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Improvement of Environmental Sustainability and Circular Economy through Construction Waste Management for Material Reuse

Stefan Schützenhofer [1,*], Iva Kovacic [1], Helmut Rechberger [2] and Stephanie Mack [1]

1 Department of Integrated Planning and Industrial Building, TU Wien, 1040 Vienna, Austria
2 Institute for Water Quality and Resource Management, TU Wien, 1040 Vienna, Austria
* Correspondence: stefan.schuetzenhofer@tuwien.ac.at

Abstract: The Architecture, Engineering, and Construction industries are allocated 40–60% of the worldwide raw material extraction. Construction waste accounts for a significant share of the total waste volume. Therefore, careless handling reduces natural resources and waste deposits (landfills). Furthermore, material reuse and recycling can reduce resource and energy consumption and environmental emissions in some cases. Waste management concepts in the fields of Architecture, Engineering, and Construction are increasingly in the European Union and worldwide focus. A circular economy can be seen as a system in which resource input, waste, emission, and energy leakage are minimised due to closed material loops. Therefore, implementing a consistent Circular Economic requires a holistic approach in which material, emissions, and energy are put into context. This paper aims to analyse dismantling, recovery, and recycling processes and link relevant parameters to assess material sustainability. The technical effort must be made, and the associated costs are compared with the influence of eco-indicators. Furthermore, the data required can be used for the following three areas: Facilitating demolition planning and on-site waste management; resource management at the local/regional/state level; and governmental tax mechanisms.

Keywords: reuse; waste management; circular economy; recycling; CDW; sustainability

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1. Introduction

The built environment is crucial for sustainable development, as the Architecture, Engineering, and Construction (AEC) industry account for 40–50% of CO_2 emissions [1,2], and buildings are responsible for 40% of the total energy consumption European Union (EU)-wide [2]. A total of 5–10% of this energy is spent on the production of building materials and the rest on operation and construction [3]. Worldwide, buildings consume up to 30% to 40% of the primary energy use [4]. Furthermore, 60% of global raw material extractions are attributable to construction activities [5]—other sources say 40–50% [6]. Construction and Demolition Waste (CDW) accounts for about 33% EU-wide [7]. Moreover, raw material demand has tripled from 1970 to 2017 [8]. Therefore, the built environment is jointly responsible for the scarcity of resources due to shrinking or even exhausted sources of raw materials and lack of waste deposits (landfills) due to high waste production. In the future, more focus must be placed on reuse and high-quality recycling, and more value must be placed on existing buildings. In order to manage the reuse of components in the AEC industry, a suggested solution is using Building Information Modelling (BIM) and radio frequency identification (RFID). By linking the RFID chips to BIM elements, knowledge about the material composition can be managed, analysed before deconstruction, and tracked with the help of the RFID chips afterwards and used for mediation [9].

This paper is structured as follows: this section gives an overview of the problem, the research question, and the next an overview of the state of the art and research on waste management, Circular Economy (CE), and digital tools to target this through literature review. The following section examines the methodological approaches of the expert interviews to design an improved deconstruction approach and an actual deconstruction object case study. The Case Study includes Material Passports (MP), Life Cycle Assessment (LCA), cost aspects, and scenario building. Next, the results are presented and discussed further on. In the final section, the conclusions withdrawn from the research are outlined, and further necessary research is indicated. The methodology of this paper employs literature research and a deconstruction case study assisted by expert interviews and MP. The main research questions addressed in this paper are: How can reuse be promoted? What hinders reuse? How does reuse influence deconstruction costs? To answer these questions, the hypotheses (HT) are in Table 1. Hypotheses (HTs) to examine the research questions were formulated and investigated in this paper. The presented research aims to enhance reuse and waste management in the AEC industry and show economic advantages that can arise from this.

Table 1. Hypotheses (HTs) to examine the research questions.

HT1	Downcycling is one of the most significant barriers to high-quality reuse and recycling of recovered materials
HT2	To reuse resources in their quality and thus avoid downcycling, careful material extraction must take place before demolition
HT3	The built environment forms an enormous storehouse of resources that, if used and recycled carefully, can meet much of the material demand required
HT4	The potential for the reuse of buildings depends strongly on the quality of the materials used in constructing a building.
HT5	A significant obstacle to a seamless material cycle is the lack of transparency and broad-based expertise in this emerging industry.

2. Literature Review

Sustainability CE are frequently used buzzwords to be understood as follows. Sustainability is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs [10]. CE is a regenerative system in which resource input and waste, emission, and waste of energy are minimised by slowing, closing, and narrowing material loops by using as little energy as possible, preferably from renewable sources—following the definition given in [11]. Therefore, whether this is ecologically sensible and the costs involved should always be questioned when closing material cycles. Prior research has shown that CE can lead to a reduction of CO_2 for specific materials. Still, in other cases (other materials, another preparation process, or an area of application), an increase in CO_2 emissions is recorded. The fact that CE goes hand in hand with reducing CO_2 is, therefore, not generally valid and must be considered separately for each material cycle [12]. Identifying building construction as the primary contributor to CO_2 emissions of new buildings and designing buildings with reusable construction parts is essential [13]. Recycling and reuse of concrete can reduce the CO_2 impact from 36% up to 59%, compared to landfilling [14].

Documentation with chips is only a solution for new buildings or refurbishments. The building stock of cities needs another solution. Crucial criteria identified to establish CE in the AEC industry: perform adaptive deconstruction, upgrade existing built environment instead of expanding it, provide decision-making tools essential for managing the reuse of built properties, and multi-criteria approaches including costs [15]. Some of those principles are embedded in the waste hierarchy to prevent and reduce the negative impacts caused by the generation and management of waste and improve resource efficiency. The principles in hierarchical order are: prevention → preparing for reuse → recycling → recovery → disposal and are defined in the waste framework directive (WFD) [16]. A step further is the concept of the 10 R's, which can be seen as an extension of the waste hierarchy to establish a comprehensive CE to include refuse, re-design, repair, refurbish, remanufacture, and repurpose [17]. In this context, it should be noted that this paper focuses on a sub-area of CE, namely reuse, recycling, and the reduction of waste that has to be thermally treated or ends up in landfills.

Furthermore, it is this sub-area that is meant when CE is mentioned. The AWG2002 requires material recovery: if this is ecologically reasonable and technically possible and if it does not involve disproportionate costs [18]. Therefore, to holistically assess CE in the AEC industry, data for LCA and expenses are required to push and implement sustainable CE properly. Processing and managing this high amount of data requires powerful digital tools that link information from buildings to building networks to take this from buildings to a higher level, such as cities. This involves defining data structures, data collection, a framework for data processing, and different processing levels. Such levels would be: (a) material level, (b) component level, (c) building level, and (d) city level and in a further step a whole country. This assessment requires networking different technologies and approaches that allow interdisciplinary data exchange. Environmental Product Declaration (EPD), cost structure for End of Life, RFID, BIM for data documentation, MP for material data providing, and GIS at a city level are technologies to support the evaluation and data tcollecting.

At the end of a building's use, it is time for dismantling and demolition. In this phase, waste management and the design of the deconstruction project are essential for the sustainable use of material resources. Furthermore, the inclusion of waste management in the planning process is critical for a holistic approach to enable the potential for reuse, the creation of high-quality products, and the implementation of waste management streams [19]. The EU has made several efforts with regulations and measures to make this sustainable. For example, the WFD [16], the Resource Efficiency in the Building Sector Report (ReR) [3], and the CE principles [20]. The WFD defines the term waste and regulates its handling and treatment. Since 2014, the ReR has provided measures to increase material efficiency, and the CE principles strongly focus on non-destructive disassembly. Apart from the European regulations, there are national regulations. In Austria, for example, the national implementation of the WFD is the waste management law AWG 2002 [18] and the Waste documentation framework [21], which regulates the documentation of wastes. The waste loads to be separated, the handling of these, and the processing and possible fields of application are handled in the Recycling Building Materials Directive [22]. The directive refers to the standard ÖNORM B3151 [23], which thus also has the character of law. Therefore, selective deconstruction is the standard demolition method in Austria. Based on the pollutant and contaminant investigation, a demolition concept is drawn up, which is not updated during the demolition process and has no binding character. According to AWG2002: Recyclable materials need to be recovered if this is ecologically reasonable and technically possible and if it does not involve disproportionate costs. The assessment of this evaluation criterion requires data and information on demolition, processing, and recycling costs and the environmental impacts linked to them.

There are studies on economic, material, and environmental information. Financial data, however, varies by region and is so far less studied [24]. This is also reflected in the existing normative cost structures. There are well-structured costs in the German-speaking countries to calculate and analyse the construction of buildings, ÖNORM B1801-1 [25] and DIN276 [26], and the expenses of deconstruction are also mentioned, but not in a way to assess material loads. Only one position for demolition costs is kept free. For proceeds of possible reuse, there are currently no explicit normative items. Different costs for selective and dismantling tend to be higher than conventional demolition. Transport routes and labour have a decisive influence here. In order to counteract this, the cost structure and methodology for the Andalusian region to estimate demolition costs are presented in [27]. Research from Portugal has shown that levies imposed by waste processors are the essential control mechanisms [24]. Comparing selective deconstruction with conventional demolition leads to the conclusion that deconstruction costs are approximately 17–25% higher [28]. Labour cost (either productivity or hourly rate), disposal cost (tipping fee and transportation), and resale value of deconstructed materials. Dividing the costs of a deconstruction project in Australia into input costs and output benefits and pointing out that selective deconstruction can be profitable [29]. Another study shows the variability over time of disposal and revenues of construction materials/waste, demonstrating that databases must be constantly maintained to assess deconstruction projects and recycling processes [30].

For the reuse of elements and materials, documentation and description are required to reuse components and materials, as it is already performed on platforms such as Harvest Map Austria [31] and Harvest Map Netherlands [32]. These platforms provide materials for reuse, from washbasins to flooring and worn bricks. Madaster is a Swiss building raw materials register that links material passports of the registered objects to a platform, serving as a basis for urban mining processes, showing circular and financial potential and the possibility of component reuse [33]. A big problem with existing buildings is the unknowledge of the material stock. SCI-BIM: aims to increase resource and energy efficiency by coupling different digital technologies and methods for data acquisition and as-built BIM using a gamification approach. The suitability of ground radar for material data acquisition is associated with laser scanning technology for geometry acquisition [34].

Production is attached to disposal in CE. In addition to using less or using materials for longer, another possibility to make material use and the CE more sustainable is a change in the production/processing technology. For example, the identified technology- and production-driven savings potential of up to 50% in CO_2 emissions from cement production in China, in addition to the reduction of energy demand [35]. A similar potential through the recycling of polystyrene is shown in [36]. Comparing the common waste treatment incineration with the feed into a production stream leads to a 47% CO_2 emission reduction. The literature review shows a gap in knowledge of LCA for CDW and a lack of considering CE in every phase of the life cycle, beginning with the design process [37]. Further critics are that the End-of-Life stage is not sufficiently considered in any BIM software [38]. The analysis of different CDW management tools and stakeholders' interviews concluded that they are not BIM-compatible, and data for LCA on CDW is not available [39]. The lack of holistic approaches and data for LCA of CDW is also criticised [40].

Essential for reuse and LCA is the knowledge of the material composition of the stock. BIM can be seen as a method to generate a digital model of buildings, including relevant data throughout the life cycle [41]. A distinction must be made between geometric and non-geometric (alphanumeric) parameters. Geometric parameters control the dimensions of the elements, and alphanumeric parameters assign cost parameters, LCA data, building physics information, etc., to them. A solution to connect physical objects with digital data represents using BIM and RFID [9]. By linking the RFID chips to BIM elements, knowledge about the material composition is created, analysed before deconstruction, and tracked with the help of the RFID chips after deconstruction and used for mediation. Further coupling of blockchain technology can further increase the traceability and transparency of material flows [42].

Anderson et al. observe the assessment of the environmental impacts of CE [12,43]. LCA and EPD are used for this purpose. The findings show the potential to increase and decrease CO2 emissions in both directions. Consistent and complete EPDs (especially module D) are the basis for buildings' LCA to assess the End-of-Life performance. However, modules C and D are not included in all EPDs, which does not allow the comparability and complete consideration of materials over the entire life cycle [44]. Using LCA to assess the impact of recycling and reusing concrete shows a potential to reduce the CO_2 impact from 36% up to 59%, compared to landfilling [14]. The basis for a survey of economic assessment parameters of CDW is presented in [30]. The study examines how much working time must be spent on selective dismantling and what disposal costs and revenues are possible for the individual material loads.

3. Materials and Methods

The employed methodological approach is based on empirical social research, including conducting a comprehensive literature review and expert interviews [45], with a case study methodology using MP, LCA and scenario building to investigate possible improvement potentials on a monetary scale level. The literature review served to analyse best practices in CDW management and CE in the AEC industry, as well as an overview of public regulations and governance. The expert interviews close the knowledge gap of how reuse can be promoted and how it influences the deconstruction process, attains better governance and process knowledge, and forms a supplement to the literature research and basis for the case study scenario building. The case study was used to analyse state-of-the-art deconstruction processes. Figure 1 presents the overview of the research methodology.

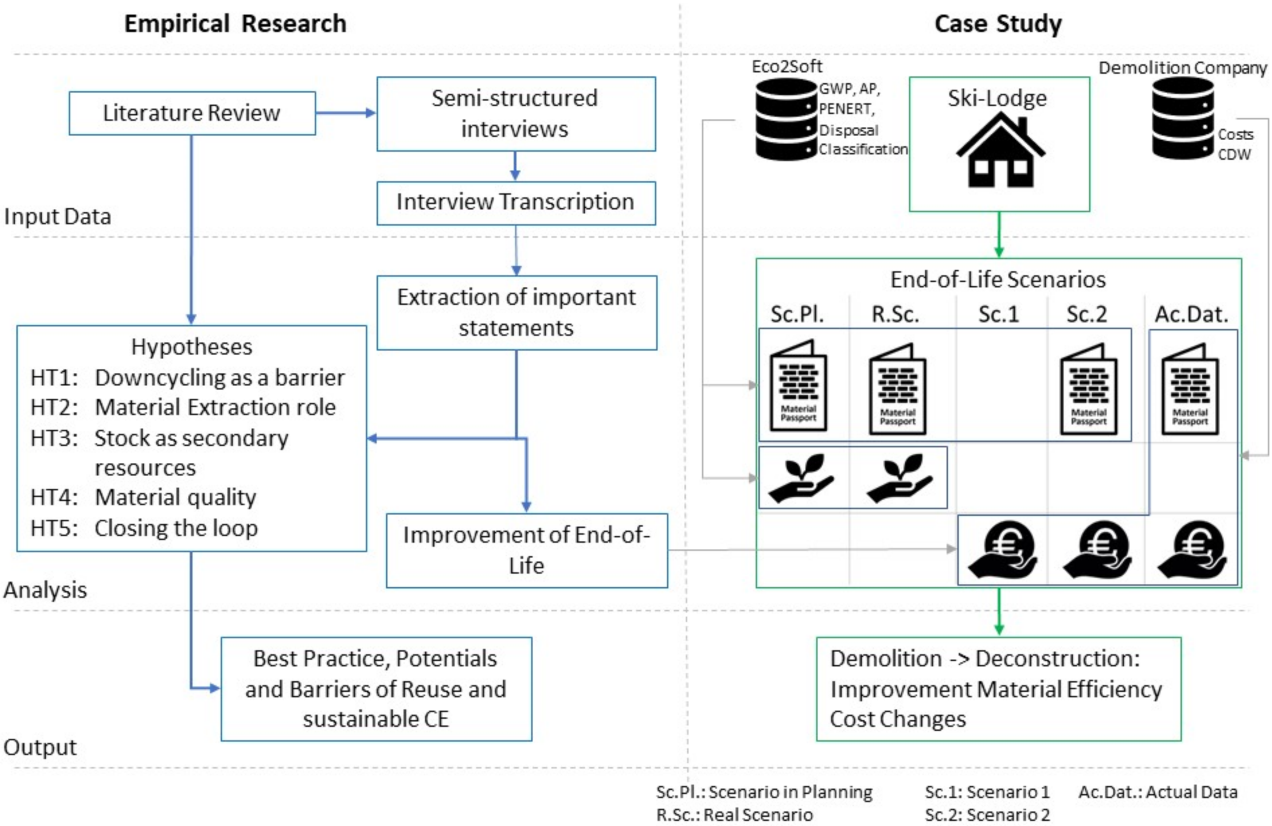

Figure 1. Overview of the research methodology and scope of the paper.

Based on the first literature review findings, the five hypotheses (HT1—Downcycling as a barrier, HT2—Material Extraction role, HT3—Stock as secondary resources, HT4—Material quality, HT5—Closing the loop), presented in Section 1, were formulated. The questionnaire includes questions about general personal and company information and subject-specific questions. An extract of the questionnaire structuring and the contained questions are presented in Table 2. After transcribing the interviews, the expert statements were structured, analysed, and reduced to their core statement. In a further step, they were assigned to the hypotheses. In addition to the hypotheses, the statements concerning the reuse of materials, which are of essential importance for improving the reuse performance of demolition buildings, were also elaborated and identified separately.

It should be noted that the questionnaires were slightly adapted and supplemented depending on the expertise and field of activity. The expert interviews were attended by an employee of a landfill site, a landfill site manager for building and construction waste, an environmental engineer, a managing director of platforms for trading building materials as secondary raw materials, and the CEO of a company specialising in demolition in the sense of CE. The interview evaluation followed the procedure of [46]. For the case study, a real demolition object was used, where the demolition process could be accompanied.

Table 2. Extract of the questionnaire for the expert interviews.

Nr.	Question
1	General personal and company questions
1a	Describe your career history
1b	Describe the field of activity of your company
1c	How advanced do you consider your company to be in the field of waste management?
1d	How do you see the development of waste management in recent years?
1e	Describe the field of activity of your company
2	Operational questions/procedures for the company (company-dependent)
2a	What are reusable materials for you?—According to which principle do you select them?
2b	What criteria do you use to assess whether reuse makes economic sense?—Quality of the products, the working time needed for dismantling, etc.
2c	Who are your primary customers? Both suppliers and buyers.
2d	To what extent do you interact with other companies that buy materials from you for reuse or with whom you have collaborated?
2e	What is the added value for clients in the use of your materials?
2f	How are you remunerated and how do you earn from the concept?

The property is a single-family ski lodge built in 1963 as a planned holiday settlement model house. The house is located at approx. 2000 m above sea level, in the municipality of Afers, near Brixen in South Tyrol, had an indoor cross floor area of 100 m^2. The project was demolished in 2021 and replaced by a new building. The demolition company provided as-built drawings, data on the actual waste masses, and the demolition offer with separately stated disposal costs. The demolition was recorded and used as a reference project to obtain more exact information about the precise demolition process, the communication between the individual stakeholders, and the current recycling potential of construction waste. For this purpose, the type and quantity of construction waste produced during demolition were recorded. The house is seen in Figure 2. The floor plan and section can be seen in Figure 3. A standard demolition method was used, and no attention was paid to reusing materials and components. In advance, as-built plans were analysed, a list of components was drawn up, and the stakeholders, the sub-processes, and the data exchange formats required for this were documented during the demolition process.

Figure 2. Photograph of the ski lodge (Studio Geoplan).

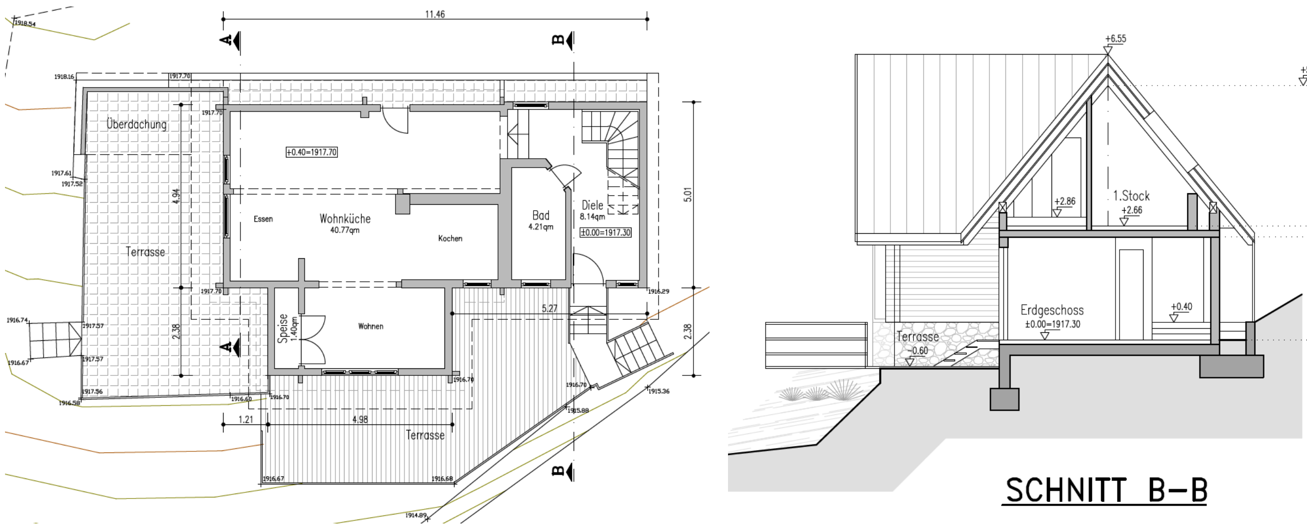

Figure 3. Floor plan and section of the ski lodge (Studio Geoplan).

Based on these documents, different scenarios were considered, that include MP, LCA and costs. Firstly, the scenario in planning: MP and LCA, as it would be accomplished in planning a new building with the expected lifetimes of the individual materials, and an exchange of these was assumed. Secondly, the real scenario: no refurbishment activities were carried out. Therefore, the distinction between "at construction" and "at End-of-Life" is no longer relevant, as the results are identical. The findings of the expert interviews were then used to create scenarios 1 and 2 by replacing materials from the actual disposal routes used in the use case with routes that need better material separation and materials that could be reused and investigating the potential savings. Scenario 1: costs with adapted utilisation ratios due to high-quality separation during the dismantling -> the disposal costs were reduced or even set to zero, but additional demolition costs were added. In the second scenario, a future revenue model was created in which materials are not given to private individuals or manufacturers (free of charge or reduced disposal costs). Still, revenue is achieved that represents a positive material value at End-of-Life. The additional costs for recovery-oriented dismantling are 17–25% higher than conventional demolition costs. For scenario 1, we have set the lower limit, and for scenario 2, the upper limit. In scenario 2, costs for the provision and procurement of materials are added. Unfortunately, no data were found for mediation and storage prices. Additional costs of 10% of the dismantling costs are assumed here, and last, the actual data: The waste documentation and demolition offer of the deconstruction company. An overview of the scenarios and the topics considered can be seen in Figure 4 and Table 3.

The methodology used for the MP and LCA is presented in [47], and based on [48,49]—only the step of calculating a building index is omitted. Here, the Global Warming Potential (GWP), Acidification Potential (AP), and Primary Energy Input non-renewable (PENRT), as well as the accruing waste and recycling masses, are balanced. The parameters required are taken from the Baubook—eco2soft database [50]. It should be noted that the material parameters listed here are available for new building materials, and the use case is a building with the construction year 1963. However, it is the only database found with consistent data of all required parameters, and it is operated and maintained by the same institution that produced the guidelines. Furthermore, we had data on demolition and disposal costs from the company. For scenario 2, it was necessary to identify potential revenues that could be generated by selling the materials for reuse, using already existing brokering platforms such as [31,51]. Those platforms give information about geometry, kind of object, and price.

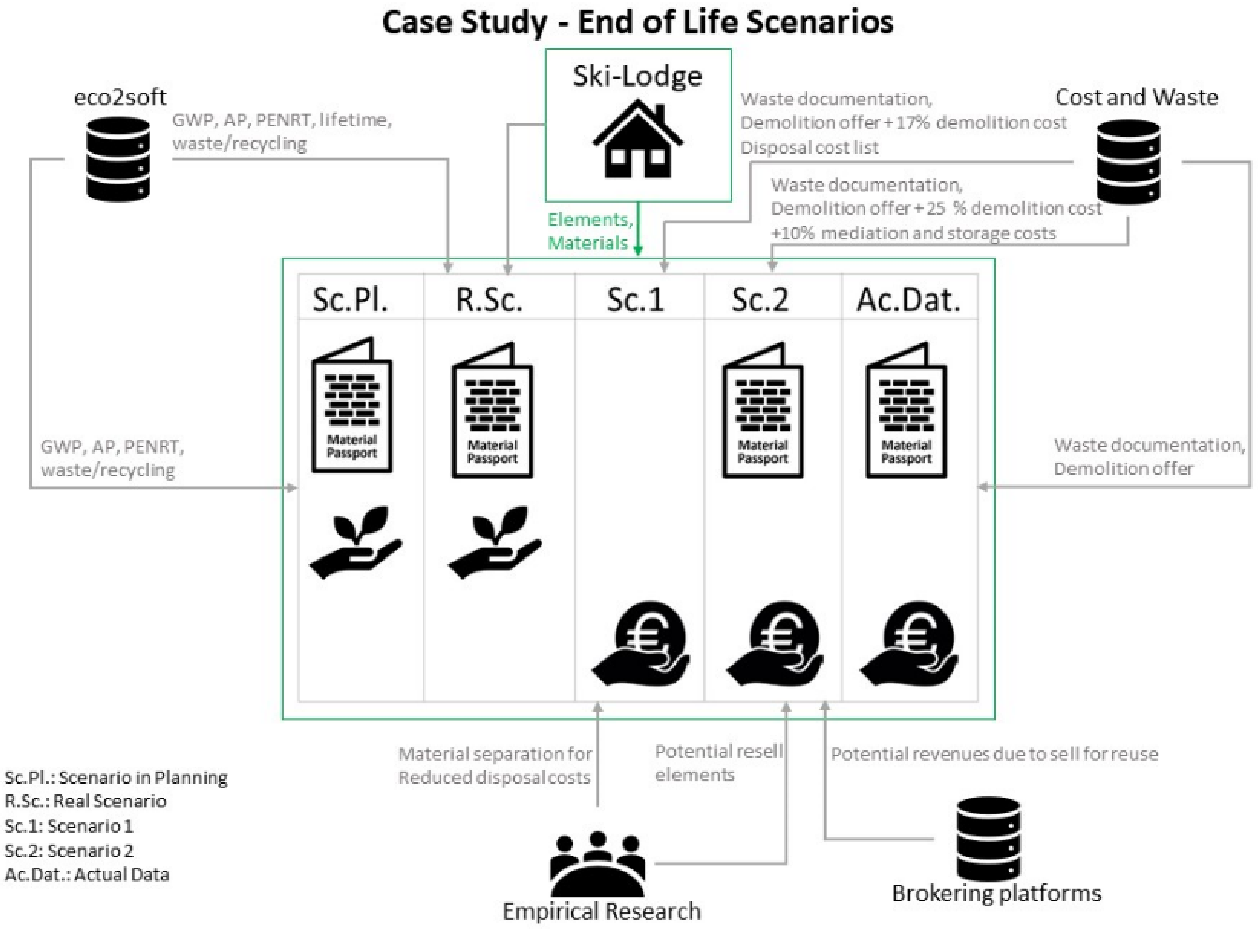

Figure 4. Methodological approach of the Case Study.

Table 3. Overview of the different scenarios, as well as the associated tasks performed.

	Scenario in Planning	Real Scenario	Scenario 1	Scenario 2	Actual Data
MP	According to [47] Framework	According to [47] Framework, but with actual service lives	-	Adapted actual MP scenario, with modified recycling potential for reusable materials	Actual waste balance of the demolition company
LCA	According to [47] Framework	According to [47], but with actual service lives	-	-	-
Cost	-	-	Based on actual waste balance, divided into cleaner fractions, with lower disposal costs	Based on material fraction from MP and cost data from material brokering platforms (private sale or direct transfer to processing companies)	Actual costs

The results of the MP were compared with the data provided by the demolition company. Furthermore, comparisons of the planning scenario and the actual scenario were carried out, both by the MP and the LCA. For 3 scenarios, costs were determined based on the cost statement of the demolition company and a list of disposal costs and compared with each other. This was performed on the one hand for the disposal costs, and on the other hand also, the follow-up costs for higher-value disposal, respectively, recycling and reuse, were estimated. On the one hand, a BIM and, on the other hand, an MP appears to be suitable methods for documenting the material stock.

As this is an old building with as-built plans, the decision was made to generate an MP based on the as-built documents, and the creation of a BIM model was left out. However, BIM seems more appropriate for new buildings and renovation objects for documentation, as digital tools facilitate the computation of material changes.

4. Results

The results presented in this paper can be divided into two areas. First, empirical research presents the results of the expert interviews, knowledge of the current state, improvement, and design of the scenario building in terms of reuse possibilities, as well as recycling possibilities and what needs to be deposited. A second area is the case study, where the results of the MP, LCA, and costs of the different outcomes are presented and show what benefits can be obtained by additional effort in the form of a recycling-oriented deconstruction and promotion of CE at the building's End-of-Life.

4.1. Empirical Research

4.1.1. Hypotheses

HT1—Downcycling as a barrier: It is important that primary raw materials can be replaced 100% by secondary raw materials. The basis of any recycling is a pure material without impurities. For example, plaster mortar residues or gypsum-containing fines, a problem especially when fine-grained concrete recycling fractions are produced, were mentioned. If certain limits are not met, the construction waste must be landfilled. If necessary, it may even have to be deposited in a higher landfill class, which leads to increased costs. Furthermore, it was shown that maintaining the materials' quality is not always the best solution. The example of recycled concrete shows that about 95% of concrete can be recycled. Starting with secondary raw material in cement production, over recycled concrete, up to the use in the construction of road substructures. However, the production of concrete from secondary raw materials is more cost-intensive. The high costs arise from crushing, screening, and analysing. Here, the primary raw material price must be taken into account. A lot is also demanded from the environment during this preparation process. It is, therefore, essential to consider the entire new life cycle. Another example is Styropor, which can be crushed and almost 100% reused as dam material in hollow bricks. However, currently, there is no solution for separating this material by type at the End-of-Life, so disposal is bypassed and postponed to the future. It would be better to process it into new insulation material.

Another problem mentioned is the warranty. It is not as severe for windows as for load-bearing elements since they do not take over static tasks. Therefore, there is no danger of collapse. However, there is an urgent need not only to recycle but to reuse materials of a consistent quality (which seems feasible in the case of windows).

Thus, it can be seen that there are different opinions on this matter. Some see downcycling as quite problematic to advance CE and urban mining, while others work entirely according to the principle of keeping materials in the cycle. Still, the type of use and quality tend to play a subordinate role here. In summary, this underlines that downcycling is an obstacle to the maximum exploitation of urban mining but that reuse, even at a downgraded level, holds enormous added value.

HT2—Material Extraction role: The basic principle is a proper inventory and exploring harmful and disruptive materials. However, there is still great potential to be seen in simple and accurate as-built surveys. In addition, early reconstruction measures are fundamental to make it possible to carefully remove the sorted material, e.g., non-ferrous metals, etc. This would not only bring ecological and environmental benefits but would also reduce the risk of environmental damage. This brings ecological and economic advantages and potentials of socio-economic word creation in the form of social urban mining Early planning with the existing materials allows for the best possible connection of the new building to the material flows obtained from the deconstruction can be planned. In the case of the waste materials generated, there should be no hesitation in carrying out analyses because the cost and effort of such studies can hardly be weighed against the potential for savings, firstly from a cost point of view and secondly from the point of view of reducing emissions.

Another critical factor is considering the project's deconstruction during the planning phase to promote reuse. Cost factors are transport, processing and storage costs.

Furthermore, the development and implementation of dismantling and reuse concepts are decisive for the extent of reuse. Thus, it is reaffirmed that the hypothesis put forward is that based on a well-thought-out and pre-planned recovery-oriented dismantling, the material yield can be maximised, and the reuse can be advanced to the highest mas. Driving factors, costs, and warranty need regulation changes to establish security for all involved. Therefore, business and government must work together and, with research's help, try to pick up and implement innovative concepts.

HT3—Stock as secondary resources: There is more than enough supply of used materials. However, the decisive factor for using these materials is always the price in the end. In the past, more emphasis was placed on reusing and recycling materials. To achieve this again, the producers' longer product lifetimes or product liability from production to disposal, repurchase options for buildings, and take-back obligations for components are inevitable. Technical building equipment poses a particular challenge for reuse. In particular, reuse is of the utmost importance to save resources. Solutions for this include long-term leasing or hot contracts.

Materials such as gypsum, whose natural reserves are limited and now almost exhausted and whose extraction by coal-fired power plants has stopped due to the closure of the plants, also play a decisive role. Gypsum boards can often be circularised if a method is developed to remove the board without harm. Closing material loops 100% will never be feasible. However, the goal should be to keep the lost material as low as possible. This is also shown by further literature research and paring data provided by research projects PILAS [52] and BAWP [53]. A comparison of the arising waste volume and comparable material demand in Austria shows material consumption is about ten times bigger than the potential substitution by generated waste (if we assume 100% reuse and recycling), as shown in Table 4. Therefore, the main solution is a paradigm shift and change in social behaviour. Still, material recycling is an essential first step to creating a future self-sufficient material cycle.

Table 4. Comparison of the annual generation of selected wastes relevant to the construction industry and comparison of current material redemands.

Material	Demand [Mio. t]	CDW [Mio. t]	Difference [Mio. t]
Concrete	23.25	1.35	+21.9
Mixed mineral	7.91	2.50	5.41
Timber	8.62	0.27	8.35
Building site waste	0.38	1.1	−0.72
Steel	0.77	1.69	−0.92

HT4—Material quality: the quality of a building has many dimensions. Since waste prevention is at the beginning of the waste hierarchy, it always makes sense first to consider the possibility of repurposing the existing building. A prefabricated building that appears primitive at first glance, but its modular layout makes it ideal for office space or shared apartment situations. Only then should the component level be considered. Here, he evaluates the reuse possibilities according to three aspects: the design evaluation, the multitude of new products that can be generated from the existing elements, and how costly the preparation of the individual materials is. The quality of the components, e.g., doors, windows, etc., is decisive for their reuse. For recycling and substituting primary raw materials, it can be stated that the type of compounds and the separability or grade purity play an overriding role. Contamination with asbestos, insulating materials, lead, and other pollutants are problematic.

Founder's time houses are the most uncomplicated buildings to dismantle and offer the most straightforward possibilities for reuse due to their pure materials. Building materials such as wood, bricks, steel, and non-ferrous metals are easy to remove and do not have to be separated in a time-consuming process.

Buildings, however, should not be viewed directly in terms of their parts. Instead, the building should be considered a whole model in terms of waste avoidance. Only after the potential for reuse has been exhausted should the consideration extend to the component level. Re-think as a basis for finding new approaches to solutions. Thus, the hypothesis could be confirmed. Furthermore, the qualities of the overall building should also be considered on a higher level.

HT5—Closing the loop: Lack of transparency and insufficient know-how are no longer excuses. Mature know-how about current technological possibilities for processing, reuse, and utilisation, especially in the legislation ranks. This leads to gaps and unfulfillable requirements in the legislation, which no one can realistically implement due to the lack of practical relevance of the bodies acting there. Therefore, much more is needed in terms of public relations and cooperation between different stakeholders, such as business and government institutions.

The hypothesis can, therefore, only be partially proven. However, more clarification is needed for expert knowledge and details, and experts with practical relevance and higher-level goals (such as environmental goals) must be harmonised for the legal framework.

4.1.2. Promoting Circular Economy via Reuse

Asbestos is directly deposited, which is also required by law. Synthetic mineral fibre insulation is suspected of being carcinogenic. Are exclusively landfilled. Mineral wool is a rather tricky material for reuse, but reuse is possible if not exposed to moisture.

Production of chipboard as a recycling option for wood, although painted wood must be thermally removed in special incineration plants.

Construction waste break on fine-grained construction waste for recycling and use in place of accumulation possible. Concrete is the most accessible recycling building material. Mineral construction waste is no problem to recycle. Reuse, however, is difficult due to the cost sensitivity of transport distance. Gypsum, asbestos, and heraclite as contamination of other mineral demolition waste are problematic. Ceramics are problematic as contamination in construction waste. Especially with fine-grained processing. Removal of tiles dependent on adhesive.

Iron back into steel production, reuse often not practised for warranty reasons, steel however optimal for analysis for reuse Scrap market very global, costs are subject to high variations.

Technical building equipment is a challenge/but also opportunity for reuse. Plastic is a rather tricky material to reuse.

4.2. Case Study

As described in Section 2, a distinction is made between the actual and a fictitious planning case when calculating the MPs and LCAs. The building was used for 58 years without any renovation or conversion work. However, suppose an MP is prepared in the earliest planning phase. In that case, a building service life and a service life of the individual components and periodic replacement are assumed. In the given case, a complete refurbishment would have been planned after about 30 years, which never happened. However, the ground floor ceiling is the only element with a service life of 100 years, and the rest of the house would have had to be replaced. Therefore, the two scenarios differ by a factor of about two. The results of the LCA are shown in Table 5. The results of MPs also differ by a factor of two and are only about half as large in the actual scenario compared to the planning scenario.

Comparing the results of the MP actual scenario with those of the waste documentation shown in Table 6 shows that MPs are an excellent tool for estimating waste streams. The difference is only about 1% (~141 t to 143 t), even though the distinction of the individual fractions is higher. The discrepancy can probably be explained because dry, clean mineral wool was assumed for the MP but had increased moisture. Furthermore, there was a significant deviation in the timber masses. However, elements such as solid wooden staircase, interior doors, and windows were not recorded in eco2soft and therefore are excluded from the MP. Doors and windows were not registered in eco2soft and are missing from the mass calculation.

Table 5. LCA of the ski lodge according to the EI3 index.

Component	Real Scenario			Scenario in Planning Stages		
	GWP [t CO_2 eq.]	AP [kg SO_2 eq.]	PENRT [GJ]	GWP [t CO_2 eq.]	AP [kg SO_2 eq.]	PENRT [GJ]
Outer wall	−5.97	24.37	59.24	−11.95	48.74	118.48
Inner wall	−1.47	10.16	22.44	−2.95	20.33	44.88
Roof	15.45	742.53	244.46	30.90	1485.05	488.92
Ground floor	10.96	32.23	98.32	11.13	44.67	125.99
Upper floor	−1.34	5.46	114.40	−2.69	10.92	228.80
Terrace flooring	−0.43	2.87	15.80	−0.85	5.73	31.60
Sum total	17.19	818	555	23.59	1615	1039

Table 6. Waste/recycling material of the ski lodge.

Ski Lodge	MP			Actual
	Waste [kg]	Recycling [kg]	Total [kg]	Actual [kg]
Pure building rubble	-	-	-	17,660.0
Mixed construction waste	-	-	-	15,020.0
Reinforced concrete	58,186.8	58,186.8	116,373.6	75,490.0
Timber	8030.4	5945.8	13,976.2	30,790.0
Rock wool	-	2633.5	2633.5	3950.0
Metal	6510.8	2170.3	8681.1	-
Sum total	72,728	68,936	141,664	142,910

It should be noted that only the masses are collected for the waste documentation, but for the MP, there is also an estimate of which materials can be recycled. Unfortunately, there is no knowledge of what happens to the waste loads after the recycling centers and operators of the processing plants have taken over the waste. Therefore, no concrete data on the recycling masses and material to be landfilled and disposed of is available. The assessment of the increase in material efficiency is based on the MP actual scenario, compared with scenario two. Through mediation on brokering platforms and reuse, the recycling rate from 49 to 94% can be increased, as shown in Figure 5.

In a further step, costs are assigned to the materials based on the demolition company's cost statement, and a cost-saving is estimated by reusing and passing on the resulting materials. This estimation is based on expert interviews and internet research of existing mediation platforms [31,54]. Cost calculation of the actual scenario with the disposal costs divided according to the various materials incurred. The actual costs amount to a total of 12,390 EUR pure disposal costs. The wage costs are neglected because it is easier to compare with the second scenario. Based on the quantity list, prices and masses are adjusted according to the scenario and the cost list provided by the demolition company. Since the outer wall and the roof are not reused, they are not included in the masses for reuse and are omitted from the accruing masses for sale. As repeatedly emphasised by the experts, reusing rock wool is very difficult, to almost impossible.

No alternative is found for this either, and the material remains an expense for the masses to dispose of. This reduces the original disposal costs of 12,390 EUR to 3544 EUR, as shown in Table 7. Scenario two, with the reuse of the materials and sale via brokerage platforms, even results in a positive material value of 12,878 EUR. Since chipboard is already cheap when new, there is hardly any value left for used material. For the present calculation, 50 per cent of the new price is used. There is also the option of selling the chipboard as sawdust. Still, a fee of 1 EUR per ton is significantly lower than the value calculated here and, therefore, only serves disposal without reuse character. For glulam, the offers vary. Therefore, a medium value was used.

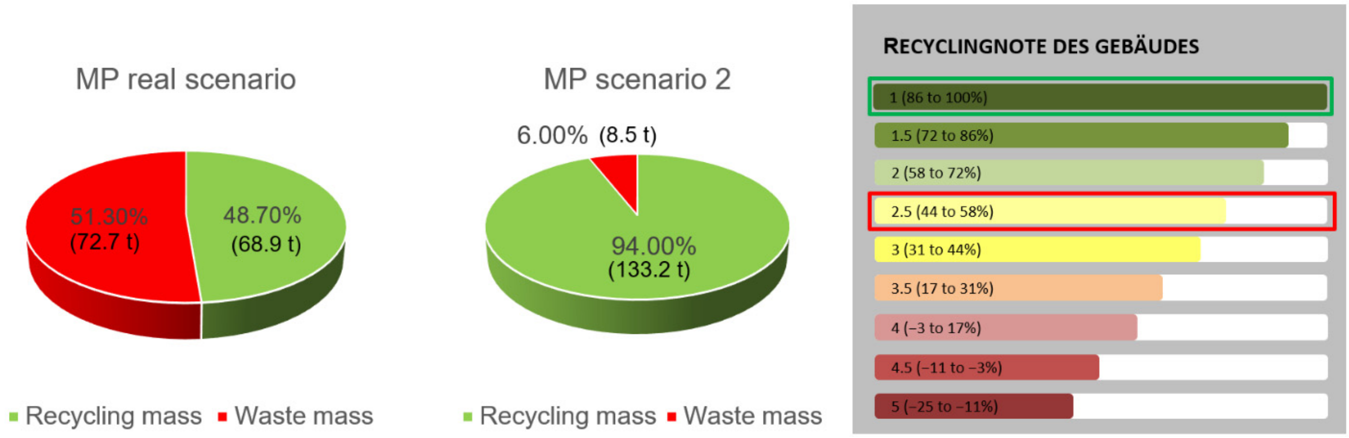

Figure 5. Comparison of different processes and improvement of material efficiency through reuse and high-quality recycling.

Table 7. Actual disposal costs and revenues of future scenarios.

	Material	Mass [t]	Units [m^2]	[m^2/Qty]	Quantity	Costs/Unit	Cost/Revenue
Scenario 2	Chipboard	3.08	139.5	1.36	102	1.5 EUR/Qty	154 EUR
	Glulam	3.20	120.6	0.72	167	10.0 EUR/Qty	1675 EUR
	Parquet flooring	1.08	120.6			5.0 EUR/m^2	603 EUR
	Oak planks	0.65	54.5	0.24	227	30.0 EUR/Qty	6813 EUR
	Copper	8.68	97.5			83.3 EUR/m^2	8125 EUR
	Roof truss						1111 EUR
	Timber	5.97				243.0 EUR/t	1450 EUR
	Rockwool	3.95				462.0 EUR/t	1825 EUR
	Reinforced concrete	116.37				20.0 EUR/t	2327 EUR
	Total						12,878 EUR
Scenario 1	Timber	30.34				- EUR/t	- EUR
	Rock wool	3.95				462.0 EUR/t	1216 EUR
	Reinforced concrete	116.37				20.0 EUR/t	2327 EUR
	Total						3544 EUR
Actual scenario	Contaminated rubble	17.66				16.7	295 EUR
	Pure rubble	15.02				92.4	1388 EUR
	Reinforced concrete	75.49				20.0	1510 EUR
	Timber	30.34				243.0	7373 EUR
	Rock wool	3.95				462.0	1825 EUR
	Total						12,390 EUR

With the dimensions 4.5 m × 0.16 m, thus 0.72 m^2 per unit price of 10 EUR leads to an approximate payoff of 1675 EUR for the present 120 m^2. The Tarkett parquet flooring can be easily removed and resold at the cost of 17 EUR/m^2. For the terrace flooring, the second-highest profit can be achieved. As the experts said, much money can be earned, especially with non-ferrous metals. A significant point is the mineral CDW. Here, the mass to be disposed of cannot be reduced, but the disposal costs can be significantly reduced through the single-variety collection. For example, contaminated construction waste can be reduced from 92 EUR/t to 20 EUR/t.

An increase in costs due to increased effort is also considered to consider aspects other than disposal costs. The demolition offer was 22.922 EUR, without tax. Adding 20% VAT, this is 27.590 EUR. Assuming that the same machinery is used under a recycling-oriented demolition, the same site equipment is available, the earthworks do not change, and the water conservation remains the same. The costs can be broken down into 15,200 EUR demolition costs and 12,390 EUR disposal costs. If these demolition costs are increased by 17% for scenario one and by 25% for scenario two to take into account the additional costs for deconstruction, the deconstruction costs amount to 17,784 EUR and 19,000 EUR, respectively. Including disposal costs, the total costs amount to 21.328 EUR for scenario one to 6.122 EUR for scenario two. Since the object mediation and storage must still be considered, costs of 10% of the dismantling are again estimated for this. Thus, the total dismantling costs of scenario two rise to 7.642 EUR. In the given case, an economic advantage can be seen. If the building is considered a mine, no profit can be achieved, but the deconstruction costs can be reduced significantly.

5. Discussion

The expert interviews showed different opinions on the topics. There is no consensus among the individual experts on all topics. However, economic aspects should be considered, as this is the driving factor for profit-oriented companies. Almost all experts noted that the reuse and recycling of all materials are possible. Above all, it is crucial that the material is sorted by type and is present in as pure a state as possible. If transport, processing, and reuse result in high costs, the secondary raw material is not competitive and thus difficult to establish on the market. Furthermore, external costs (e.g., CO_2) must also be considered. From a governance point of view, this should be investigated and implemented as a steering instrument. Essential is knowledge about costs for reuse and recycling and the comparison to primary raw materials, and for a holistic approach, the ecological aspects and environmental impacts, such as emissions, energy demand, and material efficiency. It was noticeable that during the interviews, deconstruction and demolition were used synonymously (as already mentioned, also in the ÖNORM no separation as in research, as well as the term reuse and recycling was mixed in some places).

Looking at the numbers of material demand and potential substitution with secondary material, we need measures that hook higher up in the 10 Rs of the CE principles or at the top of the waste hierarchy. Therefore, the primary solution is a paradigm shift and change in social behaviour, but material reuse and recycling is an essential first step to creating a self-sufficient material cycle in the future that hooks higher up in the 10 Rs of the CE principles, or at the top of the waste hierarchy. Furthermore, we can learn a lot from past practices, as reuse was practised, and the separability of less complex construction methods of the past is easier to separate. Transportation is a major problem, so a comprehensive logistics network is needed to enable communication between demolition projects and new buildings and to integrate released material flows into a construction project early.

The case study showed by comparing the LCA and MP results of the planning scenario with the actual scenario, environmental impacts and material demand are almost twice as large in the planning scenario. Evaluating the environmental impact and material consumption are excellent and essential planning tools to compare variants or as an optimisation tool [47]. However, it has been shown that the actual values can deviate considerably, so a subsequent balancing at the building's End-of-Life makes sense. However, this requires documentation of the renovation and conversion work carried out.

Comparing the actual MP scenario with the actual waste balance shows that the creation of an MP based on plan documents of existing buildings can be a proven means to estimate masses. The difference between total estimated waste and real waste masses was about 1%. By improving the MP method for existing buildings by supplementing the as-built plans with building surveys and on-site sampling as a basis, the differences between the individual material fractions can be improved. The interviews showed that a good data basis, a well-prepared pollutant, contaminant survey, and material knowledge are essential for a recycling-oriented deconstruction. MP as a basis, supplemented by waste management aspects for the End-of-Life phase, appears to be a good tool.

Through the mediation on brokering platforms and reuse, the recycling rate from 49 to 94% can be increased. For a complete analysis, it would also be interesting to know which costs are incurred, whether new business models such as social urban mining are needed to carry out the manual work in deconstruction projects, and which influences environmental impacts. For this purpose, a monitoring and assessment tool is required, illuminating these interrelationships and can be seen as an implementation of the AWG2002 [18] requirement for material recovery.

The actual disposal costs amounted to 12.400 EUR. By the sort-pure separation and partial passing on to processing enterprises, an improvement to 3.500 EUR disposal costs would be possible (scenario one). In the case of damage-free removal, provision of component information and mediation to third parties, and passing on all possible materials and components, the disposal costs could be eliminated, and even a profit could be achieved.

The extension of pure disposal cost consideration by the cost increase in a change from demolition to dismantling resulted in a price reduction in total, for scenario two even significant. However, some uncertainties occur, such as whether all elements and materials can be removed without damage and conveyed for the estimated proceeds or not, or the actual costs for storage and conveyance. The offer includes namely not only costs for the demolition but also the new construction, coordination services, dewatering and earthworks. Even if these services are listed separately, it cannot be excluded that, for example, machines needed for the demolition are partially integrated into the new construction costs, etc. Furthermore, it must be noted that it is a small vacation single-family house and, therefore, in no way representative of a large multi-storey residential building can be. However, the additional workload incurred makes perfect sense from an economic point of view by creating new jobs [3,55].

What both the interviews and the case study suggest, it can be concluded that there is a need for efforts on the part of execution, planning, state institutions, material producing companies, as well as research to develop innovative concepts, as is also emphasised in [17]. This concept is called Network Governance.

6. Conclusions

As shown, implementing CE in the AEC industry can save material resources and, in some cases, reduce environmentally relevant emissions and create economic benefits. Collecting cost parameters that allow for separation by type during dismantling and the addition of disposal and revenue co-components and embedding in an MP makes a consideration of costs, LCA, and material consideration possible. However, particularly in LCA, some questions arise regarding how to deal with reuse. For example, where to draw the system boundaries, how many cycles to be applied for balancing, the valuable lifetime per cycle, etc. A standardised, clearly defined approach must be used to answer these questions to make the results comparable and transparent.

Furthermore, including waste management in the planning process is essential for a holistic approach to enable the potential for reuse and creation of high-quality products and implement waste management systems. The economic effects of optimising waste management on regions and individual real estate must be investigated, and decision-making aids and planning guidelines must be developed. Of course, the increased dismantling and transport costs and possible storage and logistics costs must be considered. In order to assess this and take it into account transparently, a cost structure must be created that systematically covers dismantling projects, and, in a further step, cost parameters must be collected. It would be conceivable to analyse existing offers and tenders to derive such a standard and determine a cost range of the different cost groups in cooperation with demolition companies. However, by creating new business models and jobs, an approach to reuse, reprocessing, and increasing recycling makes perfect sense from a macroeconomic point of view because it can create new workers and thus increase employment. Therefore, it should be implemented in practice. To use digital progress and support this process, technologies such as RFID and BIM are suitable for linking to intermediary platforms.

They should be tested during pilot projects and developed for practical use. It is crucial to consider who produces data, who has it, and who manages it. For example, blockchain technology is suitable for creating and managing digital information ecosystems and can be considered further technological support.

From the point of view of disposal costs, as well as from the point of view of resource management, reuse and recycling-oriented dismantling are clearly to be aimed at. From a holistic perspective, however, the associated effects must be considered.

Therefore, the next steps in further research should include data collection in the fields of further deconstruction and planning costs, LCA for CDW processing (frequently, EPDs of the type cradle-to-work gate are available, and therefore only consider the groups A1–A3. Therefore, no conclusions can be drawn about the performance at the end of the service life), possibilities to promote mediation of used materials, and an assessment that links and contextualises cost LCA and material efficiency. The EU (and the world) is calling for both a Sustainable Construction Industry and the development and promotion of sustainable business models in the wake of the new Green Deal and Taxonomy Regulation. Thus, now is the right time to address this issue.

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Abbreviations

AEC	Architecture, Engineering, and Construction
AP	Acidification Potential
AWG2002	Waste Management Law 2002
BAWP	Austrian national waste management plan
BIM	Building Information Modelling
CDW	Construction and Demolition Waste
CE	Circular Economy
CEO	Chief Executive Officer
CO_2	Carbon Dioxide
DIN276	German code for cost planning
e.g.	example given
EPD	Environmental Product Declarations
EU	European Union
GIS	Geoinformation System
GWP	Global Warming Potential
HT	Hypothesis
LCA	Life Cycle Assessment
MP	Material Passports

ÖNORM B1801-1	Austrian code for cost and time planning
ÖNORM B3151	Austrian code for building demolition
PENRT	Primary Energy Input non-renewable
ReR	Resource Efficiency in the Building Sector Report
RFID	Radio Frequency Identification
VAT	Value Added Tax
WFD	Waste Framework Directive

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