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Developing a grading tool for sustainable design of structural systems in buildings

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“Sustainability is the art of balance
Environmental Awareness, Economic Growth, and Social Responsibility
to improve human well-being”

Linköping, Sweden
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Abstract

Construction is known for consuming large quantities of raw materials and high amounts of energy. In 2018, the construction industry was responsible for 6% of global energy consumption, 11% of global CO_2 emissions, and approximately 36% of the total waste in the European Union. These drawbacks are just a part of the gap between the construction sector and Sustainability, which can also be perceived as challenges to the industry and demands for new and innovative strategies to increase Sustainability. For example, recent efforts of EcoDesign on structural systems show a trend in the importance of materials efficiency, durability, adaptability, and reuse.

This thesis aims to create a set of guidelines that will help designers and other construction stakeholders apply Design for Deconstruction and Adaptability DfD/A principles to increase the knowledge of how structural design and structural systems in buildings can be designed to promote Sustainability. For this purpose, a grading tool to assess structural systems based on the ISO 20887 was developed.

The general methodology for this research was adapted from Design Research Methodology with a particular focus on the Product Development approach for the tool development. A literature Review was conducted in both scientific and grey literature to identify relevant information and current efforts on sustainable design of structural systems and application of DfD/A principles on the construction sector. Three additional methods for data collection were used: (1) questionnaire for identification of customer needs and expectations, (2) benchmarking to identify similar tools, strategies, and certifications systems that include sustainability performance in buildings; and (3) workshops with the purpose to rate the usefulness quality of the tool based on the application of the tool by potential users in different case studies.

A ready-to-use computer-based EcoDesign tool was developed. The assessment performed by this tool consists of an indicator system of DfD/A strategies to enhance sustainable development by improving material efficiency and stimulate a circular economy in the construction sector. A top-down approach was used for the concept generation, which starts with the ReBuilding Index as an indicator of sustainable performance for structural systems. This index is based on five categories defined on the relationship of the DfD/A principles with the design process of the structural system. A total of 20 principles are distributed in these categories, defined by 54 strategies to reach the goal of the principles.

The tool was tested by 11 potential users with different roles in the construction sector. Five case studies were selected to grade the design of five different typologies of structural systems. The usefulness quality of the tool was evaluated based on indicators of usability, utility, and user experience. It was found that developing the tool based on DfD/A principles and the ISO 20887 gave the tool a solid theoretical background and a flexible structure that can be used for sustainable design or as part of an extensive framework of certification systems or ecolabel programs.

The tool accomplishes the goal of grading and helping to improve the structural design. However, during the evaluation of the tool, many barriers and difficulties of application were found. Therefore, these findings and obstacles are instead identified as challenges and turn them into opportunities for improvements in future versions of the tool.

Key words: Construction, Design for Deconstruction, Design for Adaptability, Material efficiency, Structural Design, Sustainability.

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Andres Zabala-Mejia
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List of Abbreviations

AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
BLDG	Building
CDW	Construction and Demolition Waste
CE	Circular Economy
CLT	Cross laminated timber
CO_2	Carbon dioxide
DfA	Design for Assembly/Design for Adaptability
DfCE	Design for Circular Economy
DfD	Design for Disassembly/Design for Deconstruction
DfD/A	Design for Deconstruction and Adaptability
DfE	Design for the Environment
DfM	Design for Manufacturing/ Design for Maintainability
DfMA	Design for Manufacture and Assembly
DfWM	Design for Waste Minimization
EFD	Energy-Efficient Design
ENV	Environment/Environmental
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GWP	Global Warming Potential
HVAC	Heating, Ventilating, and Air Conditioning
LCA	Life Cycle Assessment
MFG	Manufacturing
MS/S	Material selection and substitution
NGT	Nominal Group Technique
O&M	Operation & maintenance
P&D	Planning and design
PD	Product Development
QFDE	Quality Function Deployment for Environment
R&D	Research and design
R/MFG	Remanufacturing
SDGs	UN Sustainable development Goals
SUS	Sustainability
UN	United Nations

List of Definitions

The following definitions are set to avoid ambiguities and define a specific meaning of the word, concept, or idea under the scope of this research study. The presented definitions are adapted from the "ISO 6707:2017 Buildings and civil engineering works — Vocabulary", the "ISO 20887:2020 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability", and the traditional use within the construction sector.

Accessibility: Ability for ease of access to buildings components and parts. In the context of assessment of structural systems, DO NOT refer to accessibility of people with specialized needs.

Adaptability: Ability to change or modify the functional use of the building.

Asset: Building or infrastructure with value that results from construction operations.

Building: Result of a construction process that has the purpose to provide shelter for its occupants and allow the defined functional use. Usually partially or totally enclosed and designed to stand permanently in one place.

Circularity: Ability of the structural system to return to the use phase of the life cycle by any recycling strategies (i.e., reuse, refurbish, remanufacture, recycling).

Deconstruction: A non-destructive process that takes apart a building into its components and materials. Under this definition, *reverse construction* can be used as a similar definition.

Demolition: A destructive process that breaks down a building.

Disassembly: A non-destructive process that takes apart a product or component, into its basic elements or parts. Under the scope of this research, *Disassembly* of a building or a construction, will be mentioned as *Deconstruction*.

Durability: Ability of the building or any of its components to perform its functions over a specified period of time without repair and unexpected maintenance.

Life Cycle Assessment (LCA): Compilation and evaluation of inputs, outputs and potential environmental impacts of a product or system throughout its life cycle.

Recyclability: Ability of a building's component, part, or material to be separated and reprocessed to be used as input for a different use or function.

Recyclable: Characteristic of a building's component, part, or material to be diverted from the waste stream by collection, and to be processed and returned to be use in the form of raw material.

Refurbishability: Ability of a building's component, part, or material to restore its functional characteristics to a condition suitable for continue use.

Refurbishment: Modifications and improvements to an existing building's component, part, or material, and rebuild it to an acceptable condition.

Remanufacturability: Ability of a building's component or part to be disassembled and refabricated at the end of its service life to a condition suitable for resale or reuse.

Repair: Returning a damaged or degraded building's component or part to an acceptable condition by restoration or replacement.

Reusability: Ability of a building's component or part, or the building itself, to be used in its original form more than once and maintain its value and functional qualities for the same purpose.

Re-use: Use of a building's component or part, or the building itself, more than once for the same purpose without reprocessing.

Reversible connection: Connection that can be disconnected and/or disassembled for easy alterations and/or additions to the building.

Service life: Period of time after construction during which a building meets its functional use. *Design life* and *Design service life* have the same definition.

Structural system: Organized combination of connected elements or parts designed to provide strength and stability to a building. *Structure* is used with a similar definition.

Structural element: Part of a structural system. *Structural member* is used with the same definition.

1 Introduction

This chapter gives an overview of the research study and the topic. The background will be presented from a global perspective with a general context of Europe to make it easier to understand. This is followed by the problem statement along with the aim and the objectives of the study. Finally, research questions are defined along with the limitations considered to reach the objectives.

The construction industry is known for consuming large quantities of raw materials and high amounts of energy through all life-cycle phases. This industry is responsible for large amounts of CO_2 emissions. In 2018, the construction industry was responsible for 6% of global energy consumption and 11% of global CO_2 emissions (IEA and UNEP, 2019). The waste generation of the construction industry in 2018 was approximately 36% of the total waste in the European Union (EUROSTAT, 2020). Besides just in Europe, cement production in 2018 was close to 180 million tonnes (CEMBUREAU, 2020); steel production for construction use reached approximately 4.5 million tonnes in the same year (EUROFER, 2020), and about 600 million m^3 of conventional wood-based construction materials were consumed between 2013 and 2017 (UNECE, 2018).

Furthermore, population trends suggest that for 2050 world population will grow to 9.74 billion people (Roser, 2019). From this global population, two-thirds will live in urban areas (Ritchie, 2018), which raises problems regarding the transformation of rural and urban areas due to the need for new housing and urban infrastructure projects. Living standards depend on large industrial systems that have been adapted in small and marginal changes. Still, the industry continues to be defined as a linear model that starts with resources extraction from the biosphere, passing through materials production, manufacture, and distribution, followed by consumption and use, and ends with final disposal (i.e., landfilling, recycling, or energy recovery).

The mentioned drawbacks represent new challenges in the construction industry and demand new and innovative approaches to increase productivity, optimise material consumption, and implement environmental-friendly construction techniques. Current trends of industrialisation also affect the construction sector, demanding new technologies based on resource-efficient methods and tools. This gives an opportunity to reduce raw materials consumption, reduce waste production, and enhance circular economy.

1.1 Background

Sustainability is the foremost market trend and is being integrated into all companies’ and industries’ business models. Engineering design and Product Design (PD) focus on performance, quality, and cost (Ulrich & Eppinger, 2016). With the increasing awareness of the product's harmful effects on the environment and society, companies start to face the challenge of including sustainability in their decision-making process. EcoDesign methods such as Design for Disassembly and Adaptability (DfD/A) focuses on optimising a design that can be easily disassembled or adapt at the end of the use phase; thus reuse and recycling can be enhanced (Bogue, 2007).

Building design differs considerably from product development. While products mainly focus on fulfilling one principal function, a building project results from the combination of many products, where each product must fulfil a specific purpose (Fox et al., 2001). Another important aspect is that products are manufactured in factories while the buildings are constructed on-site, even with current pre-fabrication technologies (Ipsen et al., 2021). The question is how the construction industry can push, apply, and support sustainability through EcoDesign methods.

The application of conventional EcoDesign methods to the construction industry faces a significant number of barriers. These methods require detailed studies to be introduced and effectively applied to building projects (Olawumi & Chan, 2020). However, few implementation cases indicate that even with the current efforts, there is still a lot of space and opportunities to improve sustainability in the construction industry (Ipsen et al., 2021).

Sustainability and EcoDesign methods are based on a holistic perspective where all the life cycle stage are considered to evaluate the product's performance. This aspect raises one of the most significant obstacles for applying these methods in buildings projects since these long-lasting projects bring a lack of knowledge on how the building will perform in the distant future (Ipsen et al., 2021). Therefore, many questions and doubts on how to evaluate the performance of the buildings for future stages appear. With this particularity, most of the efforts for sustainable design on buildings have been concentrated on the production, construction and use phases, leaving behind two important phases, the end-of-life and the potential for reuse and recycling.

In the construction industry, the end-of-life phase for buildings is marked by a demolition process. This destructive action consumes large amounts of resources and produces high quantities of waste and debris (Tatiya et al., 2018). This action results in a combination of materials that are difficult to recover, and in some cases, are mixed with contaminated or hazardous materials, which hinders its possible reuse (Machado et al., 2018). A different approach for this end-of-life phase that allows recovering valuable material is deconstruction, which refers to the disassembly of the building's various components, parts and materials (Thormark, 2007). Including deconstruction principles into the building's life cycle creates excellent benefits for sustainable development.

1.2 Problem description

Current trends of sustainability strategies in the construction industry focus on the construction and use phases, but sustainability should consider the complete life cycle of the building. It is essential to include in this industry methods and strategies to consider how to manage and promote sustainability in the future, emphasising the end-of-life stages and the potential of reuse and recycling that this sector hides. Different strategies have been set to create a competitive construction industry in the European region, where top priorities are energy efficiency, sustainable use of natural resources, circular economy, internal market regulation and digitalisation (European Union, 2020).

Between all this tangle of goals, laws, needs, commitments, and plans is where the opportunities for new strategies and innovative methods to promote sustainability can be found; the question is how to keep the phase of construction demand while attempting to reduce its environmental impacts. Many strategies have been adopted in the previous years, and many others are being developed. An example of these efforts is the recently published ISO 20887 *Sustainability in buildings and civil engineering works — Design for disassembly and adaptability* (ISO, 2020) that provides an overview for the integration of DfD/A principles into the design process of buildings.

Buildings are composed of different systems or layers (Brand, 1995), where each one performs a specific function. One of these systems is the Structural System, which is designed to resist the different loads applied during the building's service life and transfer them to the foundation. Compared to other systems like the façade or the service systems with an expected life of 15 years, the structure has a longer service life that can reach up to 100 years (Brand, 1995). This distinctiveness generates opportunities and barriers for sustainability strategies. Considering the benefits of promoting circular economy strategies and Resource Efficiency principles to buildings, this research study is focused on the Sustainable Design of Structural Systems in Buildings.

1.3 InFutUReWood project

This master thesis was written in collaboration with the *Research Institute of Sweden* – **RISE**, and in the framework of the **InFutUReWood**[1] project*, Innovative Design for the Future Use and Reuse of Wood Building & Components*. One of the project's main objectives is to address the reuse and recycling of timber buildings, with the purpose to study new ways to design structures to facilitate the reuse and recycling of materials, complying with buildings' regulations and standards, and investigating the needs for future changes. The project is divided into several work packages. One of them focuses on the primary design of structural systems of buildings to facilitate the transformation of the end-of-life of buildings from demolition to deconstruction.

One of the project's tasks is to develop a draft version of a tool intended for assessing the design of the structural system in timber buildings concerning their potential for deconstruction and reuse, define as *"rebuilding factor"* (Sandin & Sandberg, 2021). This thesis originates from an initial endeavour of a draft definition of an assessment tool, tested with stakeholders of the construction sector during a workshop performed in September 2020. This effort was documented in the report: *"Design for deconstruction and reuse of timber buildings - testing an assessment tool in a workshop"* (Sandin & Sandberg, 2021). As a result of this workshop, and to continue with the project's objectives, it was defined that the next step was to develop a grading tool based on the ISO 20887 *Sustainability in buildings and civil engineering works — Design for disassembly and adaptability* (ISO, 2020).

1.4 Aim & objectives

This Master's thesis aims to increase the knowledge of how Structural Systems in buildings can be designed to promote sustainability by including Design for Deconstruction and Adaptability (DfD/A) principles. To reach this aim, the following two objectives are defined:

O1. Set a list of guidelines to help designers and other construction stakeholders to apply DfD/A principles to promote sustainable design of structural systems.

O2. Develop a tool to assess structural systems in buildings based on DfD/A principles and the standard for sustainability in buildings ISO 20887.

1.5 Research questions

The following questions are stated to fulfil the objectives:

RQ1. How can DfD/A principles be adapted into guidelines to help designers and other construction stakeholders to enhance sustainable design of structural systems?

RQ2. How can the standard for sustainability in buildings ISO 20887 be interpreted to develop a tool to assess sustainable design of structural systems?

RQ3. How to promote sustainable design of structural systems by ensuring the usefulness of the tool?

[1] Project InFutUReWood is supported under the umbrella of ERA-NET Cofund ForestValue by Vinnova – Sweden´s Innovation Agency, Formas – Swedish Research Council for Sustainable Development, Swedish Energy Agency, the Forestry Commissioners for the UK, the Department of Agriculture, Food and the Marine for Ireland, the Ministry of the Environment for Finland, the Federal Ministry of Food and Agriculture through the Agency for Renewable Resources for Germany, the Ministry of Science, Innovation and Universities for Spain, the Ministry of Education, Science and Sport for Slovenia. ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773324.

RQ1 will be used to achieve O1; it focuses on understanding the impact of the DfD/A principles in the construction industry and a proper way to adapt them to the design of structural systems in buildings. To accomplish O2, RQ2 is defined to identify a suitable interpretation of the ISO 20887 and develop an indicator system that can work as a grading tool for sustainable design of structural systems. RQ3 aims to find an appropriate method to verify a good usefulness of the tool.

1.6 Delimitations

This research study is delimited to principles of DfD/A; other methods can propose similar goals regarding resource efficiency or circular strategies, but the principles used here focus on the deconstruction performance of the structural system. The tool aims to introduce and grade DfD/A principles in the structural system without evaluating the environmental performance, indicators like CO_2 emissions or Embodied Energy, among others, are not considered.

Buildings are formed by several systems. There are current methodologies and certification systems that focus on other sustainable aspects of the building. This research only focuses on the structural system; therefore, the design principles focus primarily on the structural system, and some of them may have an indirect effect on other systems. Nevertheless, it is important to mention that the structural system is an integral part of the building and interact with other systems.

Demolition management or deconstruction management are related topics because they have the same goals of resource recovery and circular economy. Still, the strategies in these methods are based on the assessment of buildings in use that are going to the end-of-life phase. This research aims to introduce DfD/A principles in the planning and design phases of the building.

Structural design has two significant drawbacks to introduce EcoDesign strategies into the design phase freely. Structural design must comply with construction and building codes, standards, and professional practices mandatory by law; most of these documents are made to safeguard users' lives. The tool developed under the framework of this research does not have the purpose of ensuring the accomplishment of these documents; instead, it suggests how to improve the design within the allowed parameters of these codes. The second one, structural designers, in regular building projects, do not directly control the project schedule and budget; thus, budget, cost, or schedule, were not considered to assess the DfD/A principles.

To conclude, the tool is not meant to be a decision-making tool; its purpose is to help designers and other construction stakeholders to upgrade the structural system in a sustainable way. Future works may consider integrating this tool with other methods or assessments, such as LCA or LCC, for a decision-making tool, or with other certification systems for Ecolabel purposes.

2 Theoretical framework

This chapter aims to give the theoretical context for the research study to help the reader understanding the most important concepts managed in the research. It starts with an introduction of the construction industry, followed by the design phase of the structural systems. Then an overview of how sustainability is works in the construction industry and the considerations and the current state of design for deconstruction in buildings is presented. This chapter ends with an introduction of the ISO 20887.

2.1 The construction industry

The construction industry is the economic sector that covers all companies involved in construction activities. This industry has different classifications, where one of these is the classification by sectors according to the use of the project. Thus, the construction industry has three sectors: building, infrastructure, and industrial. The building sector can be further split into residential projects and non-residential projects (e.g., commercial, educational, financial). The infrastructure sector includes all large civil works (e.g., highways, bridges, dams, water-related structures). The industrial sector covers all other constructions that support other significant economic activities (e.g., mining, power generation, oil & gas).

From the previous perspective, this industry directly relates to the other economic sectors as a provider of services, which suggest that the construction industry has a great potential to shape and influence the future. *"We shape our buildings and, afterwards, our buildings shape us"* Winston Churchill (1944). This implies that buildings will have the capacity to define how we live, work, and interact.

Due to its complexity and size, this industry has been delaying the adoption of a comprehensive sustainability mindset and had barely changed from its traditional procedures over the last years. Even if this industry has not led this transformation, it is not exempt from supporting the sustainable development of society through *Environmental Awareness, Economic Growth, and Social Responsibility*. Competitive and sustainable construction industry could bring plenty of benefits to society as well as many economic sectors. This industry has a moral obligation to transform towards sustainable development more than a challenge or a requirement.

2.1.1 Economic importance

The economic activity of the construction industry is complex and extensive. In the modern perspective, it involves processes from the extraction of raw materials from the biosphere to the completion of the physical work on site. In this initial approximation to the building activities, it can be identified the impacts in all three economic sectors: primary (e.g., extraction of natural resources), secondary (e.g., manufacture of product and components), and tertiary (e.g., consultancy services). This large economic chain has an impact on global economic statistics:

- In 2016, this industry represented 6% of the global GDP; where it accounted for 5% in developed countries and 8% in developing countries (World Economic Forum, 2016).
- In 2018, USD 11.4 trillion (EUR 9.4 trillion) was spent worldwide on construction (Statista, 2021).
- By 2030, it is predicted to spend USD trillion USD (EUR 14.4 trillion) for global construction (Frost & Sullivan, 2019).
- 4.5% is the estimated growth of global construction in 2021 (Reportlinker, 2020).

The impact of the construction industry is notorious in the world economy.

2.1.2 Social importance

As previously mentioned, all other economic sectors rely on construction to provide commodities and services. Value creation for almost all the economic sectors can be perceived with the construction of buildings assets. With this, the lifestyle and life quality of almost the entire global population are being affected. This social impact of this industry can be seen through the following statistics:

- In the EU, this industry accounts for 5.2 million employees in 2019 (Statista, 2020).
- In 2050 the world population will grow to 9.74 billion people (Roser, 2019).
- From this global population, two-thirds will live in urban areas (Ritchie, 2018), which raises problems regarding the transformation of the urban and rural landscapes.

In addition, an average person spends 87% of its time indoors, distributed in building/residency 69%, in the office/factory 5%, in retail/recreation/leisure 13% (Bednarova, 2020). This is a significant amount of a lifetime surrounded and influenced by the result of the construction industry. Furthermore, in the last year, after the arrival of the coronavirus pandemic and the restrictions and recommendations imposed by governments around the world, the time spent at home increased; e.g. in March 2020, during the first wave of the pandemic, the average time spent at home increased 10% in the EU countries (Our World In Data, 2021).

2.1.3 Environmental importance

The construction sector is responsible for large consumption of natural resources, including water and energy, as well as a huge producer of waste. This is an immediate threat to the environment and to our current and future way of life. These impacts are observed in the following statistics:

- In 2018 the construction industry was responsible for 6% of global energy consumption and 11% of global CO_2 emissions (IEA and UNEP, 2019).
- In 2018, the waste generation of the construction industry was approximately 36% of the total waste in the European Union (EUROSTAT, 2020).

These aspects represent two of the biggest environmental problems: natural resources extraction and waste generation. These problems are located at the beginning and at the end phases of the traditional life cycle of the construction project, and the point where the Biosphere and Technosphere merge.

2.2 The Construction project

A construction project can be described from two complementary points of view: the business project and the on-site project (Neale et al., 2016). From the business perspective, a building is a product conceived because of a specific need from the society (e.g., housing, infrastructure, education, services) or other industry (e.g., factories, offices, retails) that required financial support, produce profit, and must be based on an advanced technical design to fulfil all technical, functional, and legislative requirements. The on-site perspective is the physical construction of the asset. It involves all the procedures, activities and materials needed for this purpose (Baldwin & Bordoli, 2014).

In current construction projects, core stakeholders pay more attention to the construction and use phases of the project (Yang & Shen, 2015; K. Lauritzen, 2018). Some interests are placed on the predecessors' phases like manufacturing and extraction of the materials, mostly for economic reasons or environmental compliance (Olawumi & Chan, 2020). However, most construction owners and developers do not care enough for the end-of-life phase and hand over this responsibility to the demolition companies.

2.2.1 Stakeholders

Different stakeholders with diverse interests, needs and driving forces are involved in the construction industry (Yang & Shen, 2015). Each one has a distinct level of influence on the construction project (K. Lauritzen, 2018); thereby, it is important to identify their specific role and their influence on the results and performance of the project. *Table 2-1* describes the core, primary and secondary stakeholders of the construction industry.

Table 2-1 Construction Stakeholders

Category	Stakeholder	Role	Influence	Motivation
Core *High influence on the project*	The owner	Correspond to the high management role. This group oversees all key definitions of the project like goals, resources, budget, and schedule.	- Power - Funding - Strategic	- Profit - Invest - Image
	The designers	In charge of the technical designs (e.g., architecture, structural, geotechnical, civil, mechanical, etc.).	- Technical decisions - Quality	- Profit - Knowledge - Creativity
	The construction contractors	Companies specialized in construction activities. They are responsible for the assembly of the assets.	- Safety - Quality - Schedule	- Profit - Efficiency - Cost
Primary *Mid influence on the project*	Manufacturers & suppliers	Companies responsible for the transformation of the raw materials into products for construction. This group includes supplier of smaller products or services (i.e., electrical, plumbing, subcontractors)	- Quality - Schedule - Cost	- Profit - Material resources
	The users	This group can be identified as users, clients, or customers, depending on the use of the building. It is the actual group that uses the asset, but not always is the one that finances the project or owns it.	- Functional definition	- Well-being - Needs - Occupancy
	Public authorities	*Local authorities,* governmental entities with the duty to regulate the activities along the life cycle of the construction. *Environmental authorities* are responsible for compliance of environmental protection legislation. *Construction authorities* (housing authorities) control over construction legislation, permits, and codes.	- Legal - Environment - Social	- Permits - Urban planning - Env. impacts - Regulations
Secondary *Low influence on the project*	Demolition Contractor	Companies specialized in demolition activities, mainly by destructive methods.	N/A*	- Profit
	Waste & recycling industry	Companies in charge of the collection, sorting, and final disposal of the CDW. Some waste flows can end as recycling materials.	N/A*	- Profit - Env. Protection
	Professional associations	Associations that give support to different areas of the construction industry. Provides standardization, guidelines, and codes of good practices.	- Environment - Ethical	- Support - Guidelines - Standards

*N/A: In current construction project management, the influence of the end-of-life phase is minimal. Do not have enough power in the decision-making of other phases of the building's life cycle.

The previous description is a general overview of the main stakeholders and roles. These roles and responsibilities vary according to the nature and scope of the project. There are cases where the same company has more than one role or shared role with other stakeholders. It is important to identify who is assuming each role in each project.

2.2.2 The planning and design phase

All construction projects start with a planning and design phase P&D. This phase is considered in the industry as the most critical phase of the construction project because the goals of the project are set. All decisions taken during this phase affect the entire life cycle of the project (Muhammad, 2020). The most relevant actions and deliverables from this phase are:

- ***Financial planning*:** budget definition, including the source for funding and the distribution and availability of money along the different stages of the project.
- ***Schedule:*** planning of all activities and tasks to perform during all the project's life-cycle phases, including its duration and necessary resources.
- ***Design:*** creation a conceptual model of the building, expressed in drawings, 3D CAD models, and technical specifications. In this process, the definition of materials and components of the building are based on functional requirements, mechanical properties, and construction codes.
- ***Construction method:*** selection of the more suitable technology to transform the design into a physical asset. This is highly associated with the design definitions of the building.
- ***Procurement:*** finding and acquiring all the materials, products, and equipment needed for the construction, based on all the technical specifications defined in the design.
- ***Labour qualification*:** identification of companies with the required qualifications to perform the construction activities, and with the experience to reduce operational cost, risks, operational time, and increase quality.
- ***Documentation*:** communication among all the stakeholders and along the entire project is a critical aspect for quality. Documentation contains all the activities, specifications, design criteria, description, responsibilities, and duties among all parties.

The P&D phase is fundamental to accomplish a successful project (Neale et al., 2016). This phase defines the performance of the overall building and has a significant influence on the functional and sustainable performance of the building. Important decisions on materials usage, energy efficiency, environmental impacts, capital cost, profits, and labour occur in this phase. An optimal P&D phase of a construction project can result in a high-performance building.

2.2.3 Building components and levels

A building is the final product of the combination of different products, systems, layers, or parts (among many other definitions for the same decomposition). Each one of these components have a specific function and a distinctive performance. *Table 2-2* shows a common classification of the building's parts (Brand, 1995) along with its service life and a short description.

In addition to this classification, each layer can be further divided in smaller parts according to its function within the system and its size. There are many vocabularies that have been use in this classification, where the same word has been used to describe different levels of this categories. For instance, the ISO 20887:2020 define these categories as the building's levels. *Table 2-3* shows different definitions of levels found in the construction sector and an example on how this level system is related to the structural system of the building.

Table 2-2 Building layers/parts. Adapted from (Brand, 1995).

Layer/Part	Expected service life	Description
Site	Eternal	Geographical location of the project, also refer as lot from a legal point of view. Can be consider time independent since outlast generations.
Structure	30-300 years	Foundation and load bearing systems. Can be compares as the bone system of the building. The service life varies according to the material's properties.
Skin	20 years	Exterior surfaces of the building. According to its function can be known as façade or envelope. This layer change to keep up with performance efficiency and fashion trends.
Services	7-15 years	Internal systems of the building (e.g., electrical, plumbing, fire network, HVAC, etc.). Can be compared to the circulatory system of the building. This layer change to keep up with user demands and building regulations.
Space plan	3-30 years	Interior layout and components of the building (e.g., walls, ceilings, floors, finishes, etc.). This later change according to the use and occupancy requirements of the building.
Stuff	Daily	All internal elements like furniture, decoration, and appliances, that are not fix to the building.

Table 2-3 Building system levels.

Building layers definition				
LEVEL	ISO - 20887 [1]	VTT / Crowther [2]	BAMB / Durmisevic [3]	Example
1	System	System	System	Structure
2	Element	Component	Sub-system	Frame
3	Component	Subcomponent	Component	Column
4	Subcomponent	Element		End-Plates
5	Material	Material	Material	Steel

1: ISO 20887:2020 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability (ISO, 2020); 2: Barriers and opportunities of structural elements re-use (VTT, 2014) & Developing Guidelines for Designing for deconstruction (Crowther, 2000); 3: Design for Deconstruction (BRE, 2015) & Transformable Building Structures (Durmisevic, 2006);

The application of EcoDesign methods and sustainable development in a building, needs to be flexible to be able to reach in a proper way, each building's system, and each system's level.

2.3 Current life cycle model of the construction industry

The current life cycle model of the construction industry follows a linear model; it is easy to define the direction of the materials and where and how they lose value on the market (Durmisevic, 2006). This has been the conventional model for several years in the industry and is displayed in *Figure 2-1*.

The system starts with the extraction of raw materials from the Biosphere (e.g., minerals, wood, water); It goes through a manufacturing process where these raw materials are transformed into construction materials or products (e.g., minerals to steel, wood to timber)(Ruuska & Häkkinen, 2014). The following process is the construction stage, in which all materials and products are assembled to construct a building. The system is completed with the end-of-life and final disposal of the materials and buildings components. The traditional end-of-life scenario in the construction industry is demolition. During this process, the building is broken down into pieces or debris, which generally are considered waste or scraps. The material that still has some value to the market can be recycled and goes back to the head of the system (Danish Environmental Protection Agency, 2019). Recycling strategies in buildings has been improving over recent years but is still weak to be considered as a strong flow of the system.

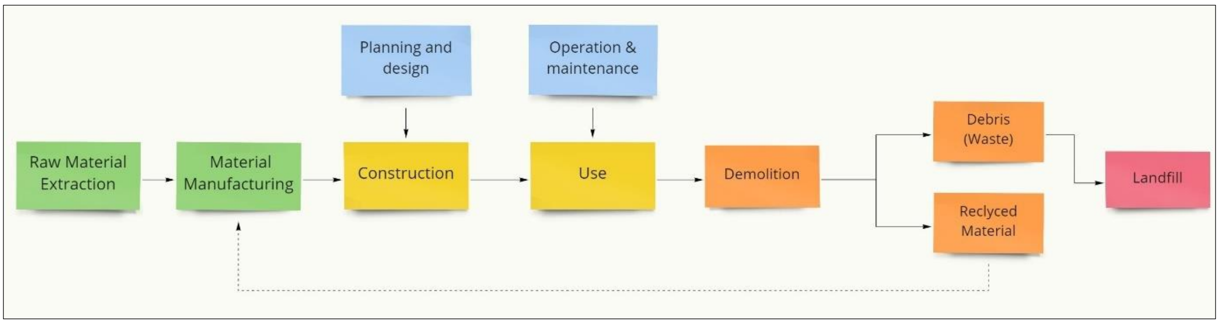


Figure 2-1 Current life-cycle model of the construction industry.

P&D has taken place before the construction phase starts. Another similar administrative phase is part of the cycle to complete the system: management and maintenance, which occurs parallel with the use phase. Its main purpose is to guarantee that the building accomplishes its functional use during the defined service life.

2.3.1 Material efficiency

In the previous section, the system was described from the perspective of the actions and processes during a typical construction project. Yet, to better understand how the construction industry influences and shapes sustainability, an analysis of material efficiency may help. Material efficiency refers to the actions that can “provide a significant reduction in the total environmental impact of the global economy” (Allwood et al., 2011). This definition mixes two aspects of sustainability: (1) proper use of materials to generate less environmental impact (2) with the most significant economic benefits.

In *Figure 2-1*, the green, yellow, orange, and red colours are associated with the upgrading and downgrading of the material value. In the context of construction projects, value can be perceived as the mix of three dimensions of the material: (1) monetary, concerning its price; (2) functional, concerning its utility; (3) and social, considering that the final user can engage services with it (Sánchez-Fernández & Iniesta-Bonillo, 2007). During extraction and manufacture, the materials gain value having an upgrade of monetary and functional value (marked in **green**). During construction and use, the added value of the materials is steady, and most of the value in these stages can be perceived as social value. The duration and steadiness of this value depend on an appropriate design and maintenance of the buildings, so the function (i.e., purpose), and the use (i.e., service), can properly occur (marked in **yellow**). At the end-of-life (marked in **orange**), when the building can no longer provide a service or perform its purpose, the value of the material is downgrading, losing its value in all three dimensions. It can be expected to recover part of its value by recycling or remanufacturing. The last phase will be the landfill, where all material value is lost (marked in **red**)(K. Lauritzen, 2018; Durmisevic, 2006; Danish Environmental Protection Agency, 2019). The P&D and Operation and maintenance (O&M) blue phases (marked in **blue**) are not considered in the material efficiency analysis since the materials do not physically go through them, but without a doubt, the decisions taken in these phases impact the value in all other phases.

The behaviour of added value in the materials is graphically described in *Figure 2-2* according to the phases. This description is based on the whole definition of the building, including all layers and levels of the building (Brand, 1995; ISO 20887:2020), where the material is present as the material itself, or as elements, component, assemblies, or systems.

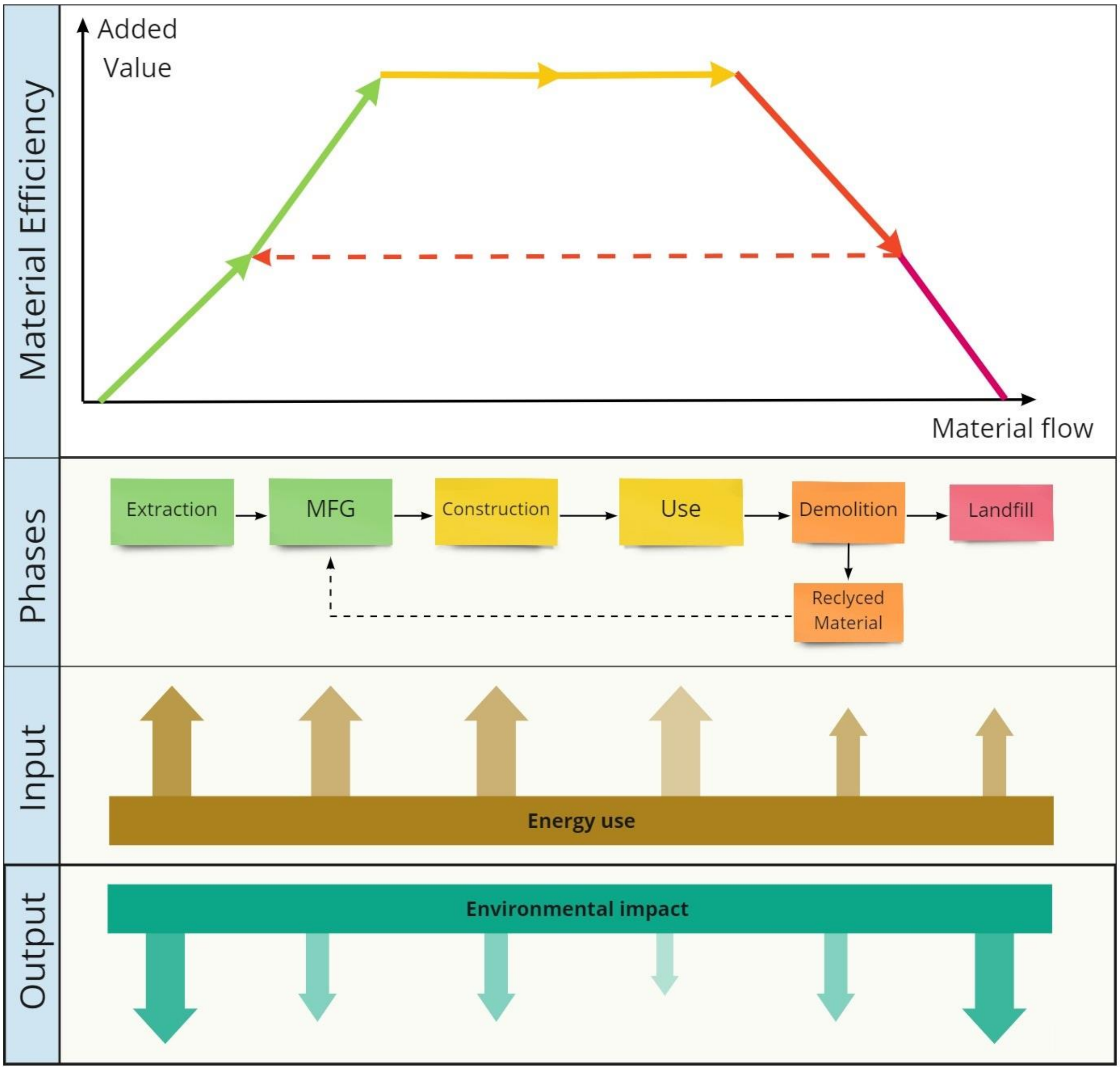


Figure 2-2 Material efficiency of the Current life-cycle model.

2.3.2 Energy use and environmental impacts

Construction materials come from oil (e.g., polymers), ores (e.g., metals) or biomass (e.g., timber) and their extraction and manufacturing are energy-intensive industries (Ruuska & Häkkinen, 2014). This energy demand is often supplied by fossil fuels, which implies a great amount of Greenhouse Gases (GHG) that impact the Global Warming Potential (GWP). Construction and use phases consume a significant amount of energy but are not as intensive as the previous phases since energy from renewable and alternative sources are available in these phases (Iacovidou & Purnell, 2016). This efficient energy use produces lower effects on GWP. In particular, the high energy consumption in the use phase is due to the duration since the service life of a building can last over 50 years. Demolition is a short phase, highly energy-demanding since most of the techniques are destructive activities and can be intensive due to the equipment used. To complete the life cycle, final disposition or landfilling require energy in terms of handling and transportation, considering that landfills are not commonly close to the location of the buildings. This trend of energy use is shown in the input part of *Figure 2-2*.

The environmental impacts related to materials usage are mostly acidification, eutrophication, and land use. The phases with the most negative impacts on the environment are the extraction of natural resources and the final disposal or landfill (Ecorys, 2014). This is because the exchange of materials between the biosphere and the technosphere occurs; therefore, there is the most substantial modification of natural cycles and ecosystems. During manufacturing, construction and demolition phases, by-products end up as waste, polluting air, land, and water. The use phase also impacts the environment, but current trends on sustainability and environmental performance of materials have reduced these impacts over the last years.

Another environmental problem is material scarcity. Natural resources are limited, and supply for construction materials in the future can be a challenge. Compared with other industries like technology, appliances, or telecommunications, which have problems regarding scarcity of rare metals for production, the construction sector currently does not have a shortage of sources in the short term (Ecorys, 2014). Nevertheless, the growing demand for buildings and new policies regarding the extraction of natural resources can bring limitations on material availability in the medium and long terms.

2.4 Sustainability in the construction industry

Construction has an important role on the quality of life and living standards of society. In the last years this sector has recognized this role and started to introduce sustainable practices into their business models and products. However, the conventional building industry has a limited understanding of building efficiency and sustainability.

2.4.1 Eco-Design in the construction industry

Many studies, investigations and research have been done to implement eco-design into the construction industry with the purpose of increasing the environmental performance of buildings. Rousseaux et al., (2017) found in their research 629 Eco-design tools and 46 of them applied in the construction sector, but even with numbers implementation in the industry is lacking (Ipsen et al., 2021). *Table 2-4* shows a summary of the most common eco-design methods that have been applied to the construction sector.

Table 2-4 EcoDesign Method applied in the construction sector. Adapted from (Ipsen et al., 2021).

Tool/Method		Description	Examples
LCA	Life Cycle Assessment	Standard method for evaluation of potential Env. impacts of a product or system throughout its life cycle.	R&D for products with low Env. impact.
MS/S	Material selection and substitution	Choose materials with less environmental impact, or substitute traditionally ones.	Use natural, local, or recycled materials.
DfMA	Design for Manufacture and Assembly	Minimize waste generation and consumption of resources for design and construction.	Pre-fabrication & standardization
EFD	Energy-Efficient Design	Reduce operational energy during use and reduce embodied energy in elements and components.	Materials design and construction methods
DfM	Design for Maintainability	Avoid physically obsolescence and reduce preventive maintenance	Durability, easy to clean & accessibility
DfA	Design for Adaptability	Avoid functional obsolescence and adapt the building to future or new uses to ensure a longer service life.	Flexibility of use.
DfD	Design for Disassembly	Recovery of the building's materials and elements for reuse, thereby minimizing waste at the end-of-life.	Material selection & connection design.
DfWM	Design for Waste Minimization	Reducing waste at all stages of the building's life cycle, by improving the use of material and its durability.	Prefabrication & modular design.
DfCE	Design for Circular Economy	Eliminate waste by transforming them into resources.	Use of recycled materials.

2.4.2 Certification systems for sustainable buildings

Along with the EcoDesign tools and methods, many assessment tools, certifications systems and standards have been putting into practice in the construction industry. It is estimated that nearly 600 certification systems and standards (Vierra, 2019) exists in the sector to help guide, demonstrate and document sustainability.

Different certification systems have been established to promote the sustainable development of buildings. Examples of these certifications are LEED, BREEM, SVANEN and EDGE. These systems reward the contribution of building design when different sustainable design strategies are applied that will contribute to the reduction of environmental impacts, enhance economic growth, and develop social welfare. These certifications use rating systems based on the whole life cycle perspective of the building, including the design, construction, use, maintenance, demolition, and disposal phases. In this context, introducing new concepts and methods for material efficiency and waste reduction are awarded extra points for increasing the potential of material reuse, recovery, and recycling.

Other actors have also made a great effort to promote the sustainable design of buildings; this is the case for the International Organization of Standardization ISO. In recent years, this Organization has published different standards to promote sustainability in building construction. Examples of these standards are:

- ISO 21929:2011 sustainability in building construction — Sustainability indicators.
- ISO 15392:2019 sustainability in buildings and civil engineering works — General principles.
- ISO 21678:2020 sustainability in buildings and civil engineering works — Indicators and benchmarks.
- ISO 20887:2020 sustainability in buildings and civil engineering works — Design for disassembly and adaptability.

2.5 The future of the construction industry

Current trends in construction and other industries, products or in this case, buildings are discarded once they reach the end-of-life. Materials are abandoned or landfilled. Traditional construction materials are not scarce materials and do not face current problems in other industries like resource scarcity, resource dissipation, or availability of materials. Still, it is foreseen that current and future changes in environmental policies, restrictions of material use, and infrastructure demand due to the growing population will affect the scarcity of the materials.

2.5.1 Improving material efficiency

The current trend of material uses in construction need to change. This change needs to be from a holistic system perspective where all phases and all stakeholders are involved. Many frameworks exist with the purpose of improving material efficiency, focus on the recover and reuse of the materials. But improving material efficiency is not just a matter of recover the mass of the material, the quality of the material needs to be also recovered (VTT, 2014). When a strategy aims to recover these two aspects, then the value of the material is also recovered.

One way of material efficiency improvement is through circularity, referring to the ability of the material to return to the same or a previous point. To accomplish this, different principles must work in collaboration. The first actions for this strategy, is to decrease the amount of material that is landfilled, waste reduction, and at the same time avoid the extraction and production of raw materials (Jensen & Sommer, 2019). Material flow is not stop; it is just redirect. To allow this new direction of flow actions are needed to guarantee a proper management of the materials value. Here is where key phases, well defined and structure, help to recover the value of the materials, and properly keep them in the loop. Strategies of Reuse, Refurbish, Remanufacturing and Recycling, retake the material from the end-of-life stage of the building through activities of deconstruction, and transform them, giving them the added value lost after use, and put them back in the manufacturing, construction or use phase again (Danish Environmental Protection Agency, 2019). The improved material efficiency cycle is show in the upper part of *Figure 2-3*.

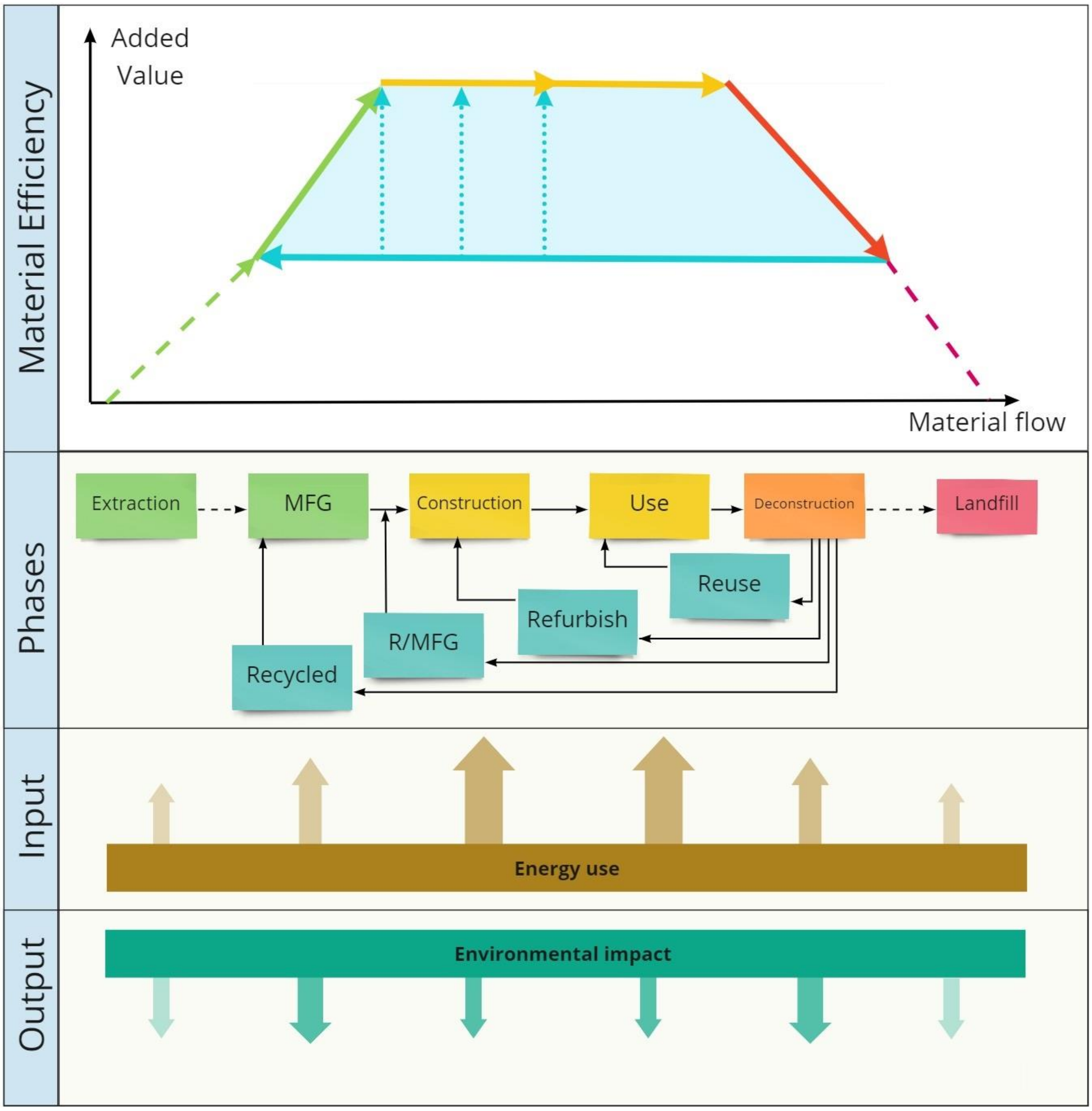


Figure 2-3 Material efficiency of the improved life-cycle model.

These improvements on the material efficiency, have benefits for the energy use and environmental impacts of the construction model. In this new scenario, the extraction and landfilling phases are reduced, and in the same way the energy use is reduced and the environmental impacts are decreased (Chau et al., 2017). Inside the loop, it is expected that energy use increase, but intensity can be low since the energy for these phases can come from renewable and alternative sources (Allwood et al., 2011). Same tendency occurs for environmental aspects.

After the introduction of Building Information Modelling BIM, constructions projects transform from the 3D projects, with the traditional geometric dimensions: height, width, and depth, to 6D projects with the introduction of the time, cost, and management dimensions. The future of the construction industry lays in 7D dimensions, where the introduction of the reuse dimension will promote material efficiency and circular economy business (Jensen & Sommer, 2019).

2.6 The gap between construction and sustainability

2.6.1 Structural systems

The structural system in most of the building projects is the largest components in terms of mass and therefore resource consumption. For the same reason, at the end-of-life stage, the structural system contributes with the biggest amount of waste, which is translated to a landfill and contamination problem (Pongiglione & Calderini, 2016). Initial efforts to include sustainability on structural systems were related to the reduction on initial embodied energy of the materials, and at the same time decreases the energy consumption and environmental impacts of extraction and manufacture stages (Webster, 2004).

In the last years different studies have broader the strategies of EcoDesign in structural systems, with special focus on: durability, adaptability, reuse, design for recycling, material minimization, energy use and life cycle assessment (Danatzko & Sezen, 2011; Pongiglione & Calderini, 2016; Webster, 2004). The resent effort on EcoDesign of structural systems, show a trend pointing to the importance of materials.

2.6.2 Design for Deconstruction and Adaptability

Design for deconstruction DfD is an EcoDesign method for product development that focuses on optimizing the building design to be easily deconstructed at the end of the use phase (Durmisevic, 2006). With this, circular economies models can be supported by the improvement of reuse, remanufacturing and recycling strategies as is shown in *Figure 2-4*.

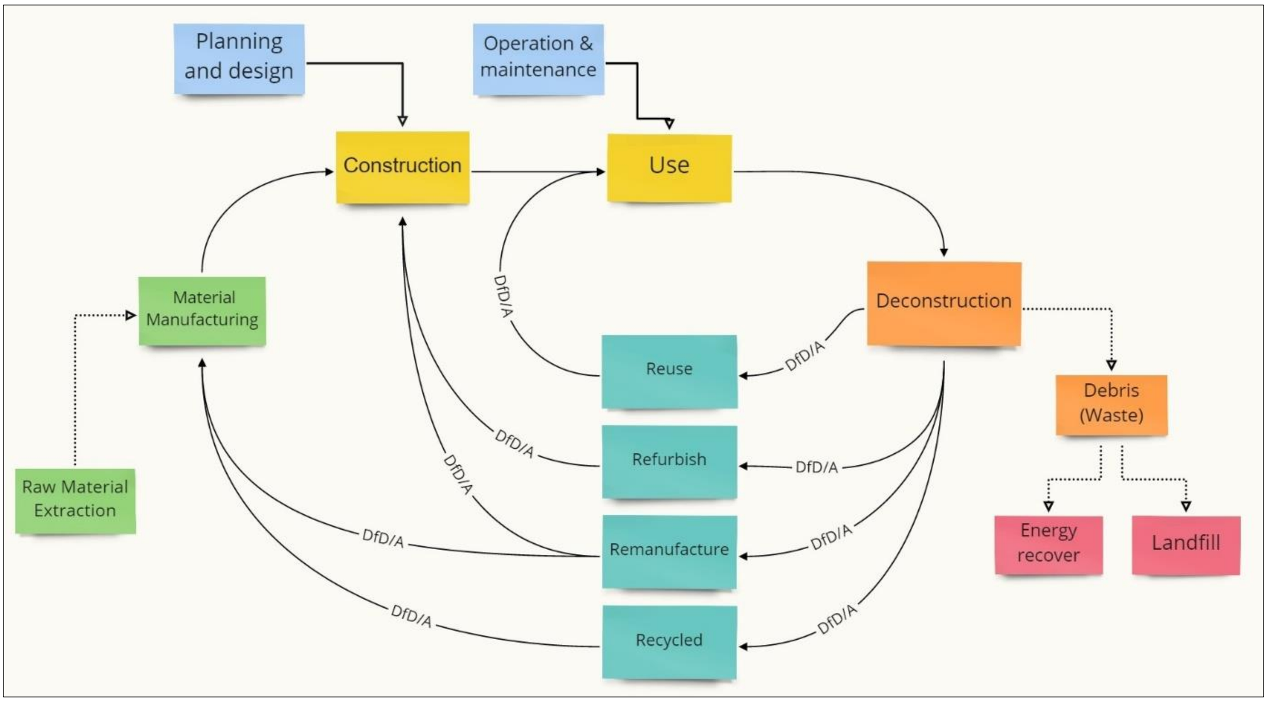


Figure 2-4 Improved life-cycle model of the construction industry.

Introducing DfD principles in the design of buildings brings benefits in all the sustainability aspects (Guy, Brad; Ciarimboli, 2005; Thormark, 2007; Durmisevic, 2006; Densley Tingley, 2012). Some of the DfD principles are:

- Ease of access to parts and components of the building.
- Reversible connections.
- Simplicity, reduce the number of different elements, components, connections or materials.
- Standardization, use common elements, components, products, or processes.
- Independence of building systems (e.g., structure, services, fixtures, finishes, etc.).
- Documentation and specification of the deconstruction process.

Deconstruction and adaptability principles are definitions that have been present in the construction industry, and some criteria from these concepts have been applied in an unconscious way for the design of buildings. Still, DfD/A have encountered a great number of barriers in the construction sector (Rios et al., 2015; Ipsen et al., 2021), that have prevented its use as an EcoDesign tool and strategies:

- Lack of suitable tools and methods
- Lack of knowledge
- Lack of professional skills
- Lack of finance resources
- Lack of cooperation
- Lack of awareness
- Lack of legislation
- Lack of market and strategies for circular economy

2.6.3 ISO 20887

The recently published standard *ISO 20887:2020 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability*, is a document intended to provide a framework for the introduction of DFD/A principles in the construction industry (ISO, 2020).

For the purpose of this research, this standard works as the foundation and central pillar from which the tool is created and developed. As a tool in itself, the ISO 20887 is conceived as a product performance standard that help to define technical approaches to achieve sustainable goals. As an international and recognized standard, this document will give to the tool strong support in systems management, sustainable performance report, and environmental certification and legislation.

The ISO 20887 is applicable to all systems and levels, as well as all typologies and uses of buildings. The standard does not define levels of sustainable performance for DfD but defines the principles to be considered and set general guidelines for each. This research study interpreted each one of these principles and translated them into strategies to assess sustainable performance in the design of structural systems.

3 Methodology

The following chapter aims to describe the research methodology applied for this research study. The chapter begins with a general overview, followed by the strategy for the literature review and the methods chosen for the tool development. Then the data collection and analysis approaches are presented including the case study description. Lastly, the research validation method is defined.

The general methodology for this research study was adapted from Design Research Methodology - DRM (Blessing & Chakrabarti, 2009). This methodology was selected because it suggests a robust list of research methods that are applicable to research studies where design is a main topic. It also helped to define a better planned and smoother research process. DRM also offers the flexibility to adapt the process to each research background and particular goals. Blessing and Chakrabarti (2009) stated *"the aim of DRM is to help design research become more effective and efficient".*

3.1 Design research strategy

The methodology proposed by Blessing and Chakrabarti (2009) consists of four stages: 1. Research Clarification, 2. Descriptive Study I, 3. Prescriptive Study and 4. Descriptive Study II. Each stage has a basic mean and main outcome. A general framework of the method is presented in *Figure 3-1*.

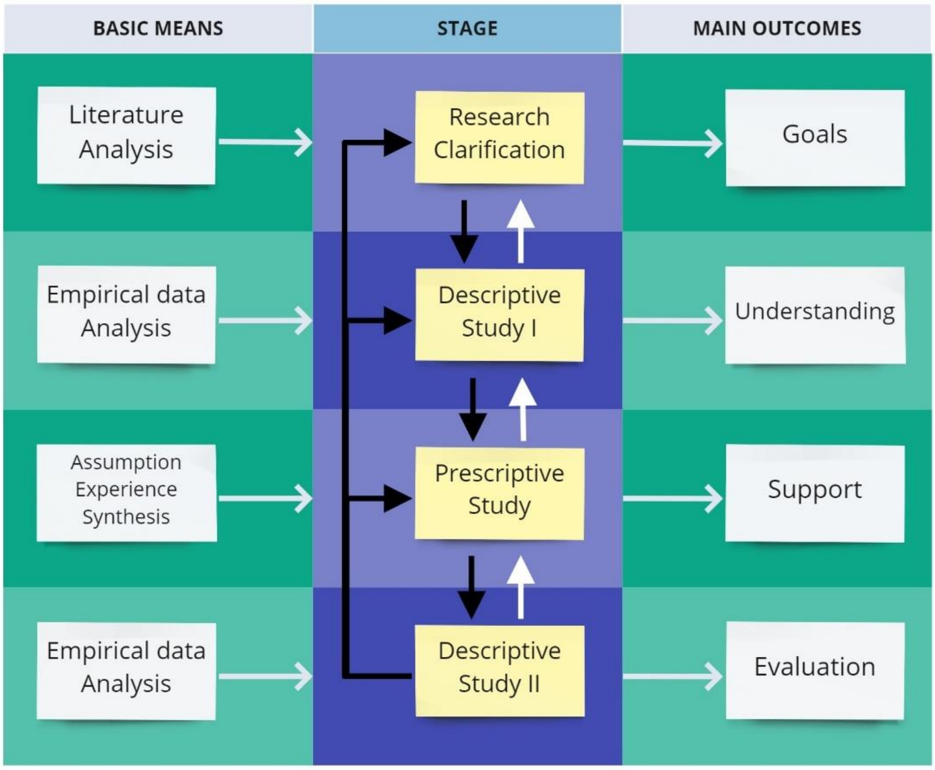


Figure 3-1 DRM Framework. Adapted from Blessing and Chakrabarti (2009).

This design methodology of this investigation is divided into the four stages of the DRM framework.

- The first stage, Research Clarification, is a definition of a base of literature that includes the state-of-art on DfD/A methods and tools that have been incorporated in the design of structural systems in buildings and similar structures. The results on this stage helped support the research assumptions and delimitations and define a more realistic research goals to answer the RQ's.
- In the second stage, Descriptive Study I, an initial version of the tool was developed according to DfD/A principles and the guidance of the ISO 20887. Relevant information

found during the literature review helped to elaborate a detailed tool structure and interface. The previous stage also helped to understand common challenges faced in the formulation of similar studies and tools. During this stage, RQ2 was partly answered.

- The third stage, the Prescriptive Study, aims to increase the understanding of the influence of the tool in the design of structural systems and evaluate if the results are according to the study's objective. This was done by selecting case studies that support the initial version of the tool and help evaluate its utility. RQ3 was partly answered during this stage.
- In the last stage, Descriptive Study II, a workshop with stakeholders from the construction industry was performed. The objective was to obtain empirical data from potential users to evaluate the usability and utility of the tool. With the results from this phase, the guidelines for design and the tool to assess structural systems were redefined to accomplish the objectives of this research study. In this phase, all RQ’s were complete solved.

This methodology had iterations during the research study, where all stages were performed on a cyclic or parallel scheme. It is considered that following the framework step by step can bring adverse effects on the results (Blessing & Chakrabarti, 2009); therefore, iterations occurred during the execution of this study to increase understanding of the developed tool.

The DRM framework adapted for this research study is presented in *Figure 3-2*, including the relation with the RQ’s. Each stage is described in detail in the following subsections.

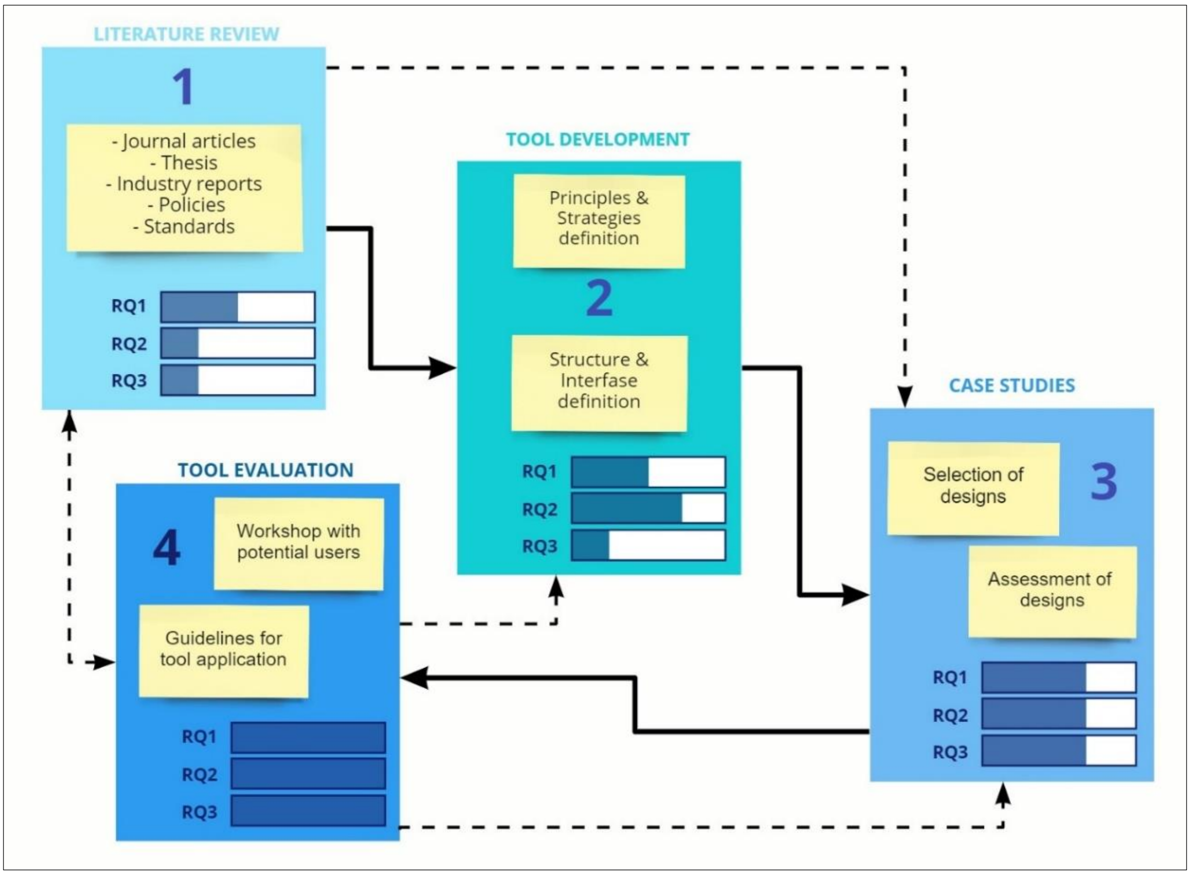


Figure 3-2 Methodology framework.

3.2 Literature review

The literature review was organized in four steps, as suggested by Snyder (2019), in order to provide quality and reliability.

Review design

A traditional Narrative Literature Review was performed to gather relevant information on the topic. Two types of search were performed: scientific and academic articles published in journals, using scientific databases such as Scopus and Web of Science. The second type of search was performed to include grey literature, consisting of conference papers, magazine articles, companies' reports, governmental documents, web reports, and academic thesis. Both types were limited to documents published between 2000 and 2021, where DfD/A has been applied in the design of buildings. The search terms were based on a combination of two topics, sustainability & buildings.

Review Conduct

During the conduct step, three searches were conducted due to the number of articles and literature found during each search and on the available time for this step. In *Table 3-1* the keywords used in each search and the purpose of the search are presented.

Table 3-1 Literature review keywords

Search	Keywords			Search purpose
1	DfD / Deconstruction	Structural Systems	-----	Detailed search on disassembly applied or used in structural systems
2	EcoDesign / Sustainable design	Structural Systems	-----	General search on EcoDesign methods applied or used in structural systems
3*	Disassembly / Deconstruction / EcoDesign	Buildings	Circular Economy	Comprehensive search for publications regarding buildings with CE strategies.

* In the last search, a third keyword was included to limit the results. The word "buildings" has a broad use for many contexts. Results using only the first two keywords shows over 1000 results.

Review analysis

For the analysis of the literature found, a two-filter selection was completed. The first selection of articles was performed according to the abstract or summary of the article or literature to ensure that it contains both review topics. The second selection was performed according to the introduction and conclusion sections of the article to ensure that it develops both review topics. The articles and literature that passed both screenings were read in full to ensure that the article met the scope of the literature review and had a clear connection to the RQs of this study. The criteria selection for inclusion and exclusion defined the quality of the literature review and helped to avoid gaps or biased studies.

Review report

Appendix 1 presents a report of the final selection of articles and literature with descriptive information that includes the authors, years of publication, type of literature, and content classification. This information was classified according to its importance to help solve the RQs. At this step, all relevant information was summarized for transparency to allow easy identification of authors and dates of publications.

Snowball literature

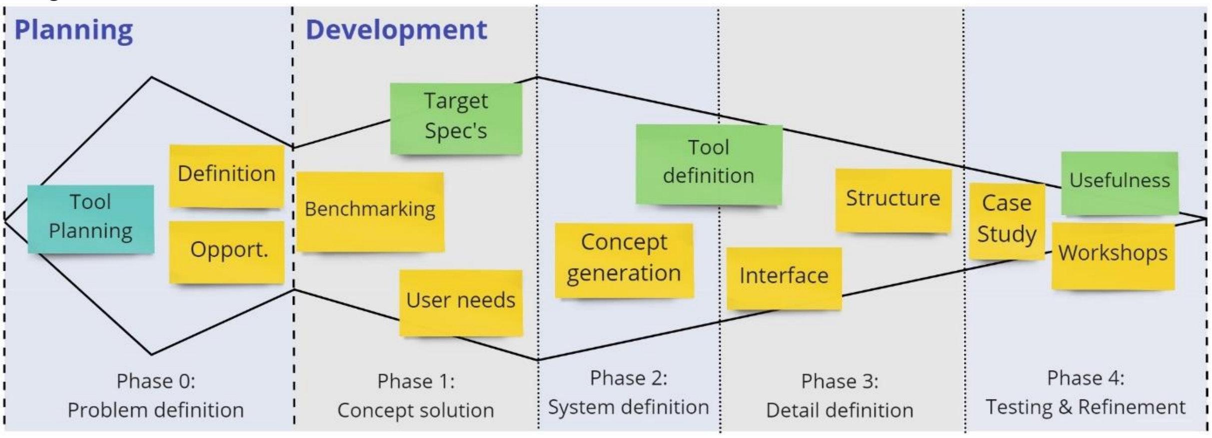
During the development of this research study, additional literature relevant to the RQs was found by snowball procedures. Snowballing in literature review refers to identifying additional documents using as a source the references and citations used in the documents from the initial literature database (Wohlin, 2014). The documents identified with this procedure are added to the database and included in the final report of the literature review presented in *Appendix 1*.

3.3 Tool development

This stage aimed to have an initial version of the tool based on the results from the previous stage. Two components composed the tool's initial proposal. The first component is a group of principles that evaluate the structural design of the buildings according to DfD/A principles. The purpose was to translate and adapt the DfD/A principles to align with the guidelines and recommendations of ISO 20887. The second component, the checklist, has the purpose of giving a qualitative score of the design. The group of principles contains complex and specific technical information regarding the structural design and DfD/A principles. In contrast, the checklist, facilitated the assessment of the design and the display of results to increase the tool's communication and interaction with the users.

The ISO 20887 provides brief guidelines on the approaches that can be made to measure the DfD/A principles. Even though these guidelines are a good starting point, a complete approach was developed to match this research's objectives. The tool will be used by different stakeholders in the construction industry, which means that the tool must fulfil specific requirements and be subjected to different needs and functional specifications from its potential users. In this way, the tool was considered as a product and was created according to Product Development (PD) methodologies.

PD can be defined as the ability to identify the customers' needs and create a product that meets these needs. It is a set of activities that start with the perception of an opportunity and ends with the production and sale of the product (Ulrich & Eppinger, 2016). Ignoring the associated definition of cost from the PD definition, the tool development is in many ways similar to the product development from the point of view that an opportunity is found for the application of DfD/A principles in the construction industry to comply with the needs of introducing resource efficiency methods and circular economy strategies into the design of structural systems in buildings. The tool development method chosen for this research study was adapted from the methods presented by Ulrich and Eppinger (2016), and show in *Figure 3-3*.



The green boxes refer to the main activities related to the RQs, and the yellow boxes refer to secondary activities related to the tool develop approach.

Figure 3-3 Tool development method. Adapted from Ulrich and Eppinger (2016).

The tool development was done in five phases, numbered from 0 to 4.

- In phase 0, the tool planning was set. For this, the primary definition of the tool was performed by identifying the core concepts, features, and parts to be included in the tool. All these aspects were clearly defined and linked to the indicator system for sustainable design of structural systems in building planning and design.
- Phase 1 was the concept solution of the tool, focused on identifying needs from potential users and target specifications of the tool. For this identification, two activities were planned for data collection. The first activity was a benchmarking of similar tools and rating systems that aim to assess DfD/A and sustainability in buildings. The second activity was to acquire information from different stakeholders in a questionnaire. Both methods for data collection are described in detail in the following subsections.
- Phase 2 was the system definition of the tool. In this phase, a detailed design of the tool was completed to create the tool structure and interface. For these definitions, a top-down approach, was selected to facilitate the connection between the DfD/A principles and guidelines with the target specification of the tool.
- Phase 3 was the concept evaluation of the tool, which aims to accomplish the usability feature of the tool. This was evaluated through workshops in which different potential users of the tool participated.
- Phase 4 was the validation of the tool. In this phase, the tool was tested to define if it works as designed and verifies if it satisfies the customers' needs. During this phase, the utility feature of the tool was tested through the application in case studies.

Phases 3 and 4 were carried out simultaneously since they do not need to be applied linearly. Both phases were conducted iteratively in order to include improvements of usability and utility in each evaluation. It is worth highlighting that, phases 3 and 4 of the tool development, correspond to stages 3 and 4 of the general design research strategy defined for this study. This correlation of phases and stages is the result of a strategic selection of research methods.

3.4 Case study

A case study is a flexible method developed to generate intensive and detailed knowledge about a single and specific case (Robson, 2011). In the context of this investigation, case study is a flexible strategy to understand the practical effect of the tool in real-life. It is a valuable method that reduce the researcher's biases, produce concrete empiric knowledge that is more valuable than predictive theories, and findings can be treat as general even coming from singles cases (Denzin & Lincoln, 2018). Case studies allows to collect about the results and process (Taylor & Bogdan, 1998), in this way the use of case studies helped to analyse at the same time the tool's results (utility) and the tool's process (usability).

A total of 5 case studies were performed with the purpose of grade the structural system according to the principles for deconstruction included in the tool. The case studies focused on having a complete experience of the use of the tool, exploring how the tool definition and structure contribute to the outcome of the assessment. The case studies were conducted at the same time with a semi-structure interview during workshops with different stakeholders of the construction sector, with the purpose of evaluate the tool usability and utility. This is further described in *section 3.6.3*.

3.5 Tool evaluation

In the final phase of the research methodology, a comprehensive analysis of the possible improvements was made to achieve the objectives of this research study. The aim of this analysis was to define a list of recommendations for the next version of the tool and help to increase the usability and utility of the tool. During this phase, the strengths and weaknesses of the assessment were identified to be used as potential improvements for the tool. This also contributed to enhance the definition of the DfD/A principles, to promote material efficiency in the design of structural systems, as well as to evaluate the impact in other external aspects, such as economic and social benefits and obstacles for implementation.

3.6 Data collection

Data collection was needed to obtain information to support the execution of the methodology described in the previous sections. Three methods were used. A questionnaire in the form of an online survey. A benchmarking, performed to collect the data about similar tool and systems. And a workshop to evaluate the experience of users when using the tool. It should be noticed that all three methods of data collection were worldwide without regional constraints.

3.6.1 Questionnaire

An internet-based survey was selected as questionnaire method for data collection to identify customer needs. This type of survey was selected for its advantages of low cost and low resources consumption. There is a good range of free website platforms with high freedom on what and how to ask (Robson, 2011). Microsoft Forms was the app used for data collection and storage. This app was selected for its ability to reach large samples in short times and without geographic restrictions. In addition to this, this app is based on a common software available on all digital devices (e.g., laptops and smartphones). The database was transferred to Excel for a better storage and handling.

However, this method has some drawbacks, and special attention was put when analyzing the information. For instance, the bias effects can be evidenced in two types, demand characteristics and experimental expectancy (Robson, 2011). The first one occurs because the respondent feels that is being evaluated and observed, and answers are likely to cooperate but can also be obstructive. The second one is a reactive effect that occurs when part of the information given to present the theory, anticipated parts of the results or findings that were evaluating. The first effect was minimized by adequately arranging the question asking about one topic but really looking for a different answer. The second one is lowered by reducing the interaction with the respondent (Robson, 2011).

Another critical aspect is population sampling. According to Robson (2011), the sampling depends on the type of design used in the method. The survey corresponds to a fixed design research with an experimental design. Since the individuals are from a known population and the research has control over the variables. For this type of survey, Robson (2011) suggest that (according to Borg and Gall (1989) and Mertens (2005)) a minimum number of 30 observations should be compiled for a homogeneous group. To reach this number a total of 55 individuals from the construction sector were contacted. A total of 38 answers were recorded. This gives a response rate of 69%, which is an acceptable rate, according to Robson (2011) most analysts of the topic consider a minimum of 60% a good rate.

3.6.2 Benchmarking

Another important method for data collection is through benchmarking. This method, more associated with commercial or business purposes rather than a scientific method, seeks to compare the performance of a product or service against competitors (Coers et al., 2002). The key advantages of using benchmarking for the tool development are (1) identification of performance gaps, (2) identification of improvement opportunities, (3) recognition of practices that works as models for improvement, and (4) reduces failures through demonstrated cases of success.

For this research study, a competitive benchmarking (Coers et al., 2002) was performed. This method aims to identify similar tools, strategies, methods, and certifications systems that include or consider DfD/A principles in the evaluation of sustainability performance in buildings.

3.6.3 Workshops

Workshops is a flexible method that allows having multiple qualitative and depth data collection (Patton, 2015) with an exclusive focus on the interaction between the respondent and the researcher (Taylor & Bogdan, 1998). In this research, workshops were used with two purposes, to collect information about the experience of the user while using the tool. This was done through a seme-structure interview; and to analyse the performance of the tool during use, by the application of the tool in case studies.

For data collection, a semi-structured interview was used to find detailed information about the expectations of the tool and how the user experience the tool. A semi-structured questionnaire is a less rigid structure that allows the respondent to have flexibility in their answers and contribute with additional important information. A set of questions were prepared as a guide that served as a checklist to ensure that all topics were covered, with the option of follow up questions that had the benefits to find undercover issues related to the research (Robson, 2011). For the interviews size and composition, Robson (2011) suggest (according to Morgan (1998)) that the minimum number of respondents is between 6 and 10. From the first questionnaire 17 respondents showed interest in taking part of the workshop, but only 11 of them participated. This is a respond rate of 65%.

3.7 Data analysis

Data collection and data analysis should happen together, all relevant findings and results are develop after the analysis of the actual data (Taylor & Bogdan, 1998). Data analysis was performed in four steps adapted from one version of a grounded theory show by Taylor & Bogdan (1998):

- ***Data collection:*** previously explained on section 3.2 and 3.6.
- ***Topic identification:*** a detailed study of the collected data was performed with the scope to identify common concepts and ideas. The identification of the topic was based on two key aspects: is meaningful for the scope of this research and support to solve the RQs.
- ***Comparison:*** the identified topics were compared among them to find relations among them. As data comes from different sources, there is a large probability that topics can overlap on the analysis and have identical findings.
- ***Confirmation and discard:*** to complete the analysis, a detail examination of the findings of the previous steps were done. The purpose of this was to discover and recognize patterns between the findings and the RQs. According to the result of the examination the findings of the analysis can be confirm as a strong result to solve the RQs, or otherwise discard them.

3.8 Quality of the research

The methodology selected for this research study is mostly based on qualitative research. Quality in this type of research is a main concern when describing how the data was collected and the methods used to analyse it. When using qualitative methods, questions on how the conclusions were made can arise from the readers, and each reader should judge its credibility (Taylor & Bogdan, 1998).

3.8.1 Credibility

The biggest barrier for quality, is the credibility of the results. The general doubt is if the analysis and results were influenced by the researcher predispositions and biases (Taylor & Bogdan, 1998). The reader does not know if the findings are affected by the prior experiences, technical knowledge, cultural attachments or research skills of the researcher (Patton, 2015). Every strategy that helps to reduce the bias or the distortion during the analysis of the data will help to increase credibility.

3.8.2 Triangulation

When using the data collected from the description to the interpretation phases, the use of a framework to explain and support the findings is needed. Triangulations refer to the comparison and cross-checking of the information looking to find consistency and to define patterns (Taylor & Bogdan, 1998). Four types of triangulation will help to support the interpretation and increases credibility and quality to the results (Patton, 2015):

- ***Triangulation of data:*** difference sources of data were use (i.e., scientific literature, grey literature, and benchmarking). In this aspect it is important to mention that data collection from participants, came from different perspectives and backgrounds.
- ***Triangulation of method*:** different methods were use along this research study (i.e., Product development, questionaries, workshops, and case study).
- ***Triangulation of theory*:** different theories and concepts were applied for the definition of the principles for design (i.e., standards, guidelines, articles, reports, thesis).
- ***Triangulation of analysis:*** this research study lacks this type of triangulation. Even with the collaboration of the supervisors of this study, it cannot be assumed their collaboration as an additional line of analysis.

Triangulation is not an alternative word for consistency, instead it helped to understand why and where of the differences (Taylor & Bogdan, 1998). Finding inconsistences during the triangulation is not an indicator of weak credibility (Patton, 2015), instead it is treated as the opportunity to have a broader understanding between the results and the aim of this research study. Using a mixed or multimethod research methodology facilitates to set findings with macro perspectives and avoid falling in single or short-sighted conclusions (Denzin & Lincoln, 2018).

3.8.3 Data collection management

To ensure proper management of all the information collected from stakeholders on the questionnaire and during the workshops, data was recorded and stored directly from the user using online apps. This strategy for data management helped to avoid errors of transcription, keep the information in a safe and accessible location, and allows an easy method to transfer and share the data base.

3.8.4 Ethics

To guarantee quality, the collected information was used ethically. The data collected for this research comes from the Literature Review, the Benchmarking and the results of the Questionnaire and Workshops carried out with different actors in the construction sector. Ethical actions refer to a correct management of the data in terms of plagiarism and authenticity.

As previously mentioned, to promote transparency, all sources of information used will include the author, the year of publication, and the type of information. With this, identification and traceability are ensured.

When a quote or transcribed statements are used in the results or discussion chapters of this research study, a double quotation mark is used. To guarantee originality and to attribute the respective rights to the original author, quotes are not revised or edit, these actions can modify the meaning of the information. In the case that a quote needs to be modify for clarification purposes, it will not be edited, and the additional needed comments will be in parentheses.

4 Data collection

This chapter presents the data collection results from both literature review and benchmarking.

4.1 Literature review summary

The literature review was conducted according to the four steps defined in section 3.2. A summary of each phase is shown in *Figure 4-1*.

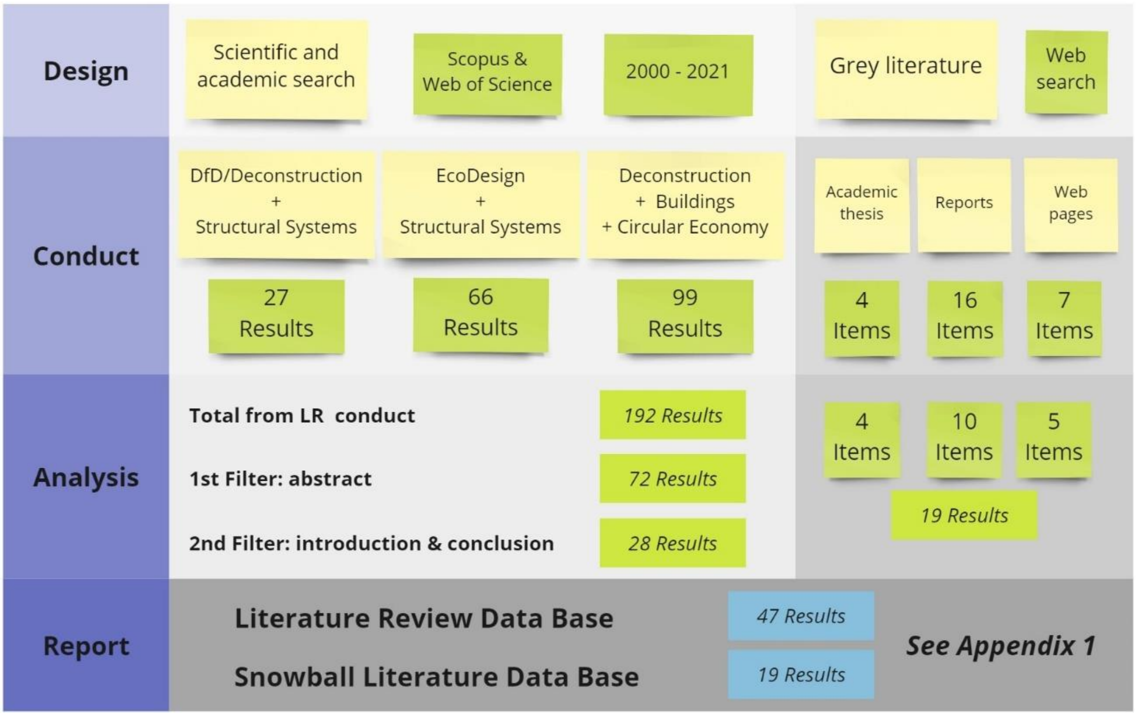


Figure 4-1 Literature review.

The final Literature Review Data Base contains 66 items, 43 from academic and scientific journals, and 23 from grey literature. The database was also classified according to the topics of each item and the importance according to the support to solve the RQs. *Table 4-1*. Displays this classification, and the complete Literature Review database is presented in *Appendix 1*.

Table 4-1 Literature review summary.

Topic	Count
DfD principles/strategies	21
DfD methodology	12
DfD metrics/assessment	7
DfD Applications/Case Studies	5
DfD barriers	8
DfD & LCA	3
DfD & BIM	2
Deconstruction Strategies	7
Material recovery/efficiency	7
Reuse of structural elements	2
Reuse and Recycling potential	9
Waste management	2
Circular economy/strategies	13
Certification/Rating systems	7

Importance	Count
High	21
Medium	16
Low	10

4.2 Benchmarking

The benchmarking was conducted on the web focused on institutions and certification systems that uses DfD/A principles in their assessment or grading systems. A summary of the tools and certification systems found is presented in *Table 4-2*. The link to the source can be found on each acronym.

Table 4-2 Sustainable tool/certifications benchmarking summary.

Assessment / Certification / Tool		Name	Author	Country	Topic
	BRE	Design for Deconstruction	Building Research Establishment	UK	- DfD Methodology - DfD Assessment - DfD case studies
	BAMB	Building as materials banks	Building Research Establishment	UK	- Circular Assessment - Materials passport - Reversible bldg. design
	EPEA	Building circularity passport	EPEA	Netherlands	- Circularity index - Cradle to cradle - Assessment example
	LEED	Leadership in Energy and Env. Design	Green Building Council	USA	- Certification system - Sus. rating system - Bldg. typologies
	BREEAM	Building Research Establishment Env. Assessment Method	Building Research Establishment	UK	- Certification system - Sus. Assessment - Bldg. typologies
	BREEAM-SE	BREEAM – Sweden	Sweden Green Building Council	Sweden	- Certification system - Sus. Assessment - Adapted to Sweden
	EDGE	Excellence in Design for Greater Efficiencies	International financial corporation	UK Switzerland	- Certification system - Energy, water, and materials savings.
	SVANEN	Nordic Swan Ecolabel	Nordic council	Nordic Countries	- Certification system - Sus. Assessment - Bldg. and schools
	SEDA	Design for Deconstruction: SEDA Design Guides for Scotland: No. 1	Scottish Ecological Design Association	Scotland	- DfD Methodology - DfD Strategies - Design examples
	LEVEL(S)	The European framework for sustainable buildings	European Commission	EU	- Web-based tool - Sus. Indicators - Circular economy
	CIRCUIT	Circular Construction in Regenerative Cities	European Commission's Horizon 2020 programme	EU	- Circular construction - Indicators for bldg., materials, and cities.
	REGENERATE	Regenerate: The Building Circularity Engagement Tool	University of Sheffield & AECOM	UK	- Computer-based tool - Bldg. design. - Circular economy
	THE STRUCTURAL CARBON TOOL	The structural carbon tool	The institution of structural engineers	UK	- Computer-based tool - Structural system - Carbon emissions

5 The Tool: An indicator system for Design for Deconstruction and Adaptability

This chapter aims to explain the development of the tool. First, an explanation of the planning phase of it is explained. Then, the definitions of the tool are presented in detail. The chapter concludes with a description of tool's interface and the structure.

5.1 Tool planning

The first objective of the planning phase was defining the different concepts and features that would be engaged with the tool. The second objective was to identify the opportunities that the tool can create or achieve with its application in the construction sector. A brainstorming session was conducted to accomplish these two objectives. During this session, all the critical components were written down to identify ideas. The session concluded with a mind map. The central idea is the tool, and from it, all the relevant ideas and concepts are set as branches. The secondary ideas were broken down into small tasks and the interconnections between them were recognized. The mind map obtained from the brainstorming is shown in *Figure 5-1*, and described below.

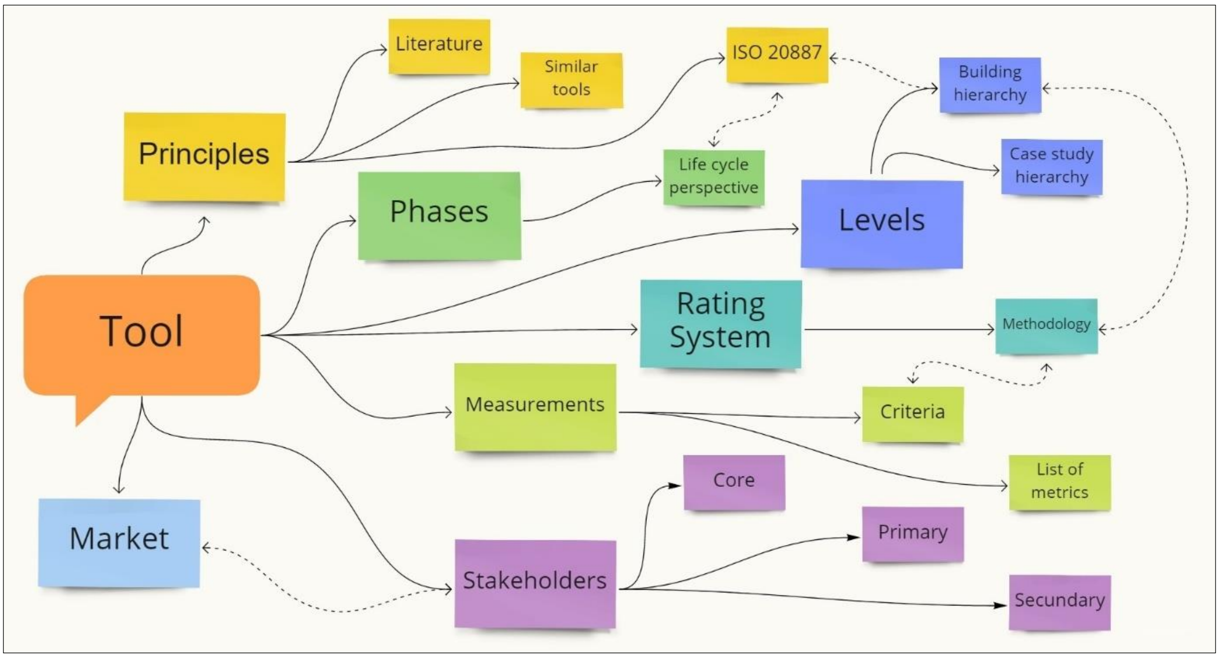


Figure 5-1 Tool planning – Brainstorming mind map.

- ***Principles:*** this refers to identifying the principles for DfD and DfA applicable to structural systems. Three sources of information were used to accomplish this identification: results from literature review (see *Appendix 1*), the analysis from similar tools or assessment systems (see benchmarking on *section 4.2*) and the ISO 20887 (see *section 2.6.3*).
- ***Phases:*** the tools, as all sustainability and EcoDesign methods, have a comprehensive emphasis on the life cycle phases of the construction sector.
- ***Levels:*** as previously mentioned, the tool was focused on structural systems and the assessment performed only graded this level of the building. Still, as the building is an integrated system conformed by different levels (see *section 2.2.3*) it is important to understand the relation with other systems and the definition of the levels of the structural system.

- ***Rating System:*** this refers to the framework used for the indicator system. Different rating scales are available to use. The selection of the scale depended on how the results of the tool are meant to be presented.
- ***Measurements:*** corresponds to the quantification of the value of each DfD and DfA principle included in the tool. This also included the definition of the metric (i.e., unit and system) and the criteria to grade this measurement.
- ***Stakeholders:*** refers to the potential use that the tool can developed according to the driving force of each stakeholder identified in the construction sector.
- ***Market:*** It is critical to identify how the construction sector can interact with the tool and if the construction market can identify the tool's utility.

5.2 Tool definitions

Once all the main ideas and components of the tool were defined, the next step is to give a proper detailed definition to each one.

5.2.1 Target specifications

The target specification is the tool specification itself, which refers to the tool requirements or what the tool must do. In a regular Product Development exercise, these definitions are based on the user needs. However, since this development is not a traditional PD exercise, and the tool is part of a new segment of tools for the design of buildings, one part of the specifications was defined based on the aim of this research study, including the adaptation of the ISO 20887 as the main framework; and the other part was defined based on the user expectations.

DfD/A principles

The principles to be implemented in the tool corresponded to the different DfD and DfA principles identified in Literature Review and found in the ISO 20887. From this point of view, the assessment included both DfD and DfA principles since adaptability and deconstruction are key to improving the sustainable performance of the structural system in buildings at the end-of-life stage. This aligns with the purpose of ISO 20887 to introduce disassembly and adaptability into the design process. *Table 5-1* presents the DfD/A principles used in the assessment, associated with literature and sources that discuss DfD principles, methods, and strategies.

Building Life cycle

All the phases of the life cycle of a building were included in the assessment. The tool is meant to be used during the planning and design phase, but the interpretation and application of the results can modify and affect all the phases of the life cycle. It is expected that most of the tool's benefits enhanced the end-of-life and reuse stages. Still, the other stages were benefited from the DfD/A design criteria. The tool can improve sustainable performance in all stages, making it a whole system perspective tool.

Structural system

This research study had some limitations since the assessment is only performed on the structural system of a building. Therefore, a subsequent delimitation was done. Since a structural system consists of several elements and components, it was important to identify at what level (see *section 2.2.3*) the assessment is applicable. Thus, the assessment system was design to be performed at a system level in order to have a proper boundary of the assessment and with the idea of having the biggest impact on the building project. The evaluation criteria are not applied at individual levels of elements, components, or materials because it was considered that the structural design work is comprehensive to the whole system level.

Table 5-1 DfD/A principles summary.

PRINCIPLE		ISO[1] 20887	CSA[2] Z782	MRPI[3]	VTT[4]	C.P.[5]	BRE[6]	G&C[7]	E.D.[8]	D.D.[9]	M&S[10]
P.1	Versatility	X	X						X	X	X
P.2	Convertibility	X	X		X	X		X		X	
P.3	Expandability	X	X								
P.4	Accessibility	X	X	X		X	X	X	X	X	X
P.5	Disassembly documentation	X	X		X	X	X	X	X	X	X
P.6	Durability	X	X						X	X	X
P.7	Connections	X	X	X	X	X	X	X	X	X	X
P.8	Independence	X	X	X	X	X		X	X		X
P.9	Finishes	X	X	X	X	X				X	X
P.10	Recyclability	X	X	X		X	X				
P.11	Refurbishability	X	X	X			X				
P.12	Remanufacturability	X	X	X			X				
P.13	Reusability	X	X	X	X	X	X				
P.14	Simplicity	X	X	X	X	X		X	X	X	X
P.15	Standardization	X			X	X		X	X	X	X
P.16	Safety	X			X	X	X	X		X	X
P.17	Reuse quality				X						
P.18	Material traceability				X	X		X	X		
P.19	CE Market				X	X					
P.20	Deconstruction process					X	X	X	X	X	X

1: ISO 20887:2020 Sustainability in buildings and civil engineering works — Design for disassembly and adaptability (ISO, 2020); 2: Canadian Standards Association CSA Z782-06 Guideline for Design for Disassembly and Adaptability in Buildings (CSA, 2006); 3: Development of policy metrics for circularity assessment in building assemblies (Mayer & Bechthold, 2017); 4: Barriers and opportunities of structural elements re-use (VTT, 2014); 5: Developing Guidelines for Designing for deconstruction (Crowther, 2000); 6: Design for Deconstruction (BRE, 2015); 7: DfD Design for disassembly in the built environment (Guy, Brad; Ciarimboli, 2005); 8: Transformable Building Structures (Durmisevic, 2006); 9: Design for Deconstruction: An Appraisal (Densley Tingley, 2012); 10: Analysis of Guidelines and Identification of Characteristics Influencing the Deconstruction Potential of Buildings (Machado et al., 2018).

5.2.2 User needs and expectations.

Before the concept generation phase of the tool's development, it was important to identify common user needs and expectations in order to define the specifications of the tool correctly. For this purpose, the questionnaire developed as part of the methodology was used (see *Appendix 2*).

Questionnaire results

A total of 38 responses to the questionnaire were obtained from different stakeholders of the construction sector. The following are some of the most relevant statistics from the results. The complete set of results can be found in *Appendix 3*.

- 29 % of the participant were structural engineers.
- Most of the participants have between 5 to 10 years of experience.
- 45 % of the answers were from potentials users located in Europe and 47 % from America.
- 20 % of the responders were familiar with assessment methods like LCA, while 24 % and 14 % were familiar with certification systems like LEED and BREEAM, respectively.
- The most recognised benefit from applying EcoDesign in buildings design is energy performance (24 %), followed by waste management and material efficiency (both with 29 %). The last two benefits are directly derived from the tool application.
- 32 % of the participants have a fair idea of DfD/A, while 24 % only related this to waste management and 24 % do not have a clear idea.

- 47 % of the respondents consider DfD/A to be suitable for structural design, but only 16 % consider that it has been already applied.
- 84 % of the participants DO NOT have knowledge about ISO 20887.

The most important results from the questionnaire related to benefits and opportunities, found from the answers of the potential users, were used for the definition of other specifications of the tool, with the purpose to account for the tool's utility.

Measurements

Two important definitions were set in order to define the measurements, related to "why" and "how". The "why" is related to the measurement definition. For this aspect, it was found that 34 % of the participants believe that sustainable benefit is the most important topic. Regarding the "how", 37 % of the participants consider that the best way to implement the DfD/A principles is through a design criteria. Based on these results, for each principle selected to be included in the tool, a sustainable benefit was defined, and an indicator was created to link and measure against the different criteria of structural design.

Rating system

The rating system is associated with how to evaluate the structural system and how to present the results. For this topic, 29 % of the responders considered having a quantitative assessment is better, whereas 16 % considered that qualitative assessment is better, and 8 % suggested an overall rating. It is worth highlighting that having an overall rating is more related to quantitative analysis than a qualitative one. Due to these results, the rating system had a hybrid framework, combining quantitative and qualitative aspects.

Stakeholders

To ensure a good usability of the tool is fundamental to identify its most suitable user. According to the answers, both the structural engineer and the architect were identified to have a 23 % each of importance in the role of potential users. This aspect is critical for the selection of the language to use in the tool development. Therefore, it would be advisable to use a language that facilitates the tool's use to this target population. In addition, it was noticed that the participants considered that the best phases to introduce the DfD/A principles are during the project definition and the conceptual design with 29 % and 16 %, respectively. Also, 21 % of the responders considered that the principles could be introduced during the described phases, and 11 % considered to be applied during the whole design phase.

Market

The market is highly related to potential stakeholders for the tools. The purpose of using the tool change according to the driving forces of the user, and these are related to the segment of the market where the user is located. According to the results, 60 % considered the tool is more suitable for the design team, while only 12 % were giving to the owner or the management team. The last two groups were part of the core stakeholders of the construction sector. The primary stakeholders (i.e., manufacturers and suppliers) only accounted for 9 %, along with the certification systems that are part of the secondary stakeholders.

5.3 Tools concept generation

As mentioned in the methodology, a top-down approach was used for the concept generation. In this way, a strong transition can be made from the DfD/A principles to the target specifications. The approach was developed from a general to a detailed view. This approach has four levels and is described in the following subsections.

5.3.1 ReBuilding Index

The first level corresponds to an overall index of the sustainable performance of the structural system, based on the DfD/A principles defined to be the part of the assessment. Its value can vary between 0 % to 100 %, where 0 % means that the design does not meet any of the principles, and 100 % means that the design meets all the principles of the assessment. This index is named the **ReBuilding Index.** This name was defined after extensively consider the scope of its value, and it was found that this is a direct interpretation of the scope of this research study. The bigger the number, the greater the potential of the structural system design to be reused more times, for a longer service time, and to adapt for different uses, which is a direct promotion of sustainable development.

5.3.2 DfD/A categories

The second level of the tool concept is the DfD/A Categories. This is a classification of the principles according to a common purpose. The assessment should be linked to the design process to follow one of the users' needs identified through the questionnaire. Because of this, the classification is performed from the perspective of inclusion of the principles into the design process of the structural system. The five categories identified are presented in *Figure 5-2* and described below.

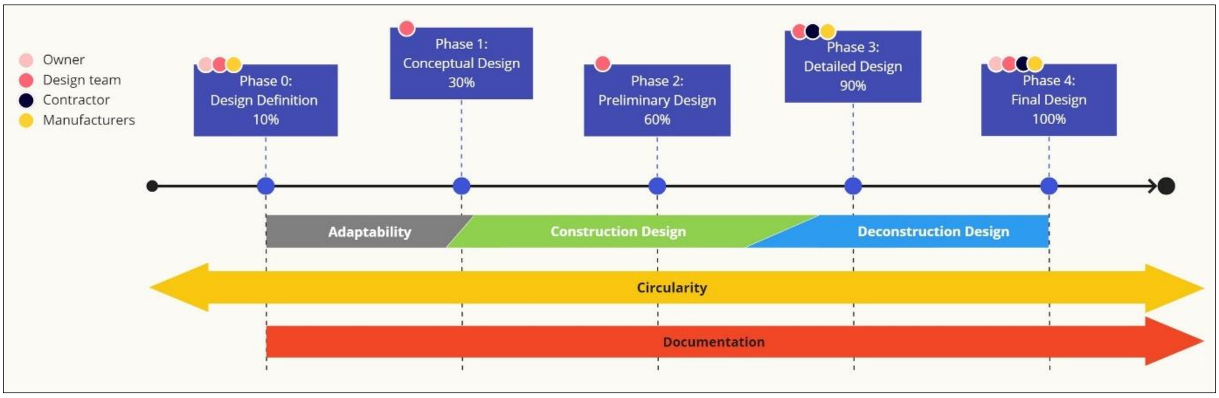


Figure 5-2 Correlation between DfD/A categories and the design process.

Adaptability

This category includes the principles related to the ability of the structural system to adapt or adjust to different uses during its service life. This type of considerations is closely related to the functional definition of the project and highly depends on the building's function. The owner is usually responsible for making these decisions in the initial part of the design process, where all the criteria and definitions are set.

Construction design

The design works start after a clear definition of the use and future uses of the building. Important decisions are taken during the initial phases of design (conceptual and preliminary), such as the definition of the structural system, geometries, materials, technologies, among others. One of the most relevant criteria used for these design decisions is the constructability of the structural system; this refers to how easy is its construction. The principles within this category share the same criteria, principles that can facilitate the construction phase.

Deconstruction design

The end phases of the design process are related to decisions about details. During these phases, detailed specifications are set. It usually includes the participation of other actors like the manufacturers and contractors to verify that all design details are covered, and the criteria are fulfilled. Detailed information is exchanged to verify that construction will not present errors, delays or over costs. At this point one result from the design process is a detailed construction program that contains specifications, activities, and resources for construction. In this phase, a valid question is: how the structural system can be disassembled? The principles involved in this category have the ability to facilitate the deconstruction process of the structural system.

Circularity

By definition, circularity refers to the fact of returning to the same point or situation. In the context of this research study, circularity is understood as the ability of the structural system to return to the use phase of the life cycle by any recycling strategy (i.e., reuse, refurbish, remanufacture, recycling). The principles included in this category aims to support these strategies and to promote a market for a Circular Economy of reuse buildings and second-hand construction materials. This category aims to improve material efficiency in using recovered materials and promote the strategies to recover them.

Documentation

A construction project generates and manages a considerable amount of information. This information is meant to guide and support all phases of the project, from planning to construction. It also has a binding and legal aspect since most of these documents are used for permit purposes to local planning and urban authorities. Typically, this documentation stops on the P&D phases, and sometimes new information is generated on the construction phase. From the lifecycle perspective of the project and to promote the material efficiency and reuse of the structural system, the project information should be available and saved during the whole lifecycle of the project. The principles in this category correspond to the advised documentation that promotes the sustainability goals of reusing structural systems.

5.3.3 DfD/A principles

The third level corresponds to the DfD/A principles identified in the technical specifications of the tool that were presented in *section 5.2*. These 20 principles are classified into the five categories described in the previous subsection. *Table 5-2* presents this classification, including the section of the ISO 20887, where each principle is defined.

Table 5-2 DfD/A tool breaks down.

L1 - Index	L2 - Category	L3 - Principle		L4 - Strategies	ISO 20887
ReBuilding Index	Adaptability	P.1	Versatility	2	Sec. 5.2.2
		P.2	Convertibility	3	Sec. 5.2.3
		P.3	Expandability	3	Sec. 5.2.4
	Construction Design	P.14	Simplicity	2	Sec. 5.3.6
		P.15	Standardization	4	Sec. 5.3.7
		P.4	Accessibility	3	Sec. 5.3.2
		P.8	Independence	2	Sec. 5.3.3
		P.6	Durability	1	Sec. 4.3.2
	Disassembly Design	P.16	Safety	2	Sec. 5.3.2
		P.20	Deconstruction process	3	Sec. 5.3.3
		P.9	Finishes	1	Sec. 5.3.4
		P.7	Connections	7	Sec. 5.3
	Circularity	P.13	Reusability	1	Sec. 5.3.5
		P.11	Refurbishability	1	
		P.12	Remanufacturability	1	
		P.10	Recyclability	1	
		P.10	Reclaimed material	1	
		P.19	CE Market	2	
	Documentation	P.5	Design documentation	4	Sec. 6.1
		P.17	Construction documentation	2	Sec. 6.1
		P.18	Disassembly documentation	3	Sec. 6.2
		P.17	Material/Manufacture information	3	Sec. 6.3
		P.18	Handling and transference	2	Sec. 6.5/6.6

5.3.4 DfD/A strategies

The last level of the approach is the strategy level. DfD/A principles work as a foundation for a system with procedures or guidelines that help and support the implementation of sustainability. In the case of the tool this system is a set of strategies that help to evaluate and promote each one of the principles. The strategies distribution is shown in *Table 5-2*.

The strategies work as the indicator system of the tool. Each of the strategies has a specific evaluation of the structural system, where a design consideration and a measure are defined. A total of 54 strategies distributed among all the principles were developed for the tool according to the definition of each principle given by the ISO 20887 and contemplating its sustainable benefit, according to the literature. It is important to emphasize that both the ISO 20887 and the literature have a general point of view of the principle's application to the overall definition of the building, which is meant to include or be applied to all the buildings layers. For the tool, the strategies were created to be directly applied only to the structural system.

5.4 Tool interface

A ready-to-use and straightforward interface is selected to facilitate the use of the tool to all the potential users and stakeholders of the construction industry. Following the digital trends in the construction sector, a computer-based solution was defined. Thus, the tool was developed as an Excel file with seven tabs, three stages for the assessment, two annexes for support, and a welcome tab. This interface of the tool has the following advantages:

- Excel software is standard among all stakeholders.
- Does not required admin credentials to install on computers.
- Version maintenance is easier compared to other programming software.

Figure 5-3 is a screenshot of the welcome tab of the tool.

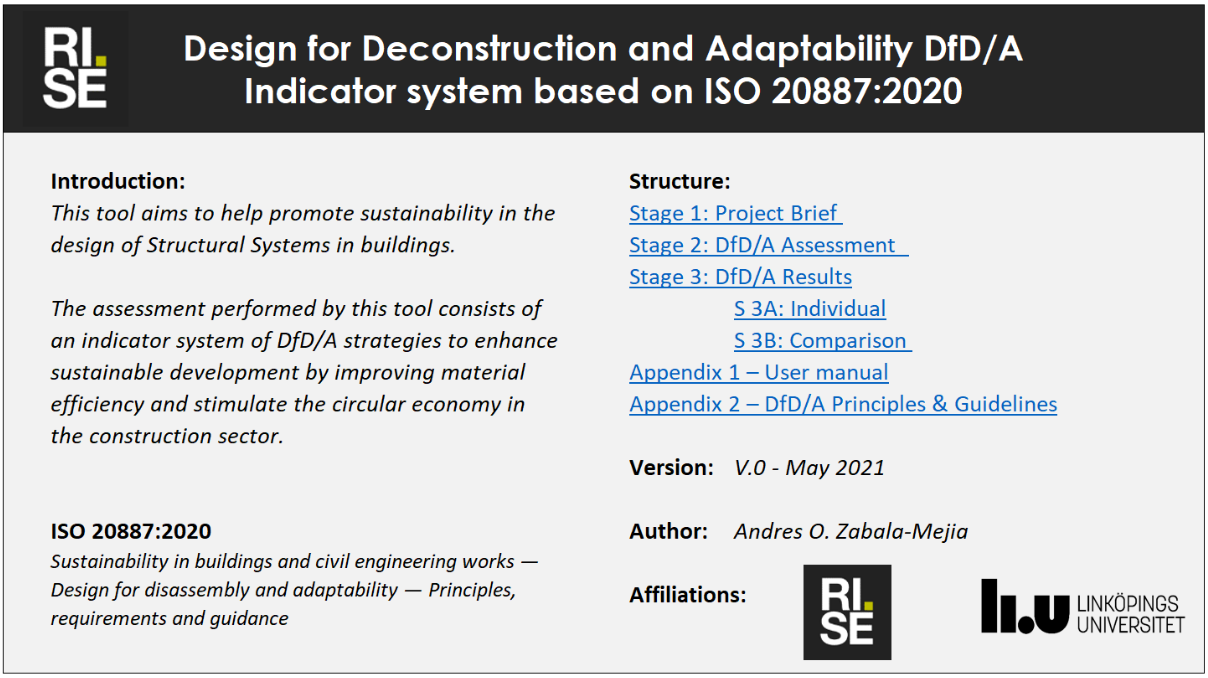


Figure 5-3 Welcome Tab of the tool.

5.5 Tool structure

With a complete definition of the DfD/A composition, the next action was to design a structure for the tool that organises all its components to perform the assessment. As the main purpose of the tool was to evaluate the structural system of a building, the main body of the structure was sketched for this purpose. At the same time, a secondary unit was built to support the tool function. Based on the previous concept on how to set the tool, the structure has a central part formed by three stages to perform the assessment and a secondary part formed by two annexes to support the use of the tool.

5.5.1 Stage 1: Project Brief

This stage aims to record a summary of the building project and the purpose of the assessment. In this part of the tool, the user must introduce relevant information regarding the project and the structural system. This stage is divided into five components, following the guidelines given by the ISO 20885 on sections 4.2 and 4.3.

- Stage 1.1. Project general information
- Stage 1.2. Project technical information
- Stage 1.3. Structural System Description
- Stage 1.4. Project context
- Stage 1.5. Sustainable performance goals

This stage has an important role because it set the alignment of the assessment and help to define the objective of the evaluation. The user defines both purpose and criteria of the assessment. A well-defined analysis assumption will help to obtain more representative results.

5.5.2 Stage 2: DfD/A Assessment

This stage can be considered as the core part of the tool. In this stage, the assessment of the structural system is performed. Here the 54 DfD/A strategies are evaluated. Each strategy is a performance indicator of the structural system.

Choosing the correct rating scale is a critical decision for both tool's usability and utility qualities; a wrong definition of the rating scale can negatively affect the interaction between the user and the tool. In terms of usability (i.e., easy to use and understand), the rating scale must facilitate the user to understand the strategy. One of the easiest methods, and common in EcoDesign, is the checklist to accomplish this aspect. This allows to verify if the strategy has been achieved or not; therefore, the answer is YES or NO. Still, utility (i.e., the ability to present relevant results) is not easily developed with just this, more in a market used to quantify everything as the engineering and finance are. This is also noticeable in the questionnaire responses, where most potential users expect a quantitative result.

A 3-point scale is selected as the rating system for the DfD/A strategies to improve both usability and utility. The intervals selected are 0, 0.5 and 1. This is similar to a checklist rating, where YES is 1 and NO is 0, but it also allows to evaluate a mid-point, which give the user the option of avoiding extreme responses (Tsekouras, 2017). It also avoids restriction and gives the user more comfortable alternatives to answer (Weijters et al., 2010). *Table 5-3*, shows an example of the rating system for one of the DfD/A principles. In this example, the deconstruction process principle has three strategies. Each strategy has a 3-point scale rating system. In the first column, the strategy is described; on the second column, the three levels of performance of this strategy are set; the following three columns are the spaced available to the user to provide the score; and the last two columns are the individual score of the strategy and the total score of the principle.

Table 5-3 Example of the rating system for a DfD/A principle.

3.0 Disassembly Design						
3.2 Deconstruction process (Sec. 5.3.7)		0	0.5	1	S-T	Total
S.3.2.a - Deconstruction process should facilitate the handling of the Structural System elements and components.	0.0: Disassembly processes require complex equipment for handling. 0.5: Disassembly processes require standard heavy equipment for handling. 1.0: Disassembly processes require standard small equipment for handling.		x		0.5	1.5
S.3.2.b - Deconstruction process should facilitate the transportation of the Structural System elements and components.	0.0: Disassembly processes require complex means of transportation. 0.5: Disassembly processes require big/heavy vehicles for transportation. 1.0: Disassembly processes require small/middle vehicles for transportation.	x			0	
S.3.2.c - Assembly/Disassembly process should be easily understood/define by visual inspection.	0.0: Disassembly process can only be understood with technical specifications. 0.5: Disassembly process can be partly-understood by visual inspection. 1.0: Disassembly process can be understood by visual inspection.			x	1	

5.5.3 Stage 3: DfD/A Results

Once the user has completed the full assessment giving a score to all the DfD/A strategies, the tool is ready to provide a result for all principles, categories, and the Rebuilding index. The first step is to consolidate all the scores for each principle. This score is the sum of the individual strategies within the same principle and normalized to an index scale (0-1) to facilitate its further combination with other principles (value shown in the third column of *Table 5-4)*. The fourth column is the total score of the category; for this, a similar process is made, all the principles within the same category are summed up and normalized to an index scale (0-100). Finally, in the last column, the weight factor of the category is shown, which is 0.2 since the tool has five categories and all of them have the same importance to calculate the ReBuilding Index.

Table 5-4 Example of the rating system for a DfD/A category.

DfD/A Category	DfD/A Principle	Principle Score	Total Score	Weight Factor
2.0 Construction Design	2.1 Simplicity (ISO20887 - Sec. 5.3.6)	0.8	64	0.2
	2.2 Standardization (ISO20887 - Sec. 5.3.7)	0.2		
	2.3 Accessibility (ISO20887 - Sec. 5.3.2)	0.9		
	2.4 Independence (ISO20887 - Sec. 5.3.3)	0.3		
	2.5 Durability (ISO20887 - Sec. 4.3.2)	1.0		

The next component of the results is the graphic results of the assessment. A spider diagram is used to show the score of all five categories. This representation of the results visually allows identifying the strong or weak DfD/A categories performance of the structural system. In order to complete the results, the ReBuilding Index is calculated as the average of the score of the five categories. *Figure 5-4* shows the mentioned results.

Category DfD/A Index

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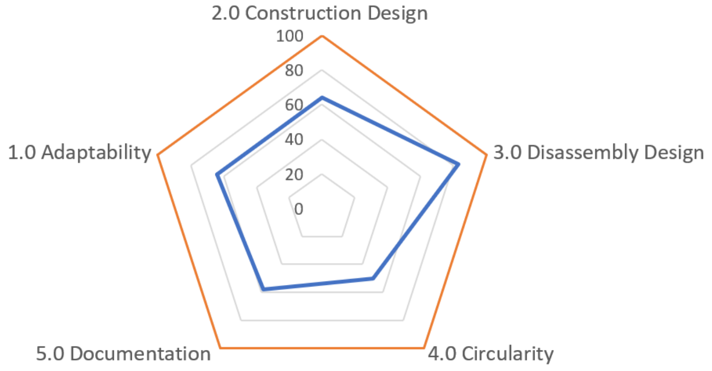

DfD/A Category	Score
1.0 Adaptability	64
2.0 Construction Design	64
3.0 Disassembly Design	83
4.0 Circularity	50
5.0 Documentation	58

Overall DfD/A Index

ReBuilding Index	64

Figure 5-4 DfD/A graphic result and ReBuilding Index.

5.5.4 Annexe 1: User manual

The user manual is a support component of the tool and is intended to assist the user in the proper application and use of the tool. It is a short description of the tool to explain its scope and structure.

5.5.5 Annexe 2: DfD/A principles & Guidelines

The last part of the tool is also one of its most critical components. This annexe is the list of guidelines that help designers and other construction stakeholders apply DfD/A principles to promote sustainable design of structural systems.

Table 5-5 shows an example of how the guidelines are defined. This is an example of the *versatility principle* that is classified as part of the adaptability category. In the third column, the general definition of the principle is set according to ISO 20887. The next column is the interpretation of this definition and translated into a general strategy applied to the whole building project. The fifth column is the strategies that can be identified from applying the principle directed to the design of structural systems. In this case, two strategies were identified for the principle. The sixth column is the design consideration on how the strategy can be used as part of a design decision, design criteria, or expected result to be effectively applied. The following column describes how this strategy will be measured in the design of the structural system. The last column of the guidelines is the consideration of the sustainable benefit that can be achieved when the DfD/A strategy is applied.

Table 5-5 Example of DfD/A guideline.

DfD/A Category	DfD/A Principle ISO 20887	Definition	DfD/A General building strategy	DfD/A Structural system level strategy	Design Considerations	Measure	Sustainable Benefit
Adaptability	Versatility (Sec. 5.2.2)	• Versatility is the ability to accommodate different type of uses with minor system changes. • Change in use can consider modification on the live load definition for the building. • Minor changes of use can be archived on a daily basis and can be quickly reverse.	• Facilitate alternative uses of the same spaces with minor systems changes. • Possible future agreements with other users or owners for shared-space agreements. • Evaluate the specific needs of the user to define possible multiple-use spaces.	S.1.1.a - The Structural System facilitate alternative uses of the same spaces without system changes.	Detailed definition of functional requirements of the building through collaborative work with the owner, users, and architect.	Consideration of potential uses during the use phase of the building.	Account for alternative uses can reduce the need for additional area or space, which reduce resources consumption.
				S.1.1.b - Live load definition should consider the highest of the possible distributed live loads.	The design should include a wide range of live load cases, and the Structural System must be designed with the most restrictive case.	Consideration of multiple live load cases.	Account for multiple live loads cases helps the structural system be used for multiple purposes without reinforcement or future adjustments.

6 Workshops & Case studies

The purpose of this chapter is to present the application of the tool in real-life designs. This chapter starts with a general description of the workshops conducted with potential users of the tool. Then, five case studies are presented, including the results of the assessment done with the tool. Finally, a summary of the users' responses from the workshop is presented.

6.1 Workshop overview

The workshop session was planned with potential users from the different levels of the construction sector. The session had four parts. First, a formulary was filled out to register and collect general information from the participants. The second part of the workshop was a short presentation of the tool, describing its objective, development, and structure. The third part was the assessment exercise; here, each participant completed the assessment based on a case study of their choice. If the participant did not have a complete design to perform the assessment, a complete example of a structural system design was shown and explained. The session concluded with a second formulary given to the participants after using the tool to rate the usability and utility of the tool once it has been tested. *Appendix 4* contains both formularies.

A total of 11 sessions were performed. The duration of the whole session was between 1 to 4 hours, with a specific duration of the assessment exercise between 40 min to 2 hours. On the first questionnaire performed during the tool development, some participants provided contact information for further discussion about the tool and voluntarily accepted to participate in the workshop *Table 6-1* present a general summary of the participants' information, including its role in the construction industry, their location, and the case study used for the assessment exercise.

Table 6-1 Worksop participants summary.

Participant	Role in construction	Location	Construction experience	Years of experience	Position	Case Study
1	Supplier company	Sweden	Villas	10	R&D Manager	1
2	Architecture company	Spain	Housing projects	4	Architect	5
3	Consultant company	USA	Infrastructure	12	Structural Engineer	5
4	Consultant company	Switzerland	Renovation	5	Environmental consultant	5
5	Academia / Research	Portugal	Building refurbishments	20	PhD student	5
6	Supplier company	Sweden	Villas	6	Sustainability manager	2
7	Contractor	Colombia	Concrete Structures	5	Contractor	5
8	Academia / Research	Spain	Civil construction	7	Researcher	3
9	Academia / Research	Spain	Timber construction	16	Lecturer	3
10	Contractor	Spain	Residential buildings	6	Architect	3
11	Design / Contractor	Philippines	Housing projects	15	Head of Technology	4

A short description of each case study is presented with the result obtained using the tool in the following sections.

6.2 Case Study 1: Stick frame timber house

A short description of the case study is presented in *Table 6-2*, and the results obtained using the tool are presented in *Table 6-3*.

Table 6-2 Case study 1 summary.

Structural Typology:	Stick frame
Main material:	Timber
Use:	Residential
Location:	Sweden
Description: Stick frame building. Roof trusses, external loadbearing wall elements and floor cassettes are produced off-site. Finished on site with gypsum plasterboards. Non-loadbearing walls are built on site.	

Credit: 6213102 © Bingram | Dreamstime.com

Table 6-3 Assessment results for case study 1.

DfD/A Category	DfD/A Principle	Principle Score	Total Score	Weight Factor
1.0 Adaptability	1.1 Versatility (ISO20887 - Sec. 5.2.2)	0.5	57	0.2
	1.2 Convertibility (ISO20887 - Sec. 5.2.3)	0.7		
	1.3 Expandability (ISO20887 - Sec. 5.2.4)	0.5		
2.0 Construction Design	2.1 Simplicity (ISO20887 - Sec. 5.3.6)	0.5	38	0.2
	2.2 Standardization (ISO20887 - Sec. 5.3.7)	0.9		
	2.3 Accessibility (ISO20887 - Sec. 5.3.2)	0.2		
	2.4 Independence (ISO20887 - Sec. 5.3.3)	0.3		
	2.5 Durability (ISO20887 - Sec. 4.3.2)	0.0		
3.0 Disassembly Design	3.1 Safety (ISO20887 - Sec. 5.3.7)	0.5	35	0.2
	3.2 Deconstruction process (Sec. 5.3.7)	0.4		
	3.3 Finishes (ISO20887 - Sec. 5.3.4)	0.0		
	3.4 Connections (ISO20887 - Sec. 5.3.2/5.3.3)	0.5		
4.0 Circularity	4.1 Reusability (ISO20887 - Sec. 5.3.5)	0.5	59	0.2
	4.2 Refurbishability (ISO20887 - Sec. 5.3.5)	1.0		
	4.3 Remanufacturability (ISO20887 - Sec. 5.3.5)	1.0		
	4.4 Recyclability (ISO20887 - Sec. 5.3.5)	1.0		
	4.5 Reclaimed material (ISO20887 - Sec. 5.3.5)	0.0		
	4.6 CE Market (ISO20887 - Sec. 5.3.5)	0.0		
5.0 Documentation	5.1 General design documentation (ISO20887 - Sec. 6.1)	1.0	70	0.2
	5.2 Construction documentation (ISO20887 - Sec. 6.1)	1.0		
	5.3 Disassembly documentation (ISO20887 - Sec. 6.2)	0.0		
	5.4 Material and manufacturers information (ISO20887 - Sec. 6.3)	1.0		
	5.5 Documentation handling and transference (ISO20887 - Sec. 6.5 & 6.6)	0.5		
			ReBuilding Index	52

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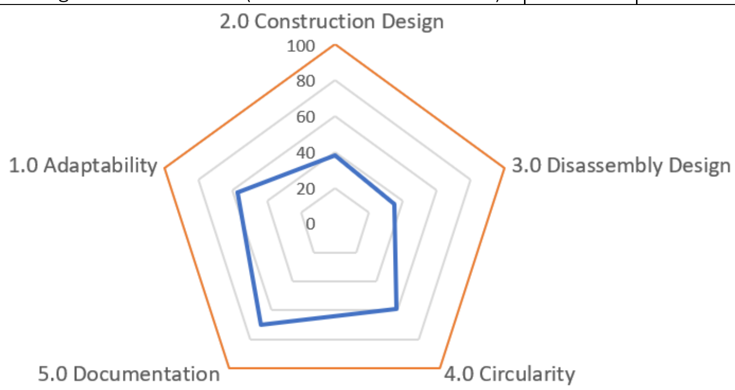

6.3 Case Study 2: Detachable timber house

A short description of the case study is presented in *Table 6-4,* and the results obtained using the tool are presented in *Table 6-5*.

Table 6-4 Case study 2 summary.

Structural Typology:	Wall system
Main material:	Timber
Use:	Residential
Location:	Sweden
Description: a 2-floor detached house. Panels manufactured offsite. Foundation of glulam (frame and columns). Specialized external wall panels + CLT floor panels + CLT interior wall panels. Roof built on site: trusses (I-joists) + roofing boards.	

643217 © Noah Strycker | Dreamstime.com

Table 6-5 Assessment results for case study 2.

DfD/A Category	DfD/A Principle	Principle Score	Total Score	Weight Factor
1.0 Adaptability	1.1 Versatility (ISO20887 - Sec. 5.2.2)	0.0	14	0.2
	1.2 Convertibility (ISO20887 - Sec. 5.2.3)	0.0		
	1.3 Expandability (ISO20887 - Sec. 5.2.4)	0.4		
2.0 Construction Design	2.1 Simplicity (ISO20887 - Sec. 5.3.6)	1.0	88	0.2
	2.2 Standardization (ISO20887 - Sec. 5.3.7)	1.0		
	2.3 Accessibility (ISO20887 - Sec. 5.3.2)	0.9		
	2.4 Independence (ISO20887 - Sec. 5.3.3)	1.0		
	2.5 Durability (ISO20887 - Sec. 4.3.2)	0.5		
3.0 Disassembly Design	3.1 Safety (ISO20887 - Sec. 5.3.7)	1.0	90	0.2
	3.2 Deconstruction process (Sec. 5.3.7)	0.7		
	3.3 Finishes (ISO20887 - Sec. 5.3.4)	1.0		
	3.4 Connections (ISO20887 - Sec. 5.3.2/5.3.3)	0.9		
4.0 Circularity	4.1 Reusability (ISO20887 - Sec. 5.3.5)	0.5	59	0.2
	4.2 Refurbishability (ISO20887 - Sec. 5.3.5)	1.0		
	4.3 Remanufacturability (ISO20887 - Sec. 5.3.5)	1.0		
	4.4 Recyclability (ISO20887 - Sec. 5.3.5)	1.0		
	4.5 Reclaimed material (ISO20887 - Sec. 5.3.5)	0.0		
	4.6 CE Market (ISO20887 - Sec. 5.3.5)	0.0		
5.0 Documentation	5.1 General design documentation (ISO20887 - Sec. 6.1)	1.0	70	0.2
	5.2 Construction documentation (ISO20887 - Sec. 6.1)	1.0		
	5.3 Disassembly documentation (ISO20887 - Sec. 6.2)	0.0		
	5.4 Material and manufacturers information (ISO20887 - Sec. 6.3)	0.7		
	5.5 Documentation handling and transference (ISO20887 - Sec. 6.5 & 6.6)	0.8		

DfD/A Assement
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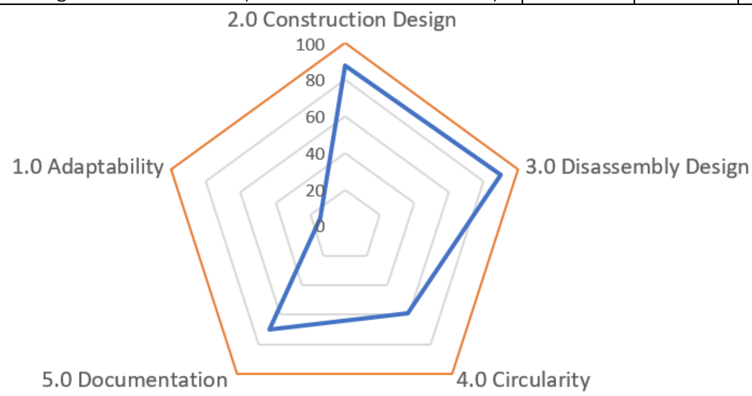

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6.4 Case study 3: Post-and-beam timber house

A short description of the case study is presented in *Table 6-6*, and the results obtained using the tool are presented in *Table 6-7*.

Table 6-6 Case study 3 summary.

Structural Typology:	Post-and-beam
Main material:	Timber
Use:	Residential
Location:	Spain

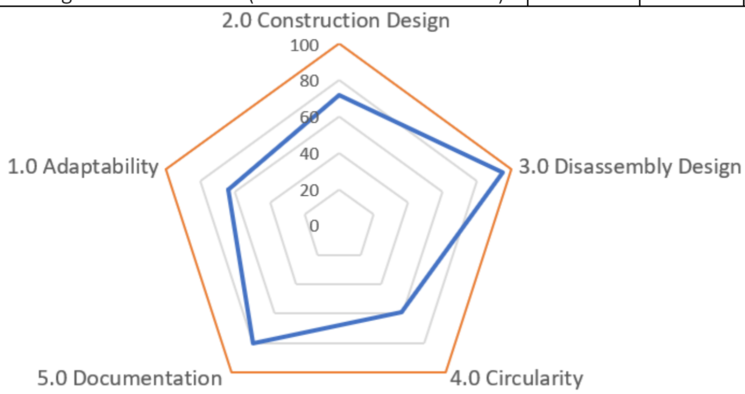
<u>Description:</u> Semi-detached two-story building. Post-and-beam massive wood structure with walls, floors, and roof panels in wooden frame. Factory manufactured elements. Quick and easy in-situ assembly. Wood-to-wood traditional connections.

Credit: 108957755 © Publicdomainphotos | Dreamstime.com

Table 6-7 Assessment results for case study 3.

DfD/A Category	DfD/A Principle	Principle Score	Total Score	Weight Factor
1.0 Adaptability	1.1 Versatility (ISO20887 - Sec. 5.2.2)	0.5	64	0.2
	1.2 Convertibility (ISO20887 - Sec. 5.2.3)	1.0		
	1.3 Expandability (ISO20887 - Sec. 5.2.4)	0.4		
2.0 Construction Design	2.1 Simplicity (ISO20887 - Sec. 5.3.6)	0.8	72	0.2
	2.2 Standardization (ISO20887 - Sec. 5.3.7)	0.9		
	2.3 Accessibility (ISO20887 - Sec. 5.3.2)	0.9		
	2.4 Independence (ISO20887 - Sec. 5.3.3)	0.5		
	2.5 Durability (ISO20887 - Sec. 4.3.2)	0.5		
3.0 Disassembly Design	3.1 Safety (ISO20887 - Sec. 5.3.7)	1.0	95	0.2
	3.2 Deconstruction process (Sec. 5.3.7)	1.0		
	3.3 Finishes (ISO20887 - Sec. 5.3.4)	1.0		
	3.4 Connections (ISO20887 - Sec. 5.3.2/5.3.3)	0.8		
4.0 Circularity	4.1 Reusability (ISO20887 - Sec. 5.3.5)	0.5	59	0.2
	4.2 Refurbishability (ISO20887 - Sec. 5.3.5)	1.0		
	4.3 Remanufacturability (ISO20887 - Sec. 5.3.5)	1.0		
	4.4 Recyclability (ISO20887 - Sec. 5.3.5)	1.0		
	4.5 Reclaimed material (ISO20887 - Sec. 5.3.5)	0.0		
	4.6 CE Market (ISO20887 - Sec. 5.3.5)	0.0		
5.0 Documentation	5.1 General design documentation (ISO20887 - Sec. 6.1)	1.0	80	0.2
	5.2 Construction documentation (ISO20887 - Sec. 6.1)	0.5		
	5.3 Disassembly documentation (ISO20887 - Sec. 6.2)	1.0		
	5.4 Material and manufacturers information (ISO20887 - Sec. 6.3)	1.0		
	5.5 Documentation handling and transference (ISO20887 - Sec. 6.5 & 6.6)	0.5		

DfD/A Assement for Structural systems



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6.5 Case study 4: Bamboo house

A short description of the case study is presented in *Table 6-8*, and the results obtained using the tool are presented in *Table 6-9*.

Table 6-8 Case study 4 summary.

Structural Typology:	Frame
Main material:	Bamboo and cement plaster
Use:	Residential
Location:	Philippines

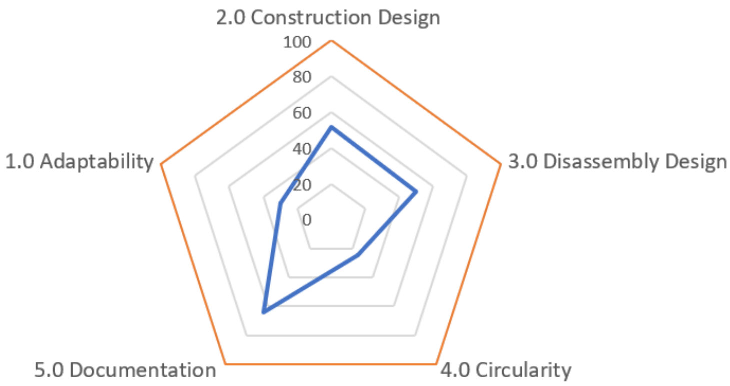
Description: one-story dwelling with a CBF (Cement Bamboo frame) structural system. It is a shear wall system made of bamboo studs, flat bars as bracing, and cement plaster covering the bamboo frame.

Credit: Base Bahay Foundation, Inc. © | base-builds.com/

Table 6-9 Assessment results for case study 4.

DfD/A Category	DfD/A Principle	Principle Score	Total Score	Weight Factor
1.0 Adaptability	1.1 Versatility (ISO20887 - Sec. 5.2.2)	0.0	30	0.2
	1.2 Convertibility (ISO20887 - Sec. 5.2.3)	0.4		
	1.3 Expandability (ISO20887 - Sec. 5.2.4)	0.5		
2.0 Construction Design	2.1 Simplicity (ISO20887 - Sec. 5.3.6)	0.3	52	0.2
	2.2 Standardization (ISO20887 - Sec. 5.3.7)	0.9		
	2.3 Accessibility (ISO20887 - Sec. 5.3.2)	0.9		
	2.4 Independence (ISO20887 - Sec. 5.3.3)	0.5		
	2.5 Durability (ISO20887 - Sec. 4.3.2)	0.0		
3.0 Disassembly Design	3.1 Safety (ISO20887 - Sec. 5.3.7)	0.5	50	0.2
	3.2 Deconstruction process (Sec. 5.3.7)	0.9		
	3.3 Finishes (ISO20887 - Sec. 5.3.4)	0.0		
	3.4 Connections (ISO20887 - Sec. 5.3.2/5.3.3)	0.6		
4.0 Circularity	4.1 Reusability (ISO20887 - Sec. 5.3.5)	0.0	25	0.2
	4.2 Refurbishability (ISO20887 - Sec. 5.3.5)	0.0		
	4.3 Remanufacturability (ISO20887 - Sec. 5.3.5)	0.5		
	4.4 Recyclability (ISO20887 - Sec. 5.3.5)	0.5		
	4.5 Reclaimed material (ISO20887 - Sec. 5.3.5)	0.0		
	4.6 CE Market (ISO20887 - Sec. 5.3.5)	0.5		
5.0 Documentation	5.1 General design documentation (ISO20887 - Sec. 6.1)	1.0	64	0.2
	5.2 Construction documentation (ISO20887 - Sec. 6.1)	1.0		
	5.3 Disassembly documentation (ISO20887 - Sec. 6.2)	0.0		
	5.4 Material and manufacturers information (ISO20887 - Sec. 6.3)	0.7		
	5.5 Documentation handling and transference (ISO20887 - Sec. 6.5 & 6.6)	0.5		

DfD/A Assement
for
Structural systems



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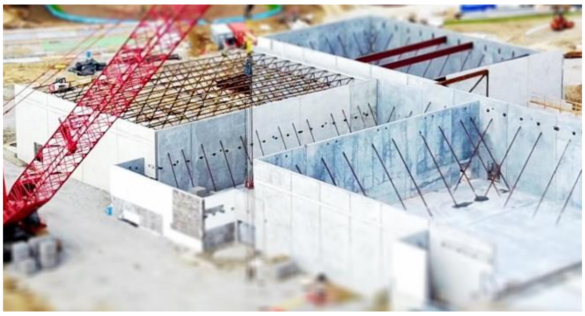
6.6 Case study 5: Tilt-up concrete warehouse

A short description of the case study is presented in *Table 6-10*, and the results obtained using the tool are presented in *Table 6-11*.

Table 6-10 Case study 5 summary.

Structural Typology:	Pre-cast walls
Main material:	Concrete
Use:	Commercial
Location:	USA

<u>Description:</u> one-story warehouse, with a Tilt-Up concrete walls system (pre-cast concrete). Connections: embedded plates on concrete, welded and anchored to other elements in situ. Roof: Steel joist with metal deck. Foundation: strap footings & mat slab.

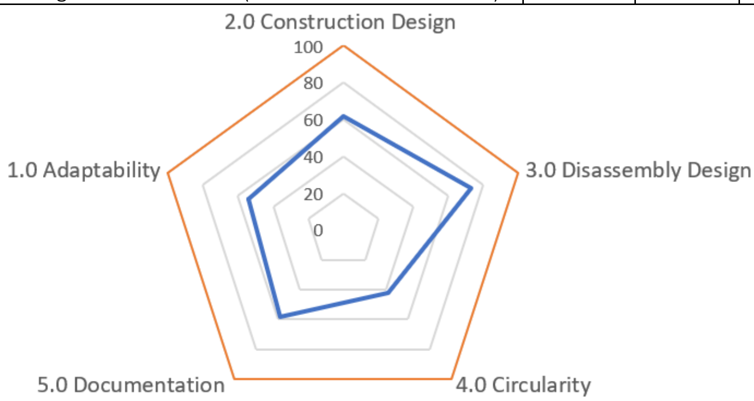


Credit: 91252958 © creativecommonsstockphotos | Dreamstime.com

Table 6-11 Assessment results for case study 5.

DfD/A Category	DfD/A Principle	Principle Score	Total Score	Weight Factor
1.0 Adaptability	1.1 Versatility (ISO20887 - Sec. 5.2.2)	0.5	54	0.2
	1.2 Convertibility (ISO20887 - Sec. 5.2.3)	0.7		
	1.3 Expandability (ISO20887 - Sec. 5.2.4)	0.4		
2.0 Construction Design	2.1 Simplicity (ISO20887 - Sec. 5.3.6)	0.5	62	0.2
	2.2 Standardization (ISO20887 - Sec. 5.3.7)	0.7		
	2.3 Accessibility (ISO20887 - Sec. 5.3.2)	0.9		
	2.4 Independence (ISO20887 - Sec. 5.3.3)	0.5		
	2.5 Durability (ISO20887 - Sec. 4.3.2)	0.5		
3.0 Disassembly Design	3.1 Safety (ISO20887 - Sec. 5.3.7)	0.8	73	0.2
	3.2 Deconstruction process (Sec. 5.3.7)	0.5		
	3.3 Finishes (ISO20887 - Sec. 5.3.4)	1.0		
	3.4 Connections (ISO20887 - Sec. 5.3.2/5.3.3)	0.6		
4.0 Circularity	4.1 Reusability (ISO20887 - Sec. 5.3.5)	0.5	42	0.2
	4.2 Refurbishability (ISO20887 - Sec. 5.3.5)	0.5		
	4.3 Remanufacturability (ISO20887 - Sec. 5.3.5)	0.5		
	4.4 Recyclability (ISO20887 - Sec. 5.3.5)	1.0		
	4.5 Reclaimed material (ISO20887 - Sec. 5.3.5)	0.0		
	4.6 CE Market (ISO20887 - Sec. 5.3.5)	0.0		
5.0 Documentation	5.1 General design documentation (ISO20887 - Sec. 6.1)	1.0	58	0.2
	5.2 Construction documentation (ISO20887 - Sec. 6.1)	1.0		
	5.3 Disassembly documentation (ISO20887 - Sec. 6.2)	0.0		
	5.4 Material and manufacturers information (ISO20887 - Sec. 6.3)	0.4		
	5.5 Documentation handling and transference (ISO20887 - Sec. 6.5 & 6.6)	0.5		

DfD/A Assement for Structural systems



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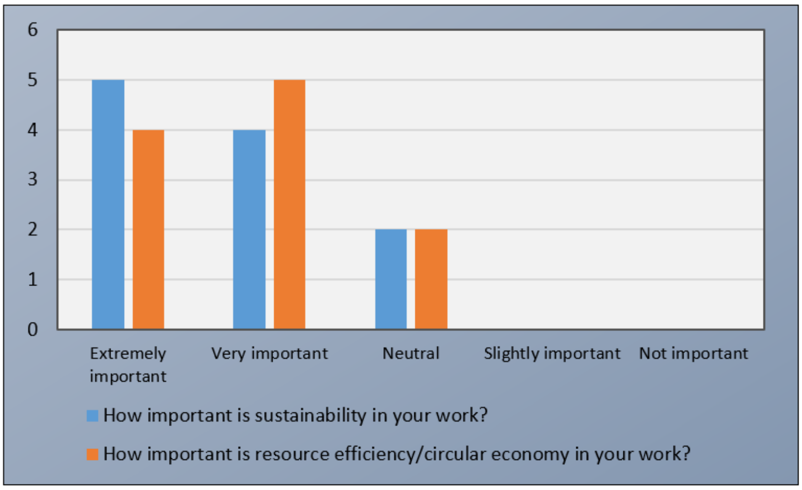
6.7 Results from the workshops

Before introducing the tool and the case studies exercises, the participants were asked how sustainability is linked to their current work. Answers are shown in *Table 6-12* with comments from the participants. The main idea from the participants' comment is highlighted.

Table 6-12 Importance of sustainability in work.

What is your main goal of introducing Eco-Design methods and tools in your work?
*"**Efficiency*** in the construction process and a sustainable performance of the final ***project***."
"Get better ***investments*** for the ***client/owner.***"
*"**Helping*** stakeholders of the built environment to reduce environmental impacts and ***resource use***."
"Extend use stage, ***reduce*** demolition ***waste***."
"To get our product and company to reach a ***circular economy***."
"Changing methods to change the ***building system*** in order to ***improve*** them."
*"**Climate change*** mitigation."
*"**Slowing*** the pace of the ***destruction*** of our planet."
"Use ***sustainable materials***, low emission natural materials."



After the workshops, the tool's usability and utility were evaluated. This evaluation was done through a formulary filled by the participants once they have experienced the tool to assess a structural design. The evaluation begins with how familiar the participant was with the DfD/A principles (see *Figure 6-1*), and how understandable they were (see *Table 6-13*).

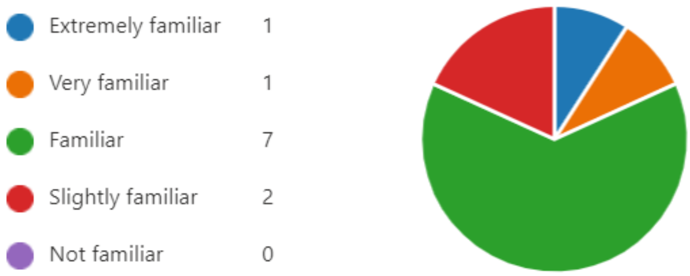
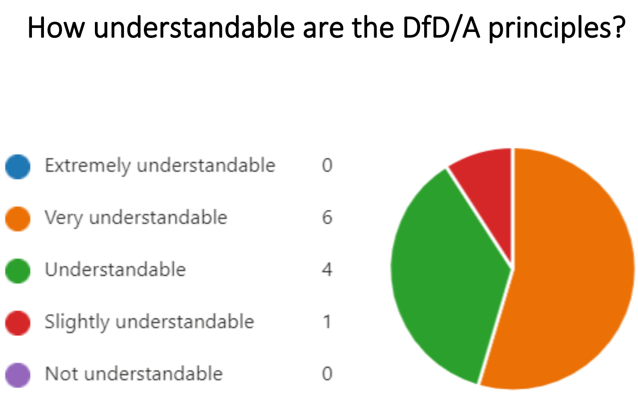


Figure 6-1 How familiar are you with the DfD/A principles?

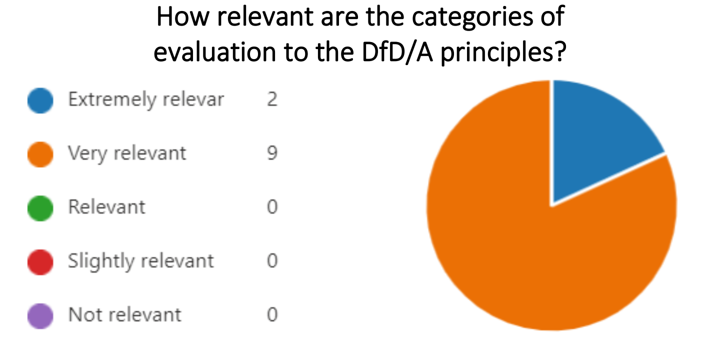
Table 6-13 DfD/A principles understanding.



If not understandable, what was the difficult part and what can be improved?
"More in-depth ***explanations*** to each measurement will be good as a teaching tool."
"Sometimes it was difficult to understand if the question refers to the ***building or element level***."
"Maybe it could be helpful to ***provide*** a small ***example*** for each"
"Probably because of lack of experience I need ***explanations and examples*** to answer most questions."
*"**The grading is*** sometimes ***difficult*** to decide upon. ***Specific quantities or percentages*** are easier to define."
"The structural system contains ***several parts/different components***, and it is difficult to give a general answer to all parts."
"I have a strong opinion that the grading needs to be ***verified by a third party***, otherwise I would not trust the answers by other companies."

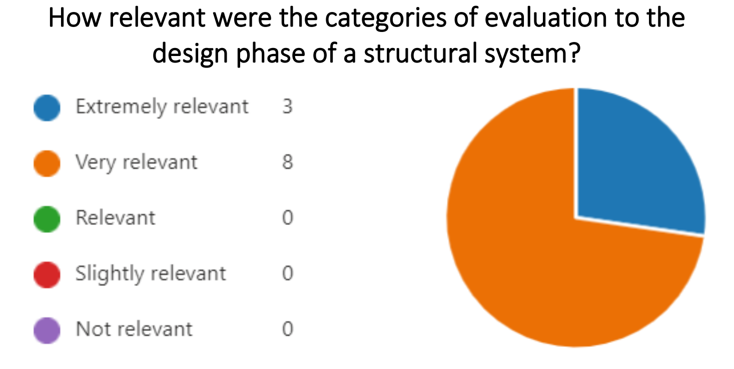
The following questions were about the relevance of the DfD/A categories, to the principles (see *Table 6-14)* and to the structural system's design (see *Table 6-15*).

Table 6-14 DfD/A categories relevance.



If not relevant, what can be improved?
No comments

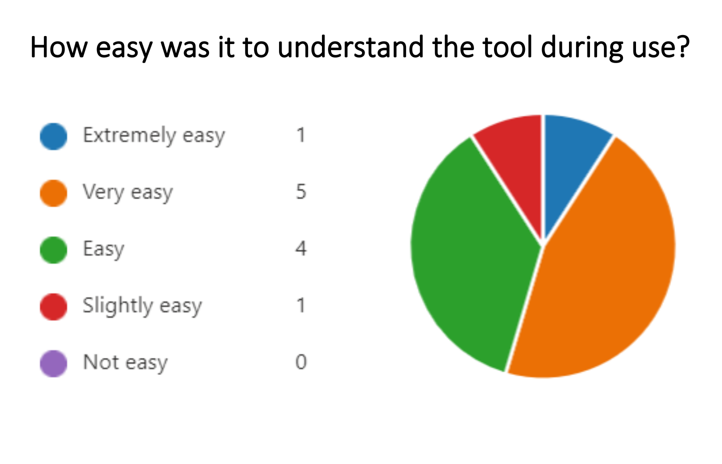
Table 6-15 Tool relevance to the structural design of buildings.



If not relevant, what can be improved?
No comments

The next question focused on the tool usability on how easy it was to use it (see *Table 6-16*).

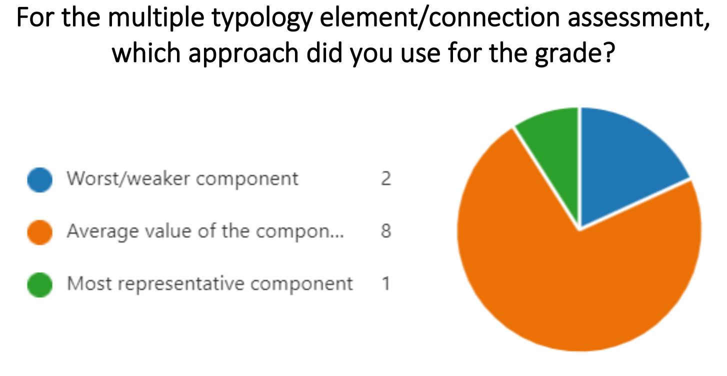
Table 6-16 Easy use of the tool.



If not easy, what was the difficult part and what can be improved?
"Maybe being ***more specific about*** the ***parts*** we have ***to evaluate***. Sometimes I was confused about what it was referring to."
"I think some ***question can*** be ***improved through*** higher specification and/or ***examples***."
"I had troubles ***understanding*** the question related to the number of ***life cycles*** and suggested it should be "lifetime" times "number of life cycles" instead."
"I think I ***should have studied the ISO standard before*** answering the questions. I should have had a deeper knowledge."
"Maybe a general overview of the tool and ***points of view*** should be ***improved***, and some ***examples*** could be included: material, products, joints, etc."

The next question focused on the approach defined by the user to respond to the questions when multiple typologies of elements and connections were assessed (see *Table 6-17*). It is worth noting that during the assessment, no instructions on this topic were given; each was unaware of this definition and completed the assessment from its own opinion.

Table 6-17 Multiple typology approach responses.



If not easy, what was the difficult part and what can be improved?
"Clarify better if it is for component or building level and if it is for building then ***which approach to use***."
"It takes time to really think through and ***analyse*** the building in the aspect of ***each question***. This cannot be changed; ***time must be allowed*** for the analysis."
"Maybe ***examples of answers*** could make the understanding easier. "
"On the other hand, if you ***give examples***, it might ***set*** the interpretation of ***the question to narrow***."

With the aim to continue with the utility evaluation, it was also asked the participants about the expectations of the tool and if they were convinced about the results of the tool (see *Table 6-18*), and if the participant were likely to use the tool in the standard design practice (see *Figure 6-2*).

Table 6-18 Responses of the tool's utility.

What were your expectations?	How convinced are you with the concept results from the application of the tool?
"Understanding of the ***general structure***, its constructive process and ***operating logic***."	"There is a lot of potential in the application of these strategies, with the 5 basic principles it is ***possible to have a good interdisciplinary communication*** in the development of the work"
"Understanding better ***how to improve design*** approaches so that designs are more versatile and ***sustainable***."	***"Fairly convinced."***
"I found it very interesting. I was not expecting that the tool could ***reflect the ISO in such a good way***."	"I have some doubts how the ***results*** will be ***when assessing*** more ***complex buildings*** with different systems combined."
"I thought the tool would be more generic and was positively surprised to see that you made a great contribution towards a ***specific quantification of DfD for structural systems."***	"I think it can be very useful. Maybe accompanying the tool with some sort of ***report that includes benchmarks*** could also ***help*** the user to better ***interpret the results."***
"To get a grading of our building ***from a deconstruction point of view*** and that was obtained."	"As mentioned before, I would prefer to have the option to choose a ***third party verifying the grading***. In that case it will be kind of a ***certification*** which I think can be very ***useful for*** us as ***a company***."
"Less than the actual concepts address."	***"Quite convinced"***
	"Very convinced. It is a very ***useful tool."***
	"Very good."

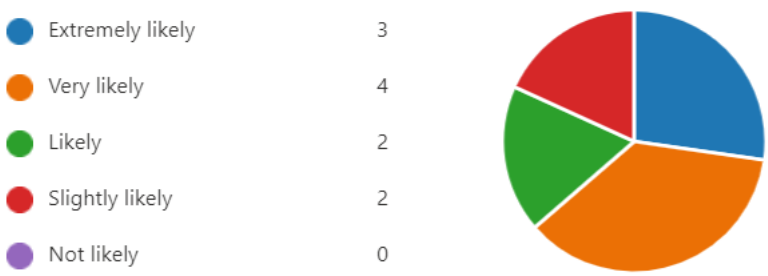


Figure 6-2 How likely is it for you to use the tool in your common design practice?

It was asked to the participants for general opinions and comments on the tool to complete its evaluation. Their answers are shown in *Table 6-19*.

Table 6-19 Final comments and opinions of the workshop.

Do you want to give any additional information or comment on the workshop or the tool presentation?
"My industry lends itself to ***single use 100-yr life spans***, and the United States as a country looks at things as bottom-line ***initial cost***, which can be difficult to overcome."
"Is not an improving question, is an academic one. In fact, it is a ***very useful tool*** for deconstruction ***but is another step more***."
"This set of strategies ***could be developed as*** parameters ***BIM*** (Building Information Modelling) software in the development of civil and architectural projects."
"Thanks for taking time and good luck on this ***very important work***! :)"
"I think it is really a ***great work behind this tool*** and that is very important **:)**"
"It is important to ***give a better definition for the level*** of the assessment and differentiate the material level from the product level."
"The use of the tool can be ***perceived as more work to do for the same money***. What can be the added value of using the tool?"
"The motivation of the person in charge to use the tool will have a huge ***impact on how to use*** the results from the tool."
"The tool provides a margin for design improvement, which ***improves the competitiveness*** of the product and allows it ***to be ahead of other systems***."

7 Discussion

In this chapter, the result and findings are discussed from the context of the research questions. The discussion focuses on three aspects: how the tool can support sustainability and its potential benefits and drawbacks; the motivations and expectations from the stakeholders of the construction sector; and the pros and cons of the tool based on its usability and utility aspects. This chapter concludes with the identification of improvements to the tool to overcome barriers and reach challenges.

7.1 Supporting sustainability

It is not easy to change the conventional way of thinking and doing things in a traditional and outdated sector, as the construction sector is. It is not because the sector does not have an active opposition to sustainable development, but rather because it has a passive mindset for change and prefers to keep the status quo. This way of thinking has created barriers and challenges to introduce the sustainability mindset into the sector. Even with all the efforts done by the academia and different actors, some of them within the construction sector, the lack of implementation is evident, as was found during the literature review of this research. This part of the discussion analyses the tool's performance according to different implementation barriers and identifies the benefits and drawbacks of using it.

Lack of suitable tools and methods

A common barrier identified for many researchers is the lack of suitable tools and methods (Akinade, Oyedele, Ajayi, et al., 2017; Ipsen et al., 2021). There is a gap between the desirable sustainable benefit and how to achieve them. Many tools suffer a phenomenon called design paradox (Chebaeva et al., 2021) that refers to the fact that the tool is limited to be used during the design phases because the data required is available in the following phases: the case of the LCA, for example. This tool that would have more benefits to be used during earlier stages needs the data from the later ones. In a similar approach, other tools can be described as reactive (Roberts et al., 2020; Lamé et al., 2017), which means that the tools are introduced at later phases of the design. The tool was developed to be used during the design; the principles cover different phases of the life cycle of the building, but its structure was defined to apply these principles for design. In this way, the objective and method of the tool are suitable for its purpose: to improve the design of structural systems and, in this way, do not fall under the definition of design paradox or a reactive tool. Furthermore, in the first questionnaire, most participants consider DfD/A as most suitable at the earlier phases of design. Also, during the workshop, the participants found the tool *"extremely relevant"* and *"very relevant"* for the design phase.

Lack of knowledge

The lack of knowledge is another aspect that makes challenging to implement a sustainable tool; this refers to the lack of evidence of the benefits from its application. There is a gap between the sustainable need and how to reach it (Ipsen et al., 2021; Denac et al., 2018). From all the answers obtained in the questionnaire, sustainability is a main concern in the construction industry, and needs are present, but from a general perspective is not clear how sustainability is or can be introduced. The tool developed under the framework of this research has a specific goal and is based on a general standard for sustainability, the ISO 20887. The work done in the definition of the strategies for DfD/A overcame this barrier of the lacking know-how and set guidelines on how to obtain the benefits from principles by applying the strategies to the design of structural systems. The case studies were carried out to collect evidence on the benefits of the tool in this aspect. The structure of the tool allows the user to conclude from the results in what category the design has the weakest performance, and from the strategies, the designer can take actions to improve the design.

Lack of professional skills

Sustainability is a comprehensive field of knowledge and should not be treat as a background topic. The professionals in charge of the building design, particularly in structural systems, are most engineers and related professions with proper education on environment and technical knowledge but still ignore relevant information on sustainability (Akadiri, 2015). Many of the tools used for sustainable design require a good level of knowledge regarding environmental impacts, such as energy use or carbon emissions. In many cases, the design's responsibility does not know how EcoDesign fits into the design activities (Lamé et al., 2017). The tool developed not only links the DfD/A principles with specific design strategies related to structural systems but also creates guidelines that help the designer understand each strategy's objective and how this can improve sustainable development. Nevertheless, the tool still requires training and education to the user, according to the second most named challenge found on the questionnaire. The fact that the tool uses a familiar structural language will facilitate closing this gap. Even though it is a point to improve, users rated the tool as very understandable during the workshop.

Lack of finance resources

Funding is a big concern when companies think about introducing sustainability into the business. There is a negative perception of the extra initial cost that these actions have on the budget of a project (Ipsen et al., 2021; Akadiri, 2015; Bilal et al., 2020). Most of the core stakeholders consider that including sustainability requires an economic investment that does not have enough return to worth the effort (Denac et al., 2018). This perception was also identified through the questionnaire; half of the participants consider this the main barrier to sustainability. During the workshop, it was noticed that this extra cost is perceived in two ways: using the tool and the cost of applying the results. The first one is related to the internal operational costs required for using the tool, which can be expressed as cost for licensed tools (i.e., software-based tools), the cost of additional information or additional time spent on this task. The second one is related to the additional production/construction cost of modifying or improving the design. Using and applying the tool may cause both extra costs. However, the impact of the cost is associated with the motivation for its application and the return benefits, both economic and environmental, which is further discussed in the next section.

Lack of cooperation

For a successful circular economy strategy, all stakeholders must have the same goal and the same strategy. During the planning and design phases, it is common to find problems regarding cooperation and communication, both internal (e.g., architects vs engineers, owner vs engineers) and external (e.g., engineer vs suppliers, owner vs contractor) (Denac et al., 2018; Ipsen et al., 2021). Improving ways of communication and data sharing is a critical factor in the construction sector. All actors are used to work on their specific duties, leaving aside the holistic perspective that should be included when implementing the EcoDesign tool to avoid future problems of sub-optimization. The tool was mainly developed to be used by the design team, but the results are displayed in a way that is easy to understand by any actor and can work as a standard line of communication to align strategies and efforts. During the workshops, comments regarding BIM implementation came up often from the participants, which is a desirable feature to enhance cooperation among actors to be explored in the near future.

Lack of awareness

Lack of awareness is a common barrier found at all levels of the stakeholders (Denac et al., 2018), which can also produce a lack of sustainable solutions demand (Agyekum et al., 2019). This opens the question of what should happen first, demand or offer. While some users claim that the construction sector is not sustainable enough, companies and designers argue that there is no real demand for EcoDesign products in the market (Ipsen et al., 2021). Participants of the questionnaire claimed that sustainability is an important issue in the sector. Still, they rated themselves as passive actors when implementing sustainability, having an average score of 4.1/10 when talking about experience in sustainability assessment. Awareness in this scenario can be closely related to the lack of knowledge and lack of professional skills. During the workshops, most participants were not aware that many of the current design criteria align with the DfD/A strategies. This trend was noticed because 80% of the participants responded that they were familiar with the principles, which means that they were conscious of the technical aspects of the criteria used for design but not on the sustainable impacts. Thus, promoting sustainable knowledge and skills in the sector is required. The tool helps to promote awareness by showing that sustainability is not strange to the sector as people think.

Lack of legislation

A compulsory framework based on legislation can help the purpose of design sustainable buildings. But in this framework is missing suitable policies, codes, and standards that can help increase the speed to adapt EcoDesign methods and strategies in the construction sector (Ipsen et al., 2021). The current legislation and policies acting in the sector are mostly focused on the use phase of the building (e.g., energy use, water consumption), but very few have a holistic view of the system (Rios et al., 2015). Legal frameworks need to grow to close the gap between the industry and the strategies for circular economy and resource efficiency. The recent ISO 20887:2020 is an example of how standards can help overcome the gap and use of DfD/A for sustainable design. The tool developed in this research took this standard as a foundation for its structure. The standard is an informative-based instrument that gives the tool support and guidance from the policy framework. Using this standard in the tool strengthens the credibility and reliability among the sector and the stakeholders, as perceived in the comments from the workshop.

Lack of market and strategies for circular economy

Circular economy strategies share many principles and targets with different EcoDesign Methods, but the construction sector has been limited to waste reduction and recycling of materials. Thus, circular economy in the construction sector lacks from a system perspective strategy (Adams et al., 2017). During the workshops, this topic was a raised up from all the participants because today's market is not aligned with circular economy, there is not a proper and stable market of second-hand construction materials, which makes that the supply chain for recover materials be a high-cost activity; this was noticed specially by participants with management roles, as well as the literature (Bilal et al., 2020). Another critical aspect of circular economy is the technical aspect of the elements. Structural design and the construction sector are under a rigorous normativity of design codes that state the structure's safety and load-resistance performance. These codes have a rigid definition of quality of materials, elements, and technologies, and at the same time have a deficiency of indicators for second-hand materials (VTT, 2014), which limit the circular economy strategies. This tool and the DfD/A principles can enable a circular economy in the sector and promote awareness to all stakeholders.

7.2 Stakeholders' motivation

Introducing sustainability in the construction sector brings many benefits and the motivations and driving forces behind this varies from stakeholder to stakeholder. Even if using the same tool and having the same results, the benefits and the expected return are different because this aligns not with the nature of the EcoDesign tool but with the motivation behind its use.

The ReBuilding index, main result from the tool, is the outcome of a set of strategies that aims to reduce waste generation, increase material efficiency in construction, and enhance circular economy strategies. Still, this index can be perceived, at the same time, as an indicator of performance for design purposes (i.e., index of sustainable design), an indicator of sustainability for commercial reasons (i.e., Ecolabel),or a possible indicator or rating tool to be included in any certification system (i.e., link to LEED or BREEAM). Some stakeholders see in this index an economic benefit (e.g., increase of revenue and decrease of production/operational cost), while other users see a more social effect (i.e., quality buildings).

All the stakeholders want to add value to its product, just from their role in the construction sector.

The tools as an EcoDesign method

From the designers, owners, and consultancy companies' perspective, the common driving forces include the necessity of increasing quality, reducing costs, creating innovative and differentiate products, managing environmental impacts, following legislation and regulations. All these motives result in a high-quality building with a high sustainability performance.

This group of stakeholder does not pay much attention to what tool to use instead to the results on how to measure sustainability (Denac et al., 2018), the results of having these added value can return to the company as economic value (e.g., income), environmental value (e.g., reduction of impact), social value (e.g., employee motivation), or a mix of all, this is highly dependent with the company's sustainable strategy. However, most of the company's focus their strategies on the economic investment and return, which makes it difficult to close the gap of EcoDesign methods in the construction industry.

The tool as a certification system

From the point of view of other actors such as contractors, manufacturers, and some design companies, driving forces are associated with external factors like market demand, competitors, image and reputation, and regulatory framework. All these strategies seek to translate the added value of the design to brand improvement, market control, and customer selection, which in the short term is perceived as an increase in revenue and sales.

In case the tools acquire this commercial feature and be part of a certification system or an eco-label program, the involvement of an independent third party is required, as it works for all the certification systems (e.g., LEED or BREEAM), and standardized tool (e.g., LCA for product declarations).

7.3 Tools' usefulness

As mentioned in the introduction chapter, a desirable feature of the tool to consider during the development is the usefulness, as the sum of its utility and usability. Both indicators must be archived to account for usefulness because missing one of these can be considered as a design failure of the tool. Usefulness is a key indicator of quality to ensure future tool development in the construction sector.

Utility

The utility is the ability of the tool to perform a task and obtain relevant results, and can be described with questions like: does it solve a real need? or does it do something that the user wants to do? (Nielsen, 2017). Both questions are linked to the purpose of the tool and for what the user needs the results. Independent of the user's motivations, the result from the tool needs to be above from then and set a more comprehensive foundation of EcoDesign and truly support the sustainable design of structural systems. The question then is, do the results support the sustainable design?

From the workshop responses after using the tool, two questions were formulated to the purpose of rate utility:

1) How relevant are the categories of evaluation to the DfD/A principles?
2) How relevant were the categories of evaluation to the design phase of a structural system?

All participants responded between "extremely relevant" and "very relevant" and did not give comments on these topics for both questions. Then it can be concluded that the tool approach (strategies → principle → category → ReBuilding index) is relevant to the sustainable design of structural systems, at the point that utility has a reasonable rate.

Doing a more in-depth and detailed evaluation on the assessment part of the tool, three main concerns were revealed from the users' responses that can have an impact on the utility of the tool:

- ***Level definition:*** on what level/part of the structural system is the assessment (e.g., the whole system, elements, or material).
- ***Scale definition:*** most of the strategies are score in a 3-point scale (i.e., 0, 0.5, and 1). The measure used for each strategy and the rank of each point is not straightforward.
- ***Criteria definition:*** for some strategies, the assessment asks to evaluate multiple elements in only one indicator (e.g., reversible connections).

For the level, it is important to recall that for this first version of the tool, one of the delimitations was to assess the whole system because, at this point, the tool does not consider any levels or elements rather than the whole structural system. Therefore, this issue has been a big concern during the development of the tool and the future. However, the ISO 20887 states that "not all principles are relevant to all situations", then the tool can be adapted according to the assessment and the level the user needs regarding the structural system. This issue is further discussed in the next section of improvements and challenges.

Scale definition is a challenging issue because of the stakeholders and the communication ability of the tool. Most strategies are set with a quantitative rank and a small number on a qualitative scale. The engineering field is a quantitative science where professionals are more comfortable managing numbers than defining something that cannot be measured. However, having a qualitative scale can be more attractive in the industry and strengths the communication ability of the tool by having a more flexible language to increase its utility among all stakeholders. Nevertheless, this also may be a point of improvement.

The criteria definition for multiple parts/elements is an important issue because it impacts the results. A good example of this is: if a structural system has five different types of connection, but the grade asks for an overall rank, does it come from the worst connection? The average of all? or the most representative (e.g., size, importance, quantities)? This definition impacts the results and affects the tool quality of comparability and reproducibility. The next section discusses ideas on how to manage this issue.

Usability

Usability is related to the ability of the tool to be easy to use and understand by the user, highly related with questions like: can the user understand it? or can the user operate it? (Nielsen, 2017). From the workshop responses after using the tool, two questions were formulated for the purpose of rate usability:

1) How understandable are the DfD/A principles?
2) And, how easy was it to understand the tool during use?

For the first question, most of the answers agreed that the tool is very understandable and understandable. For the second most of the answers is between extremely easy and easy.

From a general point of view, the tool has a good usability score, yet participants raised issues related to this topic. Including examples and short descriptions of the strategies can improve the understanding level of the user. It was noticed that the duration of the assessment among the participants varies according to this; for more expert users (i.e., structural engineers), time was lower than 40 minutes, while for other roles (i.e., researcher lecturer), it took up to 2 hours. This is due to the familiar knowledge of some of the strategies of the assessment. Including examples and better descriptions can help the tool improve communication among stakeholders, increase usability, and lower the assessment time. It is worth highlighting that during the workshop, the user received the necessary support and clarification to complete the assessment.

An important aspect of usability is the 3-point scale used in the tool, which has pros and cons. From one side, having a higher scale (5, 7, or 10 points) brings more difficulties for both user and developer. For the user, having a more flexible scale allows to lose the true scope of the indicator. In contrast, for the developer to increase the complexity on the scale definition, which is already a big concern for utility. Moreover, having a 2-point scale or checklist introduce a bias of force-choose to the assessment, which is an extreme selection scenario perceived as not comfortable by users. After completion of the workshops, the 3-point scale was considered as an adequate rating system for the tool. It was observed that having three levels of the evaluation was complex enough and required some effort from the user to respond; therefore, having a more extensive scale would require a more significant effort from the user, decreasing the usability of the tool. At the same time having 3-levels help the user to assume a position regarding the sustainability strategies, where the options are: "I am missing this…", "I am working on this…", or "I accomplish this…", this position will be translated into actions that help to focus the effort on where and how the improvement to the structural system must be made.

User experience

Another main quality indicator for new tools and products with an interactive interface is a good user experience, defined as providing a meaningful and relevant experience (Ye, 2017). This indicator was not measured directly during the workshop or either asked the participants. Nevertheless, their attitude during the workshop was always confident and collaborative, which was perceived as a positive and enthusiastic response. Moreover, the initial duration of the workshops was one hour. However, from the 11 workshops performed, four of them lasted two hours, which can be explained because of the tool complexity (required more time to understand and use) or interest and engagement of the user with the tool (preferred to complete the exercise to be able to have the results from it). As the participants were asked if they wanted to stop or continue at the initial defined time, the participants' decision to continue was a positive response. From the data collected, only two responses can be related to user experience by the text ":)", which is the key text for a happy face.

7.4 Tool challenges and improvements

It can be concluded that the tool brings great sustainable benefits for the construction sector and, in particular, for the design of structural systems. It is flexible to meet different user needs and can be adapted to diverse applications, as it was tested in five different case studies. Also, it was rated with good usefulness from the users. Still, there are many identified challenges and opportunities to improve.

General improvements

The first improvement that can be introduced to the tool is to add examples and graphic descriptions to the rating of each strategy that helps the user better understand each scale. Some strategies can be more complicated than others, according to the scope of each strategy, and some of them will not require an example. This is an immediate and fast usability improvement.

Scenario definition

A new stage of the tool called "Scenario Definition" can be developed to overcome two of the issue's identity for utility (i.e., level and criteria definitions). In this new stage, the user will have the opportunity to select from pre-set options of specific scenarios for the assessment. The user can have the option to select: (1) the criteria definition, from which perspective wants to analyse the system; (2) level definition to select the level of the system to assess; and (3) purpose definition to define the objective of for what the results are going to be used. The first two options are issues identified as opposed to the utility, while the third one is an opportunity to improve the tools communication according to the user motivation. For instance, the user can select to assess a design from a scenario of reuse of the system or recycling of the material. Adding this stage may help to improve utility communication and flexibility. Allowing the user to choose specific criteria according to their needs may improve the tool's ability to assess different structural systems, from different materials, with different technologies, and with different functional performance.

Sustainable weighting factors

It is important to recognise that barriers and opportunities differ from one country to another, from one context to another, and from one purpose to another (Agyekum et al., 2019). This is a common obstacle when trying to implement sustainability in any sector. This distinctiveness of EcoDesign methods was recognised during the development of this initial version of the tool, but due to its complexity, it was not further developed. Nevertheless, an appropriate room for its introduction was left in the tool structure. The five categories of the rating system have a weighting factor in calculating the ReBuilding Index. The future challenge is to select a suitable methodology for the calculations of these weight factors according to the Sustainable performance goals of the structure and the project's sustainable context. Examples of this are the Delphi method or the Nominal Group Technique NGT, which help evaluate and prioritise ideas and parameters.

BIM

There are a significant number of research and studies that discuss the benefits, challenges, and barriers of merging EcoDesign tool and methods with Building Information Modelling BIM (Akbarieh et al., 2020; Akinade, Oyedele, Omoteso, et al., 2017; Lamé et al., 2017). BIM capacities can help designers analyse deconstruction scenarios and make better decisions, improve the communication of the EcoDesign strategies among stakeholders, connectivity with other tools and certifications systems; enhance collaboration in the industry, and allow a proper documentation management the whole life cycle of the building.

8 Conclusion and future studies

In this chapter the research questions will be answered. An overall conclusion is presented, and future research recommendations are given.

8.1 Answer to research questions

RQ1. How can DfD/A principles be adapted into guidelines to help designers and other construction stakeholders to enhance sustainable design of structural systems?
From the literature review performed, 20 DfD/A principles were identified that apply to the design of structural systems. A total of 54 strategies were defined to reach the goals of these principles. Each strategy definition includes design considerations for the structural system, how the strategy is measured, and the sustainable benefit of achieving the principle. This framework of the principles enhances sustainable development by improving material efficiency and stimulating the circular economy. Furthermore, the support of the tool to sustainable design is analysed according to different implementation barriers and identifies the benefits and drawbacks of using it.

RQ2. How can the standard for sustainability in buildings ISO 20887 be interpreted to develop a tool to assess sustainable design of structural systems?
To achieve a strong and flexible structure of the tool, a top-down approach was used for the concept generation. This approach is based on 4 levels: ReBuilding index, Categories, Principles and Strategies. The scope and aims of each strategy and principle were established according to definition and guidelines of the ISO 20887. The categories were specified according to relationship of each principle with the design process of the structural systems. The ReBuilding index is an indicator of sustainable performance of the design in terms of deconstruction, adaptability, and reuse. This was also a tool specification according to the user's expectation on how to obtain the results from the assessment. During the workshops with potentials users, this structure was graded by all participants as "extremely relevant" and "very relevant".

RQ3. How to promote sustainable design of structural systems by ensuring the usefulness of the tool?
The usefulness of the tool was measured in terms of utility (i.e., obtain relevant results), usability (i.e., easy to use), and user experience (i.e., meaningful experience). These attributes depend on the user perception of the tool. To ensure these attributes, a questionnaire to identify user needs was performed to transform them into specifications for the tool. To verify the achievement of these needs, workshops with potential users were conducted to evaluate the performance of the tool. It was possible to use the tool to assess diverse structural systems by different stakeholders. As a result, the identified needs were covered, and usefulness was rated directly by users as a relevant, understandable, and easy to use tool.

8.2 Overall conclusion

The final product of this thesis is an EcoDesign tool for the design of Structural Systems in Buildings. It is an initial version V.0 of a tool that works as an indicator system for sustainable development. This tool was developed based on DfD/A principles and the ISO 20887, giving the tool a strong theoretical background and a flexible structure that can be used for design or part of an extensive framework of certification systems or ecolabel programs.

The tool was tested in the construction sector, where 11 stakeholders with different roles and backgrounds evaluated the tool. Case studies were selected to grade the design of five different typologies of structural systems. The usefulness quality of the tool was evaluated based on indicators of usability, utility, and user experience. The responses show that the tool has a good rate of usefulness, where 80 % of the participant were likely to use the future versions of the tool on their standard design practices.

The ReBuilding index is an indicator of sustainable performance for structural systems. It is also a flexible indicator that can be used for design improvements or certification systems. The tool accomplishes the goal of grading and helping to improve the structural design. However, during the evaluation of the tool, many barriers and difficulties of application were found. These findings and obstacles are instead identified as challenges and turn them into opportunities for improvements that are meant to be used and implemented in the subsequent versions of the tool.

Between the construction sector and sustainable development, a gap is taking time to close and with a significant number of barriers that slow, even more, the process of closing it. The tool developed in this Master thesis is the initial step of a long path to help the construction sector embrace sustainable design, focusing on the structural design.

The final product of this thesis is not just a research study on how to promote sustainability in the construction sector. It is also a living EcoDesign tool based on DfD/A principles that help the construction industry reduce waste generation, increase material efficiency, and enhance the circular economy by promoting sustainable structural design.

8.3 Future research

The future research is within the tool itself and in joint strategies with other EcoDesign tools and methods. The tool must be continually improved, great opportunities and challenges are set, and more are to come. It is expected that the next versions of the tool succeed in reaching these opportunities, overcome new barriers, and keep up to date with internal and external demands of sustainability.

The gap between EcoDesign and the construction sector is still vast, integrating it with other tools can help to narrow it down faster. Some future research suggestions are combined with LCA for studies regarding rebound effect; with LCC for developing decision-making tools, including strategies of share-ownership or Product-service systems to enhance circular economy; and BIM adaptation.

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Appendix 1 – Literature review data base

LITERATURE REVIEW DATA BASE						
Item	Type	Year	Author	Title	Topic	I*
1	Paper	2019	H. Figl, C. Thurner, F. Dolezal, P. Schneider-Marin, I. Nemeth	A new Evaluation Method for the End-of-life Phase of Buildings	DfD, separation, and recycling	M
2	Paper	2020	H. Abuzied, H. Senbel, M. Awad, A. Abbas	A review of advances in design for disassembly with active disassembly applications	DfD Methods DfD Application	L
3	Paper	2020	I. Bertin, R. Mesnil, J.M. Jaeger, A. Feraille, R. Le Roy	A BIM-Based Framework and Databank for Reusing Load-Bearing Structural Elements	Reuse of structural systems/elements Reversible design	M
4	Paper	2018	R. Carvalho-Machado, H. Artur de Souza, G. de Souza Veríssimo	Analysis of Guidelines and Identification of Characteristics Influencing the Deconstruction Potential of Buildings	DfD Characteristics DfD Categories	H
5	Paper	2017	O. Akinade, L. Oyedele, K. Omoteso, S. Ajayi, M. et al.	BIM-based deconstruction tool: Towards essential functionalities	DfD principles End-of-life strategies	M
6	Paper	2020	A. Akbarieh, L. Bhagya Jayasinghe, D. Waldmann, F. Teferle	BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review	BIM support End-of-life strategies CDW strategies	L
7	Paper	2021	Dario Cottafava, Michiel Ritzen	Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects	DfD criteria Circular economy	H
8	Paper	2018	L. Leso, L. Conti, G. Rossi and M. Barbari	Criteria of design for deconstruction applied to dairy cows housing	DfD principles Case study	M
9	Paper	2015	Vasil Diyamandoglu, Lorena M. Fortuna	Deconstruction of wood-framed houses: Material recovery and environmental impact	Deconstruction process Reuse and recycling	M
10	Paper	2017	O. Akinade, L. Oyedele, K. Omoteso, S. Ajayi, M. Bilal, H. Owolabi, H. et al.	Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills	DfD principles Material recovery	M
11	Paper	2018	Jouri Kanters	Design for Deconstruction in the Design Process: State of the Art	DfD categories Reuse potential	H
12	Paper	2020	O. Akinade, L. Oyedele, A. Oyedele, J.M. Davila-Delgado, M. Bilal, L. et al.	Design for deconstruction using a circular economy approach: barriers and strategies for improvement	DfD strategies DfD barriers Circular Economy	H
13	Paper	2015	Fernanda Cruz Rios, Wai K. Chong, David Grau	Design for Disassembly and Deconstruction - Challenges and Opportunities	Waste management DfD method	H
14	Paper	2017	Wasim Salama	Design of concrete buildings for disassembly: An explorative review	DfD method Reuse and adaptation	H
15	Paper	2008	M. Clapham, S. Foo, J. Quadir	Development of a Canadian National Standard on Design for Disassembly and Adaptability for Buildings	DfD principles DfD assessment	H
16	Paper	2012	Danielle Densley Tingley, Buick Davison	Developing an LCA methodology to account for the environmental benefits of design for deconstruction	DfD method LCA method	L
17	Paper	2018	Matan Mayer Martin Bechthold	Development of policy metrics for circularity assessment in building assemblies	DfD Metrics Assessment examples	M
18	Paper	2021	G. Bertino, J. Kisser, J. Zeilinger, G. Österreicher Langergraber, T. Fischer,	Fundamentals of Building deconstruction as a Circular Economy Strategy for the Reuse of Construction Materials	DfD principles Reuse and Recycling Circular economy	H
19	Paper	2021	Kikki Lambrecht Ipsen, Massimo Pizzol, Morten Birkved, Ben Amor	How Lack of Knowledge and Tools Hinders the Eco-Design of Buildings—A Systematic Review	EcoDesign methods Barriers and opportunities	H
20	Paper	2018	L. Malabi, H. Birgisdóttir, M. Birkved	Life cycle assessment of a Danish office building designed for disassembly	DfD method LCA method	M
21	Paper	2018	M. Eckelmana, C. Brown, L. Troup, L. Wang, M. Webster, J. Hajjar	Life cycle energy and environmental benefits of novel design-for deconstruction structural systems in steel buildings	DfD strategies LCA Method Simulation	L

LITERATURE REVIEW DATA BASE						
Item	Type	Year	Author	Title	Topic	I*
22	Paper	2020	O. Bukunova, A. Bukunov	Management of deconstruction of construction objects	Sustainable design Deconstruction	L
23	Paper	2016	Eleni Iacovidou, Phil Purnell	Mining the physical infrastructure: Opportunities, barriers, and interventions in promoting structural components reuse	Reuse potential Barriers and opportunities	M
24	Paper	2007	Catarina Thormark	Motives for design for disassembly in building construction	DfD Methods DfD opportunities	M
25	Paper	2019	K. Rahla, L. Bragança, R, Mateus	Obstacles and barriers for measuring building's circularity	Circular economy EcoDesign	L
26	Paper	2019	L. Malabi, H. Birgisdóttir, M. Birkved	Potential of Circular Economy in Sustainable Buildings	Circular economy Challenges and barriers	M
27	Paper	2020	C. Cambier, W. Galle, Niels De Temmerman	Research and Development Directions for Design Support Tools for Circular Building	Circular economy support tools	M
28	Paper	2019	FN. Rasmussen, M. Birkved, H. Birgisdóttir	Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies	Material loop DfD principles	L
29	MSc. Thesis	2020	Václav Grmela	Towards zero-waste buildings: Building design for reuse and disassembly	Reuse and disassembly design	H
30	PhD. Thesis	2006	Elva Durmisevic	Design for disassembly as a way to introduce sustainable engineering to building design & construction	DfD principles	H
31	PhD. Thesis	2012	Danielle Densley Tingley	Design for Deconstruction: An Appraisal	DfD principles	H
32	MSc. Thesis	2020	Jianli Zhai	BIM-based building circularity assessment from the early design stages	Circular design of Bldg.	M
33	Report	2014	VTT Technical Research Centre of Finland	Barriers and opportunities of structural elements re-use	Reuse of struct. elements Technical aspects	M
34	Report	2014	VTT Technical Research Centre of Finland	Re-use of structural elements: Environmentally efficient recovery of building components	Reuse of structural elements. Environmental aspects	M
35	Report	2021	InFutUre Wood	Design for deconstruction and reuse of timber structures – state of the art review	DfD strategies Timber examples	H
36	Report	2020	Philip Crowther	Developing Guidelines for Designing for deconstruction	DfD guidelines DfD strategies	H
37	Report	2019	BAMB & TUM Matthias Heinrich, Werner Lang	Materials Passports - Best Practices: innovative solutions for a transition to a circular economy in the built environment	Materials reuse potential	M
38	Report	2006	Brad Guy Nicholas Ciarimboli	DfD Design for disassembly in the built environment - A guide to closed-loop design and building	DfD guidelines DfD strategies	H
39	Report	2006	EPA USA	Design for deconstruction	DfD principles Reuse examples	L
40	Report	2019	BAMB Elma Durmisevic	Design strategies for reversible buildings	DfD Guidelines Application examples	H
41	Report	2019	BAMB Elma Durmisevic	Explorations for reversible buildings	DfD Guidelines Reversible construction	H
42	Report	2020	European Union	Circular economy: principles for building design	Circular economy strategies for buildings	L
43	Webpage	2021	ForestValue	Innovative Design for the Future – Use and Reuse of Wood (Building) Components	DfD principles Material recovery	H
44	Webpage	2016	BRE	Design for Deconstruction	DfD application Case studies	H
45	Webpage	2020	BAMB	Building as materials banks	Material Circularity	H
46	Webpage	2021	European Commission	LEVEL(S) - The European framework for sustainable buildings	Strategies for Sus. Bldg. Sustainability Indicators	H
47	Webpage	2021	European Commission's Horizon 2020 program	CIRCUIT - Circular Construction in Regenerative Cities	Circular construction Materials flow	L

*I: Importance according to the RQs. H: High; M: Medium; L: Low.

SNOWBALL LITERATURE DATA BASE						
Item	Type	Year	Author	Title	Topic	I*
1	Paper	2017	D. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, J. Tookey	A critical comparison of green building rating systems	Certification systems LEED BREAM	L
2	Paper	2016	Zezhou Wu, Liyin Shen, Ann T.W. Yu, Xiaoling Zhang	A comparative analysis of waste management requirements between five green building rating systems for new residential buildings	Construction waste Certification systems	L
3	Paper	2013	W.L. Lee	A comprehensive review of metrics of building environmental assessment schemes	Certification systems Rating systems	M
4	Paper	2019	K. Agyekum, E. Adinyira, B. Baiden, G. Ampratwum, D. Duah	Barriers to the adoption of green certification of buildings	Certification systems EcoDesign Barriers	M
5	Paper	2017	K. Adams, T. Thorpe, M. Osmani, J. Thornback	Circular economy in construction: current awareness, challenges, and enablers	Circular economy EcoDesign Barriers	M
6	Paper	2017	M. Denac, M. Obrecht, G. Radonjič	Current and potential ecodesign integration in small and medium enterprises: Construction and related industries	EcoDesign Barriers Legislation	L
7	Paper	2020	M. Bilal, K. Ahmad Khan, M. Jamaluddin Thaheem, A. Rehman Nasir	Current state and barriers to the circular economy in the building sector: Towards a mitigation framework	Certification systems EcoDesign Barriers	M
8	Paper	2021	N. Chebaeva, M. Lettner, J. Wenger, J. Schoggl, F. Hesser, D. Holzer, T. Stern	Dealing with the eco-design paradox in research and development projects: The concept of sustainability assessment levels	EcoDesign methods Barriers and opportunities	M
9	Paper	2020	Siri Willskytt, Sergio A. Brambila-Macias	Design Guidelines Developed from Environmental Assessments: A Design Tool for Resource-Eefficient Products	EcoDesign methods Usability Usefulness	H
10	Paper	2017	G. Lame, Yann Leroy, Bernard Yannou	Ecodesign tools in the construction sector: Analyzing usage inadequacies with designers' needs	EcoDesign Barriers Construction stakeholders	L
11	Paper	2017	Chethana S. Illankoon, Vivian W.Y. Tam, Khoa N. Le, Liyin Shen	Key credit criteria among international green building rating tools	Certification systems Rating systems	M
12	Paper	2020	Matthew Roberts, Stephen Allen, David Coley	Life cycle assessment in the building design process – A systematic literature review	Sustainable design LCA Method	L
13	Paper	2011	J. Allwood, Michael F. Ashby, Timothy G. Gutowski, Ernst Worrell	Material efficiency: A white paper	Material efficiency EcoDesign methods	H
14	Paper	2013	S.R. Chandratilake, W.P.S. Dias	Sustainability rating systems for buildings: Comparisons and correlations	Certification systems EcoDesign	L
15	Paper	2016	Margherita Pongiglione, Chiara Calderini	Sustainable Structural Design: Comprehensive Literature Review	Structural design EcoDesign	M
16	Report	2019	Danish Environmental Protection Agency	Building a Circular Future	Material efficiency DfD principles	H
17	Report	2019	Andey Nunes, Jordan Palmeri, Simon Love	Deconstruction vs. Demolition: An evaluation of carbon and energy impacts from deconstructed homes in the City of Portland	Deconstruction Material efficiency	M
18	Report	2014	Ecorys	Resource efficiency in the building sector	Material efficiency EcoDesign Barriers	M
19	Report	2016	World Economic Forum	Shaping the Future of Construction. A Breakthrough in Mindset and Technology.	Material efficiency Circular economy	M

Appendix 2 – Questionnaire

Design for Deconstruction (DfD) for sustainable design of buildings

Hej!

I am a master student from Linköping University in Sweden. Along with RISE (Research Institute of Sweden), I am carrying out a research study to introduce Design for Deconstruction (DfD) strategies for the sustainable design of buildings focusing on the structural systems (load-bearing systems).

This survey aims to collect opinions from different stakeholders on the relevance and expectation of introducing DfD strategies into the structural design of buildings.

All submitted questions are anonymous. Thank you for your collaboration.

Kind regards,

Andres Zabala (e-mails: andza375@student.liu.se, andres.oswaldo.zabala.mejia@ri.se)

SECTION 1 - GENERAL INFORMATION AND BACKGROUND *The following questions are for general statistics regarding the stakeholders*					
1. What is your role in the construction industry? (Please choose the one that better fits your professional experience)					
Management (owner, developer, operator, maintenance, or investor)			Construction contractor (General or subcontractor)		
Design team (other than architecture and structures)			Other (e.g., Government, academia, research institution)		
Architect	Structural Engineer	Building sustainable certifier	Manufacturer or supplier of building components		
2. How many years of experience in this role do you have?					
Less than 2 years	2 to 5 years	5 to 10 years	More than 10		
3. What is your location? (The country where you are working at the moment)					
Open question					
4. In which type of construction project are the most of your experience?					
Residential	Offices	Commercial	Industrial	Infrastructure	Other
5. What type of material was most common in this type of projects?					
Wood, bamboo or timber based		Concrete	Metal (Steel, aluminum or similar)		
Masonry (Clay or concrete)	Mixed	Other			

SECTION 2 - SUSTAINABLE CONSTRUCTION BACKGROUND *The following questions are to understand the stakeholder's background on sustainable construction*										
6. Do you have experience in making sustainability assessments?										
0	1	2	3	4	5	6	7	8	9	10
7. Do you have experience or knowledge in any of the following sustainability assessment systems? (Mark all the options that fit your experience or knowledge)										
SVANEN	LEED	BREEAM	EDGE	LCA or LCC	None	Other				
8. Which benefits do you consider happens when introducing sustainability aspects in the building sector? (Please mark the 3 that you consider most important)										
Energy performance	Water consumption	Material efficiency	Waste management	Durable products	Increase profit					
Improve image and reputation	Other									
9. What do you understand by Design for Deconstruction DfD?										
Open question										

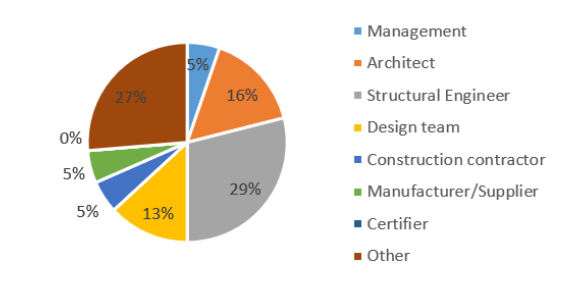
SECTION 3 - DfD FOR SUSTAINABLE DESIGN *DfD is an eco-design method for product development that focuses on optimizing the building design to be easily deconstructed at the end of the use phase. With this, circular economies models can be supported by the improvement of reuse, remanufacturing and recycling strategies.*			
10. What is your opinion about introducing DfD in the design of buildings?			
Open question			
11. Within your role in the construction sector, how do you see that you could implement DfD?			
Open question			
12. What limitations do you consider may arise for the implementation of DfD?			
Open question			
13. Do you consider DfD can be applied to all typology of constructions projects?			
Yes	No	Maybe	
14. Do you consider you are applying DfD principles today?			
Yes	No	Maybe	

SECTION 4 - DfD AND BUILDING DESIGN *We are developing a tool for the assessment of DfD principles in the design of the structural system of buildings. The following questions want to study the opinion of different stakeholders on the availability of a tool to help assess DfD in structural design.*			
15. What would benefit a person in your role having a tool that assesses the suitability of DfD?			
Open question			
16. What do you consider will be the most challenging part of using or applying this kind of tool for design?			
Open question			
17. What is the result you expect from this kind of tool?			
Overall rating	Qualitative assessment	Quantitative assessment	Guidelines to adapt the building to DfD
Approved seal or certification			
18. Have you used a tool to help to apply or measure DfD strategies on building projects?			
Yes	No	**19. If yes, please specify:**	
20. During the design process, when do you consider is the most suitable time to apply DfD?			
Phase 0: Project definition	Phase 1: Conceptual design	Phase 2: Preliminary design	
Phase 3: Detailed design	Phase 4: Final design		
21. Who do you think might be the most suitable potential user(s) for this tool?			
Management (owner, developer, operator, maintenance, or investor)		Construction contractor (General or subcontractor)	
Design team (other than architecture and structures)		Other (e.g., Government, academia, research institution)	
Architect	Structural Engineer	Building sustainable certifier	Manufacturer or supplier of building components

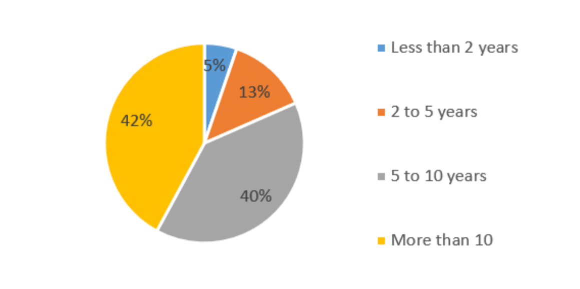
SECTION 5 - ISO 20887 *The tool will be developed according to the provisions given by the ISO 20887: Sustainability in buildings and civil engineering works — Design for disassembly and adaptability*			
22. Are you familiar with the ISO 20887 standard?			
Yes	No	**23. If yes, for what purpose have you use it?**	
24. What are your reflections on using it?			
Open question			
25. Did you use Annex C as a guide to grade the principles?			
Open question			
26. If you are willing to participate in an interview for further discussion about the topic, please provide your e-mail.			
Open question			

Appendix 3 – Questionnaire Results

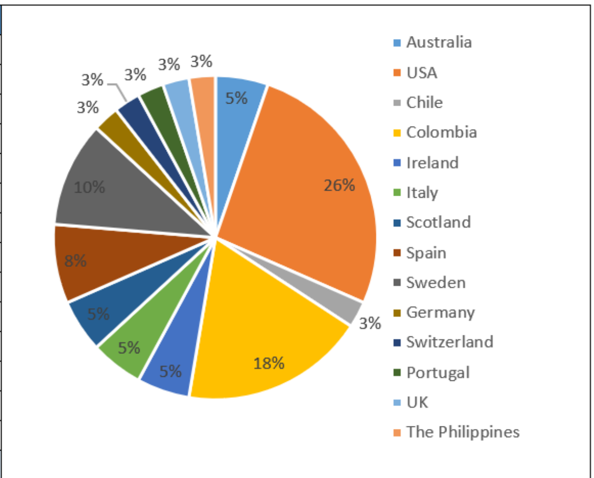
Q1 - Role	Count	Percentage
Management	2	5%
Architect	6	16%
Structural Engineer	11	29%
Design team	5	13%
Construction contractor	2	5%
Manufacturer/Supplier	2	5%
Certifier	0	0%
Other	10	26%
	38	100%



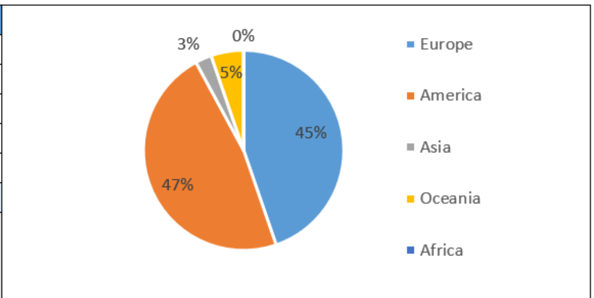
Q2 - Experience	Count	Percentage
Less than 2 years	2	5%
2 to 5 years	5	13%
5 to 10 years	15	39%
More than 10	16	42%
	38	100%



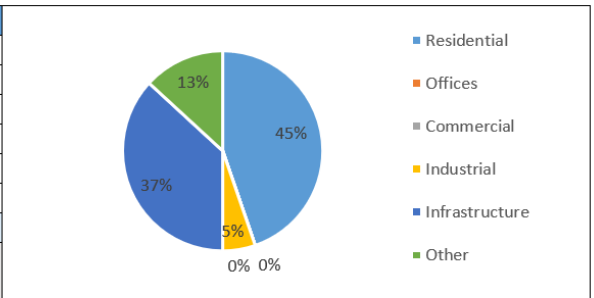
Q3 - Location	Count	Percentage
Australia	2	5%
USA	10	26%
Chile	1	3%
Colombia	7	18%
Ireland	2	5%
Italy	2	5%
Scotland	2	5%
Spain	3	8%
Sweden	4	11%
Germany	1	3%
Switzerland	1	3%
Portugal	1	3%
UK	1	3%
The Philippines	1	3%
	38	100%



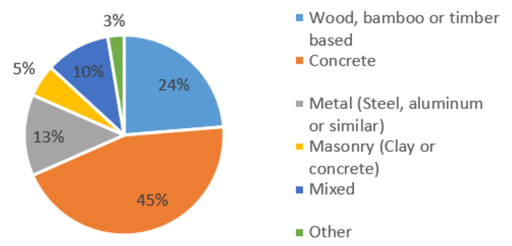
Q3 - Location	Count	Percentage
Europe	17	45%
America	18	47%
Asia	1	3%
Oceania	2	5%
Africa	0	0%
	38	100%



Q4 - Type of construction project	Count	Percentage
Residential	17	45%
Offices	0	0%
Commercial	0	0%
Industrial	2	5%
Infrastructure	14	37%
Other	5	13%
	38	100%

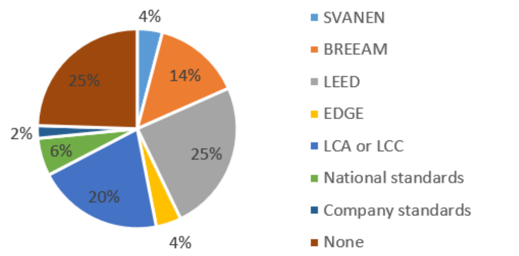


Q5 - Type of construction project	Count	Percentage
Wood, bamboo or timber based	9	24%
Concrete	17	45%
Metal (Steel, aluminum or similar)	5	13%
Masonry (Clay or concrete)	2	5%
Mixed	4	11%
Other	1	3%
	38	100%

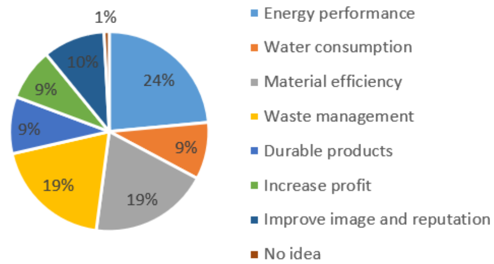


Q6 - Experience average	4.1/10

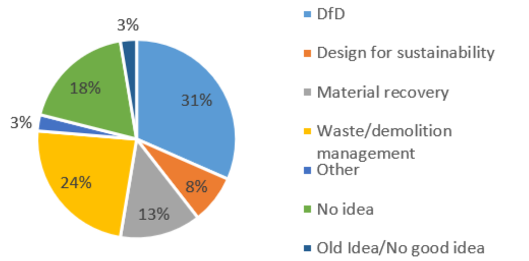
Q7 - Tools Experience	Count	Percentage
SVANEN	2	4%
BREEAM	7	14%
LEED	12	24%
EDGE	2	4%
LCA or LCC	10	20%
National standards	3	6%
Company standards	1	2%
None	12	24%
	49	100%



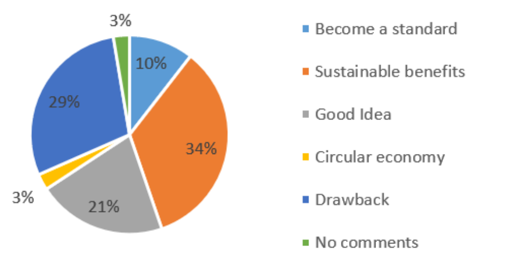
Q8 - Sustainability benefits	Count	Percentage
Energy performance	28	24%
Water consumption	11	9%
Material efficiency	23	19%
Waste management	23	19%
Durable products	11	9%
Increase profit	10	8%
Improve image and reputation	12	10%
No idea	1	1%
	119	100%



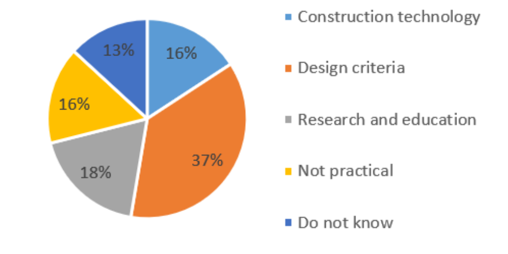
Q9 - What is DfD	Count	Percentage
DfD	12	32%
Design for sustainability	3	8%
Material recovery	5	13%
Waste/demolition management	9	24%
Other	1	3%
No idea	7	18%
Old Idea/No good idea	1	3%
	38	100%



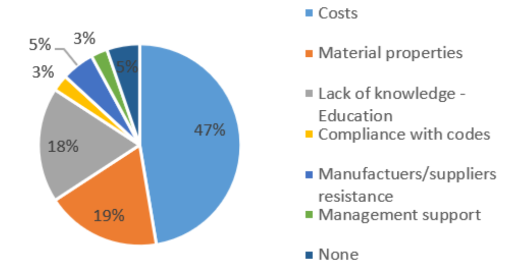
Q10 - Opinion	Count	Percentage
Become a standard	4	11%
Sustainable benefits	13	34%
Good Idea	8	21%
Circular economy	1	3%
Drawback	11	29%
No comments	1	3%
	38	100%



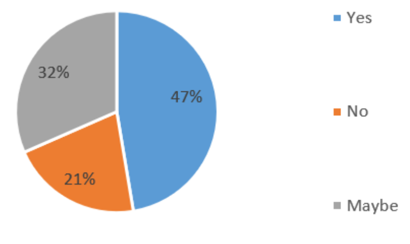
Q11 - Implementation Role	Count	Percentage
Construction technology	6	16%
Design criteria	14	37%
Research and education	7	18%
Not practical	6	16%
Do not know	5	13%
	38	100%



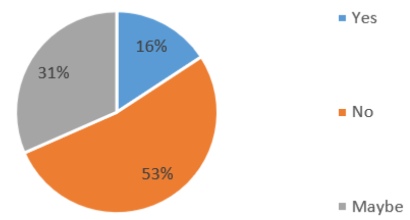
Q12 - Limitation/Barriers	Count	Percentage
Costs	18	47%
Material properties	7	18%
Lack of knowledge - Education	7	18%
Compliance with codes	1	3%
Manufactuers/suppliers resistance	2	5%
Management support	1	3%
None	2	5%
	38	100%



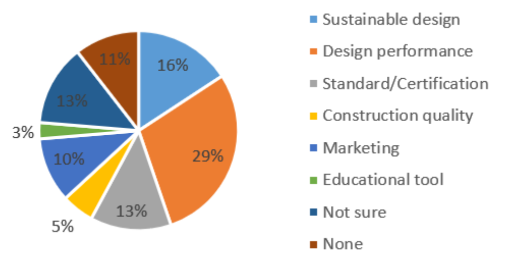
Q13 - Application to all	Count	Percentage
Yes	18	47%
No	8	21%
Maybe	12	32%
	38	100%



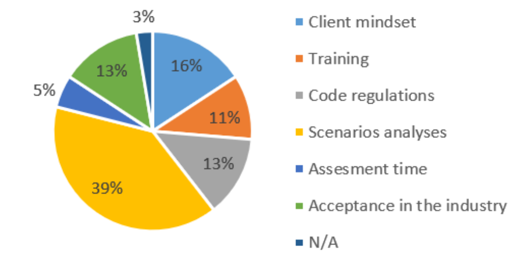
Q14 - Application today	Count	Percentage
Yes	6	16%
No	20	53%
Maybe	12	32%
	38	100%



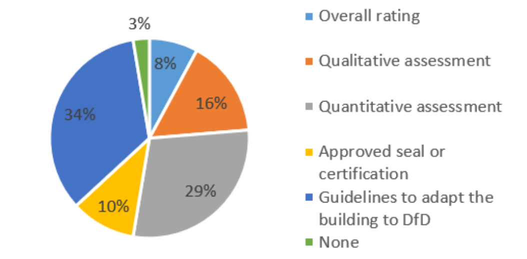
Q15 - Role Tool Befenits	Count	Percentage
Sustainable design	6	16%
Design performance	11	29%
Standard/Certification	5	13%
Construction quality	2	5%
Marketing	4	11%
Educational tool	1	3%
Not sure	5	13%
None	4	11%
	38	100%



Q16 - Tool Challenge	Count	Percentage
Client mindset	6	16%
Training	4	11%
Code regulations	5	13%
Scenarios analyses	15	39%
Assesment time	2	5%
Acceptance in the industry	5	13%
N/A	1	3%
	38	100%



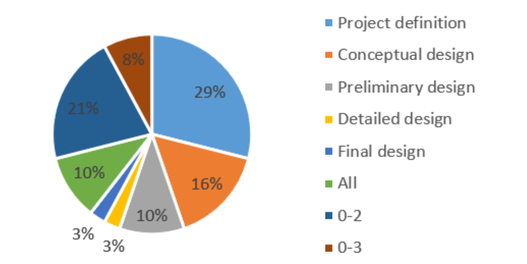
Q17 - Tool Results	Count	Percentage
Overall rating	3	8%
Qualitative assessment	6	16%
Quantitative assessment	11	29%
Approved seal or certification	4	11%
Guidelines to adapt the building to DfD	13	34%
None	1	3%
	38	100%



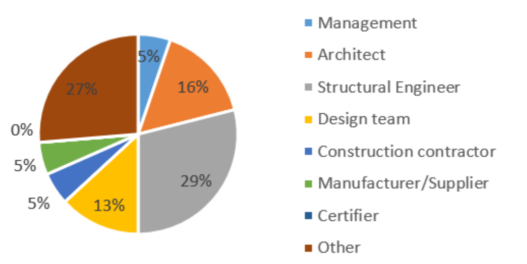
Q18 - Other tool for DfD	3

Q19 - tool
A Decision-making tool developed by UCD and used by students
Methodology developed by the Drive0 project funded by H2020
A draft of a tool has been used in a research project

Q20 - Phase	Count	Percentage
Project definition	11	29%
Conceptual design	6	16%
Preliminary design	4	11%
Detailed design	1	3%
Final design	1	3%
All	4	11%
0-2	8	21%
0-3	3	8%
	38	100%



Q21 - Role	Count	Percentage
Management	12	12%
Architect	23	23%
Structural Engineer	23	23%
Design team	14	14%
Construction contractor	5	5%
Manufacturer/Supplier	9	9%
Certifier	9	9%
Other	3	3%
	98	100%



Q22 - ISO20887	Count	Percentage
Yes	6	16%
No	32	84%
	38	100%

Appendix 4 – Workshop questionnaire

Get your view on a tool that works as an indicator system based on ISO 20887 Workshop First questionnaire - Before using the tool				
SECTION 1 - General information and background				
1. What is your name?				
Open question				
2. What company/institution do you work for?				
Open question				
3. What is your role in the construction industry?				
Open question				
4. How many years of experience do you have in the construction industry?				
Open question				
5. In which type of construction project are the most of your experience?				
Open question				
SECTION 2 - EcoDesign Information				
6. How important is sustainability in your work?				
Extremely important	Very important	Neutral	Slightly important	Not important
7. How important is resource efficiency/circular economy in your work?				
Extremely important	Very important	Neutral	Slightly important	Not important
8. What is your main goal of introducing Eco-Design methods and tools in your work?				
Open question				
9. Do you have experience or knowledge in any of sustainability or EcoDesign tool?				
Yes	No			
10. If yes, please specify which one and why you use it?				
Open question				

Get your view on a tool that works as an indicator system based on ISO 20887 Workshop Second questionnaire - Questions after using the tool				
SECTION 1 - DfD principles and categories				
1. How familiar are you with the DfD principles?				
Extremely familiar	Very familiar	Familiar	Slightly familiar	Not familiar
2. How understandable are the DfD principles?				
Extremely understandable	Very understandable	Understandable	Slightly understandable	Not understandable
3. If not understandable, what was the difficult part and what can be improved?				
Open question				
4. How relevant are the categories of evaluation to the DfD principles?				
Extremely relevant	Very relevant	Relevant	Slightly relevant	Not relevant
5. If not relevant, what can be improved?				
Open question				
6. How relevant were the categories of evaluation to the design phase of a structural system?				
Extremely relevant	Very relevant	Relevant	Slightly relevant	Not relevant
7. If not relevant, what can be improved?				
Open question				

SECTION 2 - Tool usability and usefulness				
8. How easy was it to understand the tool during use?				
Extremely easy	Very easy	Easy	Slightly easy	Not easy
9. If not easy, what was the difficult part and what can be improved?				
Open question				
10. For the multiple typology element/connection assessment, which approach did you use for the grade?				
Worst/weaker component	*Average value of the components*	*Other*		
11. If not easy, what was the difficult part and what can be improved?				
Open question				
12. What were your expectations?				
Open question				
13. How convinced are you with the concept results from the application of the tool?				
Open question				
14. How likely is it for you to incorporate the final/complete version of the tool in your common design practice?				
Extremely likely	Very likely	Likely	Slightly likely	Not likely
15. If not likely, why and what can be improved?				
Open question				
16. Do you want to give any additional information or comment on the workshop or the tool presentation?				
Open question				

“There are things you do only for love.”

Love in the Time of Cholera - 1985
Gabriel García Márquez

"What matters in life is not what happens to you,
but what you remember and how you remember it.”

Gabriel García Márquez