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Recycling Potential Comparison of Mass Timber Constructions and Concrete Buildings: A Case Study in China

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Abstract: The recycling potential (RP) indicates the ability of building materials to form a closed-loop material flow, that is, the material efficiency during its whole life cycle. Mass timber constructions and concrete buildings vary widely in RP, but the differences are difficult to calculate. This paper proposed a level-based scheme to compare the RP of mass timber and concrete buildings, and a BIM-Eco2soft-MS Excel workflow coupling Material Cycle Database and digital design tools were established to obtain information on building materials, resource consumption, and environmental impact for the RP calculation. Taking a residential building as an example, the difference in RP between mass timber and concrete at the material-level is firstly discussed. Then at the component-level, the RP of the wood structure component and concrete component is compared, and the optimization methods are proposed. Finally, the difference in RP between the mass timber building and reinforced concrete building at the building-level are illustrated. The results show that the RP of mass timber building is higher, and the disassembly ability is better. Within a 100-year service life, the RP of mass timber buildings is 73% and that of the reinforced concrete building is 34%. The total amount of material consumption and waste of the Variant CLT is 837,030 kg and 267,237 kg respectively, which is less than one-third of that of concrete buildings (3,458,488 kg; 958,145 kg). The Global Warming potential (GWP) of these two variants is -174.0 kgCO$_2$/m^2 and 221.0 kgCO$_2$/m^2 separately, indicating that the Variant CLT can realize negative carbon emissions and gain ecological benefits. A sensitivity analysis is conducted to explore the potential impacts of certain parameters on GWP and RP of buildings. The research can provide the reference for material selection, component design, and RP optimization of mass timber buildings. In addition, new ideas for assessing the potential of circularity as a design tool are proposed to support the transition towards a circular construction industry and to realize carbon neutrality.

Keywords: mass timber construction; recycling potential; material recycling; zero waste; concrete buildings

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1. Introduction

In 2020, the global construction industry produced more than 40% of carbon emissions from primary sources, of which steel and cement account for more than 50% of carbon emissions [1]. Most countries are facing severe construction waste disposal problems. In China, the average annual construction waste accounts for about 30–40% of the urban waste, while the reuse rate is only about 5% [2]. Based on the concept of sustainable development, the 14th Five-Year National Development Strategy of China regards "waste-free cities" as the focus of national ecological environment development in order to continuously promote the reduction and recycling of solid waste sources. How to reduce waste in the construction field to form a closed-loop material flow and achieve "zero waste" remains an issue that needs to be considered in urban development.

Many raw materials are now found not where they grow naturally, but in new, anthropogenic repositories. Understanding buildings as material deposits represents a paradigm shift in architectural design. The recycling of building materials is a re-examination of urban resources. In 1992, the United Nations Conference on Environment and Development adopted "AGENDA 21", which formally pointed out the disadvantages of linear material flow. Subsequently, Western countries launched a series of studies on the recycling of building materials. In 1999, American scholar Philip Crowther proposed "Design for Disassembly" (DFD), which can reduce the cost and difficulty of dismantling during the building's end of life phase through reversible structural design [3]. In 2000, the Swedish scholar Catarina Thormark proposed the concept of "Recycling Potential" to evaluate the amount of energy and natural resources contained in buildings that can be reused after recycling [4]. In 2002, American scholar William McDonough proposed the "Cradle to Cradle" (C2C) circular economy model, which replaces the linear material flow from cradle to grave with natural circulation or technological circulation material flow [5]. In 2011, Austrian scholar Paul H. Brunner proposed the concept of "Urban Mining", which regards buildings as a temporary storage place for raw materials, and furthermore regards the process of resource production–use–recycling–reproduction as the metabolism of the city [6]. In 2015, European countries cooperated to launch the "Building as Material Bank" (BAMB) project, developed design tools such as "Material Passport" and "Reversible Building Design", and proposed a building design model based on the circular economy [7]. Up to now, the focus of building material resource utilization has gradually shifted from the recycling stage to the early design stage, and from the macro-level of urban resources to the micro-level of material or component design. However, most material circulation research studies focus on steel structure, concrete structure, light wood structure, etc. [8–10]. There is a lack of research on mass timber constructions. Meanwhile, most of them are post-evaluation [11], which is weak in guiding decision-making in the early stage of architecture design.

After nearly 30 years of development, the mass timber construction system has gradually matured, and a large number of high-rise residential and middle-rise public buildings employing mass timber construction have emerged in Europe, North America, and other regions [12]. The mass timber building shows advantages in carbon emission reduction [13], energy saving [14], anti-seismic [15], fire resistance [16], and biophilic properties [17], etc., which is expected to become a new building structure system that can replace reinforced concrete structures. The material flow of mass timber construction buildings involves more than 50% biomass materials, which has advantages in natural circulation. However, its natural cycle lasts for a long time, and the uneven distribution of forest resources in the world leads to high transportation costs. It still needs to rely on technological cycles to realize the cascade reuse of high-value materials. Furthermore, forest resources are in short supply in many countries such as China, Japan, etc. Improving the utilization efficiency of mass timber construction resources is conducive to the development of mass timber construction in countries that lack wood resources.

This paper compares and analyzes the difference in recycling potential (RP) between mass timber constructions and reinforced concrete buildings from the material-level, component-level, and building-level, and discusses the method for quantitative calculation of building recycling potential, laying the foundation for the RP optimization of mass timber constructions and increasing their development potential in China.

2. Literature Review

2.1. Mass Timbers and Mass Timber Construction

The definition of mass timber is still open to debate. In the 2018 Manual of Multistory Timber Construction, construction timber was divided into solid wood products and wood-based materials [18]. In the 2021 international mass timber report, several distinct mass timber products were included in the category. Many people confuse Engineered Wood Products (EWPs) with mass timber, when in fact mass timber is a distinct class of EWPs. This paper argues that mass timbers belong to engineered wood products, which are building structural materials produced by finger-joint, gluing, pressing, etc., commonly including Cross Laminated Timber (CLT), Dowel Laminated Timber (DLT), Nail Laminated

Timber (NLT), Mass Ply Panel (MPP), and other panel structural materials suitable for roofing and floors, also including Glued Laminated Timber (GLULAM), Laminated Veneer Lumber (LVL), Parallel Strand Lumber (PSL), Laminated Strand Lumber (LSL), and other structural materials suitable for beams and columns (Figure 1). Among them, CLT is composed of three or more layers of small-sized sawn timber or wood-based materials, which are pressed and glued in an orthogonal arrangement. It is one of the most promising mass timbers, which has a long refractory time, high strength-to-weight ratio, and is widely used [19].

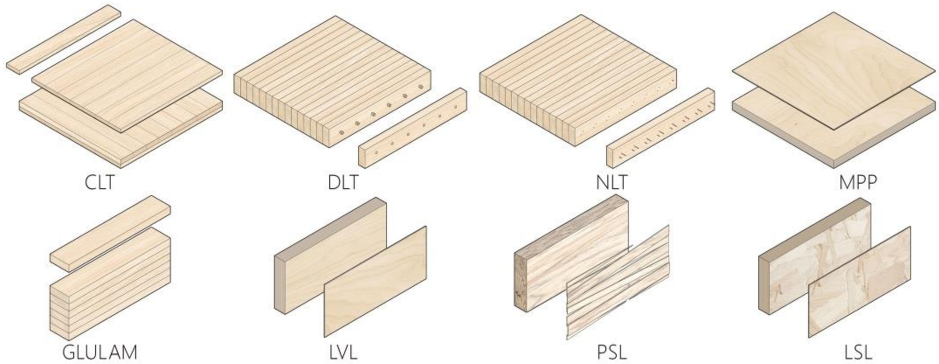


Figure 1. Main species of mass timber.

Mass timber construction is a building structure system with mass timber as the main load-bearing component. In the past 30 years, the research on mass timber construction has shown a rapid upward trend, and the main research direction is Life Cycle Assessment (LCA) [20] and building performance, including fire resistance [21], earthquake resistance [22], thermal insulation [23], insect control [24], etc.

Mass timber construction in China is at an early stage of development. In the past ten years, in order to promote the green and low-carbon development of cities, China has introduced a number of policies to vigorously develop modern wood structures, and organized the construction of demonstration projects for the application of high-rise wood structure building technologies. Although the CLT system has not been well adopted and there are only a few pilot projects for scientific research, there is growing interest in CLT. In 2017, the Ministry of Housing and Urban-Rural Development of China issued a regulation on timber construction and published a new building code (GB/T 51226-2017). The regulation extended the height of timber buildings to 56 m or no more than 18 storeys in non-seismic regions. It can be expected that the timber buildings in China will develop rapidly over the next few decades.

2.2. Recycling Potential of Materials, Components, and Buildings

A detailed data set of materials is one of the most important cornerstones of the transition from a linear flow to a closed-loop material flow. Thus, the concepts of Material Passport (MP), Material Cycle Status (MCS), etc. have emerged. Material Passport refers to keeping a record of the material composition of a product or building through detailed information about quantities such as weight, volume, dimensions, and location [25], which usually involves the steps of data generation and input into the database, the consequent generation of materials passports, and a Circularity Index [26]. Madaster is a materials passport platform, which can conduct the circularity indicator for construction, as well as generate, store, and manage individual building portfolios. This documentation system is suitable for the evaluation of completed buildings and the continuous follow-up of material resources during the operation phase [27]. Ellen MacArthur Foundation and Granta Design developed the material circularity indicator (MCI), which gives an indication of how much of the materials constitute a product circulate. It is able to measure the level of linear and restorative flows. Moreover, it provides information about the utility of a product.

Annette Hillebrandt from Universität Wuppertal summarized the Material Cycle Status of various building materials in 2019 [28], using three bars, the Material Recycling Content (MRC), Material Loop Potential (MLP), and Material End of Life (MEoL), to illustrate the recycling prospects of materials. The recycling prospects are separated into seven scenarios that can describe the material flow of a specific product or material in detail with the information from manufacturers' specifications, German Federal Government statistics, environmental product declarations, etc. This parameter is calculated based on the type of building materials and the actual situation of recycling, which can more intuitively reflect the RP of the building material level. There are also some recycling indicators in other material databases. These parameters generally serve the end of life stage of LCA, and will specify the recyclable mass ratio according to the material recycling status in different countries or regions.

The RP of components is affected by the composition of components and the ease of material separation. Felix Heisel described the process of documenting materials and products utilized in the construction of the Urban Mining and Recycling unit within the Madaster platform. He explored the method of assessing the potential of circularity indicators, the process of which involves the building material/product level and the building element level [26]. Gaochuang Cai et al. proposed a material and component bank to manage more effectively the recycling of materials and direct reuse of components, which combined with the current building information modeling, design for deconstruction, supply chain, and LCA [29]. Lukman A. Akanbi et al. developed a disassembly and deconstruction analytics system, which would ensure that buildings are designed with DFD principles that guarantee efficient materials recovery in mind [30]. D Schwede et al. developed a scientific method for analyzing recyclability in detail that takes joining techniques into account. The ILEK RecyclingGraph Editor described structural element in recycling graphs whose components represent their material elements and connections. To identify the best form of recycling, materials are each classified on a five-level scale based on a system developed by the Austrian Institute for Healthy and Ecological Building [31].

For the RP of buildings, so far, building certification systems tend to rate recycling aspects mostly in terms of quality, especially those related to the environmental impact of material recycling in the end of life stages of LCA [32]. In recent years, the research on material recycling in the early stage of building design has a raised trend. Thormark expressed the RP of a building as the amount of embodied energy and natural resources used in a building that could be made usable through recycling after demolition. Results show that the embodied energy was 40% of the total energy of the building, which can be approximately decreased by about 17% and increased by 6% through the substitution of different materials [9]. In another study, Thormark estimated the energy usage from a building life cycle and concluded that about 37–42% of the embodied energy used in buildings can be recovered using recycling. Additionally, the RP was found to be approximately 15% of the total energy associated with the building's lifetime [8]. Blengini examined the RP of a residential building in Turin, whereby the RP was assessed by 29%, considering the materials embodied in the building shell [10]. Takano et al. have carried out a study to analyze the influence of materials selection on life-cycle energy balance using a case study. It was discussed that selection materials for surface and inner components have a larger effect than others, and the recycling benefits of woods and plastics have large effects on the building's life-cycle energy balance. Condeixa et al. carried out a Material Flow Analysis for the building stock of Rio de Janeiro, where they estimated the building age and the remaining lifetime in order to make assumptions for environmental impact assessments and planning strategies for efficient use of materials [33]. Meliha Honic et al. coupled building catalogues and eco-repositories to digital design tools to evaluate the RP and environmental impact of buildings, and the results are based on element-level calculation, whereby a representative exterior wall is presented. They used the recycling weight parameter in the Eco2soft tool to assess the shares of recycling and waste of material. Results show that RP of the concrete variant is better but leads to more waste, while the variant in timber has a significantly lower impact on the environment [14]. Catherine De Wolf et al. have compared existing methodologies to quantify the global warming potential (GWP) of recycled/recyclable and reused/reusable products. They show that current quantification methods do not address the full spectrum of the reuse practice due to their limited boundaries, and that a number of critical features are currently hardly quantifiable [34]. Furthermore, in the field of building environmental impact assessment, studies considering the integration of building information modeling (BIM) and LCA are increasing. Assima Dauletbek et al. considered the feasibility of using a method of BIM-enabled LCA for the refurbishment in terms of environmental compatibility, energy efficiency, and profitability. The results demonstrate the feasibility of quantitative evaluation of building parameters using the BIM-LCA tool [35]. Baoquan Cheng et al. proposed a building life cycle embodied environmental impacts evaluation approach by integrating BIM and LCA taking a reinforced concrete structure building as a demonstrator. The results showed that the material production stage is the most crucial stage to improve a building's environmental performance [36].

3. Research Methodology

3.1. Level-Based Assessment Scheme

We propose a level-based scheme (Figure 2) to compare the RP of mass timber and concrete buildings, where the building is divided into three levels: the Material-Level, whereby the recycling status is described for one specific layer/material; the Component-Level, which is the sum of all materials' recycling parameters based on the mass ratio; and the Building-Level, which is conducted with the consideration of lifespan and environmental impact. The scheme is based on prior research from Honic Meliha, etc. [14].

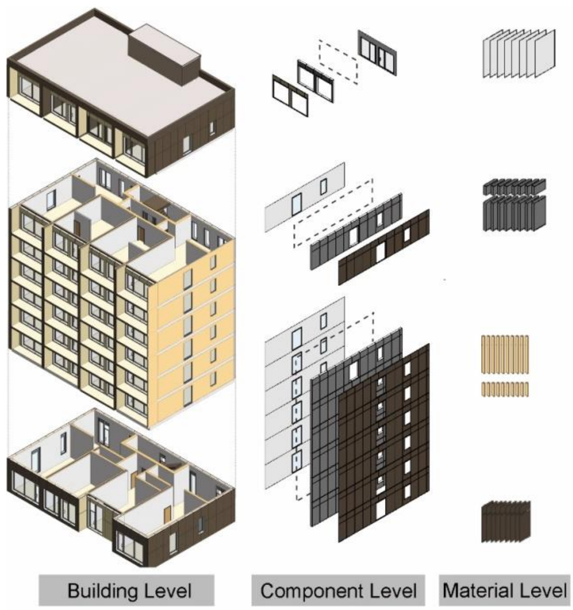


Figure 2. Level-based recycling potential assessment scheme.

The RP at the material level is obtained from the raw data of the material recycling database, which is then filtered and calculated. In order to make informed decisions at the early design stages, we choose the MCS from Universität Wuppertal to conduct the RP calculation. The material cycle parameters include sustainable-certified renewable resources (R_a), renewable resources (R_b), and secondary resources (R_c) in the pre-use phase and the proportion of resources that can realize recycling at an equal quality level (R_d), downcycling within the construction sphere (R_e), and downcycling outside the construction sphere (R_f). Based on the C2C economic model, the proportion of materials that can form a closed-loop material flow through natural circulation or technological circulation is regarded as the RP of the material. Therefore, the RP of materials is defined here as: the sum of the proportion of R_a, R_c, R_d, and R_e (Equation (1)). When the value is greater than or equal to 100%, a closed-loop material flow can be formed. The percentage of waste generated ($W_{material}$) is calculated as shown in Equation (2).

$$R_{material} = R_a + R_c + R_d + R_e \tag{1}$$

$R_{material}$ is the recycling potential of material; R_a is the proportion of sustainable certified renewable resources; R_c is the proportion of secondary resources; R_d is the proportion of recycling materials; and R_e is the proportion of downcycling materials.

$$W_{material} = 1 - R_d - R_e - R_f \tag{2}$$

$W_{material}$ is the recycling potential of material; R_d is the proportion of resources that can realize recycling at equal quality level; R_e is the proportion of downcycling resources within the construction sphere; and R_f is the proportion of downcycling resources outside the construction sphere.

Under the premise of disassembly, the RP of components is composed of the proportion of renewable resources and secondary resources that have been certified as sustainable before use and the proportion of resources that can continue to be used in the construction field after use, namely the mass weighting of the material cycle parameters for each build layer (Equation (3)). The product of the cycle parameter of a material and its mass fraction is defined as the recycling potential contribution of that material. Furthermore, the components such as self-tapping screws, expansion screws, and other connectors, as well as waterproof membranes and breathable membranes, account for a relatively low mass and are not included in the calculation of RP. In order to clarify the quality of waste, the resources that cannot be recycled are regarded as waste. Meanwhile, the detachability of a component is calculated with the ILEK RecyclingGraph.

$$R_{component} = \sum_{i=1}^{n} \frac{M_i}{M_{sum}} \times (R_{ai} + R_{ci} + R_{di} + R_{ei}) \tag{3}$$

$R_{component}$ is the recycling potential of a building component; M_i represents the mass of a material layer. M_{sum} is the total mass of the component. R_{ai}, R_{ci}, R_{di}, and R_{ei} are the cycle parameters of each material (representing the proportion of sustainable certified renewable resources, the proportion of secondary resources, the proportion of recycling materials, and the proportion of downcycling materials).

The RP of the building level involves many factors, not only the material quality and recycling parameters, but also the lifespan of the materials, the detachability of the components, and the environmental impact of the entire life cycle of the building. With the consideration of building lifespan/material lifetime and the environmental impact, the RP of a building is defined as: the building's ability to form an annular material flow, i.e., the proportion of sustainable certified renewable resources and secondary resources in the pre-use phase and the proportion of resources that can realize recycling or downcycling inside the construction sphere in the post-use phase. Starting from the material level, the RP of a building can be regarded as a mass-weighted summation of the RP of all materials in the building's life cycle (Equation (4)). The product of the recycling potential of a material or component and its mass ratio is regarded as the recycling potential contribution of the material. Similar to most RP calculations, calculating the RP of a building from the material level can only be optimized based on the overall replacement of a certain material, which has little guiding role in the early stage of architectural design, and is more suitable for post-design evaluation. In order to more intuitively evaluate and optimize the material selection and component design in the early design stages, this study proposes the building

RP based on the component level, which can be regarded as the sum of the RP of all building components in the building life cycle according to the weighted mass (Equation (5)).

$$R_{building} = \sum_{i=1}^{n} \frac{M_i}{M_{sum}} \times (R_{ai} + R_{ci} + R_{di} + R_{ei}) \quad (4)$$

$R_{building}$ is the recycling potential of a building; M_i represents the total mass of the material at the 100th year. M_{sum} is the total mass of the building at the 100th year. R_{ai}, R_{ci}, R_{di}, and R_{ei} are the cycle parameters of each material.

$$R_{building} = \sum_{i=1}^{n} \frac{M_i}{M_{sum}} \times R_{component\ i} \quad (5)$$

$R_{building}$ is the recycling potential of a building; M_i represents the total mass of the component at the 100th year. M_{sum} is the total mass of the building at the 100th year.

3.2. Variant Study

The methodology for calculating RP was tested by a typical case study, which is a high-rise passive residential building with eight floors and a total construction area of 3000 m^2. The building is a concept design for an existing site in the Nankai District, Tianjin, China, the climate of which is relatively cold in winter and hot in summer. It is a shear wall structure with a standard floor height of 3.2 m. Architectural and structural designs are based on years of team design experience, as well as building catalogues and low-energy residential building design standards, in order to obtain commonly used information such as building structure, plan, and components. The building area, form and height of the two variants are the same, and the thermal performance (U-value) of the component design is as consistent as possible to make the two types of buildings comparable.

Variant CLT is a CLT shear wall structure building that mainly refers to China's design code for medium and high-rise wood structure buildings (GB/T 51226-2017). The loadbearing parts are out of CLT. The construction of building exterior walls, floors, and roofs refers to the common practices of wood structure buildings in the Dataholz database. Due to the limitation of fire protection regulations, rock wool is selected as the thermal insulation material for most building components, and fire-resistant gypsum board is selected as the interior surface material. The other materials are mainly biomass materials (Figure 3a).

(**a**) (**b**)

Figure 3. Two variants of the high-rise passive residential building. (**a**) Variant CLT. (**b**) Variant RC.

Variant RC is an RC shear wall structure building that mainly refers to China's low-energy building design code in cold regions (JGJ 26-2018). The loadbearing parts are made out of reinforced concrete. The structural material of the infill wall is hollow concrete blocks. The construction practices of building exterior walls, floor slabs, and roofs all refer to the common practices in architectural design methods in cold regions of China. Most insulation materials are EPS, and the finishing material is plaster (Figure 3b).

For the material-level, major building materials related to Variant CLT and Variant RC are compared based on pre- and post-use availability, including CLT produced by both certified and uncertified sustainable forests, concrete, and steel. For the component level, the RP is deduced through the prototype design of the component 1 m× 1 m. Variant CLT and Variant RC exterior wall components are used to elaborate the calculation method of the RP potential of the components, and the material composition of the building components is constantly scrutinized in this process. In order to maintain the comparability of the two components, their heat transfer coefficients are both 0.15 W/m^{2}K and the construction thicknesses are kept as consistent as possible. For the building-level, detailed calculations are carried out for the exterior/interior walls, roof, ceilings, and stairs of Variant CLT and Variant RC. Foundations, doors, and windows are not the focus of this study and therefore are not considered.

3.3. Workflow, Data, and Tools

A closed-loop workflow is proposed, which involves five steps, from the variant study, BIM modeling, Eco2soft life cycle carbon emission calculation, MS Excel to integrate material cycle data, RP calculation on the material level and component level, and finally returning to the case study to provide optimization strategies, so as to realize the guiding role of RP calculation in the early design stages (Figure 4). During this process, we considered two lifetimes in total. First, the masses at time 0 year, which is the time when the building is erected, are assessed. Second, we considered time 100 years, where all masses accruing in the life-cycle are summed up. This means that the masses of elements that have to be replaced during the entire life-cycle are included in time 100 years. The GWP was chosen as the indicator of environmental impact. The two variants in Section 3.2 are studied in detail to compare the difference in RP, total waste, and environmental impact of different building structural systems.

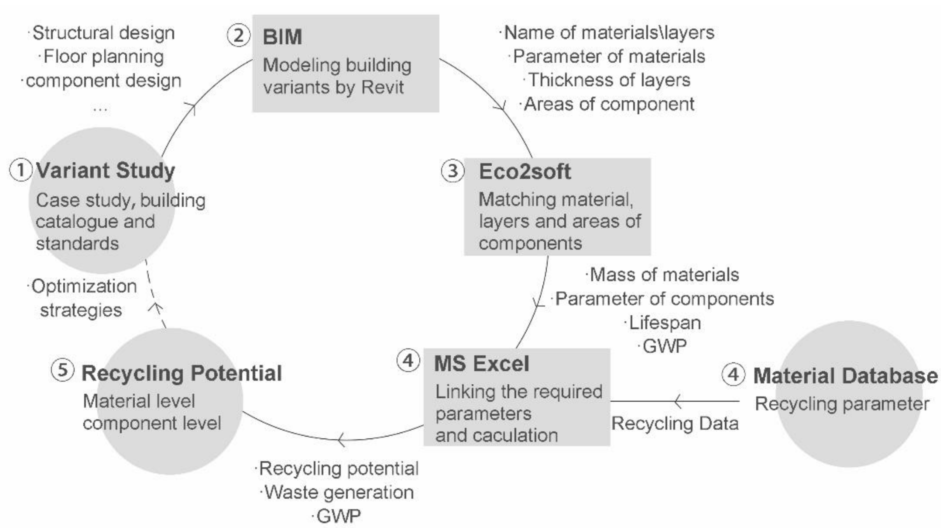


Figure 4. Work flow of data, tools, and method used for comparison study.

The variant study is mainly about the selection and design of the research object, which is described in detail in Section 3.2.

BIM-Model includes the design details and the exact measurements, which can obtain accurate building materials and area information. Therefore, it is used to simulate the material consumption and component area information of the building in the 0th year. Two variants are modeled in BIM-Software (Revit 2019, https://www.autodesk.in/products/revit/overview?term=1-YEAR&tab=subscription, accessed on 26 April 2022; https://knowledge.autodesk.com/zh-hans/support/revit/downloads/caas/downloads/downloads/CHS/

content/autodesk-revit-2019-content.html, accessed on 26 April 2022), and a structural calculation is carried out. In this step, the building components are designed to determine the thickness and the method of the material layer. The building components are named uniformly during the modeling process. After exporting the bill of materials from Revit, we were able to obtain relatively accurate component area information. The component area in this study mainly refers to the area value of the structural layer.

Eco2soft is an LCA tool utilized to carry out basic LCAs for building elements or buildings and considers the three indicators GWP, AP, and PEI. [37]. The goal of this LCA is to introduce LCA as a tool to obtain parameters related to building-level RP calculations (mass at 0 year, mass at 100-year, mass of components, etc.), while obtaining the GWP related to production, transportation, replacement, and recycling in the building life cycle. Specifically, for this case study, the goal of this LCA is to evaluate the environmental impacts of a timber building and a functionally equivalent conventional concrete building in China. Both buildings are 8-story residential buildings with 100-year service life. The functional unit in this study was 1 m^2 of floor area. As the focus of this study is on resource efficiency, only embodied impacts were evaluated. The system boundary for this assessment was cradle to grave and included several modules: A1, raw material extraction; A2, transportation of materials to manufacturing plant; A3, manufacturing and fabrication; A4, transportation to building site; B4, replacement; and C3, waste processing for reuse, recovery, or recycling (Figure 5). The operational impacts were not considered. In order to ensure the comparability of the two variants in terms of embedded impacts, we kept the U-values of all components in the two variants consistent. The data required for the calculation were mainly from the building material benchmarks database in Eco2soft, and the default values in China's standard for building carbon emission calculation (GB/T 51366-2019). Compared with other LCA software, Eco2soft (The software version number: Eco2soft 2022: https://www.baubook.at/eco2soft/?SW=27&lng=2, accessed on 26 April 2022; https://www.baubook.at/eco2soft/?SW=27&lng=2, accessed on 26 April 2022; IBO—Österreichisches Institut für Bauen und Ökologie GmbH, Wien, Austria) is a designer-friendly LCA software. It simplifies the iterative calculation process, and can directly generate LCA results through simple parameter settings, which is very suitable for fast calculation and comparison of GWP values of buildings in the early stage of architectural design. In Eco2soft, it is possible to create multi-layered elements, for example, an outside wall with a facade, a loadbearing layer, and an insulation layer, and set its parameters such as total area, material manufacturer, material life, and so on. Then the user can select the catalog of LCA indicators, service life, study period, disposal indicator, transportation method, transportation distance, recycling method, etc. in the software, and the results of the LCA can be generated. Therefore, according to the material composition, material layer thickness and member area information obtained from the BIM model. We entered the information of exterior/interior walls, roof, ceilings, and stairs in Eco2soft, and set the service life information of building materials according to the material database that comes with the software. After calculation, data such as mass, bulk density, and life cycle carbon emissions of materials, components, and buildings can be obtained.

MS Excel couples material recycling data and information from digital tools and calculates the RP according to the formula in Section 3.1. The final data sheet in MS Excel includes the following input parameters: name of the materials, lifespan [years], thickness [m], density [kg/m^3], material cycle parameters, GWP [$kgCO_2eq./kg$], and the area [m^2], based on which the final results are assessed, which are: substance consumption both at 0 year and at 100 years [kg], recycling potential [%], waste mass at 100 years [kg], and GWP [$kgCO_2/m^2$].

Based on the proposed scheme and the developed method, we obtained the sum of recyclable and waste materials and the environmental impact of each material, element, component, and building, and highlighted the main burdens.

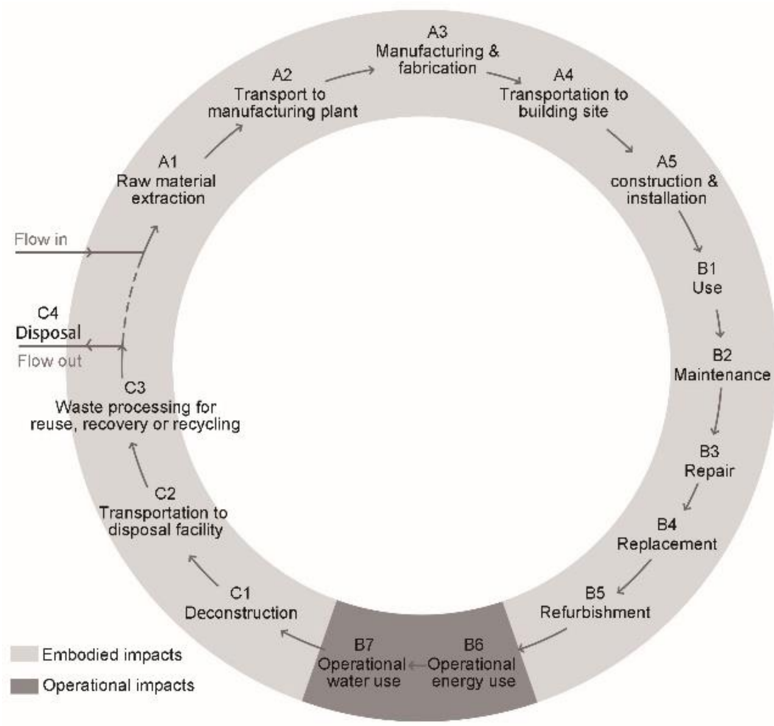


Figure 5. The product system for LCA.

4. Results

4.1. Comparison of Material-Level Recycling Potential

A comparison of material-level RP is between the load-bearing material of Variant CLT and Variant RC (CLT, concrete, and steel). For CLT made from sustainable forests (Figure 6), its glue content is about 1%–3%, and about 98% of the resources before use are renewable resources wood, so the renewable resources before use can reach 98%. After use, about 20% of the CLT can be downgraded and reused to produce building materials such as particleboard and high-density fiberboard, and the rest can be used for incineration power generation treatment (downgraded and reused outside the construction field). Therefore, the final RP of CLT made from sustainable forests is 118% (98% + 20%), which can form a closed-loop material flow. However, for CLT used for structural support materials, the final RP is 20% if the wood is not sustainably certified prior to use. For concrete, it is mainly composed of non-renewable resources such as sand and cement. After use, on average about 40% of the concrete can be used for downgrading and reuse in the construction field such as recycled aggregate and foundation cushion, so the final RP is 40% and a closed-loop material flow cannot be formed. For steel, about 35% of the resources before use are secondary resources, and about 99% of the steel can be reused at the same level after use, so its RP reaches 134% (35% + 99%), forming a closed-loop material flow.

4.2. Comparison of Component-Level Recycling Potential

We summarized the RP of the exterior wall components of Variant CLT and Variant RC with a ring diagram (Figure 7a,b). The heat transfer coefficients of the two exterior walls are both 0.15 W/m^{2}K, the thickness of the wood structure exterior wall is 435 mm, the thickness of the concrete exterior wall is 447 mm, and the surface density of the concrete exterior wall is approximately three times that of the wood structure exterior wall (327.8 kg/m^2, 117.2 kg/m^2). Before being used, the wooden exterior wall has obvious advantages in terms of renewable resources, and the total mass of material consumption is low. After use, the proportion of reuse in the construction field of concrete exterior walls is higher, and the proportion of the waste generated is slightly lower, but the total quality of waste generated is relatively higher. The final RP of the CLT facade component is 81.0%, which is much higher than the concrete component (35.0%).

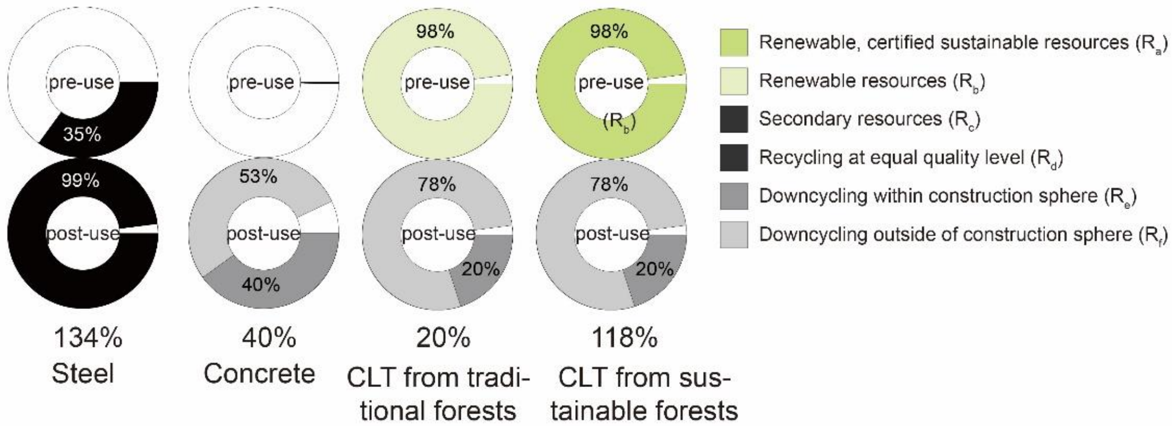
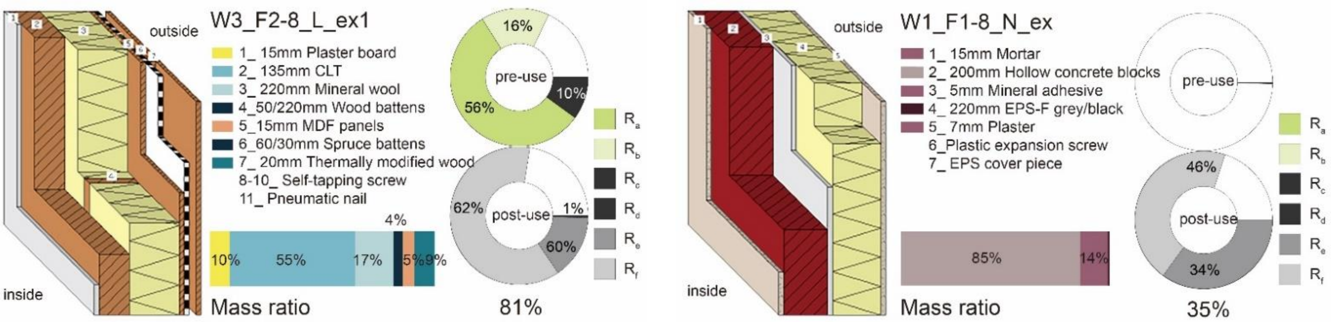


Figure 6. The recycling potential of CLT, concrete, and steel.



(**a**) (**b**)

Figure 7. Comparison of recycling potential and mass ratio of CLT and concrete exterior wall components. (**a**) Recycling potential and mass ratio of CLT exterior wall components. (**b**) Recycling potential and mass ratio of concrete exterior wall components. (calculation process are presented in the supplementary file).

The results show that the final RP of the Variant CLT exterior wall components is 81%, of which the specific data are shown in Table 1. From the mass ratio point of view, it is obvious that the CLT shows the highest need for optimization due to the significantly vast mass, followed by mineral wool and plasterboard. If the component is assumed to be used for 100 years and involves a material update, the mass ratio of these two materials will be higher. The sustainable-certified renewable resources in the components come from CLT and MDF panels, accounting for 56% of the resources, and the secondary resources are mainly from mineral wool produced from slag, accounting for 10% of the resources. After the components are used, the downgraded and reused resources in the construction field are mainly composed of biomass materials, accounting for 15%. More than half of the resources (62%) can be downgraded and reused outside the construction field by incineration and power generation. The proportion of waste is about 22%.

Compared with the variant RC exterior wall components with the same thermal conductivity (Table 2), the RP of concrete components is 35%, and the proportion of concrete mass is high (85.4%), which plays a decisive role in the RP calculation. Among other materials, cement-based materials are used for exterior finishes, bonding, and interior finishes. If the 100-year service life is considered, the mass proportion of this type of material will reach about 30%. Therefore, concrete and various plasters show the highest need for optimization. It hardly contains any secondary or renewable resources in the pre-use stage. After the components are used, they are mainly used for downgrading outside the construction field (46%), and the proportion of waste (20%) is slightly lower than that of mass timber building components (22%). However, the total mass of concrete components is large, and the total amount of waste generated per square meter of elements (≈66 kg/m^2) is more than twice that of mass timber elements (≈26 kg/m^2).

Table 1. Calculation of recycling potential of the CLT exterior wall components.

Component	Material Composition	Density (kg/m^2)	Mass Ratio	R_a *	R_b *	R_c *	R_d *	R_e *	R_f *	Waste	Recycling Potential
CLT Exterior Wall Components	15 mm plasterboard	12.2	10.4%	-	-	2%	5%	-	40%	55%	7%
	135 mm CLT	64.1	54.7%	98%	-	-	-	20%	80%	0%	118%
	220 mm mineral wool	19.6	16.8%	-	-	60%	-	-	-	100%	60%
	50/220 mm wood battens	4.2	3.6%	-	100%	-	-	20%	80%	0%	20%
	15 mm MDF panels	6.0	5.1%	46%	50%	-	-	20%	80%	0%	66%
	50/30 mm wood battens	0.6	0.5%	-	100%	-	-	20%	80%	0%	20%
	20 mm thermally modified wood	10.5	9.0%	-	100%	-	-	20%	80%	0%	20%
Sum		117.2		56%	16%	10%	1%	15%	62%	22%	81.0%

* Source of data: Material cycle status. (calculation process are presented in the supplementary file).

Table 2. Calculation of recycling potential of the assumed concrete exterior wall components.

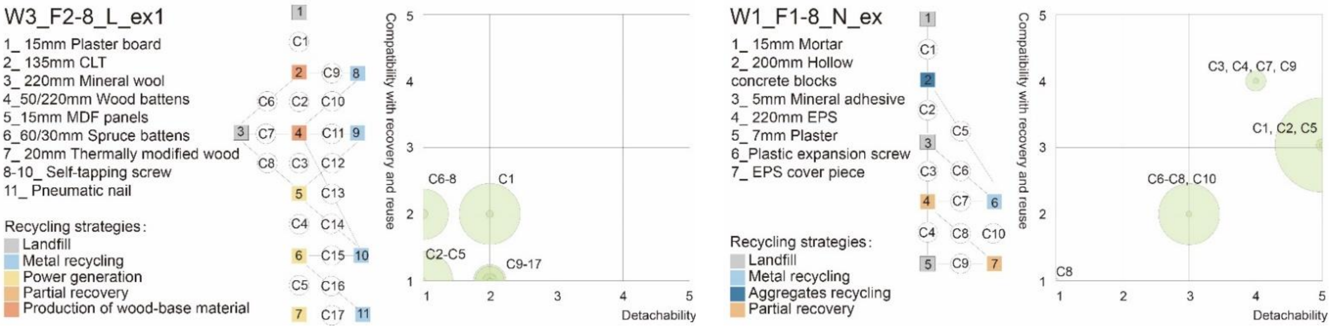
Component	Material Composition	Density (kg/m^2)	Mass Ratio	R_a *	R_b *	R_c *	R_d *	R_e *	R_f *	Waste Ratio	Recycling Potential
Concrete Exterior Wall Components	15 mm mortar	22.5	6.9%	-	-	2%	-	-		100%	2%
	200 mm hollow concrete blocks	280.0	85.4%	-	-	-	-	40%	53%	7%	40%
	5 mm mineral adhesive	9.0	2.7%	-	-	2%	-	-		100%	2%
	220 mm EPS-F	3.7	1.1%	-	-	-	-	27%	66%	7%	27%
	7 mm plaster	12.6	3.8%	-	-	2%	-	-		100%	2%
Sum		327.8		-	-	0%	-	34%	46%	20%	35%

* Source of data: Material cycle status. (calculation process are presented in the supplementary file).

4.3. The Detachiability of Components

The selective separation of materials with the same recycling method from each structural layer is the premise of material recycling. Therefore, the compatibility of co-recycling of adjacent materials and the degree of damage to the material by dismantling are the main factors affecting the material cycle at the component level. Based on the evaluation method of material recyclability proposed by Dirk Schwede of the University of Stuttgart, we further explored and compared the dismantling of the above-mentioned CLT exterior wall and concrete exterior wall.

The material connection method is represented by a wireframe, Cn represents the connection relationship between the materials, and the Cn is graded and evaluated through a coordinate diagram (Figure 8). The horizontal axis represents the impact of dismantling, the vertical axis represents the recycling compatibility of adjacent material, and the size of the coordinate point represents the mass percentage of recycled material. Self-tapping screws, tenon and mortise, and other dry connection methods are mostly used in CLT exterior walls. Although the recycling compatibility between CLT and adjacent thermal insulation materials and fireproof materials (C1, C6) is low, the dismantling has little impact on the material, it is easy to achieve material separation, and the remaining connection materials are highly compatible and can be recycled together (Figure 8a). Concrete exterior walls mostly use wet connection methods such as bonding mortar and plastering, which are more destructive to dismantling. The compatibility of most materials for recycling is low, which may cause problems such as high dismantling costs and mixed materials. The difficulty in material separation for concrete walls is larger (Figure 8b). Therefore, the materials of the CLT exterior wall components are easier to recycle and reuse after use.



(**a**) (**b**)

Figure 8. Comparison of the dismantling level of CLT and concrete exterior façade components (Materials (M1 etc.) are shown as squares, as are joining materials, e.g., dowels. Same colors represent materials that share the same recycling process. Joining principles (C1 etc.), e.g., frictional connections, are immaterial and shown as ellipses. The lower the rating of detachability, the better the parts can be disassembled; the lower the rating, of compatibility the better the parts can be recycled together [38]. (**a**) Dismantling of CLT facade components. (**b**) Dismantling of concrete facade components.

It can be seen that the total amount of material consumed by the CLT exterior wall components with the same thermal performance parameters is small, the required component thickness is small, and it is easy to disassemble. Based on the above analysis, in order to improve the RP of mass timber structures, further optimization strategies can be: (1) Select finishing materials such as metal, dry brick wall, and stone with high RP, and increase the mass proportion of materials with high RP. (2) Use biomass insulation materials such as lignin, wood fiber insulation board, wool felt, etc. to improve the compatibility of recycling between materials. (3) Use dry connections between structural layers, reduce the type and number of connectors, and improve the accessibility and disassembly of the component.

4.4. Comparison of Building-Level Recycling Potential

We first analyze the RP from the material level. For Variant CLT (Table 3), the mass proportion of CLT and fireproof gypsum board in the mass timber building is high, accounting for 51.5% and 27.7% of the total mass respectively, and the RP contribution of CLT is 60.8%, followed by mineral wool (5.5%). The building waste at the end of the life phase is mainly composed of used fireproof plasterboard and mineral wool, which accounts for about 24% of the total material consumption. The proportion of biomass materials in buildings is about 63.3%. Except for wool felt, all other biomass materials can achieve negative carbon emissions and harvest good environmental benefits.

For Variant RC (Table 4), reinforced concrete buildings have the highest proportion of concrete by mass (57.1% + 18.9%). The recycling potential contribution of concrete is 34% (25.9% + 7.6%). The contribution of other materials to the RP is almost negligible, mainly due to the low mass proportion of other materials. The difference between the RP of the reinforced concrete and that of the concrete block is mainly due to the RP of the steel bars in the reinforced concrete. Waste is mainly composed of cement mortar and concrete, which is about 28% of the total material consumption. Of all materials, reinforced concrete has the highest carbon emissions.

Table 3. Recycling potential of the Variant CLT on the material-level.

Material Used in Variant CLT	Lifespan (Years)	Substance Consumption *_ 100th Year (kg)	Mass Ratio	Waste_ 100 Years (kg)	Recycling Potential	Recycling Potential Contribution	GWP * ($kgCO_2$)
CLT	100	565,731	51.5%	0	118%	60.8%	−622,304
Plasterboard	50	304,074	27.7%	167,241	7%	1.9%	47,740
Mineral wool	50	99,996	9.1%	99,996	60%	5.5%	100,996
Thermally modified wood	50	64,622	5.9%	0	20%	1.2%	−106,626
MDF panels	50	51,138	4.7%	0	66%	3.1%	−53,184
Wood battens	100	7369	0.7%	0	20%	0.1%	−7737
Wool insulation felt	50	4760	0.4%	0	0%	0.0%	2556
Sum	-	1,097,690	100%	267,237	73%	-	-

* Source of data: eco2soft software. (result sheets and calculation process are presented in the supplementary file).

Table 4. Potential of the Variant RC on the material-level.

Material Used in Variant RC	Lifespan (Years)	Substance Consumption *_ 100th Year (kg)	Mass Ratio	Waste _ 100th Year (kg)	Recycling Potential	Recycling Potential Contribution	GWP * ($kgCO_2$)
Reinforced concrete	100.0	1,973,996	57.1%	131,329	45%	25.9%	305,969
Concrete block	100.0	653,240	18.9%	45,727	40%	7.6%	62,123
Cement and cement flowing screed	50.0	348,120	10.1%	348,120	2%	0.2%	41,774
Plaster	35.0	283,236	8.2%	283,236	2%	0.2%	50,416
Mortar	35.0	117,597	3.4%	117,597	2%	0.1%	76,556
Mineral adhesive	50.0	30,042	0.9%	30,042	2%	0.0%	10,244
Timber	50.0	22,332	0.6%	0	20%	0.1%	3685
EPS	35.0	29,925	0.9%	2095	27%	0.2%	124,787
Sum	-	3,458,488	100%	958,145	34%	-	-

* Source of data: eco2soft software. (result sheets and calculation process are presented in the supplementary file).

For the component-level, the RP of all components of Variant CLT is relatively high (from 68% to 118%) (Table 5). Among them, the recycling potential of W5, F2, R2, and S1 are the highest, which with fewer structural layers and a relatively high mass proportion of CLT. Furthermore, W3, W6, and F1 account for 67% (16.4% + 16.8% + 34.5%) of the total mass, and the contribution of the RP is about 48% (70% × 15.4%+71% × 16.9% + 72% × 34.4%). However, the RP of W7, W8, and W9 are relatively low, which is due to the mass of fireproof materials and thermal insulation materials being significantly higher than that of other building components. The waste generated by most components after use is between 20% and 30% of the consumables. Among them, W7 has the most complex material composition and the highest proportion of waste (45%). Components W4 and F1, etc., which are composed of single biomass material, do not generate waste after use. In addition, all components can achieve negative carbon emissions and the higher the mass proportion of biomass materials, the better the environmental benefits of the components.

For Variant RC (Table 6), the RP of the components is between 28% and 45%. The mass proportion of concrete can reach about 70% in all components, which plays a leading role in the RP of components. Elements formed entirely of reinforced concrete such as beams, columns, stairs, etc. have the highest RP at 45%. From the perspective of quality ratio and RP, improving the RP of F1, W1, and W3 can effectively improve the overall RP of the building. The waste generated by most components accounts for between 26% and 36% of the resource consumption. After analysis, it was found that the smaller the mass proportion of mortar in the component, the lower the proportion of garbage generated by the component. All components generate relatively high carbon emissions.

Table 5. Recycling potential of the Variant CLT on the component-level.

Type	Component Name	Area * (m^2)	Mass_100th Years (kg/m^2)	Mass Ratio	Waste Ratio	Recycling Potential__100 Years	GWP * ($kgCO_2/m^2$)
Wall	W1_F1_L_ex	212	166	3.2%	30%	72%	−57
	W2_F1_L_in	178	208	3.4%	21%	73%	−117
	W3_F2-8_L_ex1	1035	165	15.6%	32%	69%	−51
	W4_F2-8_L_ex2	219	160	3.2%	0%	90%	−152
	W5_F2-8_L_ex3	77	163	1.1%	24%	72%	−71
	W6_F2-8_L_in	925	199	16.8%	22%	71%	−107
	W7_F1-8_L_in	211	161	3.1%	51%	58%	−30
	W8_ F1-8_N_in	406	157	5.8%	28%	61%	−70
	W9_ F1-8_N_in	303	176	4.9%	25%	67%	−91
Floor	F1_F1-8_in	1715	219	34.3%	23%	72%	−104
	F2_F1-8_ex	190	139	2.4%	0%	102%	−134
Roof	R1	268	185	4.5%	31%	83%	−53
	R2	30	109	0.3%	0%	118%	−118
Stair	S1	538	28	1.4%	0%	118%	−31
Sum						73%	

* Source of data: BIM-modeling and eco2soft software. (result sheets and calculation process are presented in the supplementary file).

Table 6. Recycling potential of the Variant RC on the component-level.

Type	Component Name	Area * (m^2)	Mass_100 Years (kg/m^2)	Mass Ratio	Waste Ratio	Recycling Potential__100 Years	GWP * ($kgCO_2/m^2$)
Wall	W1_F1-8_N_ex	1132	415	13.6%	35%	28%	115
	W2_F1-8_L_in	537	610	9.5%	26%	36%	162
	W3_F1-8_N_in	1201	415	14.4%	37%	28%	51
Floor	F1_F1-8_in	1442	713	29.7%	35%	32%	134
	F2_F1-8_ex	194	550	3.1%	37%	31%	67
Roof	R1	268	705	5.5%	35%	32%	174
	R2	30	536	0.5%	38%	31%	77
Staircase	S1	538	140	2.2%	7%	45%	22
Beam	B1	2142	278	17.2%	7%	45%	43
Column	C1	700	223	4.5%	7%	45%	35
Sum						34%	

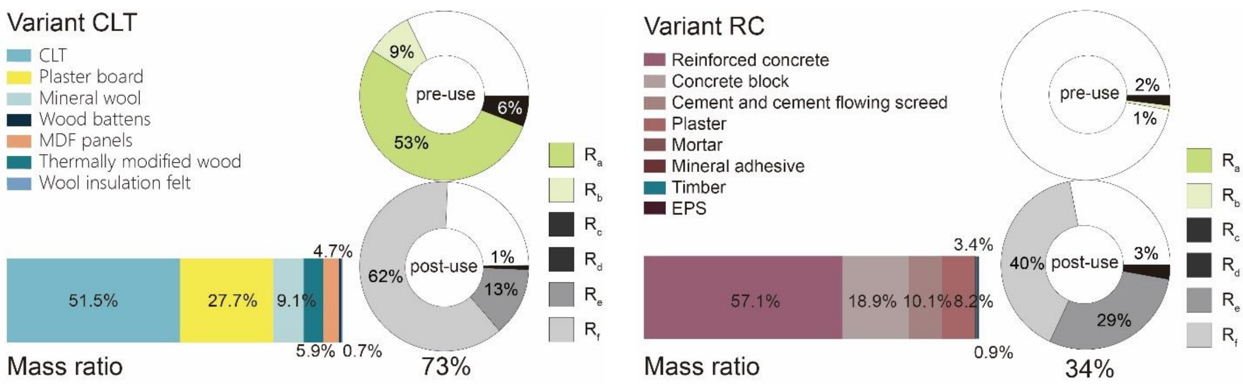
* Source of data: BIM-modeling and eco2soft software. (result sheets and calculation process are presented in the supplementary file).

Comparing Variant CLT and Variant RC, the calculation results of RP at the material level and component level are unified. The RP of the Variant CLT is 73% and the RP of the Variant RC is 34%. Other data such as the initial mass consumption, the mass consumption after 100 years, and the calculation results of the total waste after 100 years are all within 1% and can be ignored. For Variant CLT, the proportion of renewable resources and secondary resources before use is 59% (53% + 6%), while Variant RC has only 2% of secondary resources. The ecological advantages of CLT buildings are obvious. The proportion of recycled resources in the Variant CLT building after use is as low as 14% (13% + 1%). However, more than half of the materials can be downgraded outside the building sector (62%), and about 24% of the materials are converted to waste after the end of the building life cycle. For Variant RC, the proportion of recycling in the building sector is 32% (29% + 3%), which has certain advantages. In the end of life phase, about 28% of the material is converted into waste (Table 7, Figure 9a). The RPs of walls, floors, and roofs in Variant CLT are 69%, 74%, and 85% respectively, which are more than twice the values of the corresponding components in Variant RC. The main reason for limiting the recycling potential of RC buildings is the low recycling potential of concrete (Table 8, Figure 9b).

Table 7. Comparison of parameters related to recycling potential between the Variant RC and Variant CLT and mass timber building from the material level.

	R_a	R_b	R_c	R_d	R_e	R_f	Recycling Potential	Mass_0 Year (kg)	Mass_100 Years (kg)	Waste_100 Years (kg)	GWP_ 100 Years ($kgCO_2/m^2$) *
Variant CLT	53%	9%	6%	1%	13%	62%	73%	837,030	1,097,690	267,237	−174.0
Variant RC	0%	1%	2%	3%	29%	40%	34%	2,972,319	3,458,488	958,145	221.0

* Source of data: eco2soft software. (result sheets and calculation process are presented in the supplementary file).



(**a**) (**b**)

Figure 9. Recycling potential and mass ratio of the Variant CLT and Variant RC. (**a**) Recycling potential and mass ratio of Variant CLT. (**b**) Recycling potential and mass ratio of Variant RC. (calculation process are presented in the supplementary file).

Table 8. Comparison of parameters related to recycling potential between the Variant RC and Variant CLT from the component level.

	Recycling Potential						Recycling Potential	Mass_0 Year (kg)	Mass_100 Years (kg)	Waste_100 Years (kg)	GWP_100 Years ($kgCO_2/m^2$) *
	W1-8	F1-2	R1-2	S1	B1	C1					
Variant CLT	69%	74%	85%	118%	-	-	73%	837,029	1,095,860	269,508	−174.0
Variant RC	30%	31%	32%	45%	45%	45%	34%	2,972,365	3,461,079	959,895	221.0

* Source of data: eco2soft software. (result sheets and calculation process are presented in the supplementary file).

In Variant CLT, CLT accounts for 51.5% of the total mass, followed by fire-resistant materials with 27.7%. Optimizing the recycling potential of these two materials can effectively improve the recycling potential of buildings. The optimization of exterior finishing materials and thermal insulation materials can improve the recycling potential of buildings to a certain extent (Figure 9a). In Variant RC, the proportion of concrete mass is about 76% (57.1% + 18.9%), which plays a leading role in the RP, followed by cement mortar, which is about 23% (10.1% + 8.2% + 3.4% + 0.9%). Changes in the RP of decoration and insulation materials have little effect on the RP of RC buildings (Figure 9b). The resource consumption of Variant CLT in the initial stage is 837,030 kg, which is less than one-third of the resource consumption of Variant RC. It has inherent advantages from the perspective of saving resources. During the 100-year service life, due to the multiple material replacements involved, the total material consumption of the two buildings has increased significantly, but the total material consumption of the Variant CLT in the 100th year is still less than one third of that of the concrete building, which is 1,097,690 kg and 3,458,488 kg, respectively. Although the proportion of waste in the two types of buildings is not significantly different, due to the large total mass of concrete buildings, the total amount of waste generated by Variant RC after 100 years is more than three times that of Variant CLT (Figure 10).

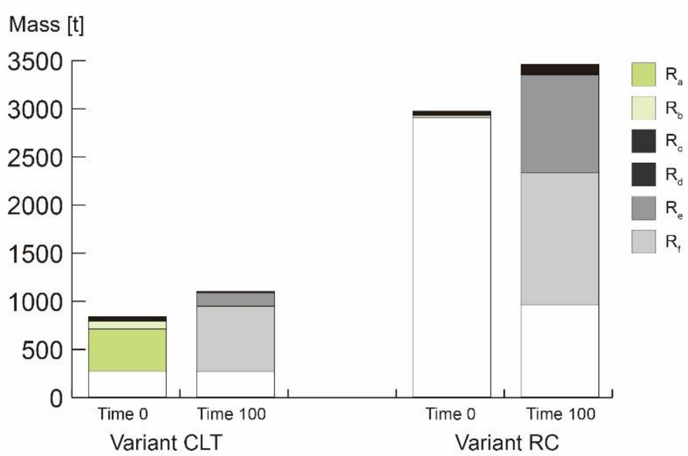


Figure 10. Resource distribution of the Variant CLT and RC.

When we compare the GWP results (Figure 11), it is obvious that the Variant CLT has a lower environmental impact than Variant RC. The GWP even has a negative value in Variant CLT, which is −174.0 $kgCO_2/m^2$, and Variant RC has a GWP of 221.0 $kgCO_2/m^2$.

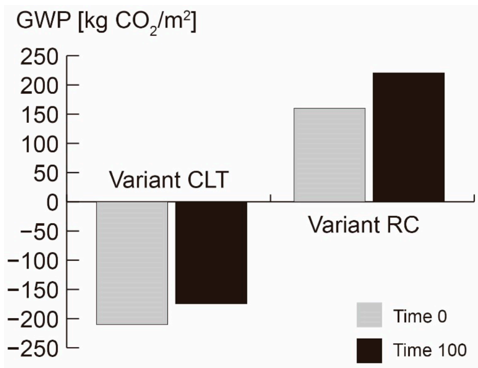


Figure 11. GWP of the Variant CLT and RC.

4.5. Sensitivity Analysis of Potential Parameters Affecting GWP and RP

A sensitivity analysis is conducted to explore the potential impacts of certain parameters on GWP and RP of buildings, such as the building lifespan, material service life, means of transportation, the distance of transportation, end of life scenario, etc. (Table 9).

The results show that building lifespan has an obvious effect on RP and GWP. For Variant CLT, when the building lifespan is 50 years and 100 years, the RP of the building has increased by 15% and 6% respectively. The main reason for the increase is that the proportion of CLT in the total material consumption has increased significantly. It can be seen that the RP and mass ratio of CLT have a greater impact on the PR of Variant CLT. In addition, when the building lifespan is 50 years, a better negative carbon emission effect can be produced. For Variant RC, the effect of lifespan on RP is similar to that of Variant CLT. However, when the lifespan is 150 years, the total carbon emission of the building doubles. For the material service life, reducing the material lifespan of the main materials has a certain impact on the RP of buildings, which mainly depends on the RP of the material. When the RP of the material is high, reducing the service life of the material will help to increase the RP of the building, and vice versa. The results also show that the structural material of the building has a greater impact on the building's RP, which is in line with the previous analysis. However, from an environmental impact point of view, choosing a material with a short lifespan will reduce the environmental benefit of Variant CLT and increase the environmental impact of Variant RC.

Table 9. Sensitivity analysis of the uncertain factors potentially affecting GWP and RP.

		Base Case	Variation	Recycling Potential		GWP_100 Years ($kgCO_2/m^2$) *	
				Variant CLT	Variant RC	Variant CLT	Variant RC
Reference		-	-	73%	34%	−174.0	221.0
Building lifespan		100	50	88%	38%	−212.0	182.0
Building lifespan		100	150	79%	36%	−54.6	410.0
Material service life	Variant CLT	CLT_100	CLT_50	88%	-	−92.3	-
		Mineral insulation panel_50	Mineral insulation panel_35	72%	-	−158.0	-
	Variant RC	Concrete blocks_100	Concrete blocks_50	-	35%	-	241.0
		EPS_35	EPS_25	-	34%	-	243.0
Means of transport	Variant CLT	CLT_Lorry transport	CLT_ocean freight	73%	34%	−174.0	-
	Variant RC	Concrete_Lorry transport	Concrete_Rail transport	73%	34%	-	221.0
Distance of transportation	Variant CLT	500 km	1000 km	73%	34%	−174.0	-
	Variant RC	40 km	500 km	73%	34%	-	221.0
End of life scenario		Recycling	default	0%	0%	−174.0	221.0

* Source of data: eco2soft software. (result sheets and calculation process are presented in the supplementary file).

The means of transport and the distance of transportation do not affect the value of RP, and the impact on GWP can be ignored. If the end of life scenario is set according to the software default value, the RP value is 0, and the GWP is almost unchanged.

5. Discussion

Through the application of the BIM-Eco2soft-MS Excel workflow, the differences in the RP of a mass timber building and a concrete building were assessed from three levels. At the material level, the RP of mass timber produced from sustainable forests is about 118%, which can achieve closed-loop material flow. At the component level, the RP of mass timber building components (81%) is higher than that of concrete components (35%), and with higher optimization potential. Meanwhile, the detachability of wooden building components is better, thus the recycling and reuse of materials can be more effectively guaranteed. At the building level, the RP of Variant CLT is better than that of the Variant RC by 73% and 34% respectively. The total material consumption of mass timber buildings (1,097,690 kg) and the total amount of waste generated (267,237 kg) at 100 years is less than one third of that of the concrete building. On top of that, due to the carbon sequestration properties of biomass materials, the GWP of the mass timber building is $-174.0\ kgCO_2/m^2$, which can achieve negative carbon emissions. In addition, the mass timber building has a higher degree of prefabrication, which is more conducive to the recycling of high-value materials.

From the perspective of a relatively balanced material mass ratio, the RP of Variant CLT has more room for optimization. For instance, improving the RP of CLT and fireproof gypsum board and optimizing the material composition can significantly improve the RP of mass timber buildings. Furthermore, reducing the number of structural layers and types of materials and using biomass insulation materials can effectively reduce the amount of waste, and achieve better environmental benefits.

Evaluating the RP from the material level can obtain analysis results quickly, but its guidance for early stage design decisions is weak. On the other hand, evaluating the RP at the component level is relatively complex. However, specific problems affecting the RP such as material selection or structural node optimization can be carried out in a targeted manner, thereby effectively improving the overall RP of the building. Furthermore, it is possible to combine the detachability analysis with the RP calculation. Future researchers should pay more attention to the evaluation method of RP at the early design stages and explore the RP of buildings from various aspects such as components, detachability, total waste, environmental impact, etc.

In addition, the ease of material separation of the components was studied. It is difficult to directly link the detachability of building components to their recycling potential, and a large number of dismantling experiments may be needed to accumulate the parametric relationship between the recyclability and the recyclable quality of materials. Meanwhile, the actual recycling process is also affected by the cost of dismantling (human and machine labor required, energy expenditure, recovery revenues and waste disposal costs, etc.). Quantitative evaluation of these factors also requires the collection of a large amount of empirical data.

6. Conclusions

The proposed method for grading RP and the BIM-Eco2soft-MS Excel workflow can be directly applied to other building typologies and designs. Differences in material selection and component type in the design do not affect the calculation of RP. However, different construction projects need to pay attention to local climate and building design specifications to obtain building materials and component information, and select the local material cycle database as much as possible for quantitative calculation of RP. Due to the lack of systematic LCA tools in China, in this study, the Eco2soft tool was used for building LCA. The advantage of this software is that it can explore environmental impacts from a designer perspective, but many of the default parameters in the software are more suitable for European buildings, and future research scholars can use more local LCA tools in this step. Most of the material cycle data for this study come from German databases, which are suitable for German national conditions. There is an urgent need to establish a building material recycling database in developing countries such as China, India, Brazil, etc. in order to achieve a construction RP analysis that is more in line with the national conditions of each country. This needs to improve the material recycling and reuse information system through national statistical data, manufacturer information collection, and other channels. Meanwhile, a more local material cycle database can also strengthen the country-specificity of the future research.

From a policy perspective, medium and high-rise mass timber buildings have obvious environmental advantages and are the promising choice for China to achieve carbon neutrality in the construction sector. The government should encourage the construction of demonstration projects of mid-to-high-rise timber buildings, and introduce relevant incentive policies to promote the development of mass timber buildings in China. On the other hand, though China has issued the technical standard for multi-story and high-rise timber buildings (GB/T 51226-2017), the updating of fire protection, earthquake resistance, and other specifications is still relatively slow. Future national policies should appropriately relax restrictions on building heights and improve relevant regulations and norms as soon as possible. The RP of a building can more clearly reflect the material efficiency of the building, which is closely related to the sustainability of the building. It is recommended to add more quantitative evaluations of building detachability and RP to green building evaluation standards in the future to guide the initial decision-making of building design, improve the utilization efficiency of building resources, and provide basic support for realizing the sustainable growth and digestion of urban building resources.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14106174/s1, Figure 7/Figure 9/Tables 1–9: 1-Recycling potential calculation; Tables 3, 5, 7 and 8: 2-CLT_Eco2soft result; Tables 4 and 6–8: 3-RC_Eco2soft result; Table 9: file 6–17 Sensitivity analysis-GWP-xxx.

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