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Expert system for building disassembly potential evaluation and inspection

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A R T I C L E I N F O

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A B S T R A C T

In architectural and construction practices, there is a need for decision support systems that include disassembly evaluations in the early design and deconstruction stages of buildings. Despite the growth of simulation programs over the past decade, there is a lack of ready-to-use applications for evaluating the deconstruction potential of buildings. Furthermore, most available tools focus on analyzing the environmental performance of a building while ignoring the technical issues of connection disassembly. In this study, an expert system was developed to classify the connections in demountable buildings and applied to case studies of newly constructed circular buildings to evaluate their disassembly potential. Disassembly criteria and barriers were identified by reviewing the literature. The fieldwork included the observation of more than 2500 connection systems in these circular buildings via standardized inspections. A statistical analysis of the disassembly barriers observed during these inspections was conducted, and their ability to dismantle the most probable connections was evaluated. The interpretation of these data allowed the creation of an inventory of measures to be implemented to ensure the ease and quality of disassembly, helping the practicing engineer and the disassembly team in their practice. This proposed expert system is considered the first step toward a thorough understanding of the impact of design on the disassembly criteria of and barriers to circularity. Its further development will contribute to the accurate forecasting of the disassembly potential of buildings and material recoverability.

Abbreviations:

BAMA	Buildings As Material Banks	DPBc&s	Disassembly Potential of the building's core and shell
BIM	Building Information Modelling	DPcpn	Disassembly Potential of the Composition of Element
BPS	Building Performance Simulation	DPCn	Disassembly Potential of the Connection
C&D	Construction and Demolition	DPcn	Disassembly Potential of the Connection of Element

(*continued on next page*)

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CAn	Connection Accessibility of Element	ECI	Environmental Cost Indicator
CDW	Construction and demolition waste	EU	European Union
CE	Circular Economy	FCRBE	Facilitating the circulation of reclaimed building elements in Northwestern Europe
CLT	Cross-Laminated timber	GDPR	General Data Protection Regulation
CTn	Connection Type of Element	GPEn	Geometry of Product Edge of element
DBn	Disassembly Barriers	HELEN	Holistic design of taller timber buildings
DfD	Design for Disassembly	IDn	Independency of Element
DfD&A	Design for Disassembly and Adaptability	LCA	Life Cycle Assessment
DfF	Design for Flexibility	MFA	Material Flow Analysis
DfR	Design for Reuse/Recycling	PDEs	Potential Ductile Elements
DIC	Disassembly Index of the Connection	SBD	Sustainable Building Design lab
DMP	Data Management Plan	SUS	System Usability Scale
DPBc	Disassembly Potential of the building's core		
DPBs	Disassembly Potential of the building's shell		
DPBc/s	Disassembly Potential of the building's core or shell		

1. Introduction

The construction sector consumes 40 % of raw materials [1] and generates 50 % of waste worldwide [2] owing to the decades-old linear economic model of "take–make–dispose." Circular economy (CE) has evolved as a new strategy for creative practices to attain sustainable economic development in response to issues such as resource shortages, environmental crises, and other challenges [3]. Disassembly potential is defined as "the ability of a building's structure to be selectively taken apart with the intention of reusing and up-cycling some (or all) of its constituent parts" [4,5]. Therefore, "design for deconstruction" is being developed in response to the need to reduce waste and move toward CE [6].

However, little consideration has been given to design for deconstruction owing to the lack of supporting tools and technical knowledge. Although there is an increasing awareness of building deconstruction [7], the problem of quantifying their disassembly potential remains in the literature [8]. In addition, it is generally believed that the lifespan of a building may not be significantly longer [9]. It is estimated that less than 1 % of building materials have been reused after demolition and their first application [10]. The literature on the circularity gap indicates a high uncertainty associated with the evaluation of the disassembly potential of buildings [8, 11]. Without measuring the disassembly potential of buildings and incorporating science into standards, such as the standardization in evaluating circular constructions [12] conducted by CEN/TC350 [13], practitioners will not be able to overcome cradle-to-grave construction practices (an extensive literature review on the methods and tools used to evaluate the disassembly potential of buildings is presented in Section 2).

The latest draft requirements of the European Union (EU) taxonomy for circularity [14], which is set to become effective in late 2024, state that at least 90 % (by weight) of the nonhazardous construction and demolition waste must be prepared for reuse or recycling [15]. Furthermore, construction designs and techniques must support circularity by incorporating the concepts of design for disassembly (DfD) and adaptability. The benefits of building deconstruction outweigh the costs if the value of building components is preserved after the end-of-life and reused [2]. The Ellen MacArthur Foundation [16] identified three important principles of a CE, all of which are driven by design: elimination of waste and pollution, circulation of products and materials, and renewal of nature through the enhancement of natural resources. However, it remains unclear which CE principle is related to building design [17]. The European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship, and SMEs [18] conducted a study to try to answer

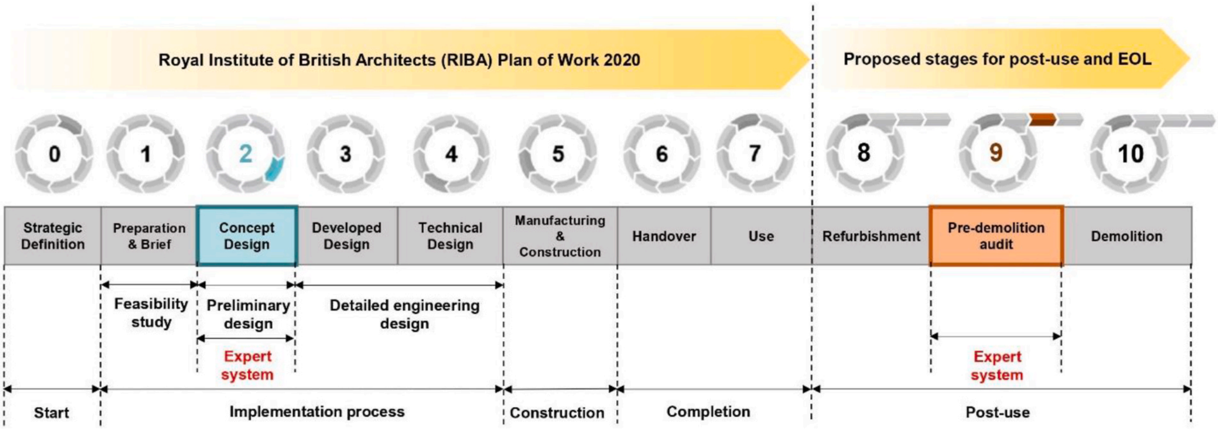


Fig. 1. Use of the expert system according to a design process inspired by the RIBA Plan of Work 2020 with post-use and end-of-life stages.

this important question.

Therefore, in this study, an expert system was developed to evaluate the disassembly potential of buildings. Furthermore, an audit sheet of the connections was established, listing their anomalies and the most probable causes. An expert system is a decision-support method represented by rules to solve complex problems by reasoning through bodies of knowledge [19]. The expert system is part of the DeConstruct [20] Project developed in collaboration with Liege University, Colruyt Group, and COST Action Circular-B on Implementation of Circular Economy in the Built Environment. An expert system is intended to be used during two life stages of a building: first, during the early design stage to improve the disassembly potential of the new construction design and, second, during the pre-demolition stage of a building's lifespan to assess its disassembly potential to recover existing building components and products for reuse (see Fig. 1). The beneficiaries of the expert system are architects, building engineers, insurance companies, and demolition contractors. In this study, the pathological characterization of structural connections was performed using this expert system. This expert system was applied to two case study projects representing circularity-inspired buildings to evaluate their disassembly potential. Based on the above discussion, this study aims to answer three main research questions.

i. How to evaluate the disassembly potential of a building?
ii. To what extent the design of a building is circular and reusable?
iii. What is the effect of design on the disassembly ability?

As an added value, the developed expert system is a starting point for the development of a widely used tool to evaluate the disassembly potential of buildings.

2. Literature review

Herein, previous studies that attempted to classify connections and determine the criteria to evaluate the disassembly potential of a building were investigated. More than 180 papers were reviewed and filtered in a previous study by Attia and Al-Obaidy (2024) as part of the expert system development in this study [8].

2.1. Connection disassembly inspection systems

The construction industry has the potential to support the principles of CE, including eco-friendly technologies, as this aids in the use of waste materials generated during production processes to reduce construction costs and preserve embodied energy [21]. Abdul Nasir et al. [22] argued for integrating CE ideals into the theory and practice of supply chain management, citing a case study that showed the benefits of adopting CE principles over linear systems, including reductions in emissions such as carbon and nitrogen oxides. Although the concept of CE is not new [23], it gained more attention after the EU's July 2014 communication on a "Zero Waste Program for Europe" emphasized the need for its adoption [24].

According to various European studies and projects, efforts have been made to create circularity indicators for assessing the environmental impact of building materials [25], and life cycle assessment (LCA) has influenced these approaches [26]. However, new groups of scientists have sought to broaden the methods used to define circularity and extend the reuse of building materials [25–28]. For example, research projects aimed at enabling a systemic shift in the building sector have been conducted, and one such project is the "Buildings As Material Banks" project [29]. This project focused on developing and integrating tools, such as material passports and reversible building designs [30,31]. The Flemish Public Waste Agency has also implemented the "Design for Change" project, which involves a consortium of Flemish institutions that published guidance documents promoting adaptability [32] and design principles for closed material loops in the building sector [33]. One of the project reports [34] provided a comprehensive overview of the technical lifespan of building construction components and reviewed more than 70 references, including the Ecology of Building Materials book [35]. The project also published 24 technical design leaflets on change-oriented building design [36]. In this project, nine disassembly criteria for circular buildings have been recommended, along with suggestions for developing a policy and transition framework [37].

One of the main problems with the LCA standards, including EN 15804-A2 and EN 15978, is the assumption regarding the number of replacements in buildings [38]. The standards ignore the influence of such replacements on the surroundings of interdependent building sections. Thus, it fails to reflect the potential advantages of DfD [39]. In light of this limitation, Vandervaeren et al. (2022) [39] presented a method for predicting the fluxes of building parts triggered by building deconstruction, both during the operation and end-of-life stages. This modeling technique considers the structural stability, accessibility, and utilization of detachable connections. It provides a time-based bottom-up material flow analysis of the entire building that can be combined with the LCA. The results of this method were compared with those obtained using EN 15978, and nine design variations were considered. The projected life cycle environmental effect using this method was up to 162 % greater than that predicted using EN 15978 for a pavilion with non-detachable connections, demonstrating the relevance of this design parameter.

The reference details are highly suitable for showing how products can be dismantled at the end of a building's lifespan; therefore, the Dutch private standardization organization ISSO [40] is developing a method to provide insights into the detachability of construction details and nodes. The standard reference details [40] offer parties who design, implement, and supervise a practical handle for excellent and sound construction as well as compliance with the minimum legal building regulations for partition constructions. Similarly, Kroll et al. (1996) [41] suggested a spreadsheet to measure the ease of disassembly. A few design factors, such as accessibility, location, force, time, and unique features of each component of the device, were subjectively evaluated, with scores ranging from 1 (easy) to 4 (difficult).

In addition, the Belgian Building Research Institute developed a deconstruction protocol [42] to organize the deconstruction process in Brussels [43]. This protocol is part of the FCRBE project, which aims to facilitate the circulation of reclaimed building components in Northwestern Europe [44]. This protocol consists of five phases occurring successively: (1) completion of the deconstruction inventory (before construction), (2) drafting the call for tenders (before construction), (3) drafting the demolition waste management plan (before construction), (4) execution and monitoring of the demolition (during construction), and (5) reporting (at the end of construction). This protocol covers all activities related to a total or partial deconstruction (renovation), from the preparation for deconstruction to the reporting of deconstruction activities. However, it does not cover the transport and waste treatment/recovery links or the production of new construction products. This protocol aims to obtain clean (inert) waste streams to be recycled into high-quality recycled aggregates.

Another study [45] discussed the design and use of a pre-demolition mapping tool to assess and promote construction and demolition waste recycling. In their study, the use of three-dimensional (3D) scanning and building information modeling was discussed in the form of case studies to estimate the type and quantity of waste generated during building demolition. Disassembly using digital tools has become very important for inventory support, material recovery strategies, and disassembly planning; therefore, Durmisevic et al. [46] developed a conceptual digital deconstruction tool to support decision-making and facilitate a CE. While the construction industry has made significant strides in developing Design for Disassembly (DfD) methodologies, valuable insights can be drawn from the manufacturing sector, which has long-established practices in disassembly, remanufacturing, and repurposing. Recent studies in manufacturing have focused on quantifying disassembly capacity through standardized metrics, such as disassembly time, ease of separation, and material recovery rates, which could be adapted to evaluate construction-specific connection types like bolts, adhesives, and interlocking mechanisms [47]. Additionally, the manufacturing industry has leveraged modular designs and standardized interfaces to enhance scalability and efficiency, principles that could be integrated into construction practices to improve DfD outcomes [48,49]. Techniques such as Product Lifecycle Management (PLM) and disassembly sequencing algorithms, widely used in manufacturing, offer the potential for adaptation to address construction-specific challenges, such as the complexity of building systems and the variability of material flows [50].

Over time, pre-demolition and deconstruction audits have gained great importance and have become mandatory in some countries

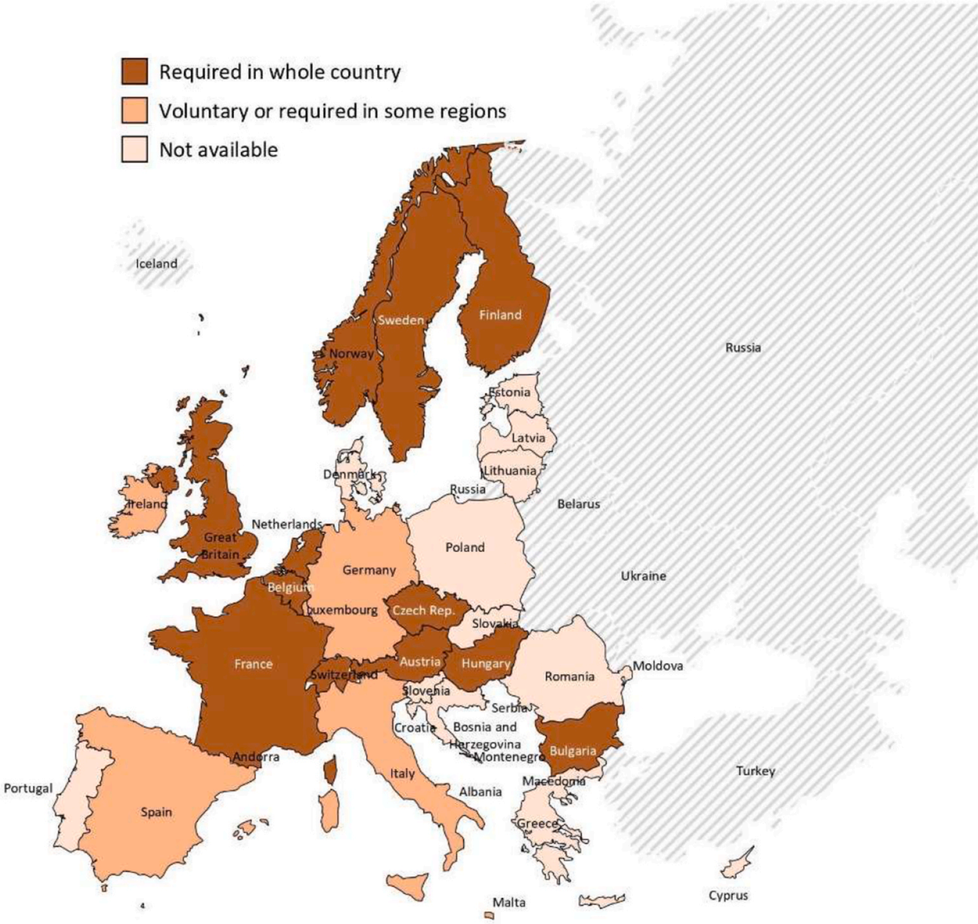


Fig. 2. Use of pre-demolition audits in the EU based on a literature review.

of the EU [51,52], as shown in Fig. 2, and this was updated by the authors based on 2023 data [8]. Pre-demolition or deconstruction audits consist of preparatory actions to collect information about the quality and quantity of building materials that will be produced during the deconstruction process [52]. This can help identify reusable and recyclable materials that are assessed based on the specific details of quality, quantity, and accessibility. This enormous number of tools is one of the reasons why establishing a unique standard is difficult, as disassembly evaluation is still dependent on the expertise of the expert performing the demolition audit and assessing the disassembly potential of a building.

2.2. Disassembly classification and criteria

According to Smeyers et al. (2023) [10], less than 1 % of all existing buildings can be completely dismantled and their materials can be reused after demolition and their first application. Researchers and practitioners have recently begun to focus on the design criteria to increase the disassembly potential of building components. Consequently, it is critical to design for flexibility, adaptability (DfAD), disassembly (DfD), and reuse/recycling to replace single components or materials without compromising other parts or layers.

Currently, there is no globally recognized standard for quantitatively evaluating the disassembly potential of buildings [8]. Researchers have proposed various methodologies and criteria [47,53]. For example, Akinade et al. (2017) [2] identified 15 determinants

Table 1
Disassembly criteria and their associated scores. Adapted from "Transformable Building Structures" by Durmisevic, E. (2006) [56] and the Dutch Green Building Council and Alba Concepts (2021) [54].

ID	Criteria	Sub criteria	Score
CT	**Connection type**		
D.c	**Dry Connection**		
D.c1		Loose (no fastening material)	1.0
D.c2		Click connection	1.0
D.c3		Velcro connection	1.0
D.c4		Magnetic connection	1.0
C.e	**Connection with added elements**		
C.e1		Bolt and nut connection	0.8
C.e2		Spring connection	0.8
C.e3		Corner connections	0.8
C.e4		Screw connection	0.8
C.e5		Connections with added connection elements	0.8
D.i	**Direct integral connection**		
D.i1		Pin connection	0.6
D.i2		Nail connection	0.6
S.c	**Soft chemical connection**		
S.c1		Caulking connection	0.2
S.c2		Foam connection (PUR)	0.2
H.c	**Hard chemical connection**		
H.c1		Adhesive connection	0.1
H.c2		Dump connection	0.1
H.c3		Weld connection	0.1
H.c4		Cementitious connection	0.1
H.c5		Chemical anchors	0.1
H.c6		Hard chemical connection	0.1
CA	**Connection accessibility**		
C.a	**Connection accessibility**		
C.a1		Freely accessible without additional actions	1.0
C.a2		Accessible with additional actions that do not cause damage	0.8
C.a3		Accessible with additional actions with fully repairable damage	0.6
C.a4		Accessible with additional actions with partially repairable damage	0.4
C.a5		Not accessible — irreparable damage to the product or surrounding products	0.1
ID	**Independency**		
I.d	**Independency**		
I.d1		No independency — modular zoning of products or elements from different layers.	1.0
I.d2		Occasional independency of products or elements from different layers.	0.4
I.d3		Full integration of products or elements from different layers.	0.1
GPE	**Geometry of the product edge**		
G.b	**Geometry of the product edge**		
G.b1		Open — no obstacle to the (interim) removal of products or elements.	1.0
G.b2		Overlapping — partial obstruction to the (interim) removal of products or elements.	0.4
G.b3		Closed — complete obstruction to the (interim) removal of products or elements.	0.1

of DfD that were aggregated into three main groups: material-related, design-related, and site worker–related factors. They identified 38 key DfD components using expert focus groups, which were classified into five categories: (1) strict regulation and policy, (2) deconstruction design process and competencies, (3) design for material recovery, (4) design for material reuse, and (5) design for building flexibility. Guy and Ciarimboli (2008) [54] described 10 essential DfD principles, and Moffatt and Russell (2001) [55] developed eight DfAD concepts: durability, adaptability, service access, redundancy, simplicity, upgradability, independence, and building information.

According to Durmisevic (2018) [31], design for deconstruction is described by three domains: (1) the functional domain is concerned with functional decomposition and separating functions into different materials; (2) technical decomposition is concerned with the hierarchical organization of construction materials as well as linkages and hierarchical interconnections between material layers; and (3) the physical domain is concerned with the interfaces that determine the physical integrity and dependencies of a building structure. As determined in a previous study [56], the weights of the seven DfD criteria are (1) functional decomposition, (2) lifecycle coordination, (3) relational pattern, (4) systematization, (5) assembly, (6) geometry, and (7) connections. Furthermore, Attia and Al-Obaidy (2021) considered the type of connection and the time of disassembly as important criteria to evaluate the disassembly potential of a building [17].

A study by the Dutch Green Building Council and Alba Concepts [57] determined four technical criteria for disassembly along with their weight factors, all of which are related to the design and determination of the physical ability to disassemble components. Each category consists of several subcategories with a certain score, where 1.00 represents the highest score and 0.10 is the lowest score. Components or products can be connected to multiple elements. To ensure that the determination of the disassembly potential does not become an unnecessarily complex calculation, it is necessary to delineate which connection is decisive in determining the disassembly potential. Table 1 presents the four technical criteria that have been proposed with associated categorical values, that is, the “fuzzy variables,” to determine the disassembly potential of buildings: (1) connection type, (2) connection accessibility, (3) crossing, and (4) form containment. This is in line with the results of a previous study in which the most important factors were identified using a survey of 122 respondents.

Research on the mechanical performance and geometric potential of joinery connections in timber buildings is scarce. Therefore, a

Table 2
Main and sub-barriers of disassembly in the construction sector based on the reported barriers in the literature and the most common barriers according to the SBD Lab database.

ID	Barriers	Sub-barriers	Score
B.d	**Design barriers**		
1B.d		Design errors	0.1
2B.d		Incompatible, omitted, or unsuitable choice of materials	0.1
3B.d		Incorrect design of the connections	0.1
4B.d		Areas inaccessible to disassembly	0.1
5B.d		Deficient care in detailing connections	0.1
6B.d		Defects in peripheral elements	0.1
7B.d		Excessive deformations	0.1
E.e	**Execution errors**		
E.e1		Use of non-prescribed and/or incompatible materials	0.08
E.e2		Application in extreme environmental conditions	0.08
E.e3		Disregard of the connection’s default lifespan	0.08
E.e4		Use of misplaced connections	0.08
E.e5		Incomplete contact between the elements	0.08
E.e6		Joints of an insufficient width or depth/missing joints	0.08
E.e7		Metal accessories unprotected in the connections	0.08
E.e8		Lack of maintenance	0.08
A.a	**Accidental actions**		
A.a1		Vandalism	0.06
A.a2		Stress concentration on the connections	0.06
A.a3		Deformation	0.06
A.a4		Fire and burnt connections	0.06
E.a	**Environmental actions**		
E.a1		Damp within connections	0.04
E.a2		Mold within connections	0.04
E.a3		Water leakage inside the connections	0.04
E.a4		Biological action	0.04
E.a5		Air pollution	0.04
M.i	**Management issues**		
M.i1		Rules or standards to organize the construction of reused materials or elements	0.02
M.i2		Limited demand for reusing materials in the construction market	0.02
M.i3		Deconstruction time compared with mechanical demolition	0.02
M.i4		Deconstruction costs compared with mechanical demolition	0.02
M.i5		Deconstruction contractual issues	0.02
M.i6		Manufacturers’ lack of interest and responsibility in reducing waste	0.02

study was conducted to develop a performance-driven design framework for the geometry of joinery connections [58]. In timber buildings, connections have a significant effect on the overall structural performance. Connections are considered potential ductile elements (PDEs) that significantly contribute to the overall ductility in the case of overloading [59]. Connections must be designed as "fuses" to avoid brittle failure, which causes the building to progressively collapse [60]. Therefore, a previous study [59] focused on the design principles of timber connections for ductility, with a particular emphasis on laterally loaded dowel-type fasteners. Timber connections are critical components of timber construction because they not only join or connect members but also affect the load capacity, stiffness, and construction ductility of the overall system.

2.3. Classification of the probable barriers to disassembly

The design process is the primary impediment to disassembly [61–63]. Buildings are designed and constructed without considering the end of life or the procedure for recovering their components and elements. Srour et al. (2010) emphasized the importance of design for deconstruction and stated that designers should be on the front lines to ensure that salvaged materials are reused [62].

There are no rules or standards for organizing the construction of reused materials or components [64,65]. Conversely, the expansion of DfD has a direct impact on the prospective improvement of standards and regulations in this sector. Building standards and regulations began to address the difficulties associated with the application of such materials through government and public involvement [66].

Material reuse is one of the most difficult challenges [24] that can be overcome as more designers start adopting DfD methods and using new techniques. Another important barrier to deconstruction is time [54,67,68]. Compared with mechanical demolition, the time required for disassembly can be three to eight times longer [14]. Deconstruction may not be a practical alternative to demolition when time is a critical factor.

Deconstruction may also be hampered by costs [54,67,68]. There is a widespread misconception that deconstruction is more expensive than demolition or disposal. However, research has revealed that this is not always the case [9,54,62,68]. Costs are influenced by variables such as material storage before the final destination; local and regional market and demand for used materials; higher labor costs; higher costs with workers' insurance; hazardous material removal; training expenses; material conditions; debris transportation; and landfill fees. Therefore, certain components can help save money.

Another important barrier to deconstruction is the contractual issue. Normally, demolition contracts do not require the reuse or recycling of materials. However, terms can also be incorporated to address and encourage these practices [66]. More time and planning are required to improve the contract, and one of the most important barriers to overcome is the lack of interest and accountability of manufacturers in reducing waste [66,67,69]. Therefore, members of the Sustainable Products Purchasers Coalition [70] used their technical expertise to persuade companies to include life cycle analysis data in their products [69]. Table 2 summarizes the probable barriers to disassembly identified in the literature and during demolition missions.

Finally, the literature review indicated a knowledge gap related to the quantification of the disassembly potential of buildings during the early design and pre-demolition stages. None of the investigated studies combined connection disassembly criteria with connection disassembly barriers to assess the disassembly potential of newly designed or existing buildings. Therefore, evaluation methods and decision support systems are needed to bridge this gap.

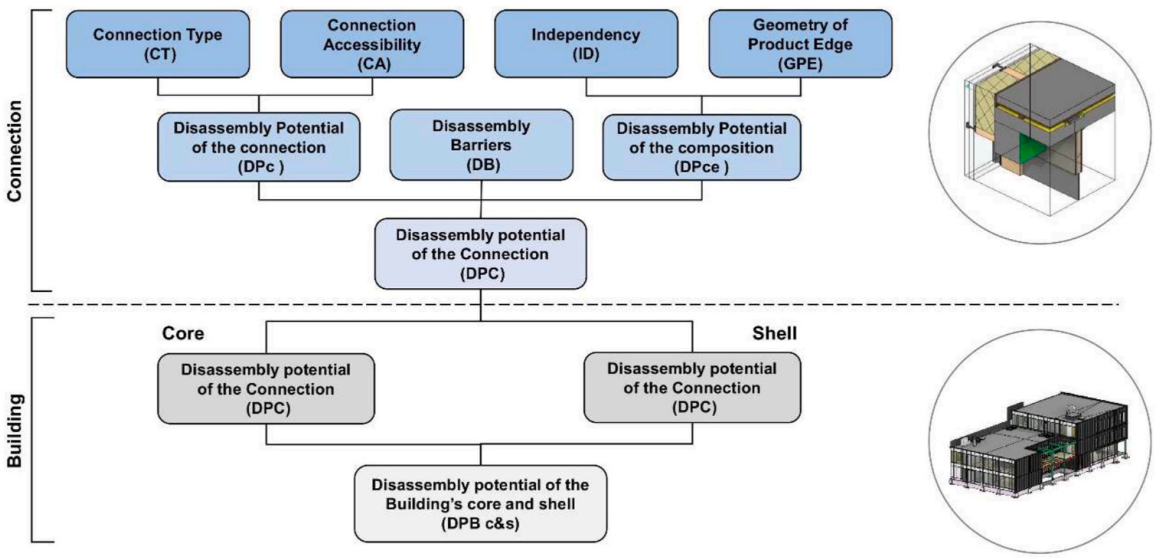


Fig. 3. Decision tree for assessing the disassembly potential of a building at the core and shell levels.

3. Methodology

3.1. Analytical approach

First, more than 180 publications were reviewed by the authors in a previous study to determine the adopted disassembly criteria and barriers to disassembly [8]. The present study focused on four main DfD criteria and 31 sub-criteria, with five main barriers and 30 sub-barriers, to evaluate the disassembly potential of buildings. The results of this review are presented in Section 2.

Second, the authors consulted the Sustainable Building Design (SBD) lab [71] database of the University of Liege for circular buildings and construction details. The database includes more than 15 buildings and 400 connection details and images [72]. The database was developed in 2016 and includes lessons learned on the most common disassembly barriers according to demolition contractors and insurance companies in Northwest Europe. The database inputs were developed and validated through participation activities of the FCRBE project (2018–2023) [10] and COST Action CA20139 HELEN (2021–2025) [73]. With the help of the literature review [8], experts from both projects were consulted, and focus group discussions were conducted to expand the bank of circular buildings and the representativeness of building junctions and connections. Access to the private database was granted with permission from the last author.

Third, an algorithm evaluation and decision tree were developed to evaluate the dismantling of the building at the core and shell levels. The authors focused on the most important connections between various components and components, as shown in Fig. 3.

Fourth, an audit sheet was developed. The audit sheet comprises all the steps that need to be performed when a building is evaluated and is filled up by an auditor. Therefore, when an expert system is used, inputs from the audit sheet should be used to feed the expert system with the necessary data. The audit sheet can be found in Appendix 3, and the expert system interface (step-by-step tutorial) and the final report can be found in Appendix 4.

Finally, for the application, three actions were performed: a case study, focus group discussions, and usability testing. Two projects were chosen as case studies (*'t Centrum* and *Green Office* buildings) to test the expert system. These buildings were chosen because they are compatible with the concepts of CE and DfD. A focus group discussion was conducted through technical meetings with experts to discuss the DfD criteria and barriers. Usability testing was performed to determine the extent to which this expert system could be used to evaluate the disassembly potential of a building (see Fig. 4).

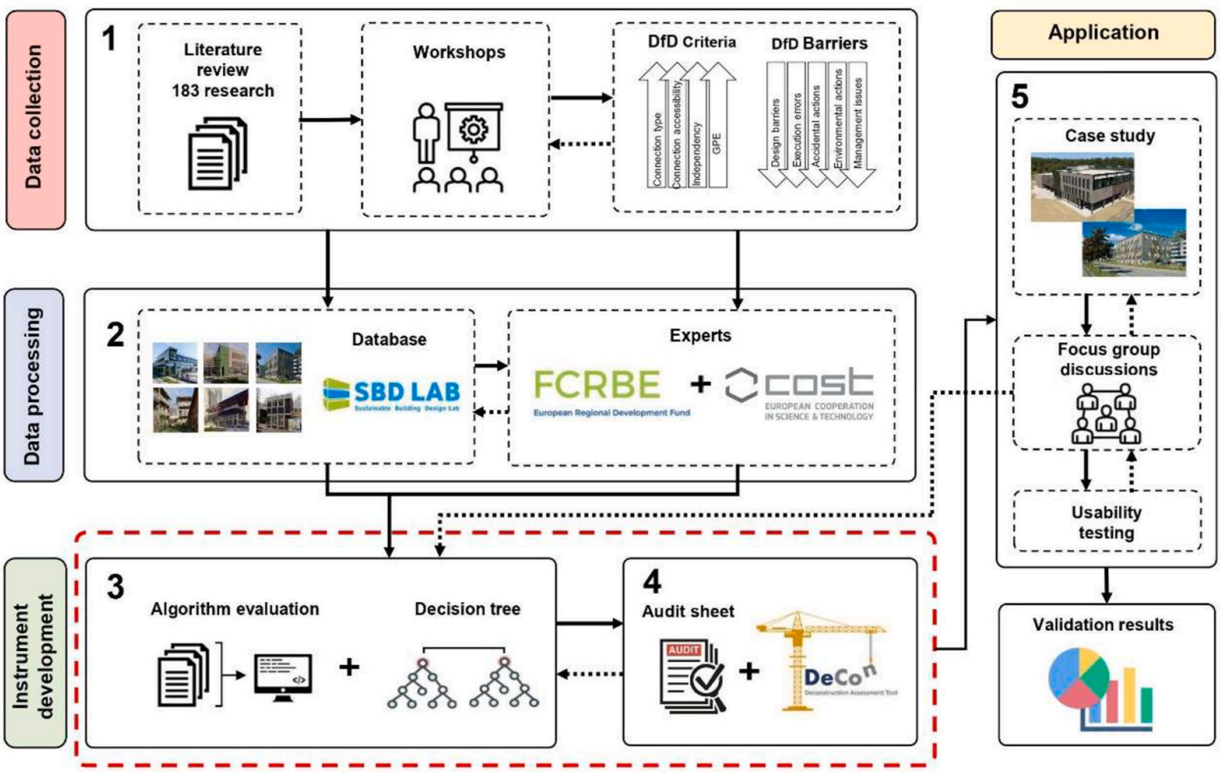


Fig. 4. Methodology framework of the study.

3.2. Inventory and inspection campaign

Demolition contractors were consulted, and an inventory of construction details for different types of buildings, such as steel, concrete, and timber, was made to observe a wide sample of connections. A complete inventory of construction connections emerged from these consultations. Moreover, the types of connections were identified and inventoried, and the disassembly potential was evaluated based on a previous study by the authors [17] that addressed the disassembly criteria for six different buildings in Belgium, the Netherlands, and Switzerland, as shown in Fig. 5. The data were collected for each project through the bill of materials with the help of experts, and focus groups were organized during technical meetings to discuss the DfD criteria.

The inspection campaign was based on an audit sheet and the creation of a database. A database was developed and programmed to collect details, images of connections, and the most common disassembly barriers. The first database (COST Action database) collects data from COST Action CA20139 (HELEN) experts [73]. By contrast, the second database, that is, the SBD lab [71] database at the University of Liege (SBD Lab database), collects data from engineers and demolition companies.

3.3. Characterization and statistical analysis

In this study, the methodology used by the Dutch Green Building Council and Alba Concepts [57] was adapted and developed in the form of a scenario describing the buildings and their disassembly potential, based on the criteria mentioned in the literature. This research is technical; therefore, the environmental cost indicator of the component was omitted from the method and a list of barriers to the disassembly process was added with their impact weights, which the authors developed based on a literature review. Barriers were included in the evaluation equations because of the lack of an important and sensitive factor for dismantling.

This research focused on four main DfD criteria and 31 sub-criteria, with five main DfD barriers and 30 sub-barriers that were developed and considered in the final evaluation results. The abbreviated IDs indicate the criteria and barriers and are presented in Tables 1 and 2, respectively.

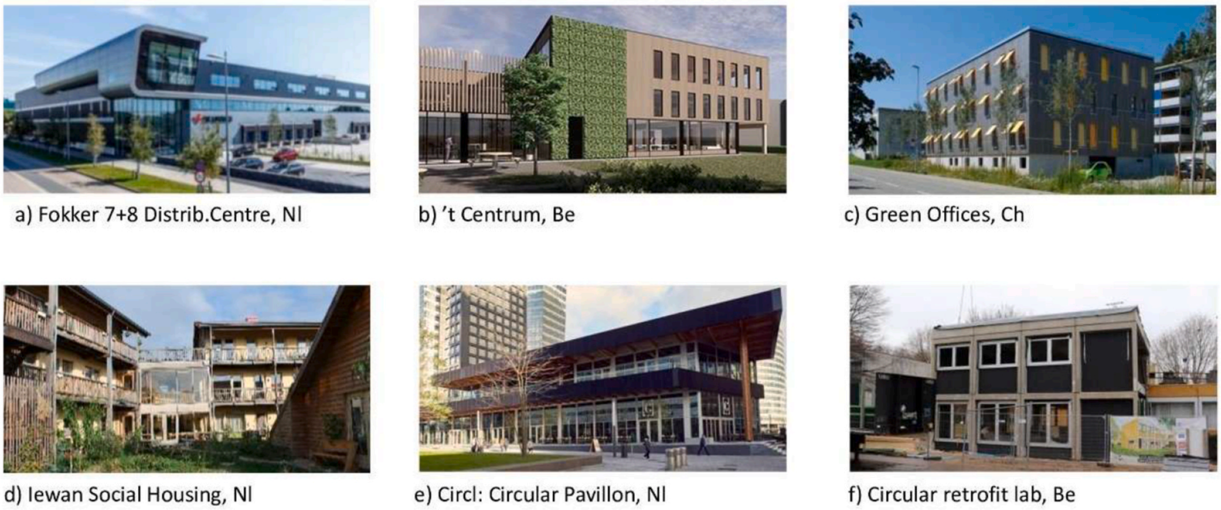
As presented in Table 1, the first criterion is the *connection type*. Various types of connections are used to connect the elements. For disassembly, dry connections, connections with added elements, and direct integral bonds prevail over soft and hard chemical compounds.

The second criterion is *connection accessibility*. The accessibility of connections refers to the physical possibility of accessing the connecting elements and the extent to which this causes damage to the surrounding elements. When accessibility is high and it is easy to reach the connecting element without causing damage to the surrounding building parts, disassembly is positively affected.

The third criterion is *independency*. This creates the integration and interweaving of objects and elements. This creates a dependence of the elements on each other. When the elements do not physically cross each other, they remain independent and disassemble more easily.

The fourth criterion is the *geometry of the product edge*. This deals with the physical containment of objects or elements and creates an inseparable connection through containment. The elements must remain open on at least one side and should not be physically enclosed to ensure disassembly. Consequently, they can be separated from each other without affecting the surrounding elements.

Table 2 presents the main DfD barriers adopted in this research, which are the five major barriers listed in the literature review section: (1) design barriers or errors, (2) execution errors, (3) accidental actions, (4) environmental actions, and (5) management issues. These barriers were examined, and their weights were determined based on a literature review and database [72] developed for



a) Fokker 7+8 Distrib.Centre, Nl
b) 't Centrum, Be
c) Green Offices, Ch
d) Iewan Social Housing, Nl
e) Circl: Circular Pavillon, Nl
f) Circular retrofit lab, Be

Fig. 5. Examples of the buildings that have been investigated to define the connection's disassembly potential and barriers based on a previous publication by the authors [17,74] and the SBD lab database [72].

this purpose.

The methodology adopted distinguishes between two types of criteria: those influenced by the connection between elements (connection type) and those influenced by the assembly of elements (connection accessibility). For each element e, the disassembly potential of the connection DPc_n and the disassembly potential of the composition $DPcp_n$ are determined. Together, these form the disassembly index of the connection in the core or shell of the building (Equations (1) and (2)).

$$= \frac{2}{\frac{1}{CT_n} + \frac{1}{CA_n}} \tag{1}$$

DPc_n = Disassembly potential of the connection of element n
CT_n = Connection type of element n
CA_n = Connection accessibility of element n

$$DPcp_n = \frac{2}{\frac{1}{ID_n} + \frac{1}{GPE_n}} \tag{2}$$

$DPcp_n$ = Disassembly potential of the composition of element n
IDn = Independency of element n
GPEn = Geometry of product edge of element n

$$DPC_n = \frac{2}{\frac{1}{DPc_n} + \frac{1}{DPcp_n}} \tag{3}$$

DPC_n = Disassembly potential of the connection
DPcn = Disassembly potential of the connection of element n
DPcpn = Disassembly potential of the composition of element n

Disassembly barriers are an integral part of evaluating the disassembly of connections. Therefore, Equation (4) was developed to evaluate the disassembly potential of the connections of the core or shell of the building.

$$= \left(\sum_{i=1}^{n} \frac{DPC_n - DB_n}{n} \right) \text{X } 100 \tag{4}$$

$DPB_{c/s}$ = Disassembly potential of the building's core or shell
DPC_n = Disassembly potential of the connection n = number of connections in the building's core or shell

Finally, Equation (5) was used to calculate the total disassembly potential of the core and shell of the building.

$$DPB_{c\&s} = \frac{DPBc + DPBs}{2} \tag{5}$$

$DPB_{c\&s}$ = Disassembly potential of the building's core and shell
DPBc = Disassembly potential of the building's core
DPBs = Disassembly potential of the building's shell

3.4. Usability testing

Usability testing is an important procedure for validating the performance of the developed method. The primary aim of this test was to assess the usability of the expert system (DeCon) and its decision-making abilities by conducting usability tests on various prototype versions. Usability testing was based on the USER-FIT framework described by Attia (2023) [75] and Attia et al. (2024) [76]. The participants were selected according to the EU General Data Protection Regulation [77] and asked for their consent. Ethical approval was not required because the responses were anonymized and an intervention was not performed. A data management plan [78] was developed to collect and consistently file all answers.

Two major iterations of usability testing were conducted during the creation of expert system (DeCon) prototypes 1 and 2 to obtain inputs from designers and potential users. Each usability iteration comprised two different types of tests. The first test was a paper-based usability satisfaction questionnaire. A system usability scale (SUS) was used to improve and validate the expert system [79]. A set of 10 conventional (predefined) SUS questions were used to ensure the internal validity of the test. A reporting structure [80] was used to analyze the replies. The second test was a usability metric test with 20 users, comprising architects, engineers, and architectural students, who measured the success of the task.

The objective was to assess the efficiency with which users could accomplish a set of tasks. A Likert scale was used for the paper-based surveys. Users answered the questionnaire on a scale of 1 (strongly disagree) to 5 (strongly agree). Scores from the survey were added, and the total was multiplied by 2.5. The mean score, ranging from 0 to 100, was calculated from the selected replies. The higher the score, the more user-friendly the website. A rating of 70 or higher indicated good usability. The SUS can be found in Appendix 5.

4. Results and validation

4.1. Case study

The case study buildings were selected after a thorough analysis of the case studies performed in a previous paper by the first author [17]. A selection list was created that included the inclusion and exclusion criteria to ensure that the case study building was constructed following the concepts and principles of CE [81].

4.1.1. ‘t Centrum building

The first case study was the *’t Centrum* building, an office building located in Belgium, Westerlo, Kamp C [82]. The building was designed by West Architecture [83] and was constructed by Beneens [84]. The building has three floors, with an area of 2200 m^2. It is considered carbon neutral and implements circularity principles. Moreover, this building acts as a catalyst for modular and circular buildings in the region. The construction was finished in March 2022. This is an example of a recent circular building designed to be dismantled 5 years after its construction and reassembled on the same site with a different design to assess its disassembly ability [85]. The building has a modular office arrangement with transformable workspaces. Consequently, the building may be completely disassembled when it becomes outdated. *’t Centrum* was built using Cross-Laminated Timber CLT, a type of connection that relies on dry fastening mechanisms. The ceiling, flooring, and internal walls were all made of timber, with partitions and floor tiles fastened using dry connections to increase the disassembly potential.

The project data were collected through technical meetings with the project consortium. The author was provided with the required drawings, necessary data, and a 3D scan view to conduct this research. The author regularly monitored the assembly process during the construction phase (see Fig. 6 and Appendix 1).

4.1.2. Green office building

The second case study was the *Green Office* building. The building was designed by Lutz Architects [86] as an ecologically optimal building with a positive impact. The building is to be disassembled and its components to be reused in the future. The Green Office building is located in Givisiez, Switzerland. It was constructed in 2005 by Vonlanthen Holzbau AG [87]. As a sustainable office building, it provides commercial spaces for companies specializing in sustainable development. The building has three floors, with a total area of 5391 m^2, and it is Switzerland’s first MINERGIE-P-ECO [88]. The design of the building was based on using the smallest amount of energy possible — less is more. This construction obtained the first label for an administrative building in Switzerland and the Watt d’Or 2008 prize [89].

The building aims not only to consume a minimum amount of energy during its operation but also during its construction by choosing materials that consume little embodied energy. Each construction material was analyzed and selected based on its environmental impact. In principle, only the so-called ecological materials were used for the entire construction, such as untreated wood for the façade, natural interior paint, thermal insulation made from waste paper, and frames made entirely of native wood. The ecological balance sheet for the entire building is very positive. Each company working in this building aims to optimize electricity use by installing, for example, low-energy lamps, flat screens, presence detectors, and a timer on the coffee machine (see Fig. 7 and Appendix 2).

4.2. Expert system and disassembly potential evaluation

The expert system was designed as a web tool called DeCon [90]. This web tool was designed in the JavaScript programming language [91] and consists of four steps. It takes 10–15 min to feed the tool with the necessary data to obtain the final result. In this web

Fig. 6. Photograph of the first case study building, *’t Centrum* [82].

Fig. 7. Second case study, the *Green Office* building [86].

tool, the evaluation process takes the form of scenarios based on a decision tree (see Section 3.1.) to help engineers avoid performing calculations or using mathematical equations. Answering some questions will be sufficient to determine the results of the disassembly potential, which is based on a group of case studies. By inputting the number of connections, connection type, component connection relationships, and disassembly barriers, the disassembly potential can obtained at the connection, core, and shell levels of the building. Using the expert system (DeCon), the final report of the disassembly potential can be downloaded at the end of the assessment. Fig. 8 shows the interface and final report of the expert system (DeCon).

After visiting and auditing the buildings and obtaining an inventory of the number and connection types using an audit sheet (see Appendix 3), the expert system (DeCon) was fed with all the necessary data to assess the disassembly potential of the buildings [90]. Fig. 9 illustrates the disassembly sequence of some components of 't Centrum building and their disassembly scores according to the expert system. As shown in Fig. 10a and b, for the *'t Centrum* building, the total disassembly potential for all connections in the core and shell was 92 %. The results of the column and foundation connections showed a decrease of up to 88 % owing to the use of prefabricated foundation blocks underground, which will require additional actions that do not cause damage to reach and remove them completely.

By contrast, the disassembly potential of the *Green Office* building was 72 %. The results of the column connection with the foundation showed a decrease of up to 18 % owing to the use of concrete buried underground (not prefabricated), which cannot be accessed or extracted, except by destroying it. In addition, another 10 % decrease was found after calculating the factor of disassembly barriers, considering that using this type of foundation is a design error when designing a building for disassembly. The evaluation of the connection disassembly depends on the ease of disassembling and isolating the components from each other and their surroundings.

As shown in Fig. 11a and b, the *'t Centrum* building at the core level achieved the highest disassembly potential in the geometry of the product edge and independence criteria, reaching 100 %, followed by connection accessibility at 97 % and the connection type at 80 %.

At the shell level, *'t Centrum* had the highest disassembly potential in the geometry of the product edge, independence, and connection accessibility criteria, reaching 100 %, followed by the connection type at 80 %. The decrease in disassembly potential to 80 % in the connection type at the core and shell levels is attributed to the use of dry connections with added connection components. The total number of barriers to disassembly potential in the core and shell was 0 %. The building is new and does not contain design barriers. It is perfectly designed for disassembly and does not even contain other barriers that hinder the disassembly process resulting from a long period of use. By contrast, the *Green Office* building at the core level achieved the highest disassembly potential in the independence criterion of 100 %, followed by the connection accessibility and geometry of product edge criteria at 82 %, and the connection type at 80 %.

At the shell level, *Green Office* had the highest disassembly potential in the geometry of product edge, independence, and connection accessibility criteria, reaching 100 %, followed by the connection type at 80 %. The total number of barriers to disassembly potential in this building was 10 % owing to the use of hard chemical connections and a classic concrete foundation buried underground (not prefabricated), which cannot be accessed except by destroying it completely.

Through a comparison between the two buildings shown in Fig. 12, the expert system (DeCon) demonstrated the superiority of the *'t Centrum* building over the *Green Office* building, with a total disassembly potential of 92 % compared with 72 % for the *Green Office* building at the core and shell levels. This comparison was made according to the disassembly criteria and barriers described in the methodology of this study.

4.3. Usability test results

According to the usability test results, the initial prototype achieved high usability for the nine questions, as shown in Fig. 13. However, for the final question, participants stated that they needed to understand how the expert system (DeCon) functioned. In addition, after the usability test, each participant was interviewed to gain useful insights into the limits of the expert system. The results were inputted into expert system (DeCon) prototype 2 before the second round of usability testing.

The second phase of usability testing was completed by organizing workshops at the SBD lab. Two user focus groups evaluated the

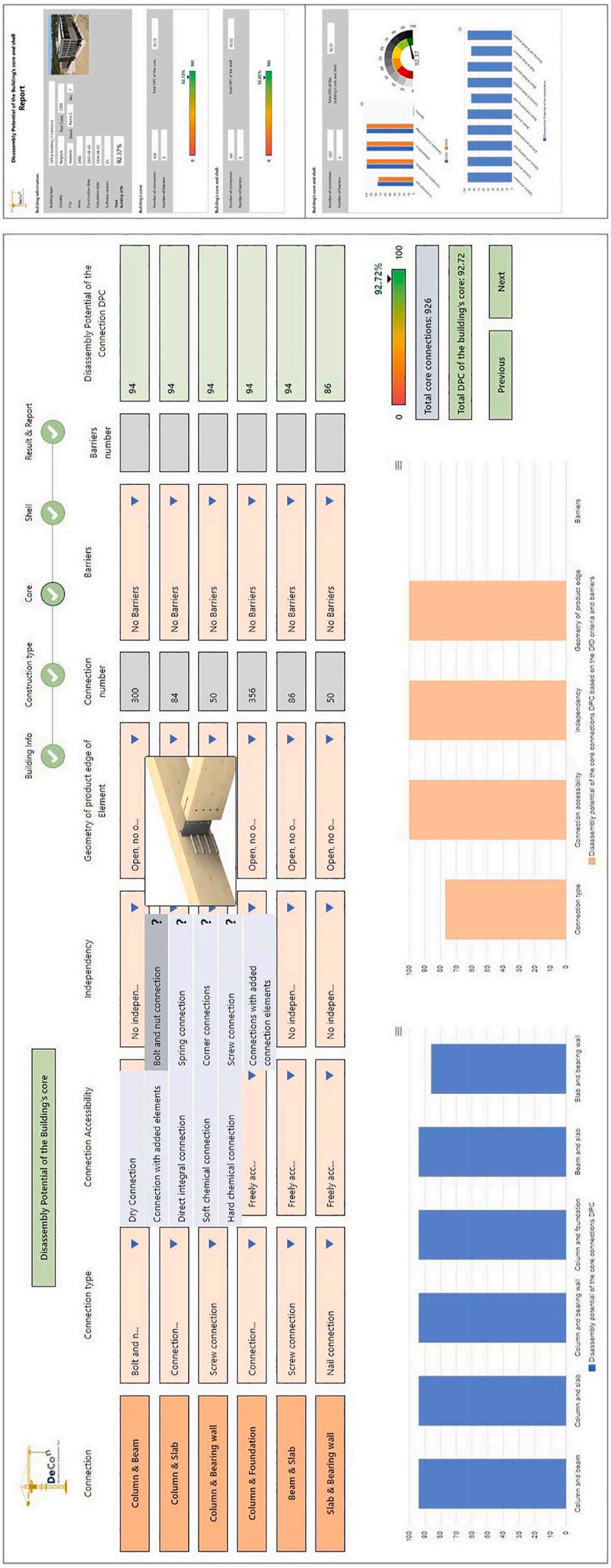


Fig. 8. Interface and final report of the expert system (DeCon) [90].

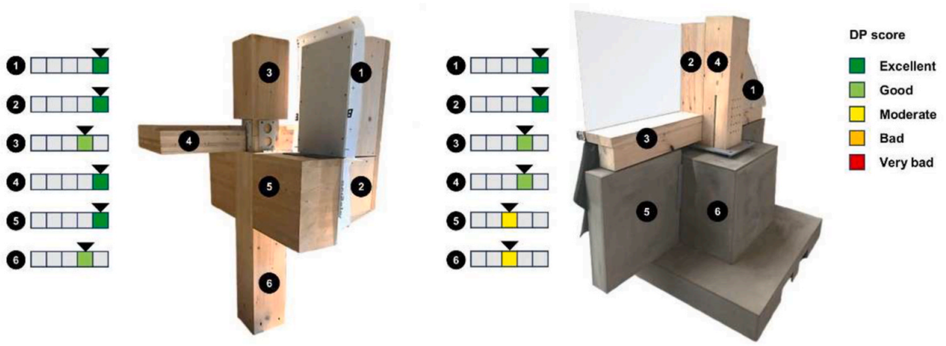


Fig. 9. The disassembly sequence of some components of ’t Centrum building and their disassembly potential DP scores according to the expert system.

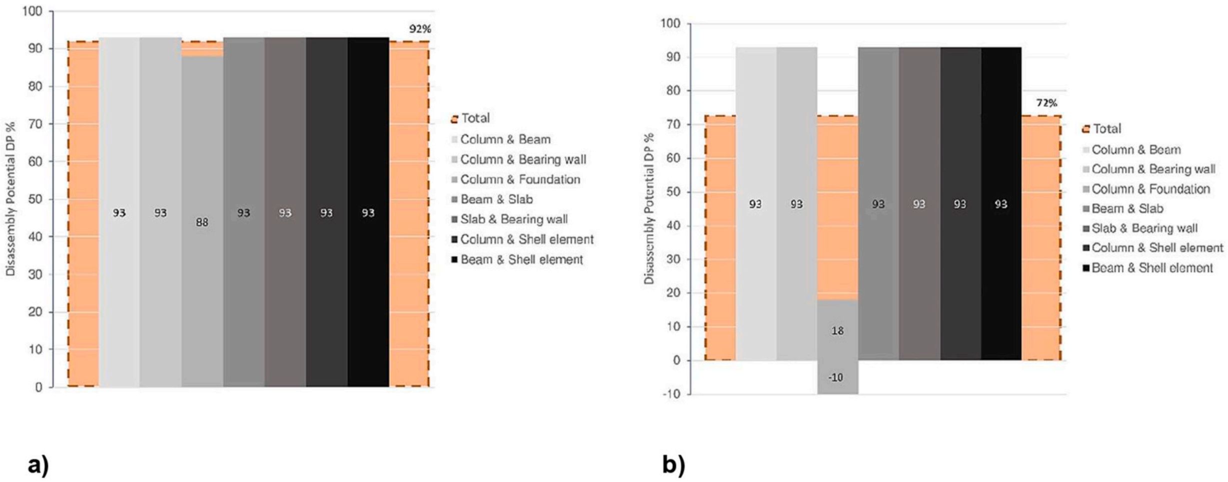


Fig. 10. Disassembly potential of connections in the a) *’t Centrum* and b) *Green Office* buildings.

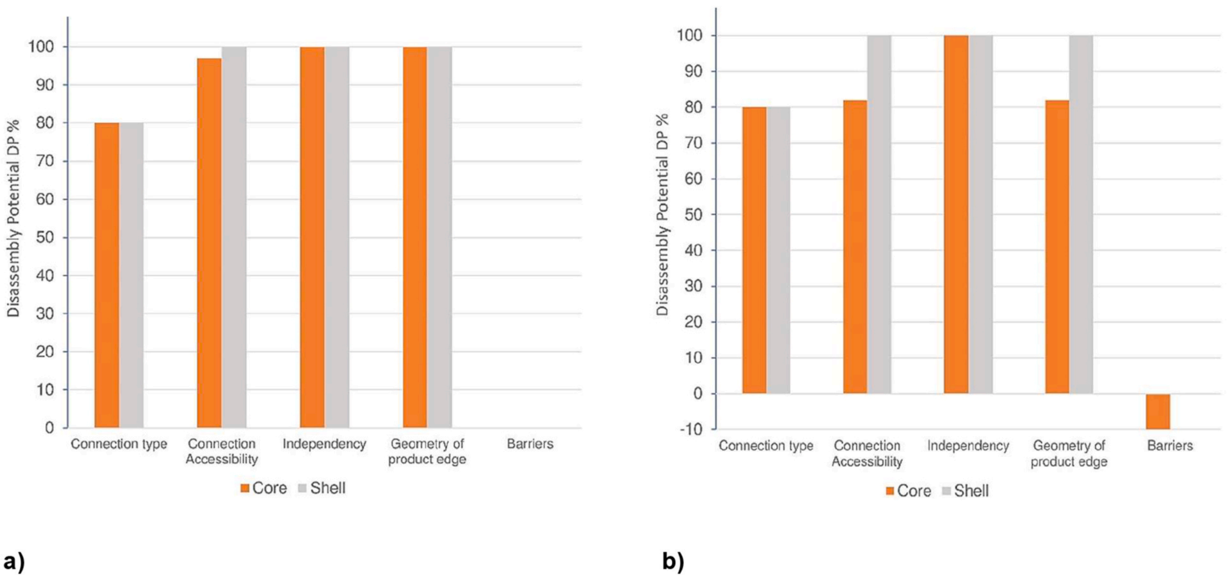


Fig. 11. Disassembly potential of the core and shell of the buildings based on the DfD criteria and barriers: a) *’t Centrum* building and b) *Green Office* building.

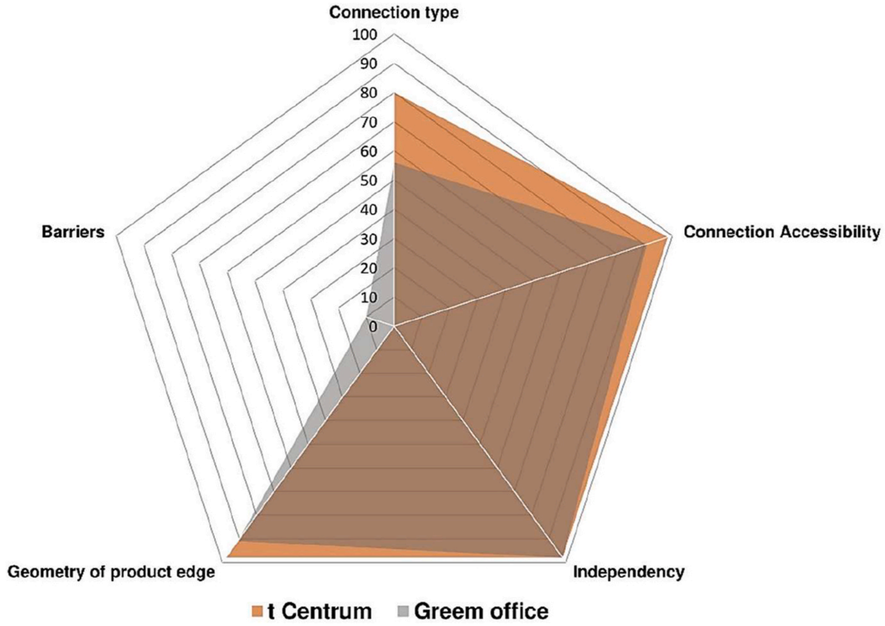


Fig. 12. Disassembly potential of *'t Centrum* and *Green office* buildings based on the DfD criteria and barriers.

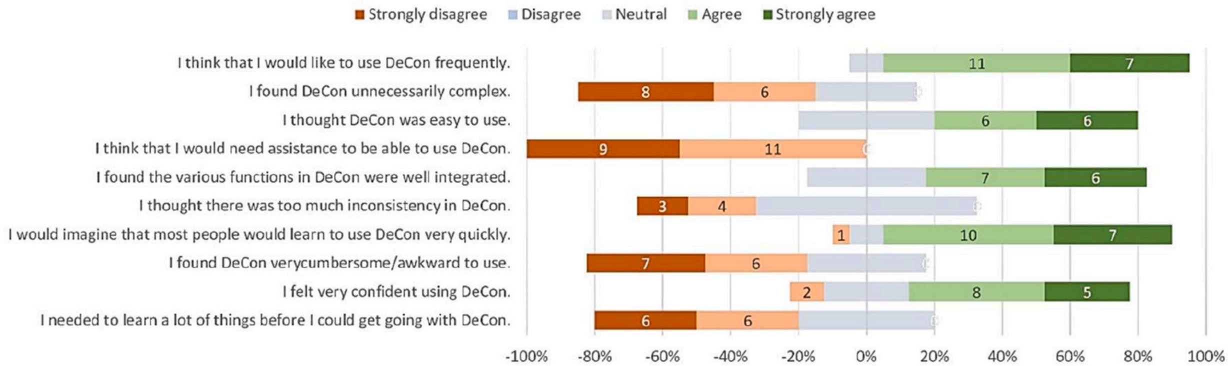


Fig. 13. Results of the usability test of expert system (DeCon) prototype 1 using the SUS.

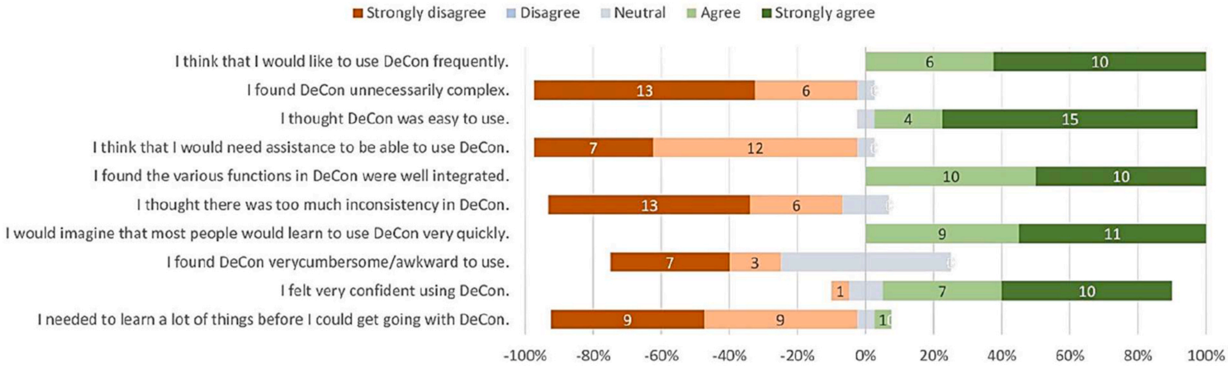


Fig. 14. Results of the usability test of expert system (DeCon) prototype 2 using the SUS.

expert system. The testing groups of architects, architectural engineers, and architectural students (20 users) were given a set of assignments outlining the steps necessary to utilize the expert system (DeCon).

Fig. 14 shows the inputs of users after gathering 20 responses. Overall, the usability of prototype 2 increased compared with that of prototype 1. The participants appeared to be more confident in using the instrument (prototype 2 vs. prototype 1: 86 % vs. 75 %). Therefore, the latest version of the expert system (DeCon) was adopted to evaluate the disassembly potential of the buildings.

5. Discussion

5.1. Summary and main findings

During the early design and deconstruction stages, the simulation-based design assistance expert system was found to promote informed decision-making regarding DfD. This boosts the understanding of DfD and reduces decision-making ambiguity. Participants who used the expert system (DeCon) reported a high level of expertise and employed an informational decision support method rather than an evaluative trial-and-error technique in their design. This alignment of decision-making and design purposes in the context of greater knowledge is consistent with our notion of informed DfD decision-making. However, based on the interface usability testing, the current prototype has not achieved a degree of usefulness that satisfies the demands of designers to address all building components. At this stage, the work of this expert system was limited to evaluating the disassembly potential of the core and shell of the buildings; therefore, this web tool is a starting point for developing a widely useable expert system with more details and many new features.

5.2. Strengths and limitations of this research

This is the first simulation-based expert system to support decision making in the early design and deconstruction stages. The strength of the expert system (DeCon) is its ability to inform design before decision making while managing huge sensitivity simulations and presenting complicated data in readily accessible, quick, and comparable scenarios. This web tool is very easy to use and has a simple interfacial structure. The web tool assists in achieving the disassembly target while investigating several ranges of disassembly designs to achieve the performance goal.

One of the reasons for the strength of this expert system is that it is a Duch-local approach and was developed based on the methodology used by the Dutch Green Building Council and Alba Concepts [57].

This expert system is purely technical; therefore, the environmental cost indicator of the component was omitted from the mentioned method, and a list of barriers to the disassembly process was added with their impact weights, which the author developed based on a literature review, to be used globally.

Informed decisions made during the early design stage and deconstruction enhance the DfD. It is envisaged that the current design trials of the expert system (DeCon) will have a greater influence on architects' decision-making and real design outputs, allowing the integration of building performance simulation tools to extend beyond the decision support level of this research.

However, the usability test results revealed that the expert system seemed more useful when used with the support of an expert or specialist in DfD. In addition, the decision-making support of the current prototype can only handle the connections between the core and shell of the building, although many users expect the system to handle more details and features. One of the main limitations identified during the workshops was the geometry input. The evaluation process took two weeks for the *'t Centrum* building to inventory the connections using the Revit model and 3 weeks for the *Green Office* building to inventory the connections from an AutoCAD file. Users suggested linking the audit sheet to the expert system (DeCon) to automatically feed the web tool by uploading the audit sheet instead of manually filling it.

5.3. Future work and possible applications

The expert system (DeCon) is a starting point for improved DfD decision making. The current version of the web tool has considerable limitations, and designers require additional information to make more educated decisions.

An expert system can be developed to include all buildings, such as hybrid or non-timber buildings, in full detail. It also includes other building configurations in terms of form, function, and connection types. Moreover, it can be developed to include additional products and components, such as doors, windows, and partitions. The interface could also be modified to include additional building systems. Future research should focus on integrating advanced data collection and processing techniques to enhance DeCon's scalability and automation. Real-time data acquisition and integration with Building Information Modeling (BIM) or Digital Twin platforms could reduce reliance on manual inputs in DeCon. Additionally, applying AI-driven predictive analytics for disassembly planning and anomaly detection would improve decision-making efficiency. In terms of usability testing, this study addressed the efficiency and effectiveness of the web tool as a supplement to satisfaction testing. At the level of decision assistance, future developments of the web tool can include economic indicators to mention the different costs and times during the deconstruction stage. Additionally, environmental indicators can be added to address the reduction in carbon emissions through efficient disassembly. For example, web tool development will continue as part of the new working group SC1/WG5 of CEN 350 for the circularity assessment of construction. These developments will be important for designers, academics, and CE policymakers.

The expert system (DeCon) could benefit from insights from the manufacturing sector, where standardized metrics like disassembly time and material recovery rates enhance efficiency. Adapting modular designs and digital tools such as Product Lifecycle Management

(PLM) could improve DeCon's accuracy in assessing construction-specific connections and material flows. Integrating these approaches would strengthen its role in promoting circular construction practices.

Finally, further investigations are required to learn more about the potential of DfD principles to accurately forecast the disassembly potential of buildings and material recoverability. Buildings must have a high level of standardization to design a building for disassembly. For the optimal completion of the disassembly process, the skills of the demolition contractors, as well as the type of workers and their availability, should be considered. This expert system would have no value if it remained within the theoretical framework and was not used practically by demolition experts or trained and specialized workers in the deconstruction of a building. Detailed guidelines for practitioners are still required, and there is a need to formalize and define the main steps of the disassembly process to be performed according to an approved protocol.

6. Conclusion

The development of the expert system (DeCon) represents a significant advancement in evaluating the building disassembly potential. By transforming complex data into quick and comparable scenarios, the expert system (DeCon) aids stakeholders in making informed decisions regarding building deconstruction. Through the literature review, the author identified critical DfD criteria and barriers, providing a foundation for the framework for the expert system. Validation through two case studies demonstrated the effectiveness of DeCon, with the system successfully quantifying the disassembly potential of the *'t Centrum* building at 92 % and that of the *Green Office* building at 72 %. These results highlight the utility of the expert system (DeCon) in promoting sustainable building practices and supporting its adoption for future projects aimed at enhancing CE principles in construction.

CRediT authorship contribution statement

Muheeb Al-Obaidy: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hilde Carens:** Writing – review & editing, Validation. **Clémentine Campain:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Enola Giannasi:** Visualization, Validation, Software, Investigation, Data curation. **Maxime Mori:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Mike van Vliet:** Writing – review & editing, Validation. **Shady Attia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.112148.

Data availability

The data that has been used is confidential.

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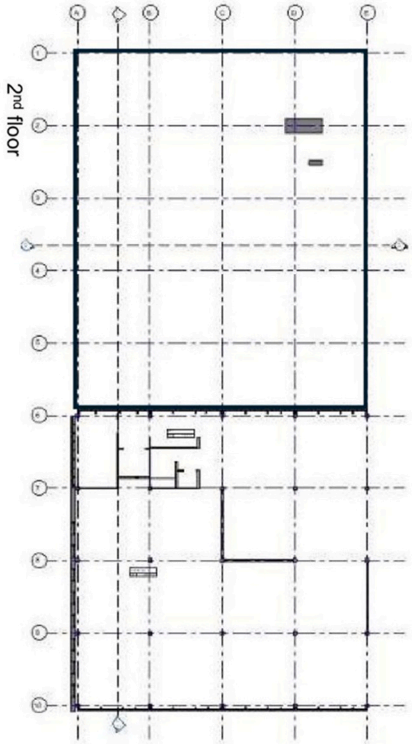
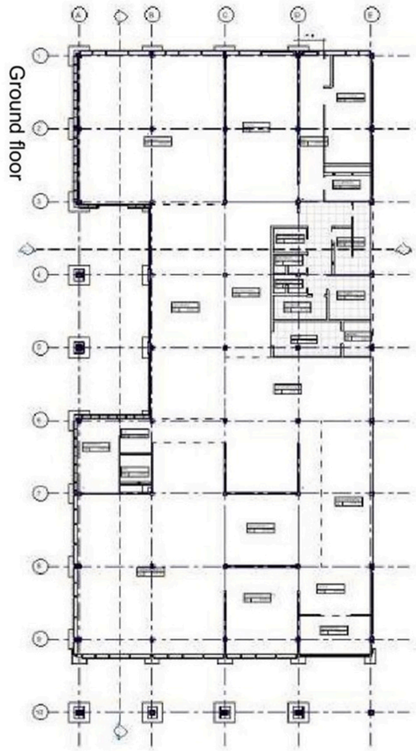
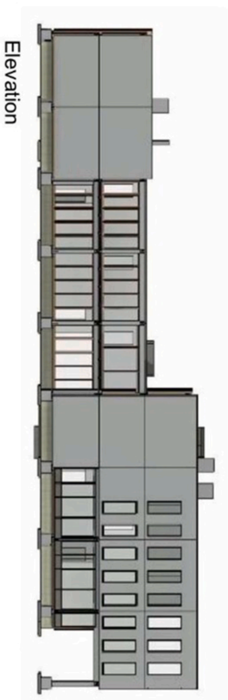
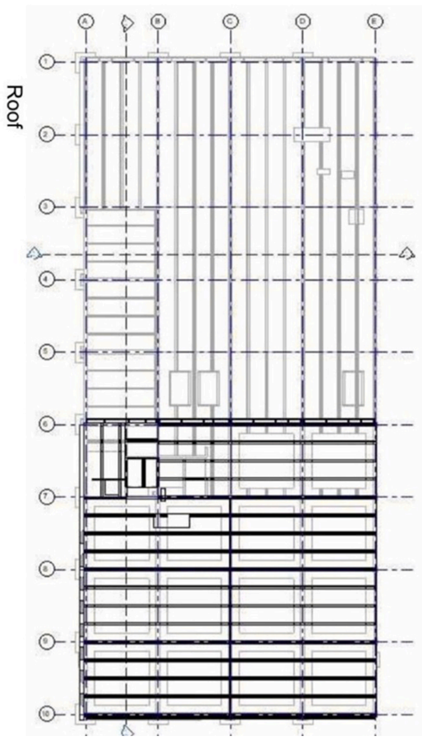
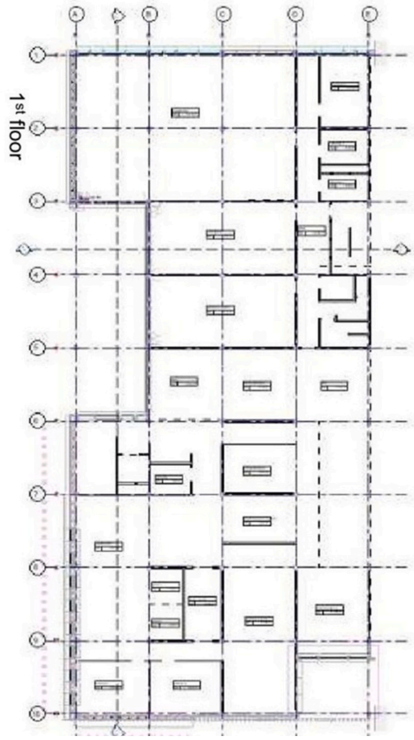
Appendix 1. 't Centrum building drawings



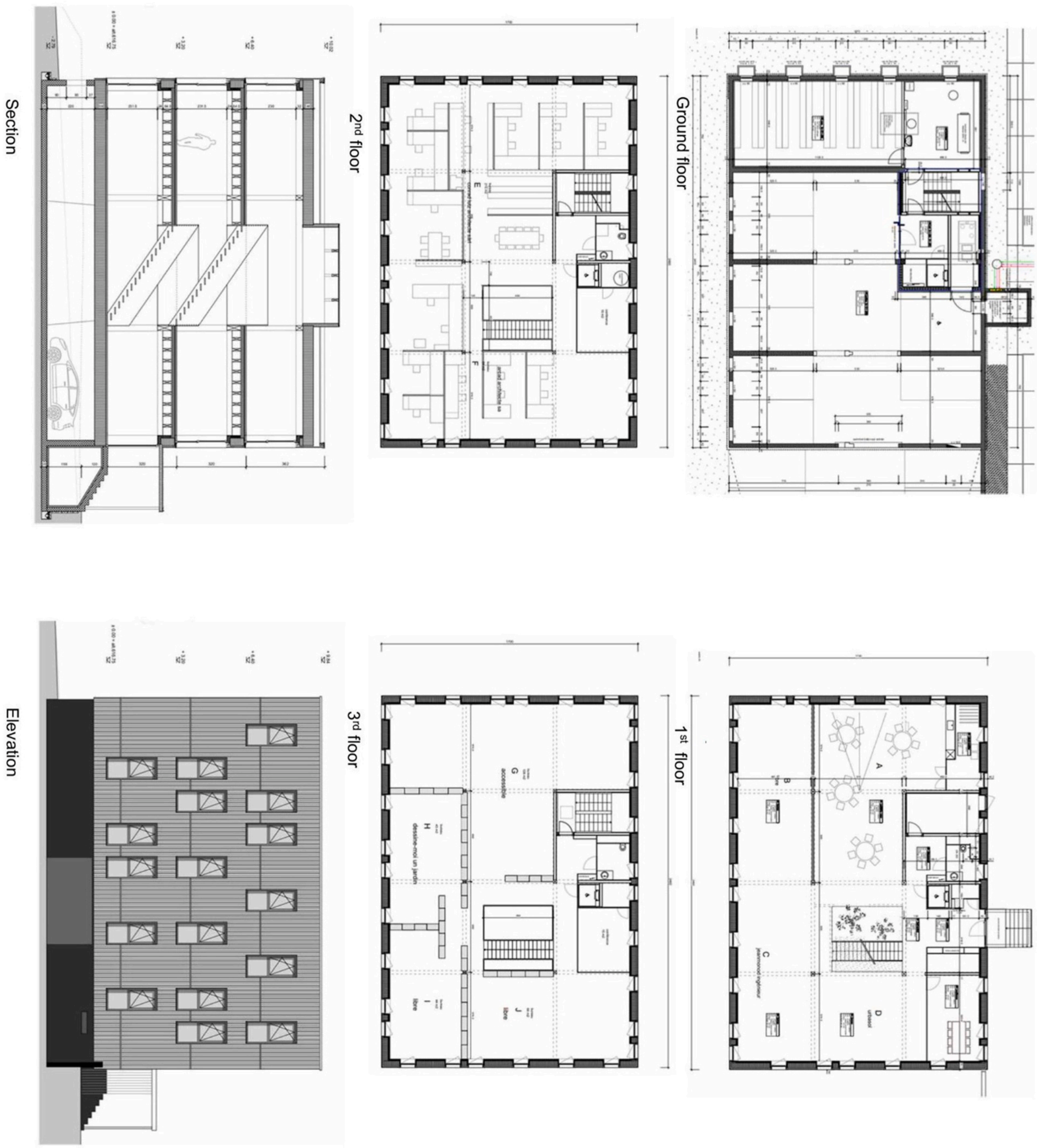








Appendix 2. Green office building drawings



Appendix 3. The audit sheet

Audit sheet to evaluate the disassembly potential ('t Centrum)

		DfD Criteria					DfD Barriers					Number
1	Core	Composition type	Connction type	Connection accessibility	Independency	Geometry of product edge	Design barriers	Execution errors	Accidental actions	Environmental actions	Management issues	
	1.1.	Column & Beam	Connections with	Freely accessible without	Occasional	Open, no obstacle to the						
	1.2.	Column & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.3.	Column & Bearing wall	Connections with	Accessible with additional	Occasional	Open, no obstacle to the						
	1.4.	Column & Foundation	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.5.	Beam & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.6.	Slab & Bearing wall	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
2	Shell											
	2.1.	Column & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.2.	Beam & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.3.	Slab & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.4.	Bearing wall & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						

Audit sheet to evaluate the disassembly potential (Green Office)

		DfD Criteria					DfD Barriers					
1	Core	Composition type	Connction type	Connection accessibility	Independency	Geometry of product edge	Design barriers	Execution errors	Accidental actions	Environmental actions	Management issues	
	1.1.	Column & Beam	Connections with	Freely accessible without	Occasional	Open, no obstacle to the						
	1.2.	Column & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.3.	Column & Bearing wall	Connections with	Accessible with additional	Occasional	Open, no obstacle to the						
	1.4.	Column & Foundation	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.5.	Beam & Slab	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	1.6.	Slab & Bearing wall	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
2	Shell											
	2.1.	Column & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.2.	Beam & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.3.	Slab & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						
	2.4.	Bearing wall & shell element	Screw connection	Freely accessible without	Occasional	Open, no obstacle to the						

Appendix 4. The expert system (DeCon) interface (step-by-step tutorial) and final report

Appendix 5. The System Usability Scale (SUS)

Participant ID: _____ Site: ________ Date: ___/___/___

System Usability Scale

Instructions: For each of the following statements, mark one box that best describes your reactions to the **DeCon** tool.

	Strongly Disagree				Strongly Agree
1. I think that I would like to use DeCon frequently.					
2. I found DeCon unnecessarily complex.	☐	☐	☐	☐	☐
3. I thought DeCon was easy to use.	☐	☐	☐	☐	☐
4. I think that I would need assistance to be able to use DeCon.	☐	☐	☐	☐	☐
5. I found the various functions in DeCon were well integrated.	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in DeCon.	☐	☐	☐	☐	☐
7. I would imagine that most people would learn to use DeCon very quickly.	☐	☐	☐	☐	☐
8. I found DeCon very cumbersome/awkward to use.	☐	☐	☐	☐	☐
9. I felt very confident using DeCon.	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going with DeCon.	☐	☐	☐	☐	☐

Please provide any comments about **DeCon** tool:

This questionnaire is based on the System Usability Scale (SUS), which was developed by John Brooke while working at Digital Equipment Corporation. © Digital Equipment Corporation, 1986.