylene or polyethylene, or thermosetting, like phenolic resin or urea formaldehyde. The use of plastic waste as feed-stock to produce wood plastic composites is a promising strategy for reusing plastic waste [1]. Thermoplastic polymers typically constitute 30-70% of the WPC's mass, whereas the wood filler – commonly 40-mesh sawmill residue – represents 30-70% [2]. WPC products contain approximately 5-10% additives to optimize the manufacturing process and improve both appearance and durability.

The primary polymer matrices used in WPCs include high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinyl chloride (PVC). Some products have introduced nylon as a polymer matrix [3]. Polymer additives used in the production of WPCs include lubricants, colorants, light stabilizers, antioxidants, and coupling agents. Certain additives, or combinations of them, may contribute to the slowing down of the degradation process. Generally, polymers and their additives are far less susceptible to biological attacks compared to wood; however, like wood, polymers are still prone to weathering from ultraviolet (UV) light and oxidation [2].

More expensive than softwood, but comparable with naturally durable, as hardwood or treated wood, WPCs are being used with increasing frequency in construction. One of the main reasons is that the initial costs are offset by the low maintenance costs, which make these materials actually cost-effective – if not irreplaceable – compared to equivalent wood products. Indeed, WPCs do not require painting or additional treatments throughout their lifespan, but closely resemble natural wood. Surveys indicate that they are highly regarded for their environmental friendliness, and there is a general perception that they require little to no maintenance [4]. The versatility, durability and low maintenance of WPCs make them a popular choice for a variety of applications, particularly outdoor use [5]. Ongoing innovation within the industry is driving the development of new products with enhanced features like UV resistance, moisture resistance, fire resistance and improved aesthetics.

Beyond all this, the issue of product recycling is important. According to current standards, WPC products can be shredded and re-extruded multiple times without losing their physical and mechanical properties. This allows for extensive reuse of the material without needing new sources of supply, resulting in a very long service span. Some studies showed that WPC made from secondary materials is both ecologically and technically superior [6].

The process of effectively combining wood flour and plastic in WPCs involves a specialized mixing and treatment technique, ensuring the desired properties of the composite. The first critical step in WPC production is preparing the raw materials: dry and uniformly sized wood flour, plastic materials and additives. Coupling agents play a crucial role in enhancing adhesion between the plastic (polymeric phase) and the wood (fibrous phase). These agents often include block or graft copolymers that have an affinity for both materials. The actual production phase – for a one-step line, is extrusion, where the mixture is fed into an extruder, heated to the melting point of the plastic polymers, and transformed into a viscous mass. During extrusion, the mass is compressed and pushed through a die to form the desired shape. The extruded material is then cooled and cut into final products like boards or other profiles.

The source and type of raw materials, whether virgin or recycled, have a significant impact on the strength and durability of WPCs. Additionally, the filler-to-polymer ratio and the method used to mix the primary components, along with production techniques and process conditions, are key factors that influence the suitability of WPC products for their intended applications [7]. The size and moisture content of the wood particles also affect bond quality – particles that are too large or contain excess moisture can weaken the final product. The ratio of wood flour to plastic must be optimized: too much wood flour reduces flexibility, while too much plastic diminishes mechanical strength.

Therefore, effective bonding of wood dust and plastic materials in WPCs results from a combination of material selection, coupling agents, process conditions, and additives. This bonding is essential for achieving the desired qualities of WPC. Precise control of extrusion conditions, including temperature and pressure, is necessary to ensure uniform mixing and a solid bond between the components [8].

It was possible to explore the topics in depth thanks to the multi-year cooperation with an Italian manufacturing company. To assess the impact of recycled polyethylene (PE) on durability, multiple Oxidation Induction Tests (OIT) on WPC samples were conducted. This test helps estimate the lifespan of the extrusion batch from which the samples originate [9].

In 2021, Novowood®, the WPC under study, obtained ReMade in Italy® certification [10], which attests to the Italian origin of the product and the percentage of recycled material it contains, a minimum of 81.5%, as declared by the manufacturer [11]. The certification analyzed the production process of the composite and verified the traceability of recycled PE and recycled wood flour from the global market. The remaining 18.5% consisted of calcium carbonate and additives, which cannot come from recycling. The use of recycled content led to a decrease in energy consumption of 4.27 kWh/kg and to a CO_2 emission reduction of 0.59 $kgCO_2eq/kg$ in stages A1-A3 of EN 15978, compared to a product without recycled material. The brand also guaranteed the conformity of the product with the CAM (*Criteri Ambientali Minimi* – Minimum Environmental Criteria) of the Italian Ministry of the Environment [12, 13].

On the regulatory front, challenges arise because composites often do not fit neatly into existing regulations that specify material categories. Due to the variability in compositions, it may be necessary to interpret or adapt legislation on a case-by-case basis. In Europe, several regulations and standards currently govern WPCs, addressing various aspects such as safety, durability, mechanical properties, and fire resistance. The EN 15534 series [14] provides specifications and test methods for wood-based and plastic composites, covering mechanical properties, durability, weathering, and fire resistance. While these regulations establish a foundation for ensuring the quality and safety of these materials, they have limitations in areas such as coverage, long-term durability, environmental sustainability, and adaptability to technological advancements. Regular updates and the incorporation of more specific guidelines could enhance the relevance and effectiveness of these regulations in a rapidly evolving market. In the past decade, WPC has achieved greater product and market stability. Nevertheless, the absence of standardized references for classifying and qualifying products means that there remains a risk of purchasing subpar products at favorable prices [15].

This article aims to suggest new strategies for the optimization of the use of WPC products in the building sector, with the purpose of enhancing environmental qualities and reducing costs during the life cycle. The study starts with the impact assessment of the products, to finally define some methodologies that can lead to the building process optimization.

2. LIFE CYCLE ASSESSMENT OF WPC PRODUCTS: A METHODOLOGICAL APPROACH

Since 2010, there has been a growing emphasis on sustainability and recycling: WPC, made from recycled wood and plastic materials, is regarded as an eco-friendly option [16]. In order to consolidate economic success, manufacturers try to demonstrate a lower environmental impact than alternative products. This necessary information is obtained through a comparative Life Cycle Assessment (LCA) [17]. In fact, combining LCA and eco-design in the early stages of product development can reveal opportunities for improvement that might otherwise go unnoticed [18]. The integration of ex ante LCA into the development process supports sustainable product development and enhances environmental product performance to its fullest potential [19]. An LCA for WPC products involves evaluating the environmental impact from raw material extraction to production, usage, and end-of-life disposal or recycling (Fig. 1).

The main key stages of LCA for WPCs can be summarized as follows:

- Raw Material Extraction (stage A1): wooden components are typically sourced from wood processing byproducts such as sawdust or wood flour, which reduce waste in the timber industry; plastic components are recycled, reducing dependence on virgin fossil-based plastics;
- Transportation (stage A2): the transport of raw materials to the manufacturing site is evaluated in terms of fuel consumption and emissions;

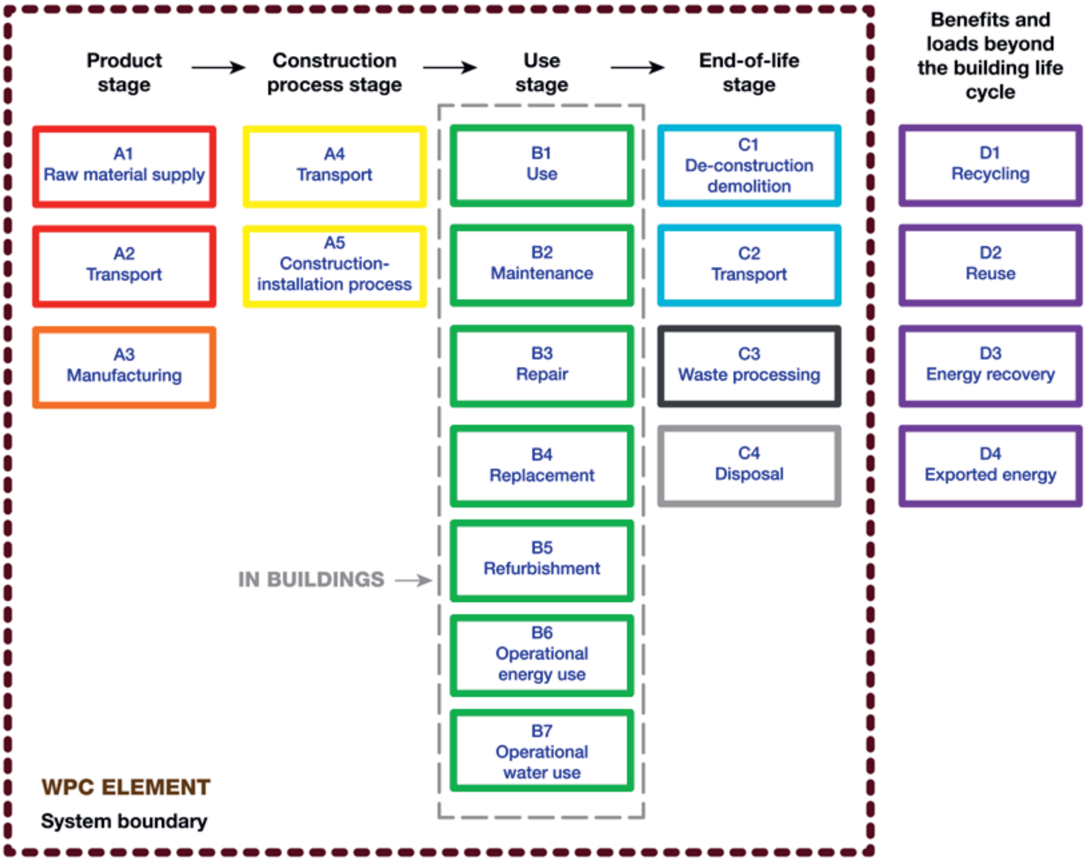

Fig. 1. *Assessment system boundary, per EN 15978 and ISO 21930 [20]. Source: © 2025, Authors.*

- Manufacturing (stage A3): the energy consumed during the blending of wood and plastic, as well as during extrusion and molding processes, is assessed; the environmental impact of using various additives (e.g., stabilizers, colorants, coupling agents) to improve product performance is considered;
- Transportation (stage A4): the distribution of finished WPC products to consumers is evaluated in terms of fuel consumption and emissions;
- Installation (stage A5): the environmental impacts resulting from the installation of the product, such as energy use for tools or equipment, are evaluated;
- Use Stage (stages B1-B7): WPCs generally have a lifespan of at least 20 years, with low maintenance requirements, reducing the need for resources over time (e.g., the need for paints or protective treatments). The ability of WPCs to reduce energy usage in buildings through applications like thermal insulation or shading systems is also examined;
- End-of-Life (stages C1-C4): WPCs can be dismantled (C1), transported to the factory (C2), shredded and re-extruded multiple times (C3) without significant loss of physical or mechanical properties, making them suitable for recycling and extending product life. If WPCs are not recycled, their disposal impact in phase C4 (e.g., in landfills or incineration) has to be analyzed;
- Benefits and Loads Beyond the System Boundary (stage D, optional): the potential benefits of recycling the WPC product after its use phase, such as reducing the demand for virgin materials in new products or reducing waste, are rarely considered.

Some Environmental Product Declarations (EPD) are available online, providing a transparent, standardized assessment of the environmental impacts of a WPC over its entire life cycle. These documents follow the international standards ISO 14025 [21] and EN 15804+A2 [22], and offer information for stakeholders, including manufacturers, designers, and consumers. The Environmental Impact Categories include Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), and Abiotic Depletion Potential (ADP). Comparing the EDPs of WPCs is complex as the materials may differ in type, percentage and the amount of recycled content. On top of that, the compositions are covered by a certain secrecy. Besides, the production processes can be significantly different. To analyze and compare the EPDs of WPCs, four companies were selected with materials supplied, produced and exported all over the world, including Europe. Recycled raw materials may come from China to be used in European factories.

Regarding the Redwoods company (China) [23], the UN CPC code of their EPD product is 36910, Floor coverings of plastics, in rolls or the form of tiles and wall or ceiling coverings of plastics. The geographical scope is China for modules A1-A3 (product stage), and mainly France, Russia, India, Canada and Denmark for modules A4/A5/B2/C/D. The declared unit is 1 t WPC sold overseas, and its installation accessories with a reference service life (RSL) of 20 years. The main raw materials for producing WPC (A1-A3) are wood powder and plastic powder ground from waste, calcium powder, HDPE, compatibilizer and inorganic pigment. The transport of raw materials (module A2) is considered, with EURO5 category diesel vehicles in different lorry sizes and small electric trucks. The WPCs for export are transported to ports (Shanghai and Ningbo, China) first, EURO5 category large diesel vehicle is chosen. Then, WPCs are transported from ports to various destination regions.

About the Wimex company (Denmark) [24], their products mainly focus on outdoor usage (decking/fencing). The declared functional unit is 1 kg, and the reference service life is 20 years. The product process is not geographically specified and clearly expressed in all phases, but the main manufacturer's address is in China. Regarding waste processing for reuse, recovery and/or recycling (C3), it is assumed that 100% of products are collected at the demolition site. Losses in the sorting process are assumed to be very small and not considered in the assessment. This aspect justifies the small impact reported for phase C3, compared to the other companies.

The functional unit of Silvadec (France) [25] is a planking/deck board (wood flour and HDPE) with dimensions 138/180 mm x 23 mm x 4000 mm, designed to last for 25 years: data are determined according to this dimension and reduced to 1 m^2 of product.

The NewTechWood company (China) [26] has a global geographical scope. NewTechWood wood plastic composite combines the proven strength of high-density, recycled PE plastic and wood/bamboo fibers with an outer shell of polymer that completely encapsulates the board in an impermeable layer of protection from weather, sun, water, scuffs and scrapes. The recycled PE polymer content is 37.9%, the natural fiber is 55.7%, the lubricant is 1.9% and the maleic anhydride is 4.5%. The transportation mainly takes place in Chinese regions, and distances may vary significantly. A 25-year RSL is assumed for the declared products.

All the companies use recycled plastic and wood at the beginning of the process in different combinations (A1-A3); LCA data, according to EN 15804, include a minimum of 95% of total inflows (mass and energy) per module. Unfortunately, transportation stages (A2, A4) are quite variable between different manufacturers and within the same companies. Typically, the recycled PE comes from the recycled material processors and is transported by road to the WPC producers, with widely varying distances between them, where it is mixed with wood flour. Data relating to impacts during the use stage (B1-B7) are generally not considered, with the exception of the maintenance phase (B2), for which the reported impact is less than 1% of that for phases A1-A3. Therefore, the declared duration of service life of 20 or 25 years does not generate significant differences in the results.

The WPC products reported in the EPDs concern extruded elements for external flooring, which constitute a large share of the market, but the impact values can be reasonably extended to similar WPC products applied to façades or other parts of buildings. The main impacts of the products during stages A and C are compared in Table 1. The EPD data are normalized by considering 1 kg of WPC, applied on the façade or laid as flooring, as the functional unit.

EI	A1-A3	A4	A5	C1	C2	C3
GWP fossil [KgCO2eq/Kg]						
RW	1,31	0,146	0,141	0,000	0,057	0,854
WM	0,772	0,255	0,019	0,00095	0,198	0,067
SD	1,01	0,073	-0,087	0,000021	0,006	0,000
NTW	1,412	0,258	0,0046	MND	0,00092	MND
ODP [Kg CFC 11 eq]						
RW	0,144*E-7	0,222*E-8	0,131*E-8	0,000	0,994*E-9	0,534*E-9
WM	0,499*E-7	0,542*E-7	0,230*E-8	0,188*E-9	0,404*E-7	0,923*E-9
SD	0,179*E-6	0,136*E-7	0,134*E-7	0,385*E-10	0,105*E-8	0,000
NTW	0,995*E-7	0,583*E-7	0,375*E-10	MND	0,218*E-9	MND
AP [molH+eq]						
RW	0,692*E-2	0,341*E-2	0,688*E-3	0,000	0,187*E-3	0,236*E-3
WM	0,487*E-2	0,730*E-2	0,180*E-3	0,915*E-5	0,563*E-2	0,111*E-3
SD [Kg SO2 eq]	0,460*E-2	0,234*E-3	0,413*E-3	0,105*E-6	0,181*E-4	0,000
NTW [Kg SO2 eq]	0,709*E-2	0,303*E-2	0,141*E-4	MND	0,422*E-5	MND
EP [Mol Neq]						
RW	0,017	0,953*E-2	0,137*E-2	0,000	0,612*E-3	0,118*E-2
WM	0,898*E-2	0,200*E-1	0,501*E-3	0,136*E-4	0,155*E-1	0,298*E-3
SD [Kg (PO4)3 eq]	0,762*E-3	0,387*E-4	0,806*E-4	0,140*E-7	0,299*E-5	0,000
NTW	0,166*E-1	0,898*E-2	0,346*E-4	MND	0,170*E-4	MND
MND = Module Not Declared						

Tab. 1. *Normalized Environmental Impacts (EI), collected from the EPDs of the following companies: RW=Redwoods (27); WM=Wimex (28); SD=Silvadec (29); NTW=NewTechWood (30). © 2025, Authors.*

Table 1 shows that the biggest impact is generated in stages A1-A3 of raw material supply, but also testifies to a significant variation in GWP values among the various manufacturers, due to the variability of plastics, processes and initial recycled content. The fossil GWP represents the carbon footprint of the product, and it is the most important indicator; the mean value of 1.126 kgCO_2eq/kg among the 4 companies is contained, thanks to the presence of recycled wood and recycled plastics. From the Inventory of Carbon and Energy (ICE) database [31], the average value of the carbon footprint of timber, excluding carbon storage, is equal to 0.493 kgCO_2eq/kg (stages A1-A3, cradle-to-gate); this means that the impact value of WPC is 2.3 times higher than that of wood. Considering that from the ICE database, the carbon footprint is 1.93 kgCO_2eq/kg for HDPE, 2.08 kgCO_2eq/kg for LDPE, 3.43 kgCO_2eq/kg for PP, and 3.10 kgCO_2eq/kg for PVC, the recycled parts allow the carbon footprint of WPCs to be brought closer to that of wood. The ICE reports a value of 1.44 kgCO_2eq/kg for WPC, which is in line with the values of the selected EPDs, which have an average GWP fossil of 1.12 kgCO_2eq/kg.

The transport phases (A2, A4) have a certain impact, caused by the large distances between the supplier and the factory, and from the factory to the site; however, this aspect is underestimated in the EPDs. Furthermore, data do not always take into account the amount of hazardous waste generated during production (A1, A3) and, at the end of life, general waste from manufacturing, use, and disposal phases (stages C1-C3) and the amount of the product that can be recycled at the end of its use (stage D). This aspect is also not very detailed in the documents.

Overall, the EPD data on the other impact factors demonstrate how these impacts are linked to the plastic component. The use stage (B1-B7) of the life cycle is not evaluated as it is considered that these products do not actually require maintenance during the reference period, except for possible mechanical breakages, which may result from design errors and assembly defects. Unlike WPC, equivalent wood products require ongoing maintenance, as they must be protected from the elements with treatments and paints. This aspect is certainly crucial in making WPCs competitive not only from the point of view of impact, but also of costs in a life cycle logic.

3. STRATEGIES FOR PRODUCT OPTIMIZATION AND CIRCULARITY, DISCUSSION AND RESULTS

Adopting circular economy principles to buildings allows societies to promote more sustainable plastic management, addressing both environmental and economic issues through effective recycling and reuse practices [32]. This study wants to promote the complete circularity of the WPC product at every stage, from the production phase to the end of life. Circularity can be understood not only from a product perspective but also by considering the context of the building and its elements. Any *crumb* of the material, whether it be off-cuts or elements resulting from production errors, cuts, assemblies, in the factory or on site, and extrusions that have reached the *end of use* (not necessarily the end of life), can always be re-introduced into the production cycle (Fig. 2).

Therefore, the research project aims to imagine a process of WPC production, building component design, maintenance and recycling that can further reduce impacts from the outset if the system boundary is not represented by the generic WPC element, but by the building and the element together, where the building is intended as a WPC accumulation and storage place. In the context of plastic recycling, the circular economy of the building and its components not only reduces the environmental impact of plastics but also offers economic advantages, such as resource conservation and job creation in recycling and reuse industries.

Experimentation is applied in this study to construction systems based on WPC elements. The study involved collaboration with the production company, which allowed for the analysis of coordination actions between the manufacturer, component designers and installers. The elements and their application in some

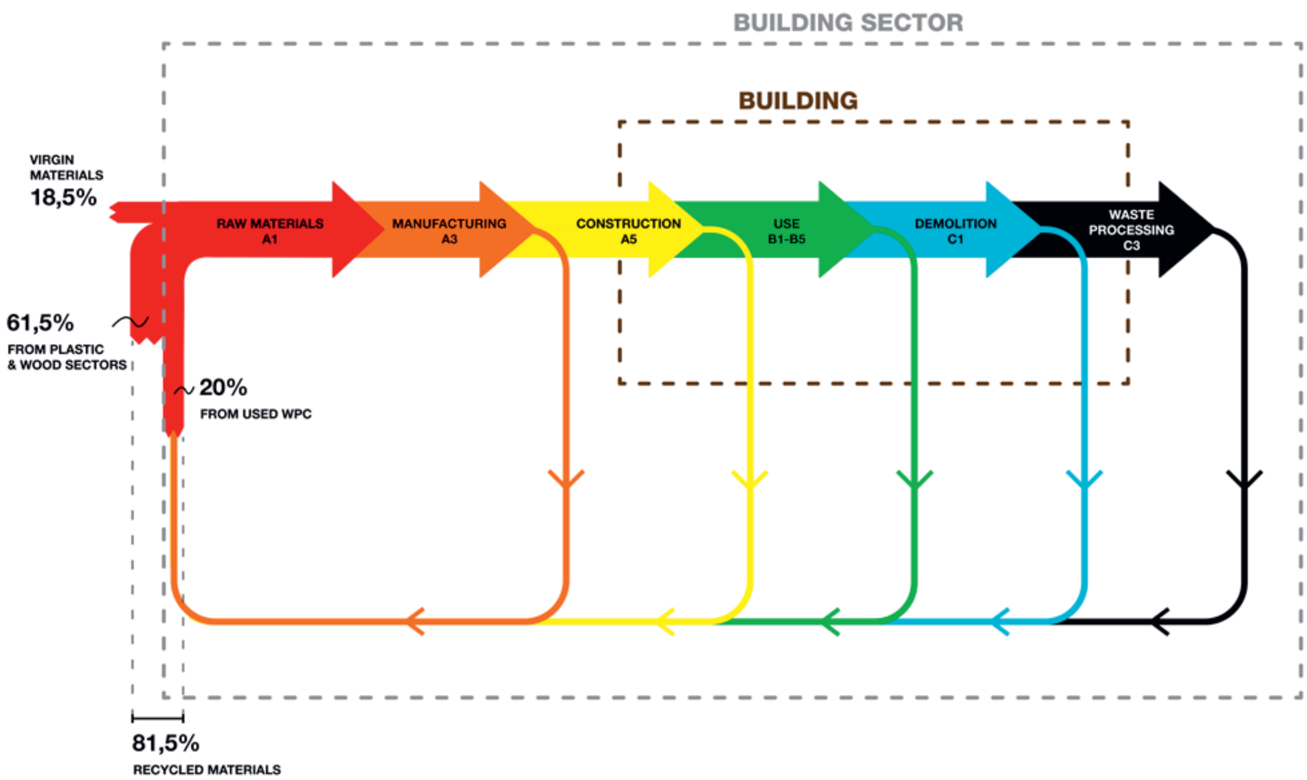

Fig. 2. *Circularity of WPC elements in the context of buildings. Novowood's current production, certified ReMade in Italy®, uses 18.5% virgin materials and 81.5% recycled materials. As part of the REMAKE project, 20% of the total, equal to 24.5% of the recycled portion (81.5%), can consist of used WPC. © 2025, Authors.*

sample buildings were then analyzed. Leaving aside flooring, WPC elements are part of more complex building components designed to fulfil their functions and connect to the main structure. Functions include shading facades, protection and general cladding of the building envelope, and the creation of ventilated or thermally insulated walls.

Extruded WPC elements generally have reduced dimensions in thickness and width, with variable lengths, which characterizes them as linear elements that reproduce natural wood elements. Typically, extrusions reproduce boards with varying thicknesses between 20-30 mm or box elements with sizes ranging, on average, from 20 mm x 20 mm to 200 mm x 200 mm. Thicknesses and sizes are produced as required for flooring or facade applications, always following commercial sizes, however. It is rare for elements, in terms of section, to be produced *custom-made*. The combination of these individual elements generates ventilated façade systems or sunshades or pavement systems for installation in buildings, mainly outdoors. The fixing of these panels to the main structure almost always occurs through the use of metal elements, in order to guarantee complete assembly and disassembly of the systems. Clearly, the sizes of the components made for individual buildings affect the reuse of the elements in other buildings.

Figures 3, 4 and 5 show the component arrangements of façade panels to rationalize assembly/disassembly and installation on the existing structure. In fact, in these cases, WPC is employed in complex panels and it is combined with other metal elements that have different profiles and properties. Therefore, it is important to balance the initial costs of all materials of the system, optimize installation and dismantling processes and minimize maintenance requirements.

In the case of façade cladding using boards, a substructure consisting of an extruded aluminium *open omega* section profile, doweled to the substrate using suitable fasteners, can be used. The type of profile al-

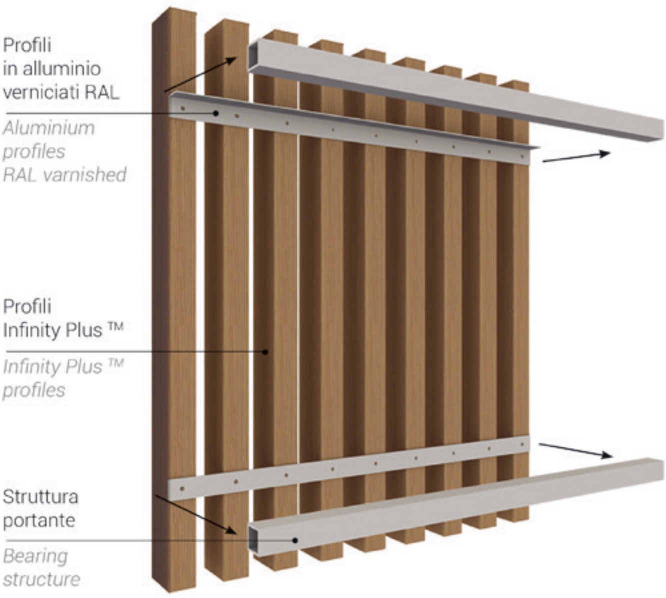

Fig. 3. *Façade cladding panel pre-assembling scheme (left) and an installation example (right). © 2025, Iperwood®.*

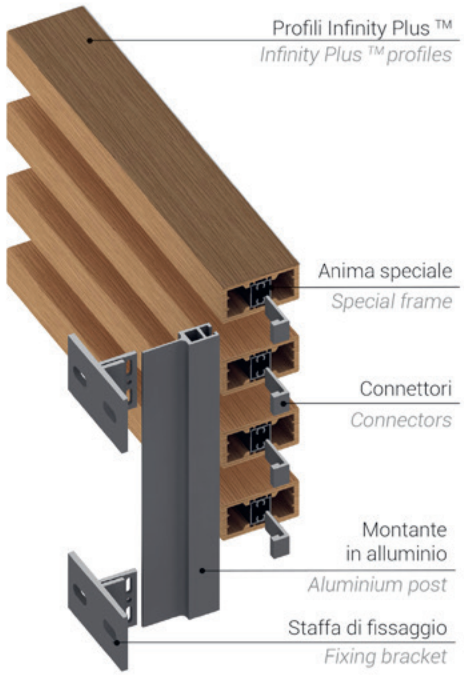

Fig. 4. *Façade cladding panel assembling and support scheme (left) and an installation example (right). © 2025, Iperwood®.*

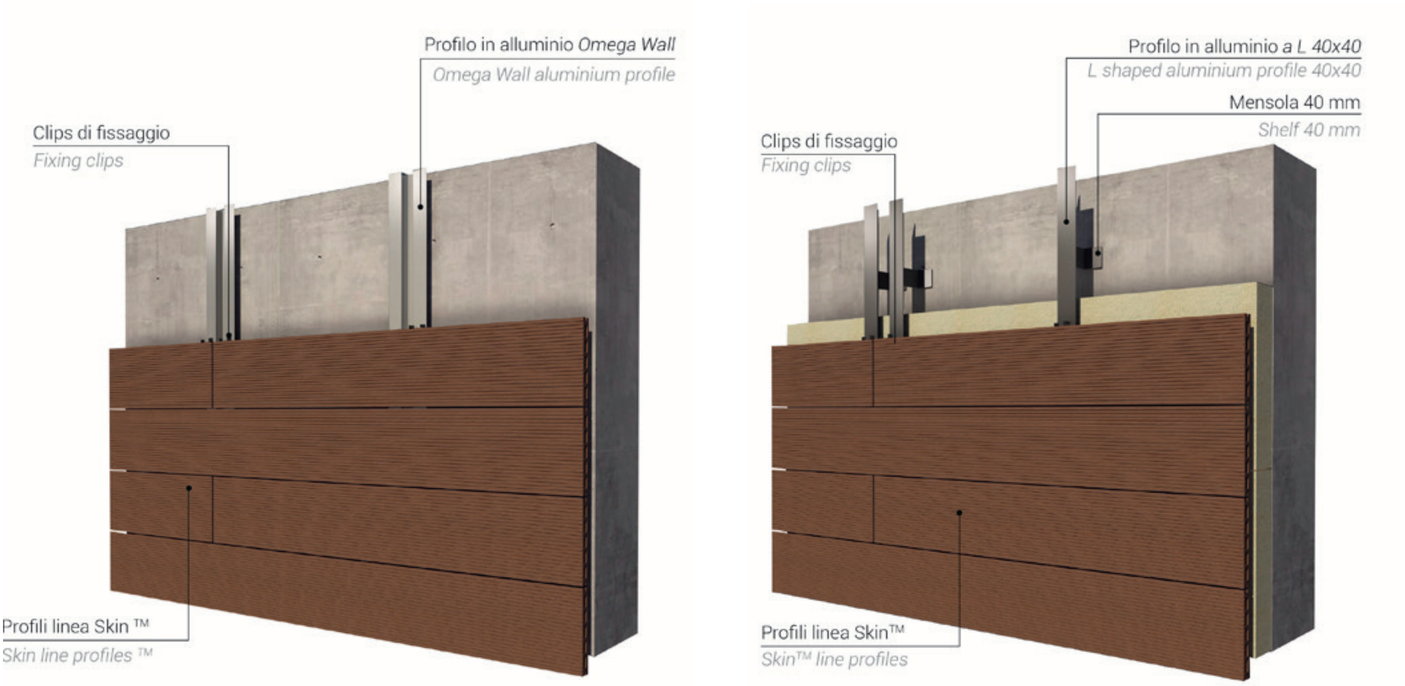

Fig. 5. *Façade cladding panels schemes: (left) with an empty space between panels and the existing structure, for ventilation and (right) with insulation. © 2025, Iperwood®.*

lows direct attachment to the structure without the need for pre-drilling, and the attachment of the WPC boards to the side wings, using stainless steel clips, the system proves practical and fast. The omega profile can be replaced by L-shaped profiles spaced from the wall support to allow the insertion of thermal insulation or ventilation if left empty. In the case of vertical sunshades, it is possible to obtain pre-assembled panels by means of suitable screws and aluminium substructures of tubular type with a square or rectangular cross-section. Another more complex type of system allows the use of WPC profiles arranged horizontally (Fig. 4). The aluminium profiles are designed to generate interlocks between them and then be secured by mechanical screw connections.

Besides, developing durable WPC cladding continues to be a significant challenge for the industry. High values of modulus of rupture (MOR) and Young's modulus (MOE) are essential for the engineering design of WPC façades, as these parameters effectively indicate the aging of the cladding. Weathering typically reduces MOE more than MOR, with UV radiation being a greater threat than freeze-thaw cycles. To minimize reductions in MOR and MOE, it is advisable to use PE in extruded panels with a low content of large hardwood fibers [33].

The strategies proposed here for product reuse and recycling come after twenty years of experimentation, practical applications and continuous research since the creation of the first composite products. The many years of collaboration with a manufacturing company, in fact, have made it possible to follow the development of WPC products and production techniques, which have obtained high physical-mechanical characteristics and durability such as to allowing the material to be completely recyclable at the end of its cycle.

The material studied, Novowood®, is produced in Italy and consists of 50-70% wood flour, 25-35% HDPE, and 10-15% additives. In Table 2 are shown some technical specifications taken from the manufacturer's published data sheets.

The material includes varying amounts of recycled content and may also incorporate recycled WPC from its end-of-life cycle, depending on the final application of the product. The material adheres to the limits established by the Italian CAM and ensures traceability of the recycled components [34].

For this reason, the company developed two programs to increase the amount of recycled product, trying to maintain the same physical and mechanical performances.

A first optimization strategy, represented by the REMAKE Project, consists of the free recovery process of composite wood waste from the construction site (stage A5) (Fig. 6). Thanks to their special formulation, these scraps can be reused by the same manufacturing company after being shredded and re-extruded, to create new products, thus contributing to the reduction of CO_2 in all the A stages, but mostly in the transportation stages, up to 50%. It is essential to raise awareness and educate both participants in the production chain and end consumers on the importance of recycling these materials [35].

Moreover, the company identified a second optimization strategy, where construction systems installed in past years are dismantled from the buildings and reused

Properties	
Density (EN ISO 1183-1)	1300 kg/m^3
Flexural strength, average value (EN ISO 178:2003)	>25 MPa
Modulus of elasticity, average value (EN ISO 178:2003)	>2500 MPa
Tensile strength, average value (EN ISO 527:1996)	>5 MPa
Tensile modulus of elasticity (EN ISO 527:1996)	>3000 MPa
Brinell hardness	68 N/mm^2
Coefficient of expansion (DIN 53752)	0,04 mm/m/°C
Imbibition index (24h) ASTM DI037 - Non-brushed surface	1,2%
Imbibition index (24h) ASTM DI037 - Brushed surface	3,5%
Fire reaction class (Italy) (UNI EN 13501 1:2009) For decking - Classified by the Ministry of the Interior	C_{FL} s1
OIT test (ISO 11357-6:2008) - Average value	>50 min

Tab. 2. *Technical specifications, from Novowood®. © 2025, Iperwood®.*

Fig. 6. *(From left to right) Big bag containing the site scraps; Shredded WPC; Shredding machine. © 2025, Iperwood®.*

in other planned operations. This process regards a series of stores of a well-known sport brand (Fig. 7). These are the data of the pilot project, which was analyzed: dismantling of approximately 200 m^2 of façade/store cladding, equal to approximately 4000 kg of composite material. The façade systems have a weight of approximately 20 kg/m^2 (excluding aluminium supports, only WPC). The replacement project involves intervention on 10-12 stores/year, which corresponds to the collection of approximately 40 t of composite material. Given this data, it is possible to estimate the GWP fossil that can be saved, following the second strategy. If we consider to save 50% of the GWP fossil of phases A1-A3 avoiding part of raw material supply, transport and manufacturing, and if we take the mean value of 1.12 $kgCO_2eq/kg$ calculated before (see Chapter 2), we have: 40,000 [kg] x 1.12/2 [$kgCO_2eq/kg$] = approximately 22.4 tCO_2 equivalent for the entire building.

The introduction of these product recycling actions during the production and installation phase, as well as

Fig. 7. *Left: store façade. Right: façade cladding systems disassembled and brought to the factory to be disassembled and shredded. © 2025, Iperwood®.*

during the component replacement phase after an initial life cycle, should lead to reducing the impacts (all stages).

From a sustainability perspective, the evaluation extends beyond the production cycle. Assessing the durability and recyclability of this composite is essential for minimizing post-use waste. Additionally, the costs of producing and implementing recycled plastic composites in construction directly influence their broader adoption as energy-efficient materials [35].

The percentages calculated in this study reach 20%, considering the complete product life cycle. The decisive factor is that recycling involves the entire material, including both plastic and wood components and additives. From this point of view, the manufacturer could develop an EPD that also takes into account the reduction phase during the product life cycle analysis. A minor impact in terms of cost reduction has been calculated, which is only a few percentage points and highly variable.

4. CONCLUSIONS

LCA demonstrates that WPCs are a promising solution for sustainable construction and consumer products. Their ability to incorporate recycled materials, reduce waste, and offer long-lasting performance makes them competitive in terms of both environmental impact and cost.

The variability in raw material sources (virgin vs. recycled and different quality of the recycled) can affect the mechanical properties and longevity of WPCs. One aspect to be considered is that not all WPCs are effectively recycled, and some may still end up in landfills, especially in regions lacking recycling infrastructure. However, this is not the case treated in this article.

Continuous innovation in manufacturing processes, design solutions and recycling methods can further enhance their sustainability profile. The use of recycled materials (both plastic and wood) reduces the reliance on virgin resources and supports the principles of a circular economy.

WPCs often have a lower carbon footprint compared to traditional wood products, especially when made from secondary materials. WPCs can be repeatedly recycled at the end of their life cycle, contributing to waste reduction and resource conservation. Considering the drawbacks and the future challenges, LCA has identified that WPCs can be sustainable, but the manufacturing process, especially extrusion, can be energy-intensive.

The study has shown, in addition, that circularity elements can be introduced during the process of production, product design, sales, installation and maintenance that further reduce the impacts found in LCA analyses. To improve WPC sustainability and reduce its carbon footprint, it is important to act on its formula in order to elongate its End of Life, use electricity from renewable sources and re-employ all WPC elements produced and placed on the market. Every new recycling cycle represents a reduction of environmental impact. Eco-design also plays a key role in the process of improving sustainability as it approaches product design by prioritizing sustainability, with the aim of minimizing environmental impacts throughout a product's life cycle. This includes material selection, production, usage, and end-of-life disposal. WPCs play a crucial role in eco-design by offering a sustainable alternative to pure plastics and traditional wood. Their durability, recyclability, and efficient material use contribute to reducing environmental impact. However, innovation is still needed in recyclability and biodegradability to maximize their eco-friendly potential. Eco-design and circular economy in architecture mean all the following aspects: *design for disassembly* in order to ensure that buildings can be deconstructed and materials reused; *adaptive reuse for converting* old structures into new functional spaces instead of demolishing them; *cradle-to-cradle approach* by choosing materials that can be endlessly recycled without degradation.

The project proposes new sources of recycled WPC that do not only come from the plastic and wood market, but can remain in a circular manner within the context of the building itself. On the one hand, WPC can provide a stimulus for new architectural solutions, but it can also be designed as a material in such a way that it can be recycled and reused in the future for multiple purposes. Buildings can be designed as storage systems for recycled plastics and wood (WPC) and thus as real mines from which to draw components of the same type. In this sense, WPC is indeed a very similar material to wood, also from the point of view of accumulating *en-*

vironmental credits. A possible continuation of the study could explore the comparison between different applications of the product in the construction sector and assess the impact of WPC in relation to the service life of other building components.

Acknowledgements

This paper is an extended version of our previous work, which was presented at the 3rd Construction Management Workshop (CMW 2024), Ravenna, Italy. The authors acknowledge the support and feedback from Prof. Kalle Kahkonen, Prof. Marco Bragadin, and Prof. Emlyn Witt, the Chairs of the International Scientific Committee of CMW 24.

The authors would like to thank Iperwood Srl, which participated in this research, for providing information and documentation on its products and production system.

Authors contribution

Conceptualization, S.L. and L.G.; Resources, S.L.; Methodology, L.G.; Writing, S.L. and L.G.; Review, S.L. and L.G.; Editing, S.L.

Funding

Published with the contribution of the Department of Architecture of the Alma Mater Studiorum - University of Bologna, as part of the Conference "New Frontiers of Construction Management Workshop 24".

References

[1] Rong X, Qinghan Y, Haoran Y, et al (2023) Visual design of high-density polyethylene into wood plastic composite with multiple desirable features: A promising strategy for plastic waste valorization. Journal of Building Engineering 63, Part A:105445

[2] Gramlich WM, Gardner DJ, Neivandt DJ (2006) Surface treatments of wood-plastic composites (WPCs) to improve adhesion. Journal of Adhesion Science and Technology 20(16):1873–1887

[3] Chen J, Gardner DJ (2008) Dynamic mechanical properties of extruded nylon–wood composites. Polymer Composites 29(4):372–379

[4] Morrell JJ, Stark NM, Pendleton DE, et al (2006) Durability of wood-plastic composites. Wood Design Focus 16(3):7–10

[5] Ibach RE (2010) Durability of wood-plastic composite lumber. McGraw-Hill yearbook of science technology, New York, pp 113–116

[6] Sommerhuber PF, Wenker JL, Rüter S, et al (2017) Life cycle assessment of wood-plastic composites: Analysing alternative materials and identifying an environmental sound end-of-life option. Resources, Conservation and Recycling 117:235–248

[7] Niska KO, Sain M (2008) Wood-Polymer Composites. Woodhead Publishing Limited, Cambridge, England

[8] Klyosov AA (2007) Wood-plastic composites. John Wiley & Sons, Hoboken

[9] Lanzoni S, Guardigli L, Pizzardi P (2025) Twenty years of applied experimental research on wood-plastic composites. An Italian case study. Discover Civil Engineering 2:44. https://doi.org/10.1007/s44290-025-00182-3

[10] ReMade Foundation (2025) ReMade in Italy® certification. https://www.remadeinitaly.it/. Accessed on October 15, 2025

[11] Novowood (2025) Sustainability. https://www.novowood.it/en/sustainability. Accessed on October 15, 2025

[12] CEN (2025) EN 15978:2011. Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011?srsltid=AfmBOooehZgMSRW3ZXkvAX-gT27e6TdQMXQ-urUlcfz0eK5Gkn8tDTl89. Accessed on October 15, 2025

[13] Ministero dell'Ambiente e della Sicurezza Energetica (2025) CAM Vigenti. Edilizia. DM 23 June 2022, n 256. https://www.mase.gov.it/portale/cam-vigenti. Accessed on October 15, 2025

[14] EN 15534-1:2014. Composites made from cellulose-based materials and thermo-plastics (usually called wood-polymer composites (WPC) or natural fibre composites (NFC)) - Part 1: Test methods for characterisation of compounds and products

[15] Najafi SK (2013) Use of recycled plastics in wood plastic composites – A review. Waste management 33:1898–1905

[16] Schwarzkopf MJ, Burnard MD (2016) Wood-plastic Composites – Performances and Environmental Impacts. In: Kutnar A, Muthu SS (eds) Environmental Impacts of Traditional and Innovative Forest-based Bioproducts. Springer, Singapore, pp 19–43

[17] Feifel S, Stübs O, Seibert K, et al (2015) Comparing wood–polymer composites with solid wood: the case of sustainability of terrace flooring. European Journal of Wood and Wood Production 73:829–836

[18] Brunnhuber N, Windsperger A, Perdomo Echenique EA, et al (2023) Implementing Ecodesign During Product Development: An Ex-Ante Life Cycle Assessment of Wood-Plastic Composites. In: Hesser F, et al. Progress in Life Cycle Assessment 2021. Sustainable Production, Life Cycle Engineering and Management. Springer, Cham. https://doi.org/10.1007/978-3-031-29294-1_3

[19] Buyle M, et al (2019) The future of Ex-Ante LCA? Lessons learned and practical recommendations. Sustainability 11(5456):1–24

[20] ISO (2025) ISO 21930:2017, Sustainability in buildings and civil engineering works - Core rules for environmental product dec-

larations of construction products and services. https://www.iso.org/standard/61694.html. Accessed on October 15, 2025

[21] ISO (2025) ISO 14025:2006, Environmental labels and declarations - Type III environmental declarations - Principles and procedures. https://www.iso.org/standard/38131.html. Accessed on October 15, 2025

[22] CEN (2025) EN 15804:2012+A2:2019, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. https://standards.iteh.ai/catalog/standards/cen/c98127b4-8dc2-48a4-9338-3e1366b16669/en-15804-2012a2-2019?srsltid=AfmBOopXC10hMHblgUen58ZOGMXkPWA78MPC7XoeJF2yjVx-pHtlpJwM. Accessed on October 15, 2025

[23] https://redwoodswpc.com/. Accessed on October 15, 2025

[24] https://wimex.dk/. Accessed on October 15, 2025

[25] https://en.silvadec.com/?_gl=1*fsxxfk*_gcl_au*ODc0ODAzNzAyLjE3NTYzMTU1ODA. Accessed on October 15, 2025

[26] https://www.newtechwoodintl.com/. Accessed on October 15, 2025

[27] Redwoods EPD (2023) Wood Plastic Composite (WPC) from Anhui Hongshanlin New Material Technology Co., Ltd. https://api.environdec.com/api/v1/EPDLibrary/Files/025d3d82-eb8e-4710-bc86-08db92ee9d2e/Data. Accessed on October 15, 2025

[28] Wimex EPD (2023) Wood Plastic Composite (WPC) Products. https://www.environdec.com/library/epd10004. Accessed on October 15, 2025

[29] Silvadec EPD (2019) Environmental and Health Product Declaration Sheet. Silvadec composite wood deck boards – Elegance and Atmosphere Range. https://en.silvadec.com/wp-content/pdf/en-epd-decking.pdf. Accessed on October 15, 2025

[30] NewTechWood EPD (2021) Wood Plastic Composite. https://www.newtechwood.ca/wp-content/uploads/Environmental-Product-Declaration-2.pdf. Accessed on October 15, 2025

[31] Circular Ecology (2025) ICE Database. https://circularecology.com/embodied-carbon-footprint-database.html. Accessed on October 15, 2025

[32] Relatório WWF (2019) Solucionar a Poluição Plástica: Transparência e Responsabilização. https://ambientedomeio.com/wp-content/uploads/2019/03/plastic_report_02-2019.pdf. Accessed on October 15, 2025

[33] Friedrich D, Luible A (2016) Investigations on ageing of wood-plastic composites for outdoor applications: A meta-analysis using empiric data derived from di-verse weathering trials. Construction and Building Materials 124:1142–1152

[34] DM 23 giugno 2022. Criteri ambientali minimi per l'affidamento del servizio di progettazione di interventi edilizi, per l'affidamento dei lavori per interventi edilizi e per l'affidamento congiunto di progettazione e lavori per interventi edilizi

[35] Ribeiro LS, Stolz CM, Amario M, et al (2023) Use of Post-Consumer Plastics in the Production of Wood-Plastic Composites for Building Components: A Systematic Review. Energies, 16:6549