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Review

Disassembly calculation criteria and methods for circular construction

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ABSTRACT

Circular economy opportunities occur at every building life cycle stage. The consistent evaluation of the disassembly potential of buildings at different scales supports the decision-making for the sustainability of construction works. The main limitation in this field is the fragmentation and dispersion of criteria and methods for circular construction. The paper provides an overview of disassembly evaluation methods using a hybrid systematic review. The review is structured into two sections. The first section investigates generic studies assessing the disassembly potential of buildings, while the second section focuses on studies that address quantitative criteria and methods of disassembly evaluation of buildings. The study discusses the state-of-the-art metrics and criteria that can be used in future European standards for circular construction. Also, the review helps researchers and building professionals to identify the most appropriate methods to evaluate buildings based on the principle of design for disassembly.

1. Introduction

1.1. General background

The construction sector is based on a linear process that exploits raw materials and the disposal of waste at the end of life. >50% of Greenhouse Gas (GHG) emissions are a result of the exploitation of raw materials [48]. In Europe, >30% of the construction sector's waste and demolition waste is downcycled [70]. To eliminate material consumption waste and encourage resource utilisation circularity principles are needed [19]. Circular economy and the application of circular economy-inspired principles [11] are becoming a critical field for the achievement of sustainable development targets, fostering the uptake of circularity principles in the built environment [60]. The importance of adopting holistic assessment methods and criteria to quantify circular design and performance has been highlighted greatly in the existing literature [33].

One of the key criteria of circular construction is the design for disassembly. Research into the potential for disassembly has been increasing to reduce the environmental impact of the construction sector. For example, in 2015, Akinade et al. developed a BIM-based score system to assess the deconstructability of buildings [5]. In 2019, Aknabi et al. presented a disassembly and deconstruction analysis

Abbreviations: BCI, Building Circularity Indicator; BIM, Building Information Modelling; CA, Connection Accessibility; CCEF, Circular Construction Evaluation Framework; CD, Connection Disassembly factor; CE, Circular economy; CEN, European Committee of Normalization; CT, Connection Type; DAS, Deconstructability Assessment Score; D-DAS, Disassembled and deconstruction analytics system; DfA, Design for Adaptability; DfD, Design for Disassembly; DfromD, Design from Disassembly; DGBC, Dutch Green Building Council; DPb, Disassembly Potential of building; DPc, Disassembly Potential of connection; DPcp, Disassembly Potential of composition; DPI, Disassembly Potential of layer brand; DPp, Disassembly Potential of product; ECI, Environmental Cost Indicator; EOL, End-Of-Life; EU, European Union; EU, European Union Construction Products Regulation; GHG, Greenhouse Gas; GPE, Geometry of Product Edge; HELEN, Holistic design of taller timber buildings; ID, Independency of Component; ISO, International Organization for Standardization; ISSO, Dutch Knowledge Centre; KPI, Key Performance Indicators; LCA, Life Cycle Assessment; PDE, Potential Ductile Elements; PDF, Product Disassembly Factor; PfD, Potential for Disassembly; RRP, Recyclability inherent in the relative product; SC, Sub-Component; SCI, System Circularity Indicator; SE, Static Entropy; SSC, Start-Of-Life Sub-sub-component.

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system [3]. In 2023, Xiao et al. developed a deconstruction evaluation method for building structures [69]. More recently, Allam et al. presented 2024 a model that supports circularity in construction with performance-based disassembly and deconstruction [6]. Those studies are just examples of the growing importance of design for disassembly principles and calculation methods. However, despite all those examples, no review to date offers an overview of disassembly calculation methods and criteria for circular construction.

1.2. Building disassembly

Building disassembly is an important research topic that has attracted the attention of several researchers during the last 15 years. According to ISO 20887, disassembly is non-destructive taking part in construction work or constructing assets into constituent materials or components [41]. ISO 20887 provides examples of how specific building components or assessments can be assessed qualitatively. Since the publication of Durmisevic's dissertation in 2006 on transformable building structures [27] and the introduction of the Circularity Indicators by the Ellen Mac Arthur Foundation [31], several scholars and building professionals investigated this topic. Indeed, there is an increasing body of knowledge on calculation methods and criteria to assess building disassembly potential. Several Green Building Councils have also been researching the Design for Disassembly (DfD). Het Centrum is an example of a recent circular building that is planned to be dismantled five years after its construction to assess its ability to disassemble [7]. Fig. 1 shows t' Centrum's beam-column connection, designed for future disassembly. Research that couples the disassembly potential to the circularity of buildings is also growing in popularity [35,49].

1.3. Motivations for the data-driven potential of disassembly indicators

This article reviews calculation methods and criteria for assessing the disassembly potential of buildings at the end of their service life through a literature search since 2004. The main aim is the identification of accurate calculation method(s) and quantitative criteria to assess the DfD of new constructions and the potential for disassembly (PfD) of existing buildings that can be used during early design stages or pre-demolition audits. The review uses a hybrid approach that combines scientometric and systematic review methods to analyze prior research on disassembly potential evaluation criteria and methods. The objective is to identify gaps and potential links between the assessment methods and criteria employed at component, product or building levels. This study is focused on timber, steel, concrete, and hybrid buildings. The review caters to researchers and building professionals, including architects and demolition contractors. Also, the work is part of EU COST Action 21,103 - Implementation of Circular Economy in the Built Environment (CircularB) and COST Action 20,139 - Holistic Design of Taller Timber Buildings (HELEN).

1.4. Research questions

The novelty of this review is twofold; it offers a unique perspective on building disassembly criteria and methods and the key knowledge gap of assessing the disassembly potential. Secondly, it advances science in the area of building disassembly evaluation based on a set of cohesive recommendations to evaluate the disassembly of buildings quantitatively. These recommendations are not limited to specific building types and encompass valuable insights for potential enhancements in quantitative disassembly evaluation methods in the future. This study is part of the EU COST Action CircualrB. It has great potential to influence construction standards and regulations -including the European standards for circular construction CEN/TC 350/SC1: Sustainability of construction works, thereby improving design practices and reducing the environmental impact of the construction industry. Hence, this review is important as it addresses the following questions:

- What are the criteria to assess the ability to dismantle buildings at the end of their service life?
- What are the methods to assess the ability to dismantle buildings at the end of their service life for existing buildings or new construction?

Fig. 1. Example of a bolted beam-column and slab-column connection that allows disassembling and reassembling.

2. Methodology

The study employs a hybrid review methodology to analyze a selected list of papers, reports and standards from the Scopus and Google Scholar databases. The hybrid literature review focuses on generic and specific studies that investigated ways to evaluate DfD and building disassembly potential using indicators and metrics. The methodology consists of three main sections. The first section involves a screening stage with inclusion and exclusion criteria. The second section includes a parallel scientometric and systematic review, as illustrated in Fig. 2. The second section is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) that seeks an evidence-based minimum set of items aimed at helping scientific authors report a wide array of systematic reviews. The third section of the methodology focuses on presenting the results of the review, identifying the gaps in literature and developing a discussion on the significant findings and contribution of the study and future research.

2.1. Document screening

The first stage comprises the document screening for the database creation. We primarily searched for articles, journals, and international standards in the fields of engineering, environmental sciences, construction and building materials. The searches were conducted in English, Danish, Dutch, French, German, and Swedish languages, spanning the period from 2003 to 2023. The diversity of the selected document languages is a result of an internal call to the members of COST Actions 21,103 (CircularB) and 20,139 (HELEN). Some articles were also manually added to the list of selected papers by the authors. Special attention was given to publications, especially standards and guides, on circularity and DfD published by Green Building Councils worldwide.

For the literature search in Scopus, the keywords and search strings in Table 1 were used to filter studies. When defining the keywords, the symbol "*" was chosen as a suffix for some keywords to account for all existing variants of these words [43]. For example, by using "disassembl*", words such as "disassemble, "disassembly", "disassembling" and "disassembled" are all considered in the query. Four sets of queries were defined to qualify the overall scope of the research, the definitions of disassembly, disassembly potential, and its quantification. The search was conducted using the "AND" operator between the different query sets for the title, abstract, and keywords of publications. Additional exclusion criteria were used based on the keywords listed in Appendix A.

Table 1
Set of queries for literature search.

KEYWORDS	MEANING
Building* OR construct* OR architect*	Overall, Scope of the Research
Disassembl* OR dismantl* OR deconstruct* OR DfD	Disassembly definition keyword
Disassembl* potential OR dismantl* potential OR reus* potential OR deconstruct* potential	Disassembly potential Keyword
Criteria* OR indicat* OR quantif* OR characteriz* OR asses* OR evaluat* OR estimat*	Disassembly quantification keyword

The number of publications obtained at the end of the search amounted to 130 items. After adding the articles manually selected by us, we compiled a list of 182 publications. An initial selection was made by removing irrelevant and out-of-scope articles. Once the first stage of the study was conducted, stage two was implemented. The methodology of the scientometric review and a systematic review are presented in Sections 2.1 and 2.2.

2.2. Scientometric review

The scientometric examination involves the statistical analysis of large bibliographic series using different metrics. This enabled us to understand the development of science and scientific practices [45]. Several software packages were used to model the document data, such as Excel, VOSviewer and Datawrapper. Firstly, we compiled the list of selected papers (from the Scopus and Google Scholar search and those added by the authors) in the Zotero library in order to be able to use the data. The Zotero library was imported into the VOSviewer software, which created graphic maps of the most frequently used words in the titles and abstracts of the publications, as well as the occurrence of

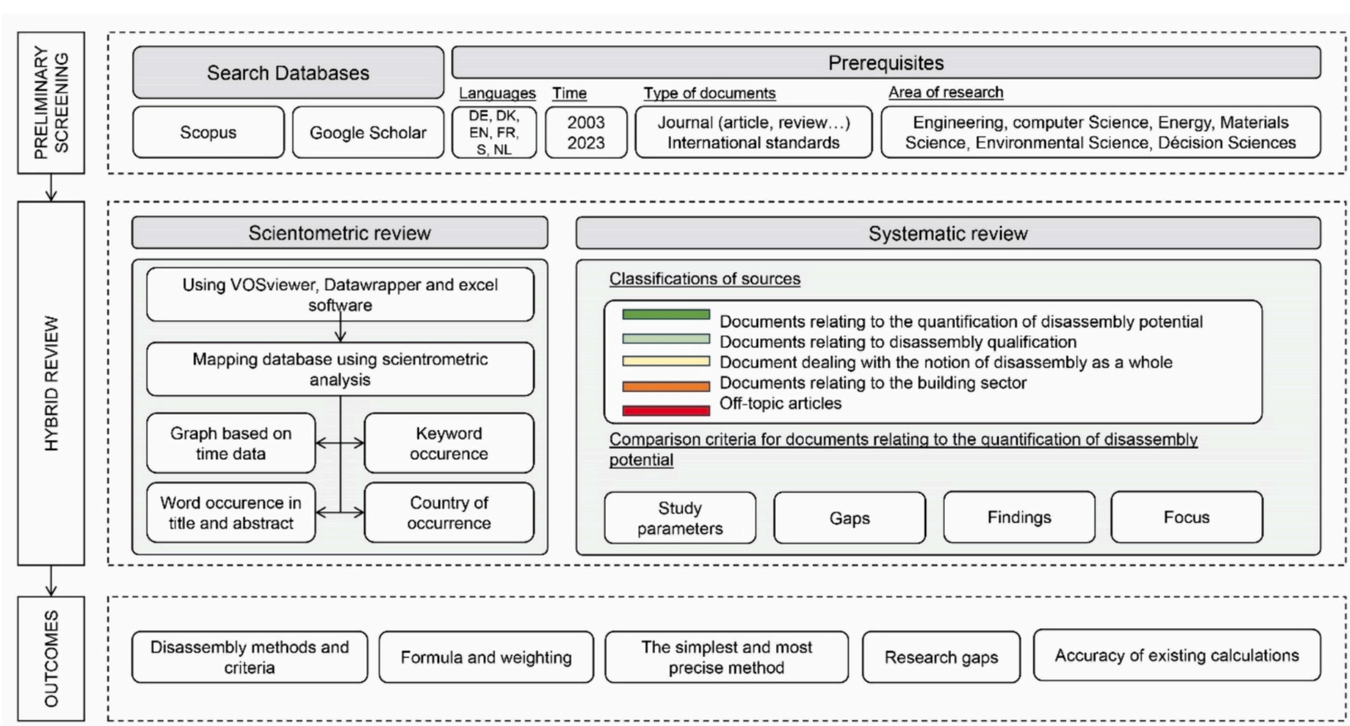


Fig. 2. Methodology of the literature review.

keywords. Using the dates of all selected articles, we produced a graph showing the number of publications per year since 2004 in Excel. To analyze the origin of each study, we drew maps (Europe and the World) of the number of articles per country using Datawrapper. The results of the scientometric are presented in Section 3.1.

Additionally, a search was carried out for case-study buildings that were designed and constructed by taking into account future disassembly opportunities. This was an important step to make this study more practicle and directly relevant to the construction industry. Eight buildings were identified, presented in Section 3.1. This list of projects is non-exhaustive, non-competitive and non-representative. Several criteria were predefined to select low and midrise buildings that can be potentially or fully dismantled. The chosen buildings needed to be designed based on the principles of circular building design and DfD with low environmental impact. The scientometric initial results indicated that Europe has the most advanced research and application of building disassembly research. Therefore, the search was limited to buildings located in Europe.

2.3. Systematic review

A systematic review involves the statistical examination of a broad range of scientific publications on the subject [43]. To accomplish this, we conducted a second round of document selection, retaining only those publications that quantitatively addressed disassembly potential based on the inclusion and exclusion criteria. The review was conducted based on the PRISMA approach to screen and select the study publications. The resulting papers at each phase of the search are illustrated in Fig. 3. This list includes the results of the keyword search (130 publications) and the publications added by the authors (53 publications), totaling 182 publications.

After skimming titles and abstracts, all publications that were out of scope were excluded. A total of 118 publications were selected initially.

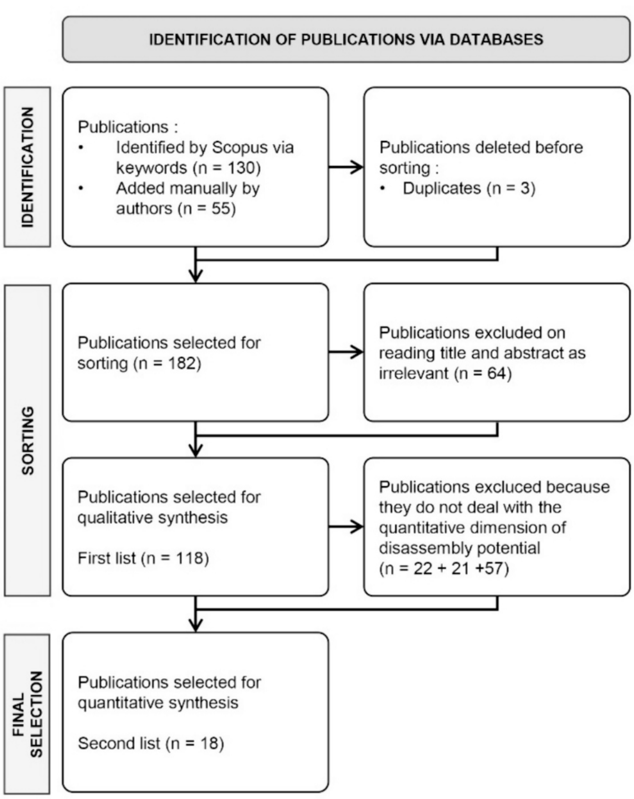


Fig. 3. PRISMA Flowchart for the selection of publications used in the literature review.

Among the publications, many publications were more focused on the positive environmental impact of buildings through life cycle assessments or building energy modelling. In other words, many studies did not address the DfD from a quantitative approach, addressing disassembly calculations with indicators and methods. Therefore, we had to filter the 118 publications to identify the publications that addressed the subject of disassembly potential quantitatively. Based on a thorough reading of abstracts and titles, publications were classified under four categories, namely dark green, light green, yellow and orange. The color dark green was assigned for publications dealing with the subject of disassembly potential quantitatively. Light green for publications qualitatively dealing with the topic. The color yellow for publications dealing with assembly potential, and the color orange for papers dealing with the building and construction sector. A complete list of all the publications can be found in Appendix B. The classification of the publications and their coloring allowed us to move from the identification and sorting stage to the final selection of the systematic review publications.

In total, 18 publications were chosen for the systematic review. The limited number of chosen publications is a result of the application of the inclusion and exclusion criteria. The focus of the study was to identify the quantitative studies that addressed the disassembly evaluation. Therefore, a thorough content analysis took place to read and analyze the 18 publications. The analysis of those publications allowed to development of a high-quality, state-of-the-art overview based on more specific details. Each document was analyzed to answer the research questions and to list and rank the most important criteria for disassembly evaluation and disassembly evaluation methods.

2.4. Results analysis and validation

Data analysis was conducted through reading and classification of themes and codes related directly to disassembly, reversibility of connections and components and buildings' demountability. The 18 publications were read and analyzed based on a content analysis. The content analysis focused on developing a coding scheme to categorize the main criteria and methods. Coding is a way of indexing or categorizing the text in order to establish thematic groups of ideas. The analysis method relied on reading and synthesis workshops following seven chronological steps: transcription, familiarization with the manuscripts, coding, developing tables of classification, application of disassembly calculation methods and criteria, charting data on flip charts, and interpreting the data. A detailed description of text processing can be found in the video by Attia [10].

Next, to validate the results and improve the analysis and conclusion of the review, the author conducted several internal workshops for content analysis. Each part of the study was designed and reviewed by the authors to ensure its accuracy. Three workshops were organized to evaluate the research strategy, including the PRISMA analysis, and improve the analysis. The first workshop took place on 10/08/2023 and aimed to define the research questions, the study guidelines, and the methodology to be adopted. The second, on 25/09/2023, was used to organize the results in terms of methods and to choose the figures to be used throughout the article. The third, on 30/11/2023, was a reflection on the results concerning the criteria and the discussion section. The fourth workshop took place on 12/01/2024 at the Sustainable Building Design Lab at Liege University to refine and elaborate the discussion section of the paper and reflect on the context of the study.

3. Results

In this section, we present the scientometric review analysis and the in-depth analysis based on the systematic review. Out of 182 publications, 57 generic publications were found related to DfD, 22 publications on the qualitative part of disassembly potential, and 21 on the notion of disassembly, as shown in Fig. 4. Only 18 publications were found to be

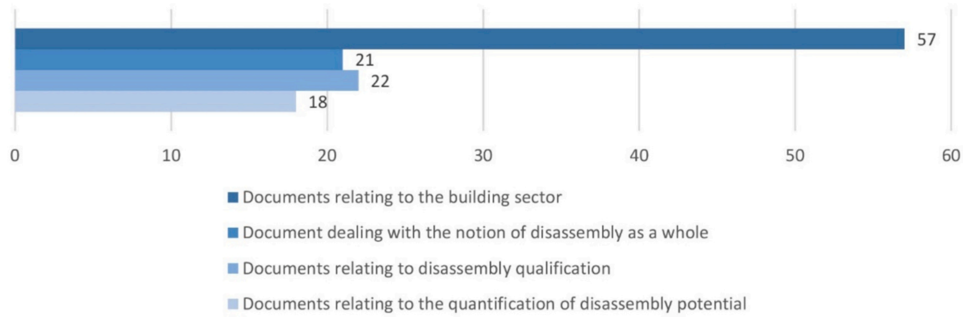


Fig. 4. Classification and quantification of publication on the potential for disassembly of buildings based on their approach.

highly relevant to answer our research questions.

3.1. Results of the scientometric review

Using VOSviewers software, publications data (authors' names, citations, countries) were presented in graphical maps based on keywords and recurring words in the title and abstract (see Fig. 5). The most recurrent words are remarkably similar between charts, for example, life cycle assessment. On the data-based mapping of the word occurrence included in the titles and abstracts, the most frequently recurring words are connection, recycling, value, circularity, construction sector, and cost. And, for the data-based mapping on the keyword occurrence, the words that stand out from the rest are environmental impact, circular economy, eco-design, architectural design, reuse, and sustainable development. The mapping revealed a proliferation of ways to measure circularity [26] and quantify or evaluate [54] buildings disassembly. The high frequency of use of the term 'connection' in paper titles reflects fragmented research that is on the rise in the area of building parts and components. Also, the high use of the term 'circular economy' in the keywords reflects a knowledge gap [4] of the interdependencies in materials reuse, material flows and building demountability [64].

Moreover, most of the studies that were associated with the term circularity or circular economy remain theoretical and discuss those concepts during the early design and modelling stages [44,57] of new construction. The graphs reflect the lack of application of circular approaches in the construction sector ecosystem [30] and the emergence of this field. None of the graphs indicated the presence of highly cited or applied indicators-related publications used for disassembly calculations. Also, the mapping did not reveal any connection or synergies to other indicators for circularity evaluation approaches. Even relevant EU frameworks and policy documents like level (s), Waste Framework Directive or Circular Economy Action Plan did not gain sufficient citations or impact in the maps of Fig. 5.

Using a software program called Data Wrapper, a world map showing the number of publications by country has been created. Fig. 6 reveals that Europe is the continent that has published the most articles on disassembly potential. Even if America or Asia have published a few articles or reports, Europe accounts for over 75% of the world's publications. To take our analysis further, on a European and global scale, England is the most advanced country on the subject, with 15 publications. Italy, Germany, and Belgium are close behind, with between 12 and 14 publications. (See Fig. 7.)

Disassembly potential is a recent topic, with the first publications appearing in 2004, but it's from 2014 to 2015 that the number of publications has increased considerably. Indeed, between 2004 and 2014, only 2 publications were published per year. Since 2015, the number of publications has risen steadily so that today, 26 publications will be published in 2022 and 2023. Since 2015, there has been a real interest in the idea of reusing and not just recycling.

To better visualize the progress in the practice of research into DfD and disassembly potential, a list of all the construction projects on this subject has been created (Table 2). To date, ten projects have been identified. These examples demonstrate the data analyzed above. The first building to take disassembly into account was built in 2007, and as time goes on, the number of projects increases.

3.2. Results of the systematic review

For a more in-depth analysis of the publications on the shortlist, a literature review was carried out using a matrix (see Appendix C and Appendix D). In this matrix, we extracted from each document the study parameters, focus, gaps, and key findings that enabled us to understand the disassembly criteria used by the authors and the methods developed. According to the timeline shown in Fig. 8 of major publications on the assessment of disassembly potential, Durmisevic initiated the subject of disassembly potential in her dissertation [27]: Design for Disassembly to introduce sustainable Engineering to Building Design & Construction.

3.2.1. What are the methods to assess the ability to dismantle buildings at the end of their service life for existing buildings or new construction?

Based on Fig. 8, we found that the most relevant work on the disassembly potential evaluation was initiated by Durmisevic in 2006 [27], Verberne in 2016 [66] and Van Vliet in 2018 (M. [61]). Circular economy approaches in the built environment are becoming more and more relevant to their impact on carbon and construction waste reduction. The master's thesis of Verbene, published in 2016, proposes a circularity assessment method for buildings: the Building Circularity Indicator (BCI). The indicator considers five scales: materials (MCI), products (PCI), systems (SCI) and buildings (BCI), which tend to represent the different levels of circularity of a building. The four indicators are evaluated in the order presented here, as each indicator is necessary for the calculation of the next. However, assessing the circularity of a building and the potential for reusing products is pointless if they cannot be disassembled without being damaged. Verberne, therefore, introduces the notion of disassembly potential at the scale of each product. The aim is to study connections and their ability to be disassembled. Taking disassembly into account in the calculation of PCI makes it a practical indicator of a product's circularity, as opposed to MCI, which is a purely theoretical indicator of a material's circularity. In 2018, van Vliet (M. [61]) further developed the work of Verberne until the Dutch Green Building Council DGBC adopted it and became a disassembly potential measurement method [23,24].

Since Durmevic Verberne's work, there has been a wide variety of other studies [19] that used his method or newly developed calculation methods for assessing the disassembly potential of a building [22]. Many are based on the methods previously developed, but none of them is really comprehensive of all criteria that impact disassembly potential. Accounting for all the criteria that make a building suitable for disassembly and calculating its potential for disassembly remains highly challenging. To answer the research question, the authors listed the most relevant methods that aimed to assess the ability to dismantle buildings using quantitative approaches. Sections 3.2.1.1 to 3.2.1.5 describe and

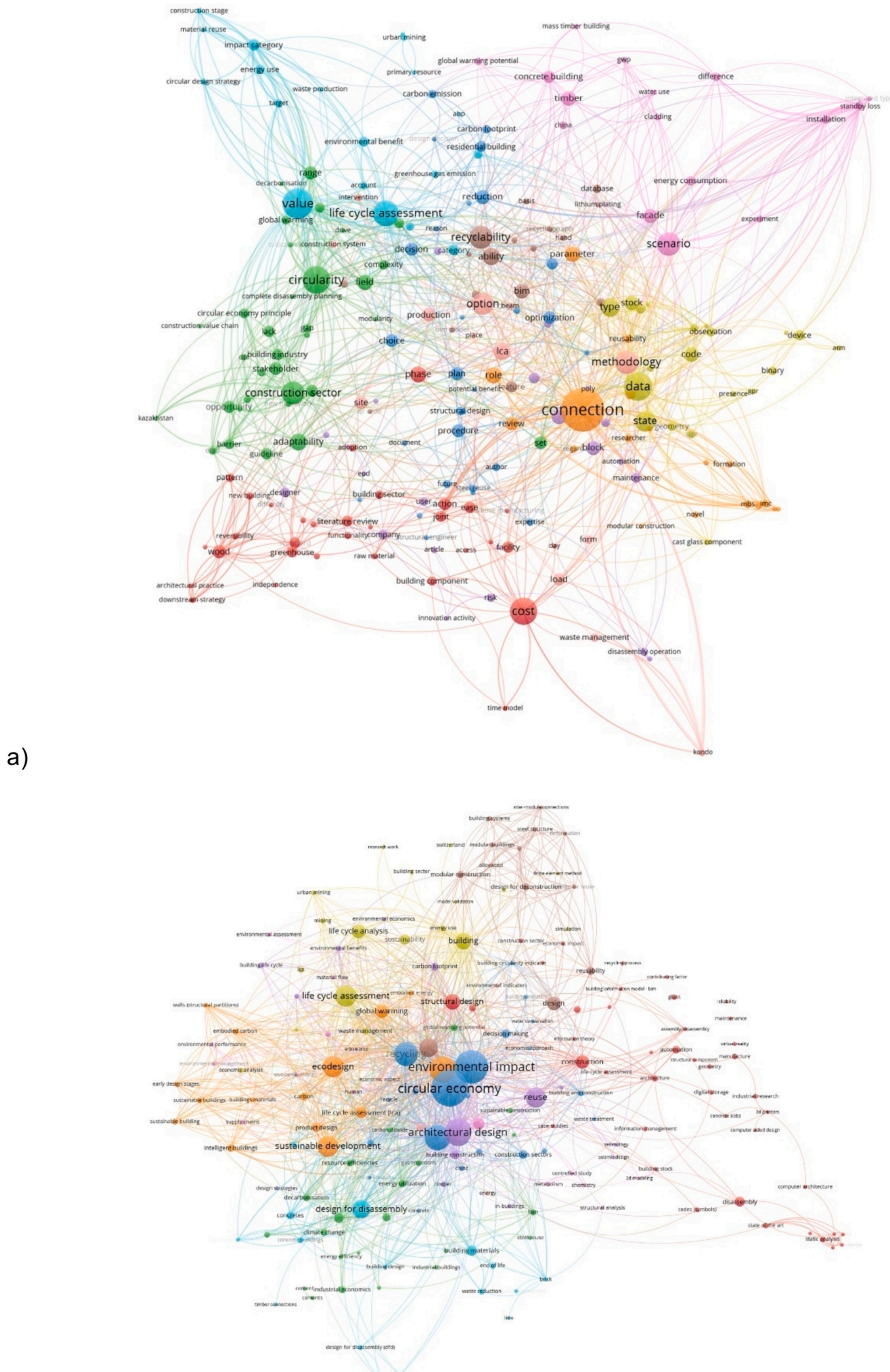


Fig. 5. Visualization for analysis of bibliometric data of all publications on the disassembly potential based on: a) word occurrence included in the title and abstract of each document, b) keywords occurrence.

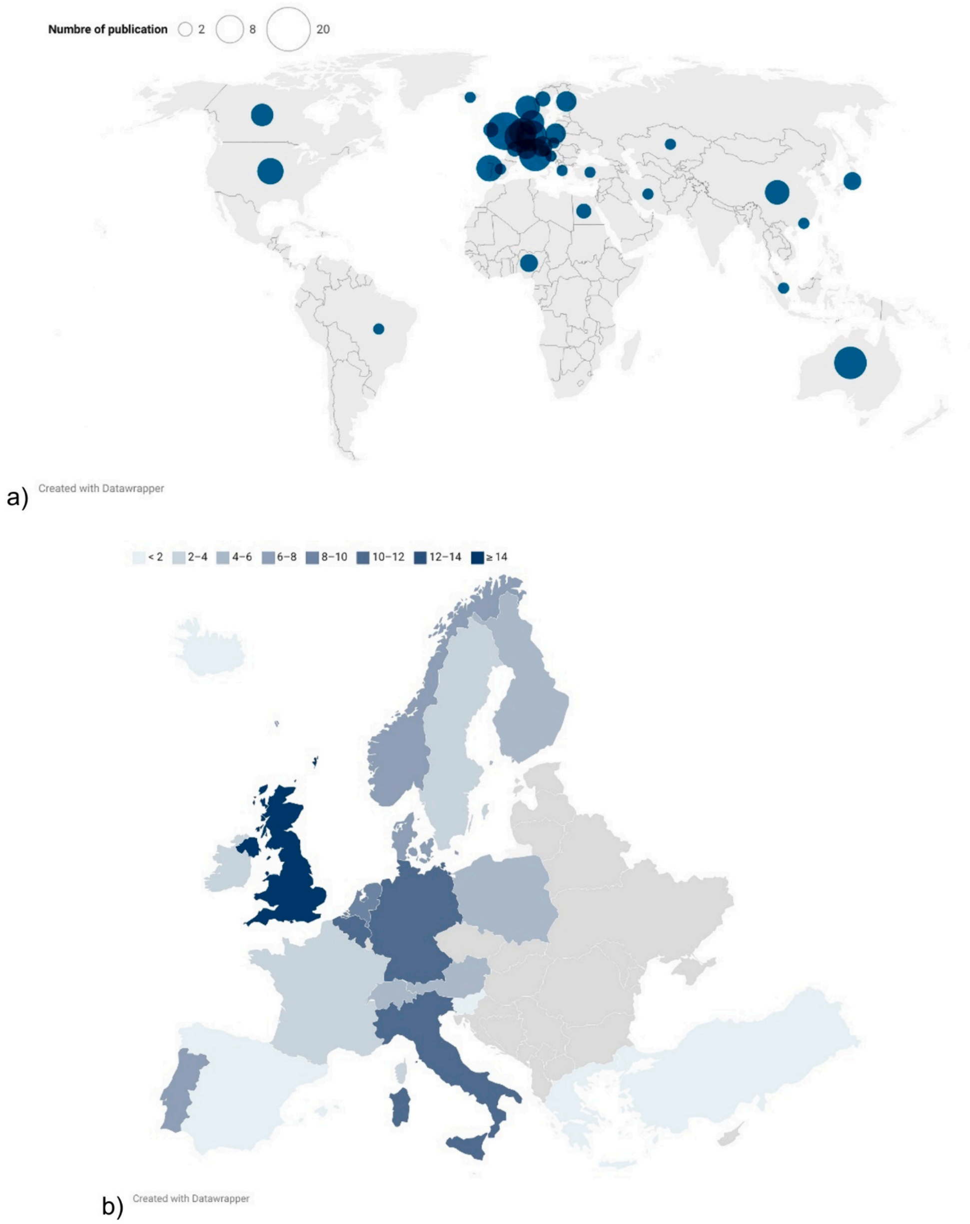


Fig. 6. Number of publications about the disassembly potential country of occurrence a) on a global scale and b) on a European scale.

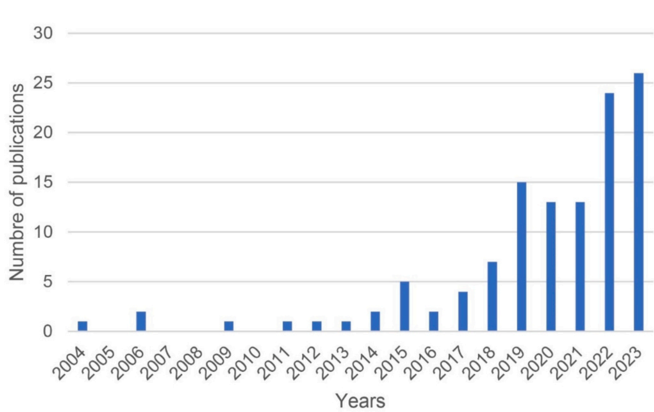


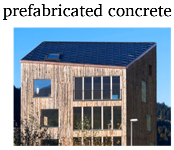
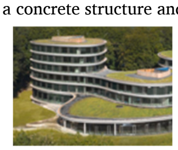
Fig. 7. Evolution of the number of publications on the disassembly potential of buildings per year.

analyze those publications.

3.2.1.1. Van Vliet method. One of the most accurate and complete methods is developed by van Vliet [63]. Inspired by the calculation method proposed by Dumirsevic dissertation on building connections disassembly potential in 2006 and Verberne in 2016, revised and improved thanks to different versions [63] is version 2.0. Mr. van Vliet's work is divided into three publications [61–63].

In his publication, (M. [61]) focuses on the disassembly potential indicator, which alone represents 50% of the BCI indicator developed by [66]. The study aims to validate the assumptions made during the development of the BCI and to refine the method for calculating the disassembly potential. Through two surveys of professionals in the sector, 12 criteria are selected and weighted. At the end of the two surveys, no criteria stand out, the idea of weighting the criteria is aborted, and only seven of the 12 criteria are finally retained: those classified as «technical requirement.» The seven criteria listed below are divided into two families: connection disassembly factor (CD) and product disassembly factor (PD).

Table 2
Examples of disassembly projects.

Project Name	Project photo	Architect	Place	Year
Het Centrum		Beneens	Westerloo, Belgium	2021
This office building is made up of standardized modular walls, floors, columns, and beams made of wood. The elements are assembled with prefabricated connectors, and the connections are dry, with screws and seals. Also, the foundation and the screed are made of cement-free concrete. And the glazed façade is easy to dismantle because it is made of aluminum profiles screwed onto a wooden substructure [67].				
Green Offices		Lutz	Givisiez, Switzerland	2007
Green Offices is made of prefabricated wooden elements. For instance, the façade and the floor units are prefabricated. And the connections between the different elements are reversible [9].				
Circl: Circular Pavilion		Architekten Cie	Amsterdam, Netherlands	2017
The load wooden structure is made locally completely dismountable. The connections are reversible because the materials are clicked or bolted together without the use of glue (the floor covering is not glued to the floor) [17].				
Braunstein Taphouse		ADEPT	Koege, Denmark	2020
This house is built with mechanical joints, and all the primary wall surfaces are free of paint and grout. The construction is made from unmixed sustainable materials [2].				
Circle House		Vandkunsten Architects	Lisbjerg, Denmark	2020
This construction is made with prefabricated concrete elements. The structural system is limited to a few different standardized elements to facilitate disassembly [65].				
Solar Direct Gain House N11		N11 Architekten GmbH	Zweisimmen, Switzerland	2014
This timber construction is made from untreated materials, composites have been avoided, and joints have been made using wooden screws or dowels (N11 [47]).				
Kalkbreite		Müller Sigrist Architekten	Zurich, Switzerland	2014
This construction is made with a concrete structure and prefabricated wooden façade [46].				
Triodos Bank		RAU	Driebergen-Rijsenburg, Netherlands	2019
The main structure is built entirely of wood. And there are unprocessed timber elements that are assembled using screws (meaning they can be unscrewed and reused [51]. The building products, components and materials are documented through a materials passport to be used in the future as 'loose property'. The building has 165,312 screws traced for future disassembly.				
Green House		cepezed Projects	Utrecht, Netherlands	2017
The Green House (Utrecht), was developed with demolished materials designed to be relocated in 15 (now 10) years [16]. The two-floor pavilion has a demountable steel skeleton of galvanized profiles. The grid sizing is based on the glass facade panels' size of the former Knoop barracks; these have been reused for the second skin and the greenhouse of the pavilion.				

(*continued on next page*)

Table 2 (*continued*)

Project Name	Project photo	Architect	Place	Year
De Tijdelijke Rechtbank		cepezed Projects	from Amsterdam to Enschede, Netherlands	2021

De Tijdelijke Rechtbank was constructed in Amsterdam and relocated to Enschede. The project was dismantled by Lagemaat BV and reassembled by cepezed projects [15]. The cepezed architects carefully dismantled and reassembled the building components in the new location, *Kennispark Twente* in Enschede [18], where it will serve as a business center. The disassembly potential of that project was determined based on the [24] method before it was actually disassembled, and a case study report on learned lessons has been published [58].

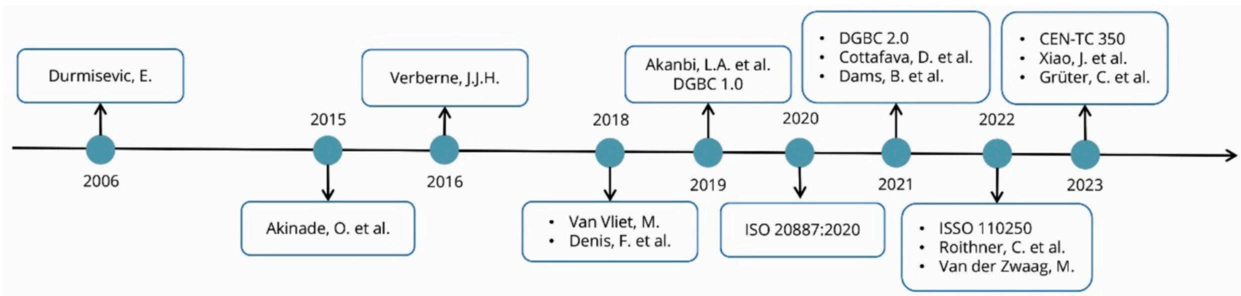


Fig. 8. Chronology of major work on assessing the disassembly potential of buildings.

1. Accessibility (CD)
2. Type of connection (CD)
3. Form of assembly (PD)
4. Independence (PD)
5. Method of manufacture (PD)
6. Assembly Sequence (CD)
7. Relational Schema Type (PD)

The formula for calculating the disassembly potential is improved compared to the work developed in [66]. The disassembly potential of each product is calculated by summing all criteria for the most unfavorable assembly. Mike van Vliet suggested the introduction of a criterion relating to the environmental impact of products. DGBC adopted this improvement and integrated it into a new method as part of a program to establish indicators of circularity [23]. The method confirms Verberne's hypothesis that it is impossible to establish a weighting between the different disassembly criteria. The main weakness of this method is obtaining the disassembly score. Indeed, summing the criteria can introduce a bias since a low score for one criterion can be compensated by a high score for another criterion.

In the 2021 publication [24], the method makes it possible to assess the disassembly potential of the entire building, starting by calculating the disassembly potential of each component and then each layer. The methodology is mainly based on the work of van Vliet, published in 2018 that includes seven criteria related to the technical potential of disassembly [61]. The methodology was adopted in the first version of the DGBC 1.0 in 2019, combining the Environmental impact as weighting for the building. The Disassembly potential product is the average of the four criteria [23] these are: 1) the type of connection, 2) the accessibility of the connection, 3) the independence of the components and 4) the geometry at the ends of the component from the composition in which it is located. Each criterion has a table with a score ranging from 0 to 1 associated with the situation encountered. In 2021, the second version of the DGBC 2.0 calculation method was released [24]. The main change was the introduction of the harmonic mean [37] of the four criteria where the disassembly potential product can be calculated. The identification of the difference between layers of components and connection is specifically stated in the latest version.

For each component, a connection disassembly potential (DPc) is determined by the geometric mean of the scores assigned to the connection type (CT) and accessibility (CA). The disassembly potential of a product is the harmonic mean of the four criteria to make it impossible to compensate for low-scoring factors. A composition disassembly potential (DPcp) is also determined by the geometric mean of the scores attributed to independence (ID) and component geometry (GPE). The component disassembly potential (DPp) is then obtained by the geometric mean of the previously calculated criteria. The scores of all components of a layer are then summed to obtain the layer disassembly potential (DPl). Finally, the disassembly potentials of each layer are summed to obtain the disassembly potential of the building as a whole (DPb).

It should be noted that the calculation method provides for weighting the disassembly potential of the components by their environmental cost indicator (ECI) in the calculation of the disassembly potential of the layer and the building. The ECI is an indicator, very widespread in the Netherlands, expressed in euros (€), which illustrates the environmental impact of a product throughout its life cycle [38]. This method calculates the disassembly potential of existing (older) buildings [58]. It has been used to calculate the disassembly potential of two newly constructed buildings: the Het Centrum and the Green offices [14]. However, the use of a digital 3D model for building connections can make the application of this methodology more easy to achieve.

3.2.1.2. ISO 20887. The ISO 20887:2020 [41] is a standard that provides a framework for the principles and issues of Design for Disassembly (DfD) and Design for Adaptability (DfA). This document covers economic, environmental, social, technical and functional aspects. This standard distinguishes the principles relating to adaptability with use and space and those relating to disassembly with material resources, as shown in Table 3. These criteria may apply to any building and civil engineering work. Whether renovation or new construction. However, certain principles are to be preferred according to the different case studies, and these principles must be applied to the main components. In this standard, no quantitative criteria or method of calculation of

Table 3
Principles developed in the standard [41].

Design principles for adaptability	Design principles for disassembly
Versatility (accommodate various functions with little change) Convertibility (anticipate the possibility of changing users' needs) Extensibility (allows the addition of new spaces, capacity, ...)	Easy access to components Independence Avoid unnecessary treatments and finishes. Support for economic models of reuse Simplicity Standardization Disassembly safety

building disassembly is developed. However, an informative guide to determine the different criteria to apply is presented in Annex C of standard ISO 20887.

3.2.1.3. ISSO 110250. The ISO [41] Reference Details standard provides examples of dismantlable building products and component connections through detailed section drawings [42]. The drawings are colored and represent the different building materials. The construction details are based on the EU CPR definition for products with CE marking. The report shows different types of connections and compositions for building products and evaluates the ease of disassembly to reuse the dismantle building components or products. The disassembly evaluation is based on characterizing the type of connection and the accessibility to the connection during the demolition process. The disassembly potential calculation approach is based on the DGBC method developed by Alba Concepts [24].

In ISSO 110250, it was not easy to show the independence (ID) and element geometry (GPE) in a technical detail drawing. Therefore, these two criteria were not included. The ISSO standard, written in Dutch, discusses the disassembly potential of existing construction details but not how those details can be improved regarding disassembly. ISSO 110250 includes circular detail drawings alternatives that include circular principles in the drawings and their scores. Also, the standard uses a color coding system (green, yellow and red) to distinguish the disassembly potential. Therefore, The document is a good start but not sufficiently useful for those who want to design and build for disassembly.

3.2.1.4. Witteveen+Bos and circular building methods. The Witteveen+Bos [68] Evaluation method is based on the [24] research for building disassembly and provides designers with relevant insights to design more modular/demountable structures [24]. The method report, written in Dutch, is based on a hierarchical classification system for building components and materials associated with life expectancy. Alba Concepts conducted a study to see what the major differences were between civil infrastructure and buildings. Witteveen + Bos elaborated on this research to determine a methodology focussed on civil infrastructure and not on buildings. The new 2023 method does discuss the disassembly potential of existing construction details but not how those details can be improved in terms of disassembly.

The method is purely theoretical and focuses on the technical aspects of disassembly, such as connection types or materials binding. The method includes several examples of technical details and section drawings in existing buildings. However, the example do not present the practice of architectural detachable details, which is the most important topic for designers and builders [50]. Witteveen + Bos is currently still conducting the follow-up on this research to determine the practical implications of the method on case studies.

Another document developed by the Dutch Circular Building is the Disassembly Details Guide [50]. This guideline goes a step further and offers concrete tools to design releasable details as well as possible in the building sector. The study of the Dutch Circular Building builds on the ISSO report and DGBC method and provides constructive feedback and guidance on improving the disassembly potential of building connections. In this case, the study further improves the details rather than just evaluating them.

3.2.1.5. Grutër, Roithner and Akanbi methods. Three articles develop methods for assessing disassembly potential different from the one published by the DGBC method [24] entitled Circular Buildings.

In the study [52], a case study is carried out on a building modeled in wood and concrete. The calculation method used is a method for assessing the recyclability of a smartphone using static entropy (developed by [39] and reviewed by [52]) but applied to a building designed to be disassembled by Honic and al. using BIM software.

Called RPR ("recyclability inherent in the relative product"), the method involves calculating the recyclability rate of a building based on its composition and structure. This method focuses primarily on the number of materials and the different mixes of materials used to design the building. The more materials are mixed, the less they can be recycled. To achieve this, they use a "material passport" for the different structural levels of a building: Product, Component, Composition and Material. In this study [52], the entire building is taken into account, as each component and material is broken down. It takes into account its components, sub-components and sub-sub-components. In this method, a sub-component is a component, and a sub-sub-component is a material. And also the different types of existing connections (screwed, bolted, glued…). This method relies primarily on the static entropy (SE) of materials, which is a good indicator of their recyclability to calculate a building's RPR. Indeed, if a material is not mixed, it will have a low SE and will be more easily recycled. On the other hand, if a material is mixed or bonded with another, its SE will be high and difficult to recycle.

This method shows that if no specific deconstruction is carried out (= demolition), concrete buildings, for example, are less recyclable. However, if a structure is built with a high number of materials at SC and even SSC levels, such as wooden buildings, the recyclability rate will be higher. The RPR decreases as the materials in a building are mixed. The method only considers wood and concrete structures. As this study was carried out only on a building designed to be disassembled, it is not known whether this method can also be applied to existing buildings.

The study by [3] focuses on the development of a D-DAS (Disassembled and Deconstruction Analytics System), which is a different version of the DAS score developed in the article by [5]. This score provides an assessment of end-of-life building performance right from the design stage. The main objective is to ensure an efficient choice of materials to ensure the circularity of a building at its end of life. The system architecture is based on existing building information. It comprises four layers that are logically connected to function as a single system. Firstly, we have the data storage layer, which collects data about deconstruction, material properties and building design. Secondly, the semantic layer offers two possibilities: the formatting of data exchange and the provisioning of data to the application layer. Thirdly, the analytical and functional layer of the architecture enables the development of D-DAS functionalities: 1. construct analysis of rendering throughout the life of the building, 2. Analysis of deconstruction of building components, 3. Pre-deconstruction analysis, 4. Design advice for deconstruction, and 5. visualize dismantling. Finally, the application layer through BIM software and visualization and simulation platforms.

Although this method allows designers to try out several combinations by proposing alternatives to optimize the building's end-of-life and provides quantified data on a building, this method only quantifies the number of materials that can be reused, not their disassembly potential.

The method proposed by [35] focuses primarily on the reuse of wooden components in the design process. This study focuses on two perspectives. The first aims to study the recyclability at the beginning of the life cycle (SOL) of buildings through a design for disassembly (DfD) strategy by calculating the potential for disassembly and reuse through a system of scoring components one by one. The second evaluates the end-of-life (EOL) potential of buildings to ensure the continuity of wooden components, using a disassembly-based design optimization tool (DfromD).

The study of these two methods revealed that it is preferable to study the potential for reuse right from the design process. It allows better optimization of building components. The DformD-optimization tool was created not only to assess the potential for disassembly and reuse but also to facilitate the use of reused components in new construction.

Finally, in these three methods, several case studies are proposed to understand better how to apply the calculation methods. In Grüter et al. [35] study, the case study is based on an existing residence in Switzerland. In Roithner et al. [52,53] and Akanbi et al. [3], the case studies are carried out on modeled buildings created to test their methods. As with the Grüter method, we cannot be certain that the methods can be applied to pre-existing buildings. However, for existing buildings, no digital mockup exists. It may be that the Grüter et al. [35] method cannot be applied either.

3.2.1.6. Conclusion. Our systematic literature review indicates Dutch approaches dominate the proliferation of disassembly calculation methods. Table 4 explains the difference between the five methods based on eight attributes that were distilled from the literature review. The eight attributes together allow us to evaluate each method and investigate its approach to define the disassembly potential. The technical nature of disassembly requires a detailed breakdown of the building as an object and as an assembly of components and materials. The reliance on LCA was not a priority when calculating the disassembly potential because LCA is mainly focused on the materials flows regardless of the ease or success of materials recovery during building demolishing. Therefore, in the first step, we compared the five methods based on their sensitivity and ability to scan building connections and products during pre-demolition audits or early design stages. The eight attributes used in Table 4 allow us to make specific distinctions on the quantitative nature of each method and its ability to score or scale the disassembly potential and handle the complexity of building nodes or details through a weighing system or agglomerated rating approach.

As a result of our review, one must distinguish theoretical and practical disassembly potential approaches to assess the disassembly potential of a building. Most of the listed calculation methods above are theoretical. The theoretical methods are purely based on technical aspects of disassembly, such as the connection types or materials binding as indicated in the abovementioned methods. Also, the object, whether a building or infrastructure, of dismantling, plays a major role in influencing the disassembly method. For example, Witteveen + Bos tried to implement some practical factors regarding weather influence and the surrounding infrastructure. Our review shows that taking into account external factors like weather underground parameters is more suitable for civil engineering project disassembly evaluation and less for buildings. Civil engineering objects are always part of a 'network.' Buildings are 'connected' with each other during their lifetime. However, it is usually feasible to surround a building with fences and 'start deconstructing' without influencing the surroundings.

Thus, the practical or empirical approach is missing. The practical approach should contain the process and financial factors associated with disassembly at the end of a building's lifespan. The practical approach is influenced by other factors, such as material degradation due to weather influences, the effect of construction work on the surrounding infrastructure and the method of disassembly. The practical approach should involve demolishing contractors and post-demolition approaches to develop consistent disassembly evaluation methods that combine theoretical and practical approaches towards accurate and reliable calculation methods.

3.2.2. What are the criteria to assess the ability to dismantle buildings at the end of their service life?

In defining the potential for disassembly, Elma Durmisevic, in her 2006 doctoral thesis, introduced the principle of disassembly criteria [27]. She identifies 17 sub-criteria necessary to assess the disassembly potential of a building. These criteria are classified into three main categories: functional, technical, or physical. Functional decomposition criteria are used to determine the degree of functionality of a component. Then, technical decomposition criteria are used to determine the order in which products are assembled. The physical decomposition criteria are used to assess the importance of components and whether any replacement is possible. Although there is general agreement that the sub-criteria developed by [27] work form a sound basis for disassembly, they do not take into account all the crucial aspects of disassembly. Indeed, most of these sub-criteria are characterized as technical. However, the environmental and economic aspects of disassembly are not taken into account.

Numerous criteria and principles for disassembly have been introduced as a result. In 2007, Guy & Ciarimboli formulated ten main principles for DfD, taking into account material properties and deconstruction methods, connection types and accessibilities, electrical and plumbing systems and component handling, deconstruction safety, simplicity and interchangeability [36]. These major principles are taken up by most of the scientific community and reformulated in the form of criteria for inclusion in calculation methods. In 2016 and 2018, Verberne revived the methods of Durmicevic and refined them (see Section 3.2.1.1). In 2020, the ISO 20887:2020 report introduced a new criterion based on reuse through the support of economic models. In 2021, the criterion "existence of a detailed plan for disassembly" was developed in the publication by [22] [22]. This is also part of the material passport requirements, where many material passport instances imply the requirement of a disassembly plan. More recently, in [52,53], an approach that takes greater account of building design parameters. Roithner developed an approach that counts the number of materials, the number of components, the mass of each material, the total mass of the product, the mass shares of components, etc. [53]. Very recently, a

Table 4
Comparison of the five calculation methods based on eight attributes extracted from the literature.

Method/ Attribution	Sets terms & definitions for building disassembly	Defines detailed disassembly criteria (technical criteria)	Defines economic criteria (cost-related)	Defines environmental criteria (LCA-based)	Evaluate the disassembly potential based on material components	Evaluate the disassembly potential based on connection composition	Set a quantifiable score for disassembly criteria or subcriteria	Allows to calculate an aggregated indicator for overall disassembly
Van Vliet Method	✓	✓ 7	✓ 1	✓ 1	✘	✓	✓	✓
ISO 20887	✓	✓ 5	✘	✘	✘	✓	✘	✘
ISSO 110250	✓	✓ 3	✘	✘	✘	✓	✓	✘
Witteveen+Bos & CB Methods	✓	✓ 5	✘	✘	✘	✓	✘	✘
Grutër, Roitner & Akanbi Methods	✘	✓ 4	✘	✘	✓	✘	✓	✘

study on design for and from disassembly was published by [35] [35]. They developed a calculation method and a design aid based on numerous criteria divided into 4 categories: reusability (inspired by Hradil et al. [40] [40], structural connections inspired by Enzio Pozzi [32] as well as damage caused during disassembly and accessibility/ independence, the importance of which was guaranteed in Thormark's work [59].

Thus, numerous ways have been developed to assess the disassembly potential of buildings, depending on the different study cases or approaches desired. In most cases, however, the same method is used to evaluate the criteria. Their evaluation or grading follows Durmisevic's subjective scale-based evaluation. In other words, each criterion can be assigned a real value between 0 and 1 (or 0 and 5) depending on the situation encountered, 0 being the most unfavorable situation and 1 (or 5) the most favorable. The personal justification of the grading and the subjective interpretation of each detail and connection requires developing more robust ways of evaluation. Our review indicates more than twenty or so publications in existence with calculation methods. The results of our review of indicators across those studies are summarized in Table 5.

As many building disassembly evaluation methods rely on previously developed criteria and make different interpretations for their implementation, the title and wording of each criterion and their definitions may vary between methods or can be found very similar. Table 5 is for information only. The names of the criteria may differ between the appellation in the method and the table. For example, independence may be called crossing [20]. Based on Table 4, six criteria were identified as the most important based on their recurrence across the identified methods. In addition, a hierarchy of criteria from the most important (and recurring) to the least important has been established. The following paragraphs illustrate the criteria individually and list them based on their level of importance, with criterion 1 being the most important and criterion six the least important.

- Criterion 1: Type of Connection

Introduced by Durmisevic [28], this criterion is the most widely used and, therefore, the most important. In fact, almost all the methods for calculating the potential for disassembly use it. This criterion is qualitative. In other words, the evaluation is based on the quality of the connection and not the number. This criterion is generally accompanied by an evaluation scale that assigns a score to a connection according to its type. For example, the score will be higher if the connection is dry (bolt, screw, etc.). If the connection is chemical (glued, welded, etc.), the score will be lower.

- Criterion 2: Component accessibility

The accessibility of the connection is also a very important qualitative criterion. The potential for disassembly will differ if the connection is directly accessible or if there are manipulations to be carried out before the products linked to the connection can be disassembled.

- Criterion 3: Independence of the component

Independence means that the different components of the same layer or different layers are intertwined with each other, either completely, partially or, in the best case, not at all. This criterion is, therefore, a qualitative criterion used in many calculation methods.

- Criterion 4: Geometrical Composition or geometry of product edge

This criterion, which can be confused with the independence of the components, will enable a qualitative assessment to be made of how the components are placed in the composition. It determines whether the composition is open or closed and, therefore, whether the component

Table 5
Comparison of the different calculation methods and the criteria used.

Publications	Criteria Assemblysequence	Componentaccessibility	Degreeoffreedom	Disassemblysafety	Dismantlingdamage	Easeofassembly	Easeofdisassembly	Elementcomplexity	End − of − lifewaste	Functionalseparation	Geometryofproductedge	Independency	Manufacturingmethod	Normalization/standardization	Reusability	Reversibility	Simplicity	Structuralstrength	Supportingbusinessmodels	Transportability	Treatmentandfinishing	Typeofconnection	Typeofelement	Typeofrelationalmodel
[3]													×			×					×	×	×	
[5]													×			×					×	×	×	
[19,20]		×									×	×										×		
[22]		×		×								×		×		×					×			
Denis et al. 2018		×					×								×	×		×		×	×			
[27]	×	×									×	×		×							×	×	×	×
[35]		×	×		×	×	×	×	×			×	×		×			×			×			
[41]		×		×								×		×			×		×		×			
[42]		×									×	×										×		
[52,53]								×				×												
[64]		×									×	×										×		
[24]		×									×	×										×		
[61]	×	×									×	×	×									×		×
[66]	×	×								×	×	×		×								×		
[69]												×	×									×		

can be disassembled without obstruction.

- Criterion 5: Treatment and Finishing

The treatment and finishing criterion is mainly used for the reuse of materials. However, depending on the different coatings or materials used for finishing, the disassembly potential of a building can be considerably reduced. For example, if asbestos has been used, there will be a safety issue as it is a toxic material and will complicate dismantling. It is, therefore, a qualitative criterion.

- Criterion 6: Dismantling Damage

Dismantling damage is a criterion used less frequently in the methods. It was developed by Grüter et al. [35] and is only used in this method. However, this criterion is relatively important as it will reduce the potential for disassembly and limit the reuse of materials. This criterion is qualitative but can also be quantified according to its use.

4. Discussion

Literature highlights how there is a need for best practice guidance, tools, methods and indicators [33] to disincentivize building demolition towards more sustainable design practices that promote building disassembly and reuse of its parts and components. Building material waste and demolition are design mistakes that can be avoided through the DfD. In this hybrid review, we identified the key criteria and methods that have been developed in the last twenty years to assess building disassembly potential. This field is not new, dating to the work of Brand [13] on what happens after with building they are built and the work of many schools in the 1990ies [21]. However, the EU Circular Economy Action Plan published in 2015 [29] and the introduction of level (s) framework for building sustainable assessment [25] attracted the attention of researchers to this domain. The study is an enabler to future frameworks and tools that aim to provide design for disassembly decision support in the built environment. This is the first comprehensive review of building disassembly evaluation methods and criteria, providing practical recommendations to foster circular economy principles uptake in the construction industry. In the following sections, we discuss the study's key findings and articulate a series of recommendations towards a standardized and comprehensive approach that allows assessing the potential for disassembly of buildings and future reuse of building materials. We further reflect on the strengths and weaknesses of this study and provide future perspectives for policymakers, building stakeholders and scientists.

4.1. Study findings and recommendations

Our review indicates the proliferation of evaluation criteria and methods of building disassembly potential. The scientometric review results confirmed the leadership of the EU member states in the field of DfD, disassembly and reversible building connection systems. The mapping in Fig. 5 revealed a proliferation of ways to measure circularity [26] and quantify or evaluate [54] building disassembly. The high frequency of use of the term 'connection' in paper titles reflects fragmented research that is on the rise in the area of building parts and components. Also, the high use of the term 'circular economy' in the keywords reflects a knowledge gap [4] of the interdependencies in materials reuse and building demountability [64].

Out of 182 publications published between 2004 and 2024, only 18 publications developed quantitative criteria or methods to evaluate the disassembly potential of new or existing buildings. The 18 publications analyzed and presented in Appendix C provide a variety of approaches and methods to evaluate building connections, components, and products on a component level of building level. Also, the study identified eight existing buildings (Table 2) that are constructed based on the DfD principles and can be used as case studies or reference buildings.

More importantly, the systematic literature review presented the most important methods and criteria to assess the building disassembly potential and measure circularity. We found the DGBC method as one of the most relevant and consistent methods [24]. The method is flexible and can evaluate the dismantling potential depending on the type of connection, number of connections for components, products, and structures. Despite the monetization and integration of the environmental impact of materials, the method can be used universally if those aspects are excluded. The Building Circularity Indicator (BCI) indicator remains the most logical criterion to evaluate building connections. Based on the study findings, we strongly recommend the use of the six criteria listed in Table 5 and Section 2.2. Also, the study allowed us to see that accessibility of the connection and dismantling damage criteria are tightly connected in one-factor criteria in most calculation methods. On the other hand, it is better to separate them and rely on the six disassembly criteria listed in Table 5.

On the other hand, the recommended criteria and methods require further development. Most of the reviewed methods remain theoretical and do not emerge from field experience. None of the investigated studies addresses the disassembly sequence for the building components and connections and the structural and accessibility dependencies of construction components, products and materials [1]. The feedback of demolition contractors and workers in real demolition conditions or through demolition audits is missing. Furthermore, most of the methods are generic. There are no specific methods for assessing the future reuse potential of timber or steel building infrastructures [56], for example. In addition, the geographical concentration of the investigated studies in Europe highlights a regional bias in the available research. The lack of a universal, standardized method for calculating building disassembly potential and future materials reuse potential remains a major challenge. The interpretations of the criteria and application of the DGBC method [24], particularly regarding composition and connections, can vary remarkably [14].

4.2. Strengths and limitations of the study

The mixed research methodology that was used, combining both scientometric and systematic methods, was successful in providing a general and specific overview at the same time. The study was able to track most English-speaking publications in a representative and objective way based on Scopus and Google Scholar. However, non-English speaking documents depended on the author's network through the EU COST Actions and CEN committees and the author's search in foreign languages. The non-English speaking content was more random, but we made sure to provide a short English description of those documents in Appendix D. While the literature identified over 50 qualitative and generic studies, there are only around 20 quantitative studies. It demonstrates the lack of maturity in this field. Therefore, we cannot claim to present a fully representative overview. However, to our best knowledge, this work is the first and most date review in this area. The chronological review made it possible to understand the evolution of the methodologies over the study period (2004–2024). We organized more than four workshops to validate with all the authors the method and the results found. We thus ensured the robustness of the approach and its utility during early design stages and pre-demolition audits. One of the main strengths of the study is that many methods have been reviewed, analyzed, and compared. This made it possible to establish links between the different methods and their criteria and to be able to interpret them.

On the other hand, it is important to acknowledge the limitations of the study. Firstly, we deliberately decoupled the evaluation of disassembly potential from its environmental impact and LCA studies. It is important to note that a building exhibiting high disassembly potential is not necessarily a sustainable building. Also, our content evaluation methodology was based entirely on reading and human content analysis.

We did not rely on machines to interpret the text. Finally, the reviewed evaluation methods were not tested on real case studies. Despite the presence of many disassembly methods and projects [55], like the *Tijdelijke Rechtbank* [58], listed in Table 2, we could not find pre-construction examples that applied the disassembly methods. We focused on answering the research question first to identify the most relevant methods for conducting case study-based calculations or benchmarking. Therefore, we believe that our review provides valuable information on the disassembly of buildings. However, it remains theoretical because case studies can shed light on several critical aspects within the field of building demolition and end-of-life.

4.3. Implication on practice and future work

The implications of the research results for practice call for strategic interventions to quantify the sustainability evaluation approaches of the construction industry. Firstly, it is necessary to accelerate the development of a standardized calculation method for assessing the potential for disassembly. There is an urgent need for standardized methods based on case studies and exemplary buildings and databases for building connections. Investing in such a knowledge ecosystem will allow us to learn how to perform the building disassembly evaluations more consistently. Standardized demolition audits are also recommended to ensure a systematic approach to the assessment process. The creation of digital models in BIM format coupled with material passports for disassembled buildings is crucial to evaluate their disassembly potential accurately and swiftly.

Such an approach of standardization and development of evaluation methods should be used not only at the national level but also at the EU and even the international level. This would ensure consistency and effectiveness across borders. The evaluation methods can be coupled with building permit issuing steps and building performance certification. This disassembly evaluation could be linked to building materials passport for all buildings, as well as an obligation to produce digital twins to facilitate dismantling at the end of a building's life. For sure, there are limitations of digital twins and material passports due to the post-occupancy modifications. Builders can glue, cement, or pour a flooring system or create wall finishing that impedes the disassembly potential. Therefore, standardization must go hand in hand with testing the disassembly sequence and materials recovery potential of the most common construction components connections in experimental destruction labs and on-site settings. There is a need to display the structural and accessibility dependencies at connection and product levels to calculate the disassembly potential and, finally, the building materials recovery potential. Experimental investigation can ensure that disassembly and reuse are considered right from the design phase.

We need to remind the reader that the main reason for a low rate of building components reuse and disassembly is 1) the high cost/time needed to disassemble a building [34] and 2) existing standards are not aiding the circular reuse of building components [8]. Current regulations do not allow the reuse of building components and products. Safety, durability, and stability are paramount in the construction, but we need to spread decentralized third-party material testing facilities to cross this barrier. From a research point of view, several major projects need to be carried out. In parallel, the development of the demolition sector, including contractors and workers, should prioritize the acquisition of technical skills for effective on-site dismantling abilities. There is also a need to provide learning material and good scoping/guidelines for the interpretation of disassembly evaluation methods.

Therefore, we believe future research should focus on more detailed case study evaluation to ensure that the disassembly evaluation methods are accurate and can be applied consistently. In addition, there is a need to develop and customize disassembly assessment methods for specific construction technologies, such as wood, steel, concrete, and hybrid constructions. We believe modularity will play a major role in the construction industry under the influence of DfD. This targeted approach will ensure the applicability and accuracy of disassembly potential assessments for various construction materials and methodologies. Through modularity and specialization of the disassembly evaluation methods based on the construction technology, we will be able to steer and manage the positive change towards modular and low-impact buildings in the construction industry.

5. Conclusions

The paper reviewed and discussed evaluation criteria and methods for building disassembly potential. The study approach combined a scientometric approach reviewing >180 publications and systematic reviews of 18 highly relevant publications. The importance of disassembly and revisable connections was highlighted, and examples of DfD-based projects were listed. The paper recommends the calculation methods developed by the Dutch Green Building Council as one of the highly relevant approaches. It presents six key criteria to assess the disassembly potential of buildings, namely: 1) Connection type, 2) Connection accessibility, 3) Independence of the component, 4) Geometrical Composition or geometry of product edge, 5) Treatment and Finishing, and 6) Dismantling Damage. Several challenges were identified, and future research recommendations included the evaluation of case studies and standardization of the disassembly evaluation method based on the study recommendations.

CRediT authorship contribution statement

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

Declaration of competing interest

None.

Data availability

A dataset is availavle and cited in the text with a DOI.

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Appendix A. Keywords excluded from the Scopus search

- Amino Acids	- Human cell
- Animal	- Hydrogen-Ion Concentration
- Animals	- In vitro study
- Apoptosis	- Medical application
- Biomedical Applications	- Medical nanotechnology
- Cell Deaths	- Molecules
- Cell Line, Tumor	- Mousse
- Cell Nucleus	- Nanoparticle
- Chemistry	- Nanoparticles
- Controlled Drug Delivery	- Nanostructures
- Cyclodextrins	- Neoplasm
- Cytology	- Neoplasms
- Diseases	- Particle Size
- DNA	- PH
- Doxorubicin	- Polyethylene glycols
- Drug delivery	- Polyethylene oxides
- Drug delivery system	- Proteins
- Drug release	- Scanning electron microscopy
- Enzymes	- Silica nanoparticles
- Flocculation	- Sodium
- Fluorescence	- Sulfur compounds
- Genes	- Supramolecular Chemistry
- Hela Cell Line	- Targeted Drug Delivery
- Hela Cells	- Unclassified Drug
- High Resolution Transmission Electron Microscopy	- Zeta Potential

Appendix B. Complete list of review publications

No.	Publication ajouté par les auteurs
Aborde le potentiel de désassemblage de manière quantitatif	
	Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction : A BIM based Deconstructability Assessment Score (BIM-DAS). Resources, Conservation and Recycling, 105, 167-176. https://doi.org/10.1016/j.resconrec.2015.10.018
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	Campain (2023), Evaluation du potentiel de désassemblage des batiments en bois en vue d'une réutilisation.
	CEN-TC 350-SC 1_N139_Gap consultation draft report
	Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings : Addressing the gap between embodied impacts and design aspects. Resources, Conservation and Recycling, 164, 105120. https://doi.org/10.1016/j.resconrec.2020.105120
	Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P., & Emmitt, S. (2021). A circular construction evaluation framework to promote designing for disassembly and adaptability. Journal of Cleaner Production, 316, 128122. https://doi.org/10.1016/j.jclepro.2021.128122
	Denis, F., Vandervaeren, C., & Temmerman, N. D. (2018). Using network analysis and BIM to quantify the impact of Design for Disassembly. Buildings, 8(8). Scopus. https://doi.org/10.3390/buildings8080113
	Durmisevic, E. (2006). Design for disassembly as a way to introduce sustainable engineering to building design & construction.
	Grüter, C. et al. (not published) Design for and from Disassembly with Timber Elements: Strategies based on two Case Studies from Switzerland
	ISSO 110250 Circulariteit in referentiedetails. (s. d.). ISSO. Consulté 7 juillet 2023, à l'adresse https://open.isso.nl/publicatie/isso-rapport-110250-circulariteit-in-referentiedetails/2021
	Platform CB'23 (2023) Losmaakbaar detailleren, in Dutch, Platform CB'23, Version 1.0, Delft, The Netherlands.
	Roithner, C., O. Cencic, M. Honic, et H. Rechberger. « Recyclability Assessment at the Building Design Stage Based on Statistical Entropy: A Case Study on Timber and Concrete Building ». Resources, Conservation and Recycling 184 (2022). https://doi.org/10.1016/j.resconrec.2022.106407.
	Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance ISO 20887:2020. Consulté le 7 juillet 2023.
	van der Zwaag, M. (2022). Data-Driven Decision-Making for Circular Building Design : Development of an automated decision-support framework for an improved circular design workflow. https://repository.tudelft.nl/islandora/object/uuid%3Ad4752ebd-7d70-4136-b0d7-685fc070ac56
	Van Vliet, M., Van Grinsven, J., Teunizen, J. (2021). Circular Buildings Meetmethodiek Losmaakbaarheid version 2.0. Alba Concepts.
	van Vliet. (2018). *Disassembling the steps towards Building Circularity*.
	Verberne, J.J.H. (2016). Building circularity indicators an approach for measuring circularity of a building
	Xiao, J., Zeng, L., Ding, T., Xu, H., & Tang, H. (2023). Deconstruction evaluation method of building structures based on digital technology. Journal of Building Engineering, 66, 105,901. https://doi.org/10.1016/j.jobe.2023.105901
Aborde DfD de manière qualitatif	
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	Askar, R., L. Bragança, et H. Gervásio. « Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings ». Applied System Innovation 5, no 1 (2022). https://doi.org/10.3390/asi5010024.
	Check-list Conception Réversible, Guide bâtiment durable
	Crowther, P. (2018). Re-Valuing construction materials and components through design for disassembly. In Unmaking Waste in Production and Consumption : Towards The Circular Economy (p. 309-321). Scopus. https://doi.org/10.1108/978-1-78714-619-820181024
	Crowther, P. « Exploring the Principles of Design for Disassembly through Design-Led Research ». In IOP Conf. Ser. Earth Environ. Sci., édité par Behm M., Aranda-Mena G., Wakefield R., et Mellencamp E., Vol. 1101. Institute of Physics, 2022. https://doi.org/10.1088/1755-1315/1101/6/062031.

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	Fatourou-Sipsi, A., et I. Symeonidou. « Designing [for] the Future: Managing Architectural Parts through the Principles of Circular Economy ». In IOP Conf. Ser. Earth Environ. Sci., Vol. 899. IOP Publishing Ltd, 2021. https://doi.org/10.1088/1755-1315/899/1/012014.
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	Honic, Meliha, Iva Kovacic, et Helmut Rechberger. « Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study ». Journal of Cleaner Production 217 (20 avril 2019): 787-97. https://doi.org/10.1016/j.jclepro.2019.01.212.
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	Kręt-Grześkowiak, A., & Baborska-Narożny, M. (2023). Guidelines for disassembly and adaptation in architectural design compared to circular economy goals—A literature review. Sustainable Production and Consumption, 39, 1-12. https://doi.org/10.1016/j.spc.2023.04.020
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	Ostapska, K., Gradeci, K., & Ruther, P. (2021). Design for Disassembly (DfD) in construction industry : A literature mapping and analysis of the existing designs. Journal of Physics: Conference Series, 2042(1), 012176. https://doi.org/10.1088/1742-6596/2042/1/012176
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The spreadsheet list can be found in [12].

Appendix C. Literature review matrix

Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	**REFERENCE**	**STUDY PARAMETERS**	**FOCUS**	**GAP**	**FINDINGS**
1	Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Davila Delgado, J. M., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. Journal of Cleaner Production, 223, 386-396. https://doi.org/10.1016/j.jclepro.2019.03.172	* P = La performance de la construction dans le temps * RU = La fraction réutilisable des matériaux de construction * RC = La fraction recyclable * γ = La fraction de performance * t = Âge du bâtiment en année D15 * NC = Nombre total de connexions * ne = Nombre total d'éléments de construction possibles * ndc = Nombre de connexions démontables * nFb = Nombre d'ensemble préfabriqué * νSf = Volume de	Conception d'un système d'analyze de démontagne/ déconstruction (D-DAS: disassembly and deconstruction analytics system) afin de prendre en compte l'analyze des performances en fin de vie dès le processus de conception et de construction. Intergrer au BIM Fonctionalités developpées: - Analyze la perormance du bâtiment sur toute sa durée de vie - Analyze de la déconstruction des elements - Conseil pour la conception en vue de la déconstruction	Quantifie la quantité de matériaux pouvant être réutilisés, pas leur potentiel de désasemblage.	Cette technique permet aux concepteurs d'essayer plusieurs combinaisons. Fourni des données chiffrées. Le plug-in propose des alternatives pour optimiser la fin de vie du bâtiment. Quantifie la démontabilité via DAS [5]

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Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		matériaux sans finitions secondaires * νm = Volume total des matériaux de construction * νhtt = Volume de matière sans contenu dangereux * α = Durée de vie du batiment * β = Facteur de pondération de l'importance de l'utilisation de connexions démontables sur la réutilisation des matériaux de construction en fin de vie * λ = Facteur de pondération de l'importance de l'utilisation d'ensembles préfabriqués sur la réutilisation des matériaux de construction en fin de vie * μ = Facteur de pondération pour l'importance de spécifier des matériaux sans finitions secondaires sur la réutilisation des matériaux de construction en fin de vie * ρ = Facteur de pondération pour l'importance de la spécification de matériaux sans contenu dangereux sur la réutilisation des matériaux de construction en fin de vie	Appliqué au BIM (plug-in BIM ou visioneuse BIM)		
2	Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction : A BIM based Deconstructability Assessment Score (BIM-DAS). Resources, Conservation and Recycling, 105, 167-176. https://doi.org/10.1016/j.resconrec.2015.10.018	* DAS = Score d'évaluation de la déconstructibilité * M = Ensemble de matériaux, c'est-à-dire M = {M 1, M2, …, Mn} * C = Ensemble de composants, c'est-à-dire C = {C 1, C2, …, Cn} * E = Ensemble de connecteurs, c'est-à-dire E = {E 1, E2, …, En} * DMD = Modèle de conception pour la déconstructabilité * r1 = Est vrai si l'échantillon est. réutilisable * r2 = Est vrai si l'échantillon est. recyclable * P = Est vrai si l'échantillon est. préfabriqué * c = Type de connexion; c = {cf., cb, cn, cd} * cf. = Connexion fixe * cb = Connexion Boulonnée * cn = Connexion clouée * cd = Connexion grace à des cheville	Création d'un model mathématique pour évaluer le potentiel d'un batiment par un score indicateur la déconstructibilité: Building information Modelling based Deconstructability Assessment Score (BIM-DAS) en phase de conception. 3 objectifs: -Identifier les principes de conception critiques qui assurent la déconstructibilité du bâtiment. -Développer un système objectif, i.e. BIM-DAS pour noter le degré de déconstuctibilité des bâtiments -Pour tester les performances et la convivialité du BIM-DAS	Même poids pour le score de déconstruction et de récupération. D'autres critères pourraient être considérés: manipulation du matérial, …	Méthode de calcul developée: - Variables: matériaux, composants, connexion, nombre,position, orientation, toxicité, … - Sortie: Perte, énergie perdue, éléments récupérables, … - > Somme pondérée de Score de déconstruction & Score de récupération = DAS Score Organization en sous-systèmes: couches. Conception de sous-systèmes indépendants Principes de conception DfD: - utilisation de boulon plutôt que de colle - matériaux durables - matériaux sans finitions secondaires - matériaux non toxiques - ensembles préfabriqués + minimise le nombre de type et le nombre de composants et de connexions Economiquement, (CoûtduDfD) < (ValeurdesMatériauxRecylcable) – (CoûtdeElimination)

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Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		* n = Nombre totale d'échantillon * t = Type de materiaux de l'échantillon; t = {acier, béton, bois, etc.,} * tn = Rapport type-nombre de materiaux pour le sous-système * x = Est vrai si l'echantillon est. toxique * s = Est vrai si le materiau a des finitions secondaires * v = Volume de l'échantillon en mm3 * φ = Position spatile et orientation de l'échantillon * p = Position de l'échantillon dans l'espace 3D * r = Rotation de l'échantillon dans l'espace 3D * Ew = Le total des déchets en fin de vie * Bq = Nombre totale d'elements dans le batiments * Tr = Total d'élement récupérable dans Bq * ε = Résidus * Ee = L'énergie perdue en fin de vie * Ec = L'énergie grise totale et l'énergie nécessaire à la construction du batiment * Ed = L'énergie grise totale et l'énergie nécessaire à la déconstruction du batiment * Dscore = Score de déconstructibilité * Rscore = Score de récupération * dc = Rapport des connexions démontables			
3	CEN-TC 350-SC 1_N139_Gap consultation draft report	Pas de paramètre d'études puisque pas de mise en œuvre de méthode pour évaluer le potentiel de désassemblage	Passe en revue toute les lacunes des articles, normes, documents sur la circularité des batiments.	A part une section qui aborde le potentiel de désassemble avec le DfD et le Design for reuse, ce document ne fournit pas d'information sur les méthodes de caluls pour le déssassemblage. Ce n'est. qu'une revue des lacunes des normes et des études à propos de la circularité des batiments. Même si le sujet du désassemblage est. abordé puisqu'il fait parti de la circularité d'un batiment.	Les normes à propos du potentiel de réutilisation d'un building ne devraient pas être seulement sur la structure mais aussi sur l'ensemble du bâtiment. Il faudrait ajouter des design/conception avec une espérance de vie indéfinie. Dans l'ISO 20,887 il devrait ajouter des règles par catégories (acier, béton, bois …) Les études devraient prendre en compte la sécurité lors des démolition et déconstruction. Besoin d'un guide/normes et pour réutiliser les éléments de construction, pour écarter la « peur de réutiliser des parties de structure » La facilité et la capacité à déconstruire et réutilisé est. influencer par: - Le type de connexion - Le poids des matériaux - Si le bâtiment est. construit sur site ou avec des éléments préfabriquer H19
4	Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings :	* BCIplein = Indicateur de circularité du bâtiment (version complète)	Ce concentre éssentiellement sur le développement d'une méthode de calcul servant à	Ne présente pas une méthode de calcul pour évaluer le potentiel de	Dans cette étude, il est. dit que de nos jours (en 2021) il n'existe pas de norme mondialement reconnue quant à la

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Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
	Addressing the gap between embodied impacts and design aspects. Resources, Conservation and Recycling, 164, 105120. https://doi.org/10.1016/j.resconrec.2020.105120	* BCIsimplifié = Indicateur de circularité du bâtiment (version simplifié) * ICE = Indice de circularité des éléments * Fd = Somme de tous les poids maximaux * Fje = Poids nominal * fj = Facteur pondéral du produit j dans la formulation PBCI * Frj = Fraction de materiau recyclé pour le produit j * Fuj = Fraction de materiau réutilisé pour le produit j * Je = Indice des critères de conception * IR = Recyclabilité intrinsèque * J = Nombre de composants pour l'ensemble du batiment * j = Indice de produit * Js = Nombre total de composants pour la couche s * Lav,j = Durée de vie moyenne d'un produit similaire sur le marché par rapport au produit j * Lj = Durée de vie du produit j * LFI = Indice de débit linéaire * LK = Niveau d'importance * LKs = Niveau d'importance pour les couches s * MCIp = Indicateur de circularité des materiaux pour le produit p * Mj = Masse totale du produit * MADAME = Score de réutilisation des materiaux * Ms. = Masse totale de tous les composants de la couche s * n = Nombre total de critères de conception * PBCI = Indicateur prédictif de circularité des batiments * PBCIplein = Indicateur prédictif de circularité des batiments (version complète) * PBCIsimplifié = Indicateur prédictif de circularité des batiments (version simplifié) * PCIp = Indicateur de circularité du produit * RC = Contenu recyclé * RPI = Indicateur du potentiel des ressources * S = Nombre total de couches de construction * s = Création d'un indice	quantifié la circularité d'une batiment. Il ne prends donc pas que en compte le désassemblage, mais aussi ca réutilisation.	désassemblage mais seulement une méthode pour calculer un indice de circulrité des batiments.	conception pour le désassemblage car ils existent énormément de méthodes. Akinade et al. (2017) ont identifié 15 facteurs regroupé en 3 groupes pour le DfD: - Les facteurs liés aux matériaux; - Les facteurs liés à la conception; - Les facteurs liés aux travailleurs du site. Ils ont également identifié 38 facteurs critiques regroupé en 5 catégories: - Les lois et les politiques rigoureuses - Les processus de conception de déconstruction et compétences - La conception en vue de la réutilisation des matériaux - La conception pour la réutilisation des matériaux - La conception pour la flexibilité du bâtiment Moffatt et Russell (2001) ont introduit quelques principes de DfAD: 1) durabilité, 2) polyvalence, 3) accès aux services, 4) redondance, 5) simplicité, 6) évolutivité, 7) indépendance et 8) information sur les bâtiments.

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Méthode utilisée

Lecture des introductions, résultats et discussions des articles de la short list.

No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		de calque * SCI = Indicateur de circularité du système * SCIs = Indicateur de circularité du système * Uav,j = Marché intensité moyenne d'utilisation par an du produit j * Uj = Intensité d'utilisation par an du produit j * Vje = Valeur de l'évaluation * ERV = Efficacité des ressources basée sur la valeur * W0j = Déchets non valorisables provenant de l'écoulement linéaire pour le produit j * WFj = Déchets non valorisables issus du processus de valorisation du produit j * Wj Déchets non valorisabels pour le produit j * Xj = Utilitaire du produit pour le produit j			
5	Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., Walker, P., & Emmitt, S. (2021). A circular construction evaluation framework to promote designing for disassembly and adaptability. Journal of Cleaner Production, 316, 128,122. https://doi.org/10.1016/j.jclepro.2021.128122	Pas de paramètres d'étude puisque ce document est. un rapport de ce qu'il manque aux différentes études	Création de l'outil CCEF (Circular Construction Evaluation Framework) pour quantifier le niveau de circularité d'un projet. Application sur 4 cas d'étude de différent type (matériaux conventionnels, préfabrication avec matériaux conventionnels, préfabrication avec matériaux bio-sourcés, construction modulaire). Mise en application des directives internationnales, notamment ISO 20887:2020. Béton, acier, bois.	Notation peu précise: comment savoir avec précision dans quelle tranche de pourcentage se trouve le projet? Pas de pondération des critères.	Le CCEF prend en compte les critères: Conception (désassemblage, adaptibilité, simplicité), sécurité, durabilité, matériaux, traitement, connexions. Chaque critère est. noté de 0 (non circulaire) à 5 (circulaire). Si l'évaluation du critère est. oui ou non, oui=5 et non = 0. Si l'évaluation du critère se fait en %, le pourcentage est. traduit en une note de 0 à 5. Notation de 0 à 5: - 0: <10% - 1: 10–29% - 2: 30–49% - 3: 50–69% - 4: 70–89% - 5: > 90% Résultat sous forme de tableau, une section pour la globalité du bâtiment et une section pour les élements/composants. Le score maximal pouvant être obtenu est. 70, pouvant être converti en pourcentage pour donner unenote globale au bâtiment.
6	Denis, F., Vandervaeren, C., & Temmerman, N. D. (2018). Using network analysis and BIM to quantify the impact of Design for Disassembly. Buildings, 8(8). Scopus. https://doi.org/10.3390/buildings8080113	* Accessbibilité de la connexion, * Transportabilité (en lien avec le poids et le volume du matériaux), * Résistance (point de rupture pour deux éléments liés par une connexion irréversible), * Masse, * Reversibilité de la connexion, * Temps de désassemblage, * Dépendance séquentielle.	Developpement d'une méthode: DNA (Disassembly Network Analysis) pour quantifier l'impact du désassemblage sur les bâtiments. Etudie l'interdépendance des élements. Application de la méthode à 2 exemples: un assemblage linéaire et un assemblage complexe.	Méthode de calcul qui se concentre plus sur des résultats techniques: temps de désassmeblage estimé,transportabilité des composants extraits, … plutôt que sur une quantification du potentiel de désassemblage. Pourrait permettre d'avoir une note pour le potentiel de désassemblage en soustrayant le nombre d'élements récupérés et le nombre d'élements perdus?	Méthode divisée en 4 étapes: - vérification rapide (détermine si l'élement peut être déconnecté) - définition des chemins potentiels (liste des moyens d'accéder de rompre la connexion) - quantification des paramètres (temps de désassemblage, nombre d'élements perdus, …) - résultats
7	Durmisevic, E. (2006). Design for disassembly as a way to introduce sustainable		Etudie les design de conception pour les bâtiments transformables.		2 critères clés: indépendance (fonctionnelle: design) et échangeabilité (technique: ordre hiérachique et physique: connexions)

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Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
	engineering to building design & construction.				Resultat: diagramme radial. KPI for transformation: - décomposition fonctionnelle - systématisation et regroupement - relations hierarchiques entr éléments -spécification de l'élement de base - séquence d'assemblage - géométrie de l'interface - type de connection - coordination du cycle de vie assemblage/désassemblage+G36 Décompositionn technique - schéma relationnel - spécification de l'élement de base Décomposition physique - géométrie desbords - séquence d'assemblage - connexion - coordination du cycle de vie assemblage/désassemblage Décomposition fonctionnelle - Indépendance fonctionelle - systématisation
8	Grüter, C. et al. (not published) Design for and from Disassembly with Timber Elements: Strategies based on two Case Studies from Switzerland				
9	ISSO 110250 Circulariteit in referentiedetails. (s. d.). ISSO. Consulté 7 juillet 2023, à l'adresse https://open.isso.nl/publicatie/isso-rapport-110250-circulariteit-in-referentiedetails/2021				
10	Roithner, C., Cencic, O., Honic, M., & Rechberger, H. (2022). Recyclability assessment at the building design stage based on statistical entropy : A case study on timber and concrete building. Resources, Conservation and Recycling, 184. Scopus. https://doi.org/10.1016/j.resconrec.2022.106407	* le nombre de materiaux (Nm), * le nombre d'élément (Ne), * la masse de chaque materiau (Mi), * la masse total du produit (Mp), * les parts massiques des composants (mj; mj = Mj / Mp) Ce qui va permettre de caluler: * la concentration de chaque matériaux (cij) * l'entropie statique (Hj) de chaque partie, * l'entropie statique total (Hp) Grace à l'entropie statique hypothétique maximal (Hmax), on calcule la « recyclabilité inhérente au produit relatif » RPR.	Revoit la technique de Honic et al. [39]. Le document se base sur un seul batiment, qui à été concu pour etre par la suite désassemblé. Technique de calcul appelé RPR (« recyclabilité inhérente au produit relatif ») qui consiste à calculer le taux de recyclabilité d'un batiment en fonction de sa composition et de sa structure. Elle prends en compte ses composants, sous composant et SSC. En appliquant cette méthode, le résultat dinal est. un pourcentage de recyclabilité. Démonstration de la méthode sur un batiment designé et modéliser grace à un logiciel BIM en bois ou en béton. Utilisation d'un passeport pour les différent composant.	Ne prends en compte que les structure en bois et en béton. (voir si il y en à d'autre meme peu utilisée) Etude réalisée seulement sur un batiment concu pour ettre désassemblé. Pas de vérification sur d'autres batiments, déjà construit.	Le batiment en béton est. d'avantage recyclable si aucune déconstruction précise n'est. réalisé (= démolition brut), or comme le batiment en bois utilise un nombre de materiaux plus elevé, au niveau des SC et même des SSC, cela permet d'avoir un taux de recyclabilité plus élevé. Le RPR diminue à mesure que les matériaux d'un bâtiment sont mélangés.
11	Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance ISO 20887:2020. Consulté le 7 juillet 2023.		Vise à fournir un cadre pour les principes de DfD/A et les points clés qui necessitent d'être questionnées par les acteurs de la construction, permettant ainsi d'integrer ces principes au projet. Applicable à tout type de bâtiment et d'ouvrage de génie civil et à tout type de projet (construction neuve, rénovation, …) Les principes décrits dans le document doivent être appliqués aux	Le document n'a pas pour vocation d'établir une méthode de calcul du potentiel de désassemblage. Il dresse un guide succint avec des notations simples (oui/no ou 0 à 5). Il n'a aucune hierarchisation des citères ni note globale.	Les principes à privilegier varient en fonction du scénario d'étude. Par exemple, un principe sera à privilegier plutôt qu'un autre en fonction de la durée de service du bâtiment d'étude. 3 principes de design pour adaptibilité: - versatilité (accueillir diverse fonctions avec peu de changement) - convertibilité (anticiper la possibilité de changement de besoin des utlisateurs) - extensibilité (permet l'ajout de nouveaux espaces, capacité, …) 7 principes de design pour le désassemblage:

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(*continued*)

Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
			élements et composants principaux, (négliger les élements qui pourraient être obsolètes ex: système de vetilation). Traite des aspects environnementaux, sociaux, economiques, techniques et fonctionnels		- facilité d'accès aux composants - indépendance - éviter les traitements et finitions inutiles - soutien des modèles économiques de réutilisation - simplicité - standardization - sécurité de désassemblage 5 niveaux d'étude: système, élements, composants et assemblage, sous-composant, matériaux. Annexe C: Guide succint pour mesurer le DfD sans hiérachisation entre les critères. Critère qui penvent être groupée sous forme de check-list dans une matrice. - facilité d'accès aux composants (0 à 5) - indépendance (0 à 5) - éviter les traitements et finitions inutiles (yes/no) - soutien des modèles économiques de réutilisation (% or yes/no) - simplicité - standardization (% par catégorie dimension, composant, connexion, modularité, interopérablité) - sécurité de désassemblage (0 à 5)
12	van der Zwaag, M. (2022). Data-Driven Decision-Making for Circular Building Design : Development of an automated decision-support framework for an improved circular design workflow. https://repository.tudelft.nl/islandora/object/uuid%3Ad4752ebd-7d70-4136-b0d7-685fc070ac56				
13	Van Vliet, M., Van Grinsven, J., Teunizen, J. (2021). Circular Buildings Meetmethodiek Losmaakbaarheid version 2.0. Alba Concepts.	* Type de connexions, * accessibilité de la connexion, * indépendance, * géométrie,	Methode de calcul du potentiel de désassemblage en construction Champ d'application: - pour developper des connexions facilement désassemblables Version anméliorée par rapport à celle de 2019 grâce aux retours et recommandations	Méthode de calcul qui semble être la plus précise.	Le potentiel de détachabilité n'est. pas une indication de circularité à lui seul. La méthode doit donc être appliquée en relation avec d'autres principes de circularité. Attribution d'un score compris entre 0 et 1 pour chaque paramètre en fonction du tableau de référence fourni. Mise en place d'une équation reprenant tous les paramètres (pondérés) pour calculer le potentiel de désassemblage de chaque ensemble plus du bâtiment dans sa globalité.
14	van Vliet. (s. d.). *Disassembling the steps towards Building Circularity*.	* Accessibility to connection * Type of relational pattern * Assembly sequence * Method of fabrication * Independency * Assenmbly shape *Type of connection * Deconstruction safety * Dasassembly instructions * Disassembler expertise * Number of operations * Disassembly costs	une révision de la méthode de calcul l'indicateur de circularité BCI (Building Circularité Indicator) (Verdener, 2016). L'étude se concentre sur l'indicateur « disassembly possibility of a building » qui représente à lui seul 50% sur résultat BCI. Elle tend à valider les hypothèses faites lors de l'élaboration du BCI et à affiner la méthode de calcul du potentiel de désassemblage.		
15	Xiao, J., Zeng, L., Ding, T., Xu, H., & Tang, H. (2023). Deconstruction evaluation method of building structures based on digital technology. Journal of Building Engineering, 66, 105901. https://doi.org/10.1016/j.jobe.2023.105901	* Ddéconstruction * Ed = énergie totale libéré au cours du processes de déconstruction * Eq = énergie nécessaire à la déconstruction * Er = ressource énergétique des objets déconstruits	Développement d'une méthode pour évaluer la déconstruction des structures des bâtiments grâce à l'utilisation d'une technique de balayage laser. Cette technique de balayage sans contact permettrait d'évaluer la déconstruction, améliorer la sécurité et faciliter la		

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(*continued*)

Méthode utilisée					
Lecture des introductions, résultats et discussions des articles de la short list.					
No.	REFERENCE	STUDY PARAMETERS	FOCUS	GAP	FINDINGS
		* ε = énergie libéré pour d'autres raison (pertes) * Dr. = mesure dans laquelle l'élémetn de structure du batiment peut etre déconstruit * Rr = N qui peuvent etre recyclé * Or = enironnement ou se situe le batiment * ti = rapport des différentes formes de structure * di = rapport du mode de connexion des composants * ri = rapport entre les éléments préfabriqués ou les unités directement décomposables *pi = rapport entre les composants ou les unités et la position dans la structure du bâtiment à déconstruire * R1…Rn = forme de ressource de chaque élément structurel après avoir été déconstruit * tm et sm = conditions exterieurs (toxique ou suffisant) * hm = facteurs humains * pm = processus technique * mm = méthodes de construction * i = type de facterus d'influence pertinents * n = nombre total de parties structurelles * CCi = cout de la déconstruction * RPRi = cout de materiaux directement recyclables et déconstruit * CDL = cout économisé par l'élimination de déchet * ACCi = le coût de modification de l'utilisation secondaire des composants après la déconstruction de la structure, * CTi = cout de transport engendré par l'utilisation des ressources * CDi = cout de déconstruction * CRi = cout de l'utilisation des ressources * Cde = cout de la déconstruction * Vu = valeur d'utilisation * Cdi = cout de l'elimination	transformation de la démolition destructrice en une démolition optimale		

The spreadsheet list can be found in [12].

Appendix D. Explanations for key non-English references

Author(s)	Report Title
[23]	***Circular buildings: Meetmethodiek Losmaakbaarheid versie 1.1. the Hague, The Netherlands.***
The document is developed by the Dutch Circular Building with Disassembly Details Guide. This guideline goes a step further and offers concrete tools to design releasable details as well as possible, both in the building sector. The study of Dutch Circular Building builds on the ISSO report and DGBC method and provides a constructive feedback and guidance on how to improve the disassembly potential of building connections. In this case, the study goes one step further to improve the details rather than just evaluating them.	
[42]	***Rapport 110,250 Circulariteit in referentiedetails. Rotterdam, The Netherlands.***
The ISSO (2020) Reference Details report provide examples of dismantlable building products and components connections through detailed section drawings. The drawings are colored and represent the different building materials. The construction details are based on the EU CPR definition for products with CE marking. The report shows different types of connections and compositions for building products and evaluates the ease of disassembly to reuse the dismantle building components or products. The disassembly evaluation is based on characterizing the type of connection and the accessibility to the connection during the demolition process. The disassembly potential calculation approach is based on the DGBC (2022) method developed together with Alba Concepts. The ISSO report, written in Dutch, does discuss the disassembly potential of existing construction details, but not how those details can be improved in terms of disassembly. The document is therefore a good start, but not yet sufficiently useful for those who want to design and build for disassembly in practice.	
van Vliet et al. [62].	***Circular buildings: Meetmethodiek Losmaakbaarheid versie 1.1.***
This document is an early version of the Dutch Circular buildings: Disassembly potential measurement method version that was published in November 2019, the report 'Circular Buildings – a measuring methodology for releasability' has been published containing the first five practical examples. These are calculated using the Detachability measurement method v1.0. One of the practical examples is the Temporary Court on the Zuidas in Amsterdam. Various circular design principles were used in this project. Most of the document is embedded in DGBC v2. [24]	
Platform CB'23 [50]	***Losmaakbaar detailleren. Delft, Netherland.***
This guideline provides concrete tools for releasable details as well possible to design, both in the building construction and civil engineering sector. The guide builds on this existing initiatives, such as the aforementioned measurement methods, the ISSO report and the Platform CB'23-guidelines Facilitating future reuse (2023) and Circular design (2021), both of which address disassembly. The guide states that the type of connection and the accessibility and replaceability of connections in existing buildings are often not drawn but are essential for the disassembly. Also recording information about the materials, construction products and elements, so that later it is known what can and should be done with it (for example in a materials passport). Broad disassembly of building components principles is formulated. The purpose of this guideline is to encourage designers to provide releasable detailing. Therefore, the guidance contains many example details. The guide includes valuable terms and definitions of disassembly and related concepts in circulation.	
Teunizen et al. [58]	***Meetmethodiek losmaakbaarheid—Casestudy Tijdelijke Rechtbank. Dutch Green Building Council.***
Based on the disassembly calculations method of DGBD (2021) this report presents a case study for a courthouse in Amsterdam. A building inspection concluded that the disassembly index v2.0 of the Temporary Court is 62% and therefore lower than the dismantling index v1.0 of 88%. The main reasons for this lower score are the factors 'intersections' and 'form containment' of the connections that are of little use where it is the main supporting structure and facade, which means: the disassembly is positively influenced by a proportional weighting of the four releasability indicators included in the formula at v1.0. During the building inspection it turned out that spacious 90% of the products match exactly the way with the as the built drawings. The quality/lifespan, where disassembly influences both elements. After all, is loosening a bolt or nut requires more labor, and non-detachable products provide consequential damage to underlying products and therefore a limited reuse value.	
Witteveen+Bos [68]	***Beoordelingsmethode Losmaakbaarheid in de GWW. Versie 1.0***
The Witteveen+Bos [68] Evaluation method for buildings disassembly provides designers with relevant insights to design structures that are more modular/demountable. The method report, written in Dutch, is based on a hierarchical classification system for building components and materials associated with the life expectancy. Discusses the disassembly potential of existing construction details, but not how those details can be improved in terms of disassembly. The method is purely theoretical and is focused on the technical aspects of disassembly, for example the connection types or materials binding. These methods to measure detachability are already widely used. However, these publications do not discuss the practice of architectural detachable details, while that is the most important topic for designers and builders.	

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