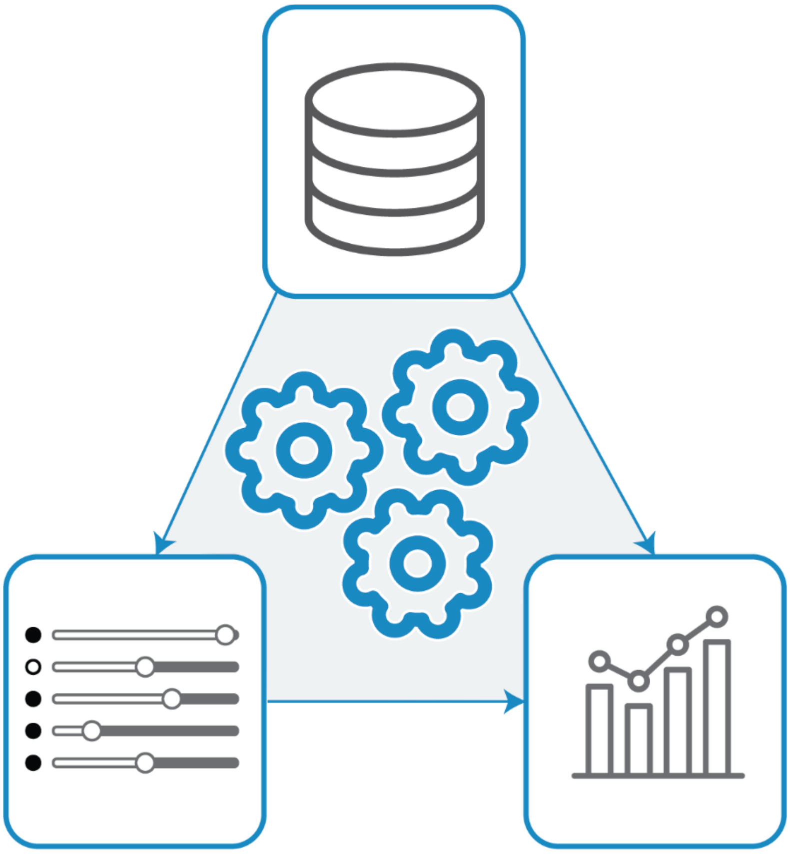
# DECISION SUPPORT SYSTEM FOR CIRCULAR INTEGRATED FLOOR-SYSTEM DESIGN IN OFFICE BUILDINGS

# (NETHERLANDS)



Research report

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# Acknowledgement

A master thesis is often associated to a sprint that merely touches upon the true essence of all that the world of science can offer to the humanity. To reflect back, my journey in the course of nine months dedicated to this sprint has been rough but endearing one, especially in times of a pandemic. One of the main challenges was juggling multiple assignments at the same time, being the chair-person of BouT (Study association of Building Technology track), working part-time (16 hours a week) as a project engineer at Physee Technologies, and interning as a graduate student at ABT BV. This experience has taught me the importance of good organization and time management skills in a hard way.

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I hope the readers of the report can recognize the expanse of research this thesis has undergone to accomplish the end result. No thesis can ever be the only answer to the defined problem, however, it is the one answer when viewed from the perspective of the author, followed by limitations and further recommendations. Lastly, any finding be it ‘good’ or ‘bad’ is never the less a contribution to the scientific community.

# Abstract

The past few years has seen an increase in number of demolitions of office buildings due to the lack of adaptability based on rapid user change demands, in the Netherlands. Furthermore, the construction industry contributes towards 50% of the raw material consumption and is responsible for 40% of the total waste generation in the country. Leading to adopting circular design practices within the industry which is incentivized by the nationwide programme towards creating a 100% circular economy by 2050 with an intermediate goal to reduce the use of primary raw materials and by 50% until 2030. This has led to exploring flexible and adaptable design strategies in office buildings.

In a building floor-systems cater to more than 50% of the total material usage, thereby contributing to the highest impact on the environment. But a floor-system in a building is not always a standalone component, it shares heavy interactions with services such as mechanical, electrical and plumbing installations. Services integration into the floor-system poses flexibility related challenges, as it often interacts with building products that are of varying have varying durability (life spans). An integrated floor-system approach is a multi-disciplinary problem and one of the key challenges is flexibility. Furthermore, multi-disciplinary design decisions made in the early design stages create a huge impact on the flexibility, environment and material circularity aspects.

Therefore, this research aims to address the complexity of this problem by developing a knowledge based decision support system driven by data and heuristic logic, that can support the decision-makers involved in the early design stages of an integrated floor-system design. The objective is for the system to demonstrate the impact of design decisions on circularity related indicators by sharing quick insights.

**Keywords:** Decision Support System, DSS, Circularity, Design for Adaptability, Integrated floor-system design

# Abbreviations

AaaS – Analytics-as-a-Service

AEC - Architecture, Engineering and Construction

BCI – Building Circularity Indicator

CE – Circular Economy

CE marking - an administrative marking for building products sold within the European Economic Area (EEA)

C&U - Civil Engineering and Utility Construction

CWD - Construction and demolition waste

DDT – Dashboard based design tool

DfD – Design for Disassembly

DfX – Design for X

DSS - Decision Support System

DM – Decision Maker

ECI – Environmental cost indicator

EMF – Ellen MacArthur Foundation

EU – European Union

GWR - Ground, Water and Road construction

NMD – National Milieu Database

MCI – Material Circularity Indicator

MPG – Milieuperstatie Gebouw (Environmental performance of buildings)

TLC – Technical life cycle

ULC – Use life cycle

# Contents

# I

# Research Design

# 1. Introduction

## 1.1. Background

*Global and European context*

The year 2020 surprised the world with a pandemic that has shaken the global economy. Now economies worldwide are trying to crawl back to normal, however, isn't this the best time to rethink normalcy? Humanity has yet another opportunity to redefine the functioning of different sectors within the global economy keeping the major environmental concerns of natural resource depletion and its adverse effect on the global CO2 emissions in prime focus. It is high time to change the linear take-make-waste economy approach to a reduce-use-reuse-recycle-regenerate circular economy approach.

Circular economy in essence is a new model that decouples the economic development from the consumption of finite resources. The concept stresses on closing or slowing the resources loop by restorative regenerative means to keep the products, components and materials at the highest level of use and value (Munaro et al., 2020). The Global Circularity Report (2020) states a reduction in the circularity percentage from 9.1% to 8.6% in the past two years. It also highlights three main reasons for this decrease, excessive extraction of raw materials, the continuous stock build-up and decreased levels of end-of -use processing and cycling.

22nd August 2020, marked the calculated Earth Overshoot Day, which implies that between the 1st of January until the 22nd of August, the humanity has consumed the amount of resources that nature can regenerate in a calendar year. Therefore, from the 22nd of August onwards the resources being consumed by the humanity is an overshoot or in other words a debt from nature. (Lin et al., 2020) While this creates awareness amongst humanity, it emphasizes the rapid need to transition towards conscious consumption of resources.

*Figure 1:State of the total raw materials consumed per year(in billions). Adapted from: Circle Economy*

From Figure 1, the building/infrastructure industry consumes 31 billion tons of the global resources and 32.6 billion tons is wasted and only 8.6 billion tons is recycled.

The European Commission on the 2nd of December 2015 decided to set out an action plan for the Circular Economy at the European Union level, to achieve the stated Sustainable Development Goals by 2030, with focus given to sustainable consumption and production. Under the highlighted priority areas, construction and demolition is included. The action plan states,

*"The Commission will take a series of actions to ensure recovery of valuable resources and adequate waste management in the construction and demolition sector, and to facilitate assessment of the environmental performance of buildings."*

*Netherlands context*

The construction industry within the Netherlands contributes towards 50% of the raw material consumption, 40% of the total energy consumption, 30% of the water consumption and approximately 35% of the CO2 emissions. Additionally, the construction and demolition waste contributes to approximately 40% of the total waste in the Netherlands. (Government of the Netherlands, 2016) It has the third largest resource footprint, making it very resource intensive. (PACE, 2019)

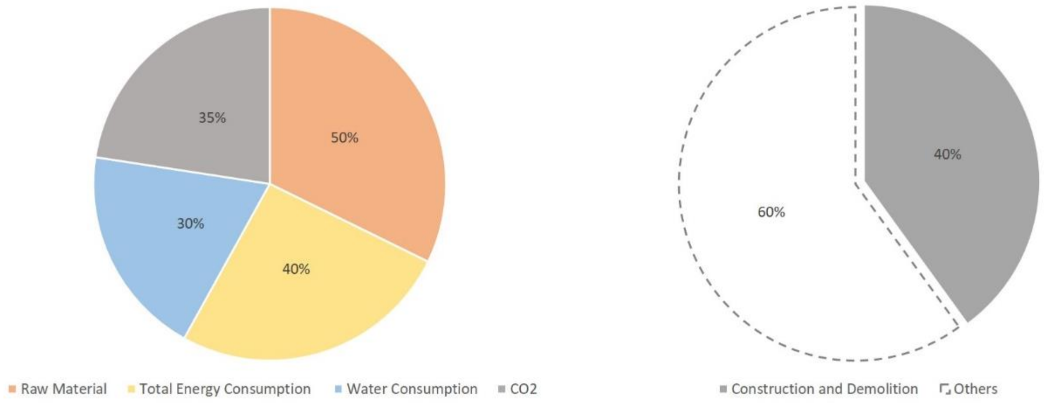


*Figure 2: (left)Construction industry in Netherlands (right)Total waste generated by the construction industry in NL*

The construction industry is largely divided into two sectors Civil Engineering and Utility Construction (C&U) and Ground, Water and Road construction (GWR). While both sectors function independently, the construction and demolition waste (CDW) generated by these sectors tend to get recycled or reused within itself. The trend of waste recycling is unidirectional, wherein C&U construction waste gets downcycled to be used for GWR construction. However, a circular economy demands waste or resource to flow at the highest value within the C&U construction sector (Transitieteam Bouw, 2018).

In accordance to European Union's action plan, the Netherlands launched a national programme towards creating a 100% circular economy by 2050 with an intermediate goal to reduce the use of primary raw materials such as minerals, fossils and metals by 50% until 2030.(Government of the Netherlands, 2016)

According to the government of Netherlands (2016) the vision of 2050 states;

*"By 2050, the construction industry will be organised in such a way, with respect to the design, development, operation, management, and disassembly of buildings, as to ensure the sustainable construction, use, reuse, maintenance, and dismantling of these objects. Sustainable materials will be used in the construction process, and designs will be geared to the dynamic wishes of the users. The aim is for the built-up environment to be energy-neutral by 2050, in keeping with the European agreements."*

## 1.2. Basic Problem Analysis

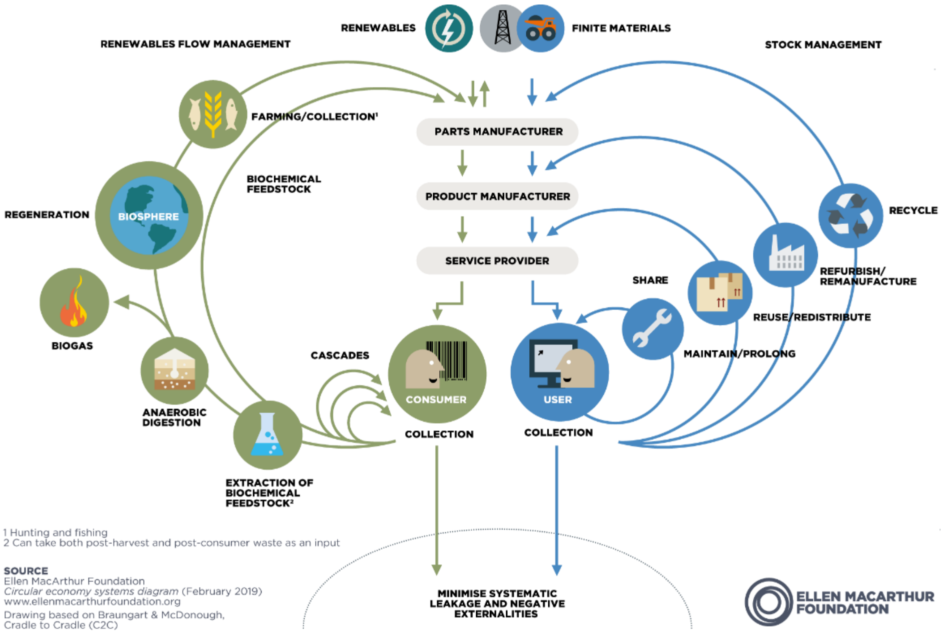
### *Circularity in Building Construction*

Circularity in construction has many definitions, the Netherland's government frames the following in the Transition Agenda (2018):

"Circular construction is defined as the development, use and reuse of buildings, areas and infrastructure without unnecessarily exhausting natural resources, polluting the living environment, and affecting ecosystems. Construction in a way that is economically sound and contributes to the well-being of humans and animals."

The Ellen McArthur foundation states the three foundational principals of Circular economy is designing out of waste and pollution, keeping materials and products in use, and regenerating natural systems. The butterfly diagram, as shown in figure 2, suggests materials and products to remain largely in the inner cycles of reuse, repair or remanufacture rather than flow towards recycle to ensure highest level of utility and value.

To incorporate these principals into the construction sector, researchers agree it requires a systems thinking approach of the construction value chain throughout the building's lifecycle.(Carra & Nitesh, 2017; Geldermans, 2016; PACE, 2019) Furthermore, defining circular goals in the early design phase can contribute to a significant impact. To transition to a circular economy, design in the early phase of the building must consider long term thinking, design for deconstruction, flexibility versus durability, innovation and collaboration. (Carra & Nitesh, 2017)



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

**SOURCE**
Ellen MacArthur Foundation
*Circular economy systems diagram* (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

*Figure 3: The butterfly diagram showing the product and material flow in a circular economy*

The Ellen Macarthur Foundation along with ARUP reinforce this by stating, design and construction are strongly linked and the decisions taken at design phase keeping circular principals at core will drive material sourcing and innovative construction methods. The design will also impact the operational phase in terms of efficient maintenance and adaptability. (Ellen MacArthur Foundation, 2019)

Many design strategies are developed in architectural practice that contribute towards maintaining high-quality reuse of recovered materials at end-of-life and help postpone the flow of materials to landfill. Design strategies such as Design for Disassembly, Design for Recyclability and Design for Adaptability reduce the carbon footprint of building structures(Geldermans, 2016).

*Current stock of Office Buildings*

The total office building stock in the Netherlands has seen a decline since 2015 as seen in figure 4. The statistics from CBS on the number of new constructions reveal a decline from 2012 to 2019, and records an increase in the number of demolitions since 2017. The increase in the numbers of demolition of office buildings does not align with the precondition of reduction in waste generation to achieve circular construction by 2050.

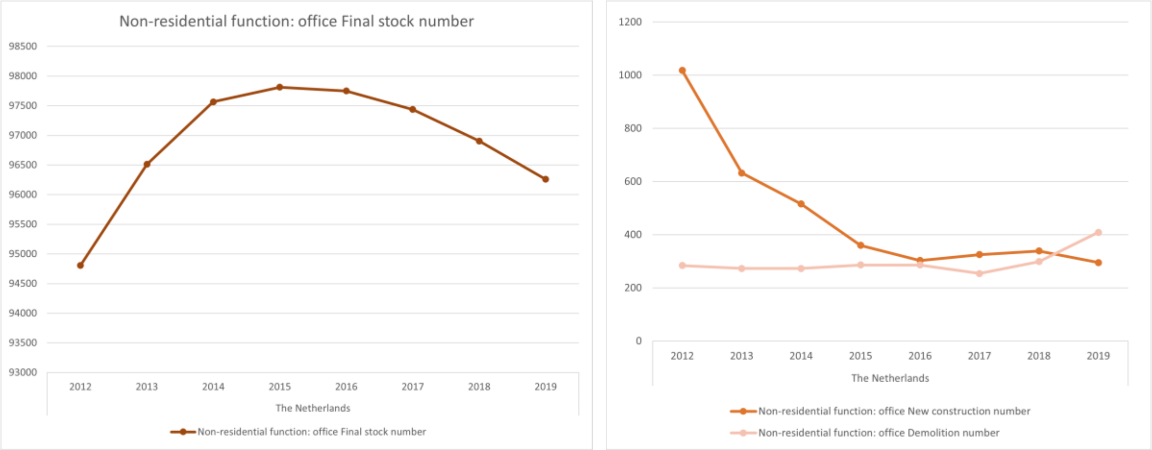


*Figure 4:(left) Chart showing the trend in building stock, for office buildings in the Netherlands from 2012-2019 (right) Chart showing the trend in number of new constructions and number of demolitions Source: CBS*

The reason for demolitions of buildings as stated by Durmisevic (2006) are, lack of flexibility, deterioration of technical characteristics or mostly due to the lack of adaptability towards changing user needs. In 2015 a huge stock of office building were left vacant in the Netherlands, as illustrated in the graphs of Figure 5, which reportedly lead an economic crisis.

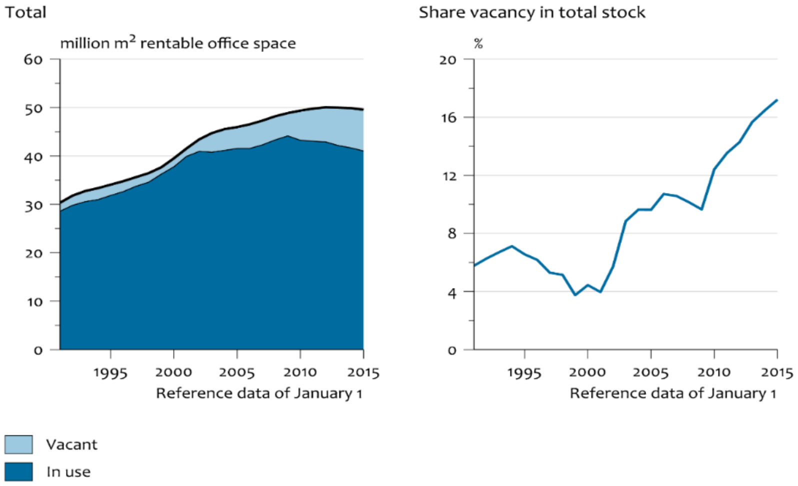


*Figure 5: Graphs showing rentable floor-space and vacant office building stock. Source: Bak; edited by PBL*

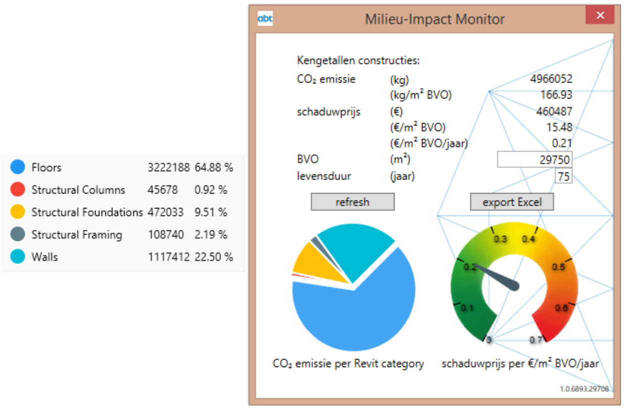
Extensive research is carried by Hilde Remøy from TU Delft on vacant office buildings in the Netherlands, where the researcher highlights the causes for vacant office buildings as mono-functionality and low layout flexibility at location and building level respectively. To prevent this at building level, she highlights adaptive reuse and adopting the industrial, flexible and demountable (IFD) design framework to enhance transformation potential of office buildings (Remøy, 2010). A building's structural skeleton plays a major role in defining adaptive reuse when the building's function changes. Therefore the structural skeleton should be designed for maximizing structural system reuse.(Pongiglione & Calderini, 2016)

### *Structural design in non-residential buildings*

The aim for design in non-residential buildings is flexibility during use and in the event of changing use, considering the live loads towards a higher limit of 5 kN/m2 and ensuring column-free spans of at least 5.4 meters and 7.2 meters on either sides respectively (Cie, 2016). In the absence of intermediate columns the vertical loads are transferred to Facade system and central core, where, conventional concrete floor-system's structural height ranges between 300mm to 500mm. Additionally, in non-residential buildings there is a large amount space to consider for MEP installations that are to be accommodated below the raised floor or above in the false ceiling, leading to higher floor heights compared to residential buildings that ranges between 3.3 meters to 4 meters. The choice of the floor height is a trade-off between flexibility and costs. Furthermore, the mass requirements for the floors are considered secondary to the strength and fire-safety requirements in design.

### *Environmental impact of floor-systems*

A study on the right choice of floor system by Van Haalen (2018) revealed that 60% of the environmental impact is due to the materials used in building construction. Out of this more than half of the building's material mass requirements are used in floors. A conventional concrete floor system contributes to more than 64% of CO2 emissions as shown by the Milieu-Impact Monitor (MIM) tool developed within ABT, Figure 6. Therefore, highlighting that selecting the right floor system can greatly decrease the environmental impact of the buildings.



| | | |
|---|---|---|
| ● Floors | 3222188 | 64.88 % |
| ● Structural Columns | 45678 | 0.92 % |
| ● Structural Foundations | 472033 | 9.51 % |
| ● Structural Framing | 108740 | 2.19 % |
| ● Walls | 1117412 | 22.50 % |

Milieu-Impact Monitor

Kengetallen constructies:

| | | |
|---|---|---|
| $CO_2$ emissie | (kg) | 4966052 |
| | (kg/m² BVO) | 166.93 |
| schaduwprijs | (€) | 460487 |
| | (€/m² BVO) | 15.48 |
| | (€/m² BVO/jaar) | 0.21 |
| BVO | (m²) | 29750 |
| levensduur | (jaar) | 75 |

*Figure 6: Milieu-Impact-monitor, a tool developed to calculate the environmental impact of the choice of structural floor system in building construction (Van Haalen, 2018)*

### *Decision making during early stages of design*

The decision made in the earl design stages of a project proves to have much greater impact on reducing environmental impact and cost by improving performance of design, as shown in the graph in figure 7.

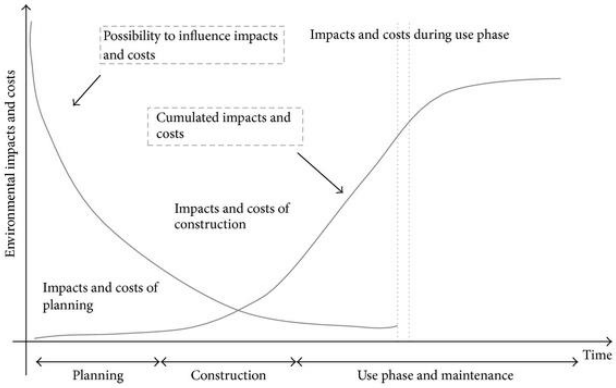


*Figure 7:showing the impacts on design decision in early stages of a project* (Bragança et al., 2014)

# 2. Research Framework

## 2.1. Problem Statement

According to the European Union sustainable development goals of 2030 and the Netherlands government launched National programme of 2050, there is a common goal to transition towards a circular economy in the construction sector. The importance of circularity in building construction practices is given priority due to its large resource footprint and resource intensive practices.

From the statistics provided by CBS portal, in the Netherlands, it is clear that there has been an increase in the number of demolitions of office buildings since 2017. Such demolitions contribute to the CDW which accounts for approximately 40% of the overall waste generated in the Netherlands. Currently most CDW is downcycled and used in the GWR construction sector. However, the Netherlands government envisions a 100% circular economy by 2050 and a 50% reduction in use of primary materials by 2030 by reusing materials, products and components within the building construction sector by disassembling buildings components.

To prevent demolitions and avoid office buildings from becoming obsolete in the event of occupancy changes, literature recommends the buildings must be designed for flexibility and adaptive re-use (Geldermans, 2016; Remøy, 2010). Design for adaptability and design for disassembly as design strategies aligns with this problem and also contributes towards circular building construction practices. These strategies help in prolonging the operational life and allow for reuse at end of life respectively of the building and its components. However, while there are some innovative projects that implement such designs, Geldermans states it is far from common and not implemented at large scale in the Netherlands. (Geldermans, 2016)

The structural skeleton of a building is very crucial in determining the reuse and adaptability of a structure. Therefore, sustainable structural design must be practiced. (Pongiglione & Calderini, 2016) However, in a building's structural skeleton, floors are responsible for more than half of the mass and materials. The function of floors is not only to provide for structural stability in a building, but also accommodate services such as mechanical ventilation, heating, cooling, electrical cables, light fixtures and fire sprinklers either concealed in the raised floor or suspended ceiling. This increases the complexity of a floor-system when considering an integrated design approach especially aiming for flexibility and adaptability. Largely due to the combination of materials/products/components that have varying technical and use life spans.

An ideal floor-system aims for good technical, environmental (circularity) performance and feasibility. However, the factors that influence the decision for an integrated floor-system are multifold and the stakeholder involved such as clients, architects, structural designers and MEP consultants are together responsible for the choice of the floor-system. Therefore, it is vital to assist these stakeholders during the decision making process by indicating the consequences caused by their decisions on the technical performance and the degree of circularity achieved.

## 2.2. Research Questions

*Main research question*

How can a **decision support system** assist the **stakeholders** involved in the **preliminary design phase** of an **integrated floor-system**, to compare design options based on **technical performance** and **degree of circularity** to make a suitable design choice to **facilitate adaptability** in **office buildings**?

*Sub questions*

1. What are the main principles and strategies for circular design under a Circular economy in the built environment?

2. Which design strategy can facilitate adaptability in office buildings and what are the key design aspects to consider?

3. What are the circularity indicators and how can they be evaluated especially in case of building material and systems?

4. What is the role of an integrated floor-system in a building?

    - What factors influence the design?
    - What are the key technical performance criteria?
    - What are the existing integrated floor systems or typologies commonly used in buildings?

5. Who are the stakeholders involved and what are the main considerations for a decision-making process for an integrated design approach in preliminary design stage for floor-systems?

6. What is the suitable computational decision support system approach for preliminary design stage?

## 2.3. Research Objectives

The main objective is to design a decision support system for assisting the stakeholders involved in early design phase of an integrated floor-system by assessing the technical performance and degree of circularity to make a suitable choice to facilitate adaptability in office buildings in the Netherlands.

*Sub objectives*

1. To identify the criteria and indicators of circularity.

2. To identify circularity assessment to be used in case of floor systems

3. To identify the key performance criteria for floor-system design in office buildings

4. To identify the key design aspects that facilitate adaptability in floor systems

5. To identify the multiple stakeholders involved during the decision-making of a floor-system in early design phase.

6. Map multi-disciplinary relationships (through literature and interviews) for an integrated floor-system design

7. Design a decision support system for an integrated floor-system design

    - that incorporates the use life span scenarios as one of the starting points and
    - drives the design decisions based on degree of circularity and the other performance indicators
    - Show implementation of the framework using a test case scenario

- Ensure the framework is flexible for re-formulation of design criteria

*Expected end result*
A computational decision support system explaining the workflow and demonstration through a prototype.

## 2.4. Scientific Relevance

The research positions itself at the confluence of multiple streams of scientific knowledge, i.e. Circularity, Building Physics, Structural Design and Computational design. The research associates its relevance to combining all different multi-disciplinary knowledge into a centralized knowledge based decision support system. The scientific contribution of this research is the in-depth analysis of the multi-disciplinary criteria that play an important role towards the design of an integrated floor-system, especially by demonstrating its impact towards circularity indicators. It further contribute towards systematic breakdown and understanding of all the fundamental key criteria that impact a circular integrated design of a floor-system. The main contribution is combining all the knowledge into a data -driven heuristic logic that is computationally realized into a decision support system.

## 2.5. Research Structure

The thesis follows a design by research methodology. To answer the main research question, the research is planned in five different stages starting from P1 to P5. These stages each define a certain level of progress within the thesis research. The organizational plan throughout these stages are indicated in the Figure 7, and explained below.

*P1: Background studies*
During this stage, preliminary research was carried out towards understanding the need for transition into a circular economy in the building construction sector globally and nationally (The Netherlands). Additionally, the environmental impact caused by current office building stock and the contribution of floor-systems towards it was researched to identify the problem. This was carried out by referring to statistics provided by CBS, published research papers, articles and published action plans by governmental organizations.

*P2: Defining the Problem statement, objectives, research questions and literature review*
The preliminary research in the previous stage helped analyze the problem and define the problem statement. The problem statement further guided the formation of research objectives and research questions. Both the objectives and research questions are divided into main and sub-categories, to perform the research in a comprehensive manner. The research questions formed the base towards formulation of keywords and structure the literature research. The findings from the literature review are the inputs for the next phase of design and development.

*P3: Identify relationships between design criteria and parameters*
To gain more insight into the decision making processes that involve multi-disciplinary stakeholders a qualitative 1 to 1 interview questionnaire is prepared. The goal of the interview is to get a basic understanding of collaboration between disciplines, factors that impact integration of components within a floor-system, incorporation of circular strategy in design process and the practice of assessing environmental impact and degree of circularity.

In this stage the multi-disciplinary design criteria and aspects are identified based on literature and interviews. Relationships are drawn between the design aspects that influence a decision and main criteria are highlighted

An overall structure will be conceptualized to indicate the flow of data for decision making.

*P4: Framework Design development using a test case and Results*

In this stage a computational decision making framework will be developed to structure the formulated relationships between the multi-disciplinary design criteria and input parameters. A test case scenario will be used to explain the framework.

*P5: Refinement, final conclusion and recommendations*

Fine-tuning for the framework and translation into a visual dashboard based tool prototype is the focus for this stage. Final conclusions of the research are drawn and recommendations are suggested for innovative integrated floor-system design strategies in line with circularity and adaptability for office buildings.

## 2.6. Report Outline

The report is structured in 6 parts , each part corresponds to the kind of data or information covered.

Part 1- *Research design* : It covers all the relevant information pertaining to the background of the research and the research framework defining the problem statement, research questions , research objectives, relevance, structure and outline.

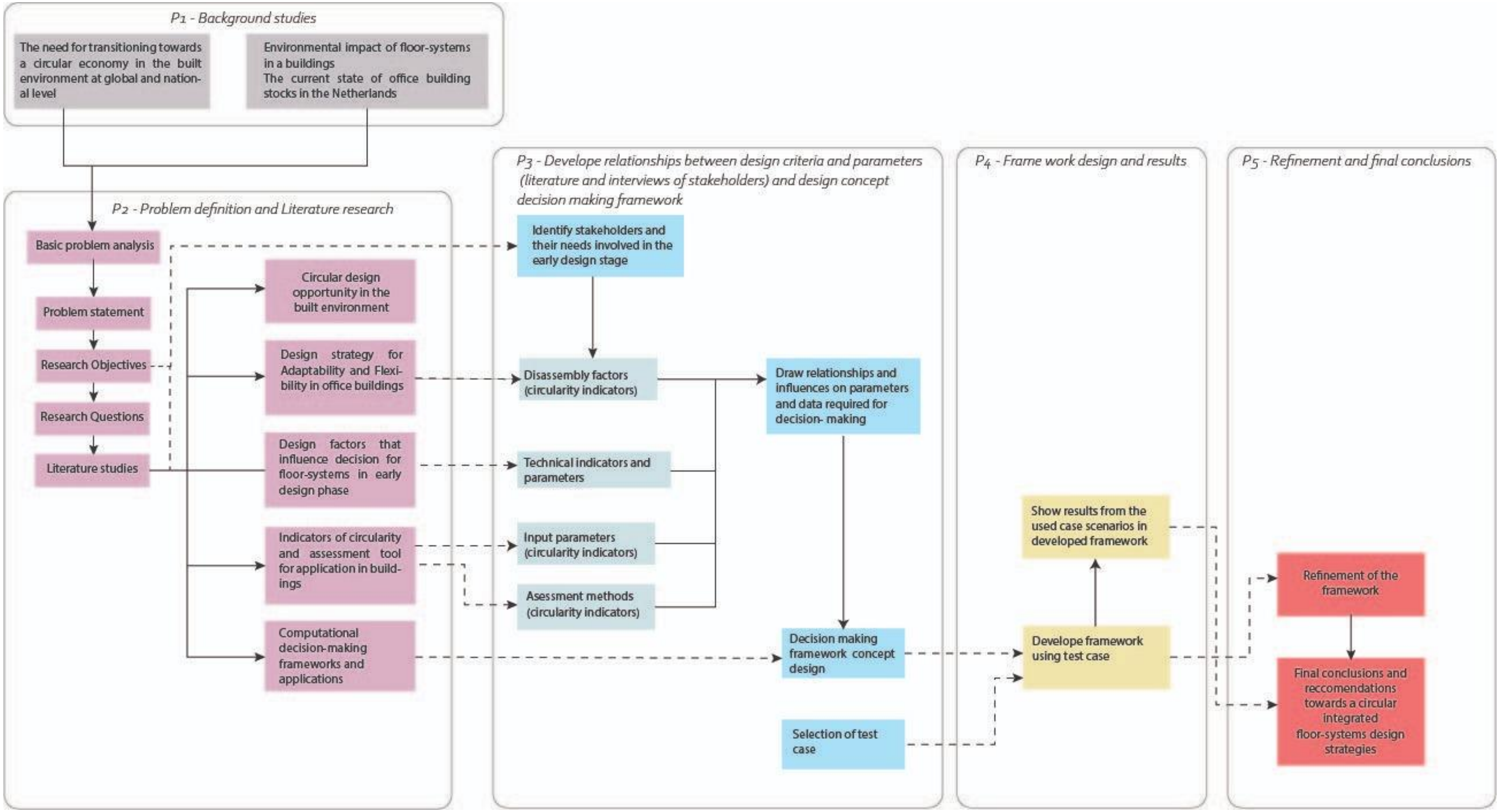
Part 2- *Literature review*: It is part of the report that discusses in details the findings from the literature review on topics of Circularity and assessments methods, Integrated Floor-systems and its technical performance criteria, Decision support systems and computational applications.

Part 3 - *Interviews and Data analysis*: It discusses the findings of the interviews carried out with experts in the field i.e. Structural Engineers, Architects, MEP consultant and Clients, to understand the practical influences that certain decisions have for the design of a circular integrated floor-system. Furthermore, it analyses all the multi-disciplinary data gathered to draw relationships between them.

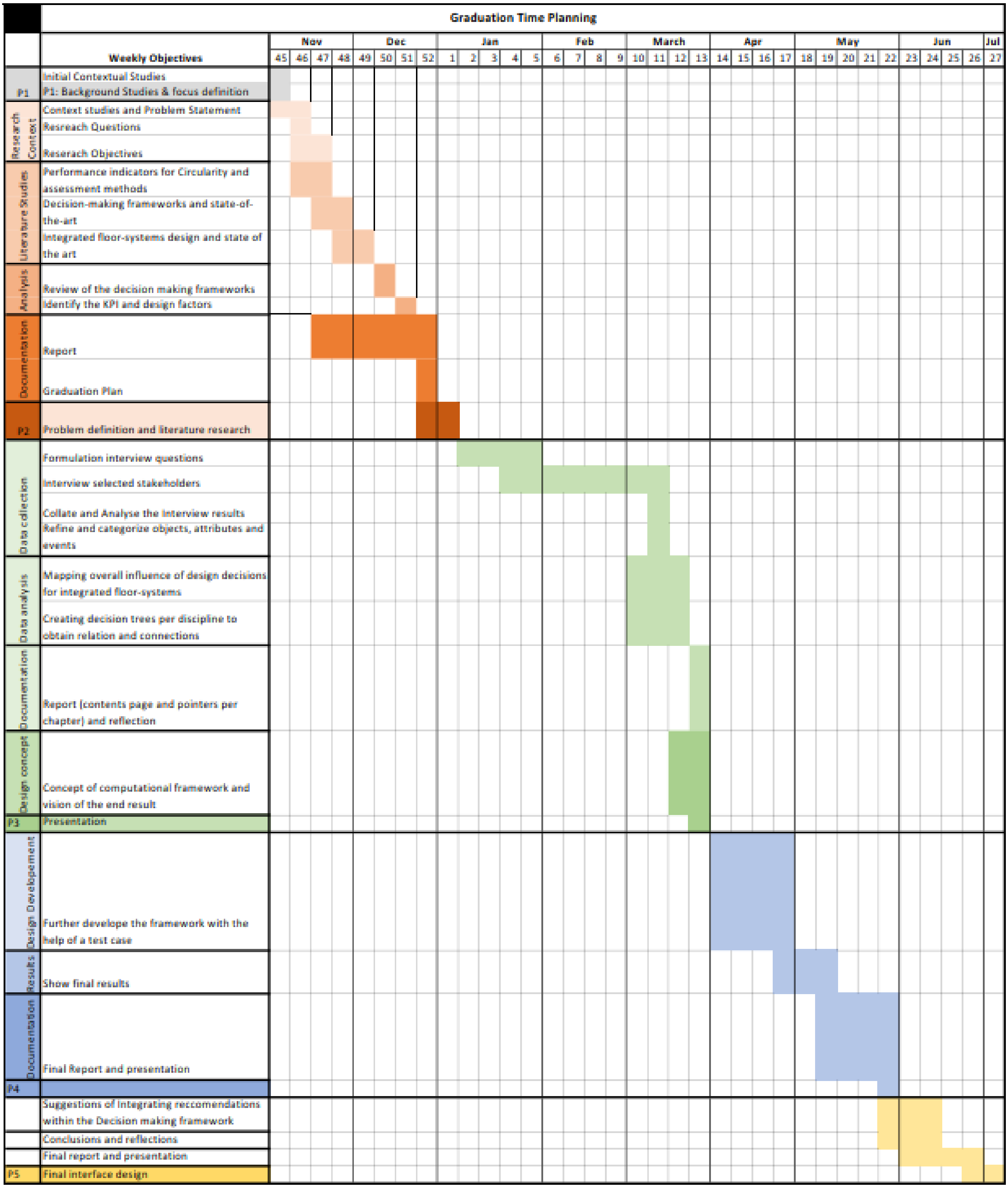
Part 4 - *DSS Development:* It explains the purpose and steps taken towards the development of a Decision Support System. It explains the development scheme of the DSS in detail and explains the adopted computational approach towards implementation.

Part 5 – *DSS Prototype and Testing:* This sections explains the development of the prototype, starting from the assumption and boundary conditions set followed by an overview on the configuration and finally a single case based stepwise demonstration of the prototype . It also discusses the findings of a user testing carried out with 2 Structural engineers and 1 MEP consultant to check the potential and scope of the developed DSS prototype. Finally shares the limitations and further developments.

Part 6 – Conclusions: The last part of the report covers the final conclusions by first answering all the sub questions and finally the main research question.


P1 - Background studies
The need for transitioning towards a circular economy in the built environment at global and national level
Environmental impact of floor-systems in a buildings
The current state of office building stocks in the Netherlands
P2 - Problem definition and Literature research
Basic problem analysis
Problem statement
Research Objectives
Research Questions
Literature studies
Circular design opportunity in the built environment
Design strategy for Adaptability and Flexibility in office buildings
Design factors that influence decision for floor-systems in early design phase
Indicators of circularity and assessment tool for application in buildings
Computational decision-making frameworks and applications
P3 - Develope relationships between design criteria and parameters (literature and interviews of stakeholders) and design concept decision making framework
Identify stakeholders and their needs involved in the early design stage
Disassembly factors (circularity indicators)
Technical indicators and parameters
Input parameters (circularity indicators)
Asessment methods (circularity indicators)
Draw relationships and influences on parameters and data required for decision- making
Decision making framework concept design
Selection of test case
P4 - Frame work design and results
Show results from the used case scenarios in developed framework
Develope framework using test case
P5 - Refinement and final conclusions
Refinement of the framework
Final conclusions and reccomendations towards a circular integrated floor-systems design strategies

## 2.6. Planning and organization



# II

# LITERATURE RESEARCH

This section of the report comprises of the literature reviewed for the different topics of enquiry in context of this research. The fields of enquiry can be related to the keywords as mentioned in the main research question of this thesis, i.e.

*Circularity, Adaptability, Measuring degree of circularity, Integrated floor-systems and its technical performance criteria, Decision support systems and state of the art computational approaches in AEC*

It briefly discusses the foundational theory of circularity in the built environment and elaborates the drivers, aspects and the main criteria towards design for adaptability in office buildings. Followed by a detailed overview of circularity indicators, assessment models and frameworks that can be used to measure degree of circularity in the built environment. Furthermore, the role of an integrated floor-system is introduced with a discussion on its functional and technical performance criteria. And finally, the theory of decision support system is covered with an overview of the state of the art computational applications in the Architecture, Engineering and Construction industry.

# 3. Circularity and Design for ‘X’ Strategy

The building construction industry is resource intensive and has the third largest resource footprint in the Netherlands. It contributes towards 50% of the raw material consumption and 40% for the total waste generation in the country. To address this problem, the concept of circularity is investigated for the built environment. Furthermore, to address the problem of vacant office buildings and demolitions caused due to lack of flexibility, the suitable design strategy of adaptability is explored.

To summarize, this chapter identifies circularity as a sub-set to sustainability from the definitions found in literature. It highlights the main principals of creating value in a circular economy and categorizes them as circular design goals. Furthermore, it reviews the value retention strategies and the associated design for X (DfX) strategies in the built environment. The DfX strategy of Design for Adaptability is then elaborated upon to emphasize its significance for office buildings in the Netherlands. The drivers for adaptability are identified and the key criteria of disassembly are discussed.

## 3.1. Circularity as a sub-set to sustainability

There is no one direction in the relationship of circularity with sustainability in existing literature. It is found that circular economy (CE) is perceived either as a condition or a benefit or a trade-off for sustainability in literature (Geissdoerfer et al., 2017). However, this research views circularity as a subset of sustainability establishing a beneficial relation, in line with the EU commission (2019) where circularity is one among the several solutions to foster sustainability. Transitioning towards a Circular economy has attracted many policy makers and governments because of the different implementable strategies that exist in this field. The implementation of CE is usually targeted at meso (companies or consumers), micro (symbiotic associations) and macro (urban or nationwide) scales, as seen in the national programme targeting 100% Circular economy by 2050, in the Netherlands (2016).

Circular economy has been defined in multiple ways by literature, however for foundational understanding and clarity of the circular economy concept two definitions are mentioned. An extensive literature review by Geissdoerfer et al. (2017) concluded in coining the definition;

“Circular economy, as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling.”

A close relation to this definition is seen with the Ellen Macarthur Foundation’s (an international think tank that promotes circular economy) definition;

“The circular economy is an economic and industrial system that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles.”

Both definitions imply efficient material flows i.e. minimizing the resource consumption where by materials/products/components are designed to last for a long duration while being kept at its original or at a higher value of use.

### *3.1.1 Main principals*

Circular economy changes the take-make-use-dispose approach to a take-make-reuse-repair-recycle and reduce waste to zero approach (Carra & Nitesh, 2017). The three main principals of circular economy as stated by the Ellen Macarthur foundation are ‘designing out’ waste, keeping materials and products in use, and regenerating natural systems, thereby closing the linear material loop (EMF, 2018).

Ellen Macarthur Foundation (2018) and Geldermans (2016) state separating the resource loops into technical and biological cycles are key to achieve these principals and maintain highest value of materials, illustrated in the figure 7, whereby;

1. Technical Cycles: Comprise of material/products or components that constitute of technical nutrients and flow between post-use to production through re-purposing, remanufacturing, re-use or recycling.
2. Biological Cycles: Comprise of bio-material/resource that flow between post-use to regeneration of raw material through cascading, bio-degrading or composting such that the resource is again one with the nature.

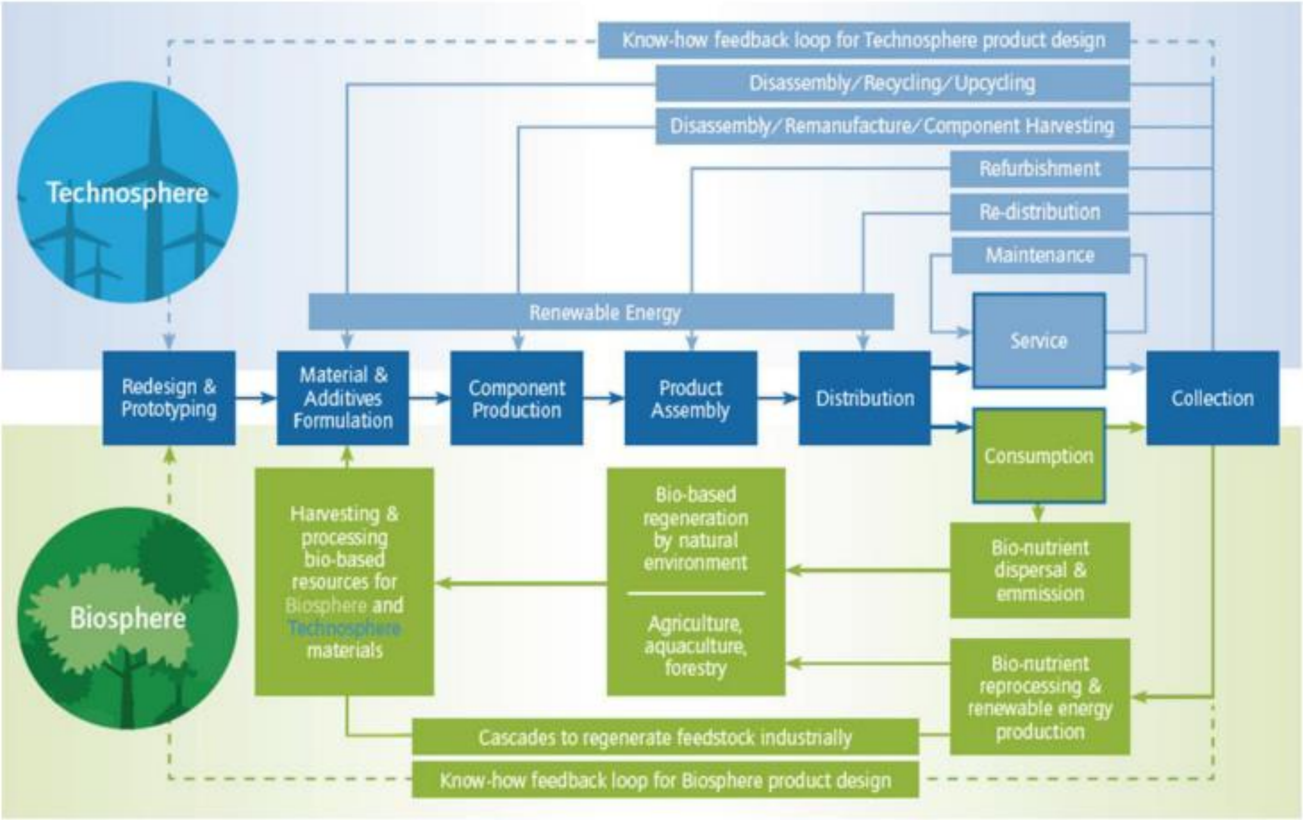


*Figure 2: Material flow in Circular economy* (Geldermans, 2016a)

Figure 8 illustrates the four principles that create value in a circular economy and these are (EMF,2012);

1. Power of the inner cycle – Associating value to savings of embedded costs in terms of materials/product, labour or energy, by initiating tighter inner cycles.
2. Power of circling longer- Keeping material/product in use for a longer time to avoid the procurement of new resources, energy and labour consumption to produce a new one.
3. Power of Cascade use- refers to creating value by reusing the materials in the resource flow to substitute the input of virgin material. It has an associated economic benefit as the cost of the non-virgin resource is lesser compared its alternative.
4. Power of pure, non-toxic or easier to separate inputs and designs – It is associated to maintaining a purity of materials in a product/component, such that it is easier to separate them post-use/consumption, to re-use or recycle the material at higher value.

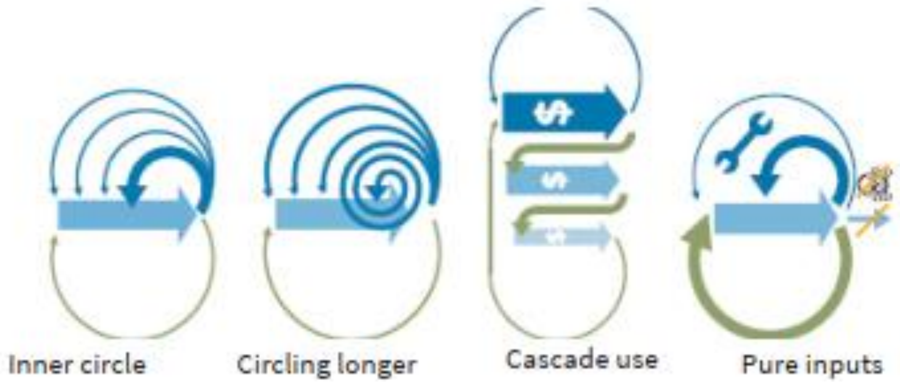


Figure 8: Four value creating principles in circular economy (EMF,2012)

### 3.1.2 Circular design goals

Circular design adopts a systemic approach as designing out of non-virgin resources (waste) for multiple life-cycle use requires holistic thinking with creative foresight from material procurement, manufacturing, utilization to end-of-life. (Carra & Nitesh, 2017; Geldermans, 2016; Government of the Netherlands, 2016; Munaro et al., 2020).

Literature categorizes circular design goals largely into three umbrella categories of narrowing, slowing and closing the resource loop, as illustrated in Figure 8 (Bocken et al., 2016; Geissdoerfer et al., 2017).

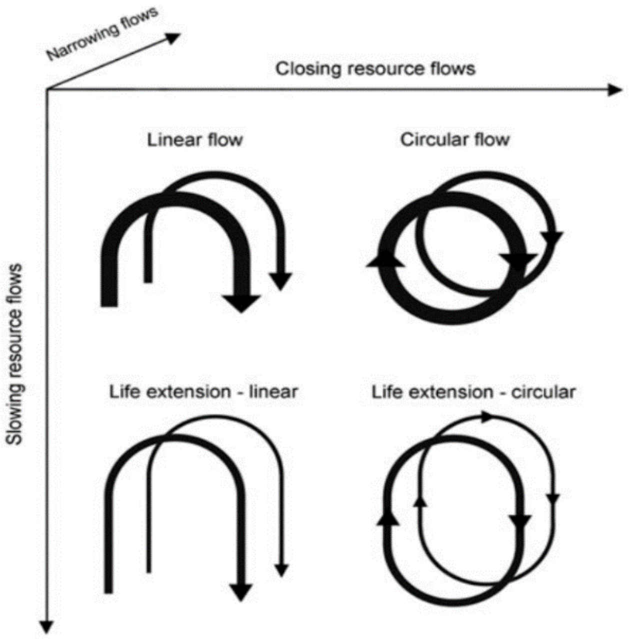


Figure 8:Categorization of resource flows into narrowing, slowing and closing loops. (Bocken et al., 2016)

1. Narrowing the loop aims at reducing, rethinking and refusing resources for products/components resulting in decreasing the utilization of new resources. Thereby narrowing resource flow by efficient resource use without considering the dimension of time, which makes this approach different from the two other approaches.
2. Slowing the loop largely aims at prolonging the operational phase of the material/product/component by repairing, reusing, refurbishing, remanufacturing, or repurposing it to extend its utilization period.

3. Lastly, closing the loop aims at eliminating waste by recycling or recovering the material/product/components between post-use and production phase ensuring circular flow of resources.

### *3.1.3 Value retention Options*

Many researchers including the Ellen Macarthur foundation (EMF) have developed R-strategies that offer value retention options for resources that align with the three circularity goals, as summarized in Every R-strategy has a design aim and these are explained as found in the literature (Bocken et al., 2016; Potting et al., 2017; Reike et al., 2018) and its integration within a product's life-cycle is illustrated in Figure 4.

R-list for Narrowing the loop:

1. Refuse: To avoid using new resources and making do with what is already existing
2. Reduce: To consciously decrease the amount of resources utilized.

Table 1. The term value retention was coined by D.Reike et al. (2018), stating, "it refers to the idea of resources carrying an intrinsic value as opposed to economic notions of value." Therefore, resource value retention implies preservation of resource as close to its original state or reusing it with minimum entropy (Reike et al., 2018). This reinstates that decoupling of economic value from the resource value is a key aspect of value retention.

Figure 3, illustrates the incorporation of the six R-cycles as proposed by EMF (2012) within the linear industrial system. Most R-lists proposed in literature are ordered in a hierarchy of low to high circularity potential, which aligns with Lansink's ladder of waste hierarchy.

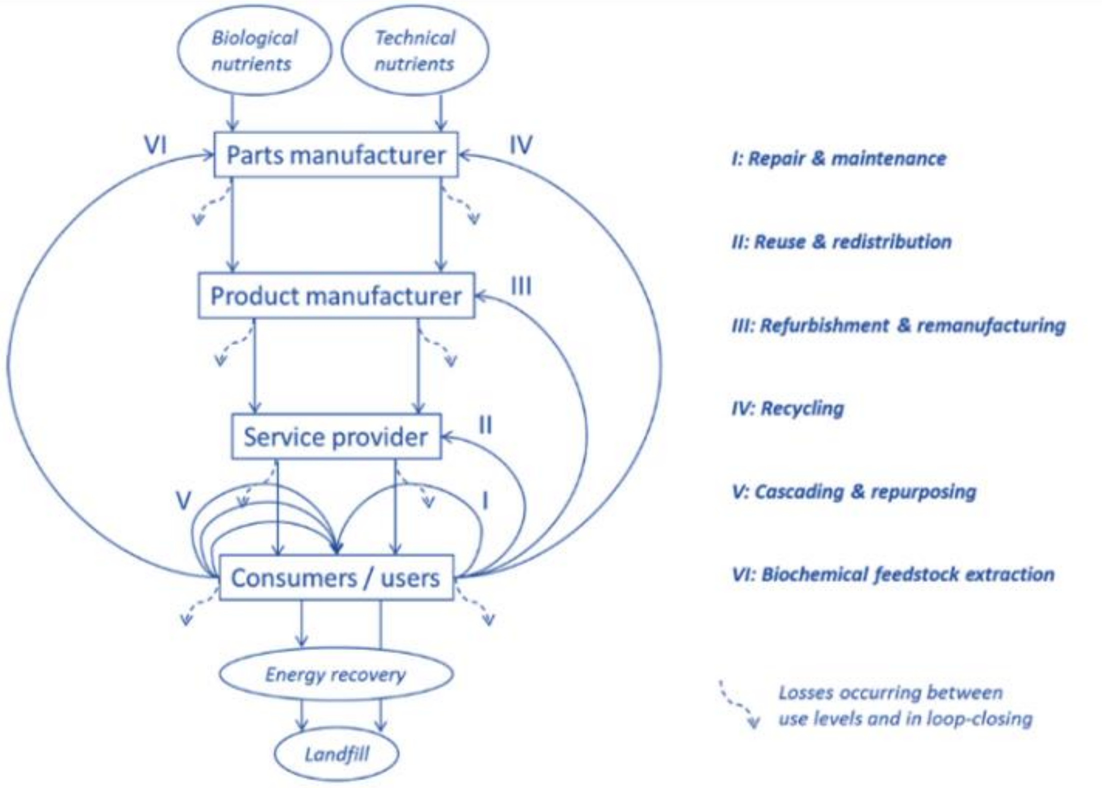


*Figure 3:The six R-cycles as proposed by EMF(2012)*

Every R-strategy has a design aim and these are explained as found in the literature (Bocken et al., 2016; Potting et al., 2017; Reike et al., 2018) and its integration within a product's life-cycle is illustrated in Figure 4.

R-list for Narrowing the loop:

3. Refuse: To avoid using new resources and making do with what is already existing
4. Reduce: To consciously decrease the amount of resources utilized.

*Table 1: Summarizes the different R-lists found in the literature for circularity levels ordered in priority and categorizes them into the three circularity goals.*

| Circularity Goals | | Circular levels of R-strategies ordered in priority | | | |
|---|---|---|---|---|---|
| | | Waste hierarchy | Butterfly diagram | 9R strategy | 10R strategy |
| | | *Ladder of Lansink* | *Ellen Macarthur Foundation* | *Potting et al., 2017* | *Reike et al., 2018* |
| High | Narrowing the loop | | | Refuse | Refuse |
| | | | | Rethink | |
| | | Reduce | | Reduce | Reduce |
| | Slowing the loop | Re-use | | Reuse | Resell/Re-use |
| | | | | Repair | Repair |
| | | | Refurbish | Refurbish | Refurbish |
| | | | Manufacture | Remanufacture | Remanufacture |
| | | | Cascading and repurposing | Repurpose | Repurpose (rethink) |
| | Closing the loop | Recycle | Recycle | Recycle | Recycle |
| | | Energy | Biochemical feedstock | Recover | Recover (energy) |
| | | Incineration | | | |
| Low | | Landfill | | | Re-mine |

R-list for Slowing the loop:

5. Re-use: To use a product again by incorporating minimal changes to retain its original value
6. Repair: Maintaining a product at its original value
7. Refurbish: To replace or repair a large portion of the product/component to bring it back to its original working condition
8. Remanufacture: To recover functioning parts/elements of the product or components for producing the complete product again at its original state
9. Repurpose: Reusing the product for a new function

R-list for Closing the loop:

10. Recycle: The process that changes the state of a product or material into either a higher value or adding functions by upcycling or into a lesser value by downcycling from its original value or functionally recycle to its original value by recovering or re-purposing it.

11. Recover (energy): To convert non-recyclable material into usable form of energy such as fuel, heat, electricity.
12. Incineration: To burn the waste as per the legal guidelines
13. Landfill: To dump the waste into a demarcated land as per legal guidelines
14. Re-mine: To mine the old valuable resources/materials sorted in landfills and other waste plants.

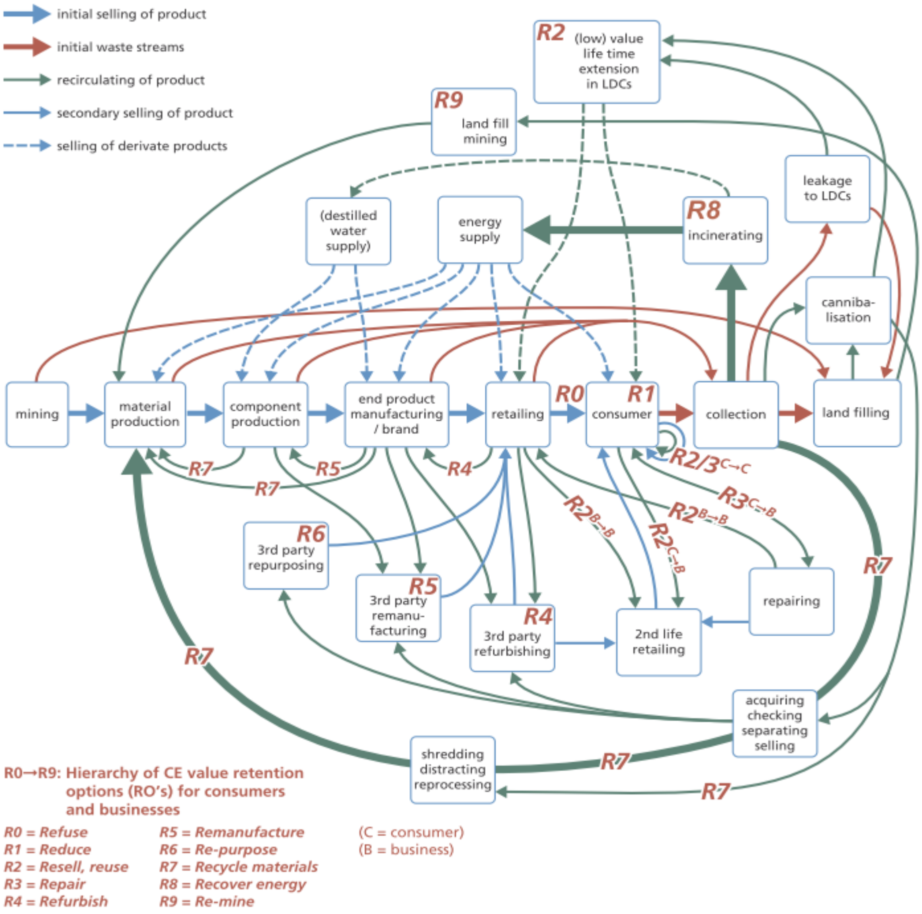


*Figure 4:Mapping the value retention options for a product's life-cycle* (Reike et al., 2018)

### *3.1.4 DfX strategies*

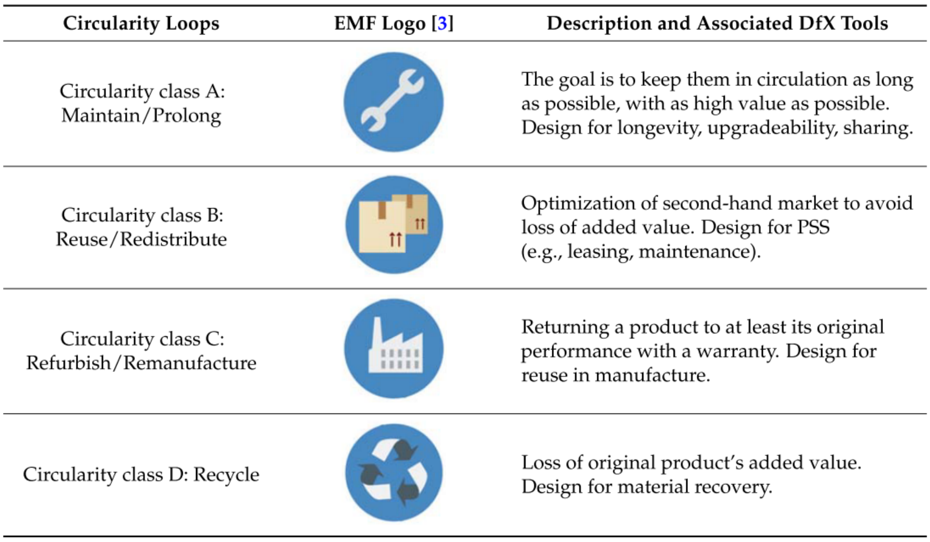
Design for X (DfX) is a concept for design development towards achieving the circularity levels, where X stands for an activity (Arnette et al., 2014) that can be analyzed using the R-strategies mentioned in the previous section. For example Design for Adaptability or Design for disassembly are design strategies that can effectively contribute towards the circularity goals of slowing or closing the loop respectively. The various DfX strategies are categorized under the two circular loops by Bocken et al. (2016), as illustrated in Table 2. From all existing DfX strategies, Geldermans (2016b) states Design for Disassembly (DfD) and Design for Recyclability (DfR) has gained ground in the building sector to mitigate the negative environmental impact. The DfD and DfR are technical design approaches to ensure recycling of construction materials and products at end of life by easy separation and disassembly. Interestingly, the DfD approach facilitates both circular goals of slowing and closing the loop. This strategy allows for easy separation of parts that also enables not only recycling but also re-use of the material/elements (Bocken et al., 2016).

In a literature review on DfX strategies Arnette et al. (2014) find that these strategies are very practitioner oriented, however, they guide the design team to consider the overall life cycle of the product from procurement to end-of-life. Additionally their research classifies DfX as a subset to Design for Sustainability (DfS).

Saidani et al, (2017) classifies the DfX strategies for the associated circularity levels or R-strategies indicating maintenance or prolonging life span of product/system holds highest priority as per circularity levels in Figure 5. Drawing relations between table 2 and figure 5, Design for longevity i.e. maintenance or repair and Design for upgradability or adaptability are strategies that belong to this class A level, that help retain products/materials at highest value.

*Table 2: Showing the categorization and description of DfX strategies for circular goals of slowing and closing the loop. Source: Adapted from Bocken et al.* (2016)

| Circular goal | Circularity levels / R-strategy | Design Aim | DFX | Description |
|---|---|---|---|---|
| **Slowing the loop** | Reuse<br>Repair<br>Refurbish<br>Re-manufacture<br>Re-purpose | **Long life products (long utilization period)** | Design for attachment and trust | refers to the creation of products that will be loved, liked or trusted longer |
| | | | Design for durability | relates to physical durability, material selection is an important part of this process |
| | | | Design for reliability | refers to designing for a high likelihood that a product will operate throughout a specified period without experiencing a chargeable failure, when maintained in accordance with the manufacturer's instructions. |
| | | **Product-life extension** | Design for ease of maintenance and repair | Enables products to be maintained in the best condition |
| | | | Design for upgradability and adaptability | Ability of a product to continue being useful under changing conditions by improving the quality, value, and effectiveness or performance |
| | | | Design for standardization and compatibility | creating products with parts or interfaces that fit other products as well |
| | | | Design for dis- and re-assembly | ensuring that products and parts can be separated and reassembled easily. It is a strategy that can be applied to increase the future rates of material and component reuse. |
| **Closing the loop** | Recycle | | Design for dis and re-assembly | It is about ensuring that products and parts can be separated and reassembled easily. It is vital for separating materials that will enter different cycles |
| | | | Design for Technological cycle | To develop products in such a way that the materials ("technical nutrients") can be continuously and safely recycled into new materials or products. |



| Circularity Loops | EMF Logo [3] | Description and Associated DfX Tools |
|---|---|---|
| Circularity class A: Maintain/Prolong | 🔧 | The goal is to keep them in circulation as long as possible, with as high value as possible. Design for longevity, upgradeability, sharing. |
| Circularity class B: Reuse/Redistribute | 📦 | Optimization of second-hand market to avoid loss of added value. Design for PSS (e.g., leasing, maintenance). |
| Circularity class C: Refurbish/Remanufacture | 🏭 | Returning a product to at least its original performance with a warranty. Design for reuse in manufacture. |
| Circularity class D: Recycle | ♻ | Loss of original product's added value. Design for material recovery. |

*Figure 5: Classification of the DfX tools as per the circularity levels* (Saidani et al., 2017)

### *3.1.5 CE strategies and built environment*

Transition towards circular economy in the building construction sector implies a system level approach, whereby the construction and demolition waste is not simply downcycled, as per the current practice of recycling in the Netherlands, as highlighted in the introduction. Downcycling means recycling material for a function that has lesser value than the material's original value. Circular practices ensures the material/product/ component is reused or refurbished to retain its original value (Minunno et al., 2018).

The CE strategies of value retention options and DfX tools show immense potential towards transitioning into circular economy, however, applying these into the built environment poses certain barriers to traditional building practices.

Minunno et. al (2018), highlights the barriers and opportunities of applying seven such CE strategies into buildings, these are tabulated in Table 3, and feasibility of the application in the context of prefabricated buildings and traditional buildings is shown in Table 4.

*Table 3: summarizes seven CE strategies, opportunities and barriers* (Minunno et al., 2018)

| Strategy | Opportunities | Barriers |
|---|---|---|
| Reduction of construction waste and lean production chain | Integrating the lean production in the prefabrication phase of building components | The degree of complexity and variable measures pose as barrier toward lean production |
| Integration of scrap, waste and by-products into new components | Use of recycled aggregates into concrete fosters second life for the byproducts | Strategy limited to the use of concrete, which, by itself, is highly carbon-intensive |
| Reuse of replacement parts or entire components | A second life to building components by doing so supply chain could be reduced.<br>Supply chain could be integrated in business planning | Technological barrier of disassembling monolithic building;<br>economic barrier if components are not designed toward reuse.<br>Supply chain for reused components is yet to be |

| | | |
|---|---|---|
| | | developed in the building sector |
| Design towards adaptability (reduction through life extension) during operational stages | Planning of flexible spaces and design of adaptable elements to reduce the waste due to modifications in the operational stage of buildings | The degree of adaptability is proportional to the mobility degree of the building. Traditional buildings are built on-site to be permanent, and thus, are not adaptable |
| Design towards disassembly of goods into components to be reused | The use of BIM in prefabrication allows for material tracking, identification, and cataloging | Cost effectiveness and technological feasibility hinder the practical application of disassembly |
| Design for recycling of construction materials | Steel can be recycled, and concrete is commonly down-cycled. Building with steel would then increase the material saving | Transport of recycling components and the recycling processes themselves are carbon-intensive for both concrete and steel |
| Systems to track materials and components within their supply chain | Track materials and components throughout the life cycle of buildings | Location of materials and time when those would become available |

*Table 4:The feasibility of applying CE strategies in prefabricated and traditional buildings. (-) not possible, (+) possible, and (=) applied in either contexts of buildings* (Minunno et al., 2018)

| Strategy | Traditional Buildings | Prefabricated buildings |
|---|---|---|
| Reduction of construction waste and lean production chain | - | + |
| Integration of scrap, waste and by-products into new components | + | - |
| Reuse of replacement parts or entire components | = | = |
| Design towards adaptability (reduction through life extension) during operational stages | - | + |
| Design towards disassembly of goods into components to be reused | = | = |
| Design for recycling of construction materials | - | + |
| Systems to track materials and components within their supply chain | - | + |

From the tables 3 and 4, the opportunity for circular strategy of design for adaptability that prolongs or maintain the product life span are that it reduces waste during the operational stages of the building and provides for spatial flexibility, however, the barrier is that adaptability is only as good as the degree of mobility of the building or building elements. Therefore, design for adaptability as a circular design strategy is feasible in prefabricated buildings as opposed to traditional buildings that are built keeping permanence as the focus (Minunno et al., 2018).

## 3.2 Design for Adaptability offers flexible Office Buildings

Flexibility has been a prominent issue in office buildings as the rate of change due to user/market demand is higher in public buildings than in residential buildings (Durmisevic, 2006). Duffy states, *"Only those corporate users who have the imagination to link the organizational development to design imagination are likely to procure buildings that will escape obsolescence."*

### *3.2.1 Drivers of adaptability*

Flexibility is defined as, "the ability to change and adapt a building to altered activities through its physical and administrative environment" (Israelsson & Hansson, 2009). Gosling et al. (2013) identify, flexibility as an enabler for adaptability in buildings. Furthermore, they classify the drivers for adaptability as technical obsolescence and economic obsolescence. Technical obsolescence relates to technological advancements drives change in mechanical/electrical installations and the fit-out systems such as raised floors, suspended ceiling and ducting systems. Economic obsolescence refers to changes in spatial characteristics of the building due to legislative/consumer/market expectations, such as extensions, free partitioning, functional mutation, and multi-functionality (Durmisevic, 2006; Gosling et al., 2013).

El. Durmisevic (2006) mentions spatial systems (characteristics) cannot be considered independent of the technical systems, arguing that "mutations of space are directly related to the technical compositions of a building," as illustrated in Figure 6. Therefore, providing flexibility in technical systems will directly imply spatial flexibility that will in turn result in an adaptable design.

Furthermore, the design for flexibility strategies that align with these technical flexibility indicators discussed by Gosling et al. (2013) are;

1. *Layering of building elements* – aims to layer building elements as per service life to facilitate maintenance of the decaying element without causing damage to the rest. It saves time and cost of maintenance.
2. *Indeterminacy*- designing for the worst case scenario wherein a large range of variable functions or configurations can be accommodated to enable flexibility. In short, designing all building components such as structure, services and spaces at overcapacity. While considering layering as per service life and standardization (prefabrication) of building elements to enhance flexibility.
3. *Interchangeable components* – proven to be effective for office design, this strategy focuses on modular, standardized and prefabricated building elements that can be replaced or interchanged with new elements. For instance, interchanging the standardized service installations to the latest models in the ceiling through accessible ceiling systems.
4. *Design for deconstruction/Integration of components*- focuses on the integration of components suggesting design for disassembly with consideration of layering and standardized elements for easy repair, reuse and refurbishing of the system, to offer high adaptability potential.

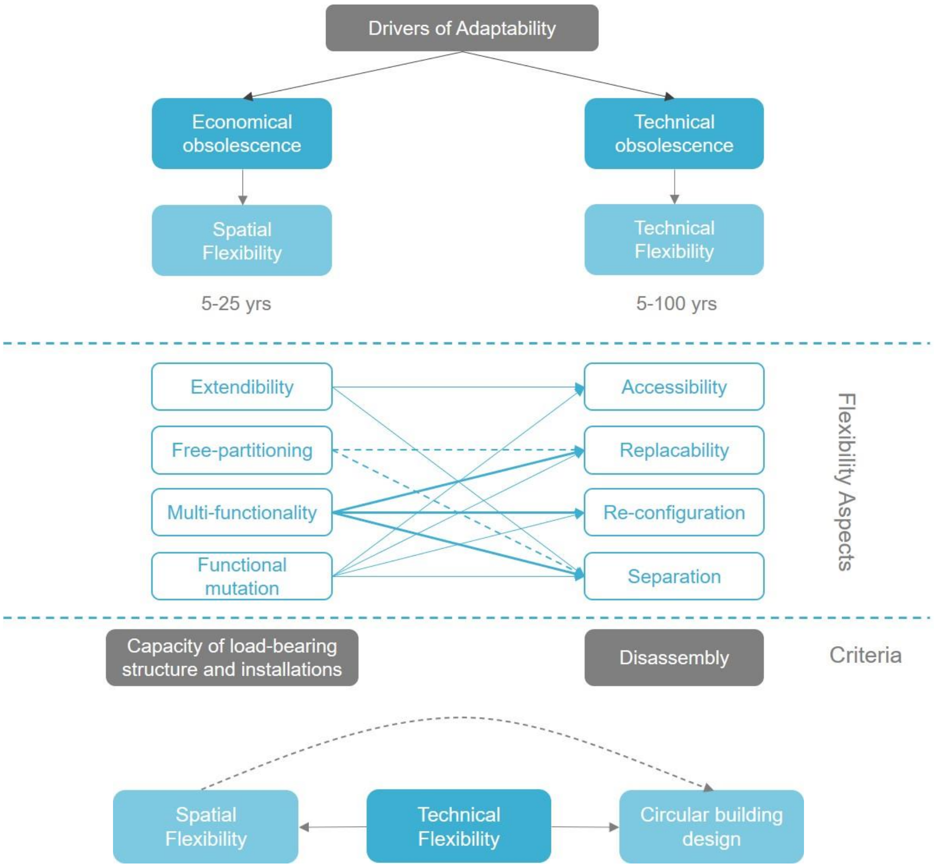


*Figure 6: The inter-dependency between spatial and technical flexibility.* (Durmisevic, 2006)

Elma Durmisevic (2016) states in order to facilitate spatial flexibility and adaptability in the context of circularity such that the systems/components/materials can reused, reconfigured or replaced, buildings must be reversible. A reversible building has three levels of transformation, i.e. at material, structural and spatial. This three-dimensional model is represented in the Figure 7, wherein disassembly is the main criteria for structural transformation for durability, spatial adaptability and material/element reuse or recycle.

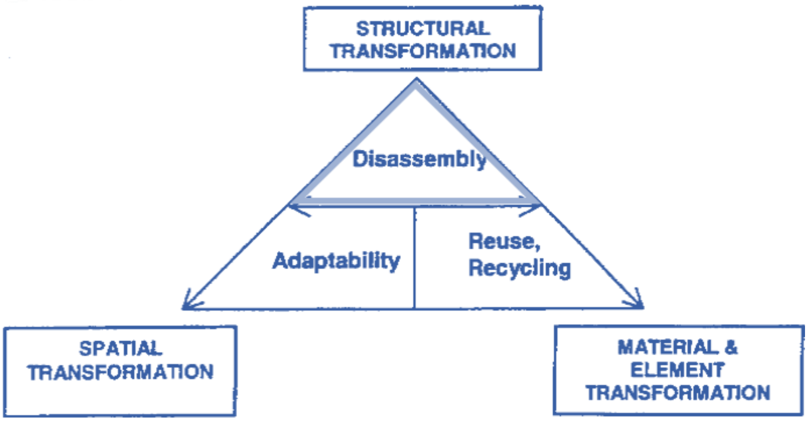


*Figure 7:The three-dimensional model for transformation* (Durmisevic, 2006)

### *3.2.2 Building layers*

El. Durmisevic (2006) establishes that demolitions of buildings occurs due to the static approach of construction. Static approach is a closed integration of building components and systems ignoring the innate variations in their durability periods, making it difficult to change only a part of the whole building component. Therefore, landing up in the waste stream as significant amount of energy is consumed to separate the elements for repair or reuse. Furthermore, the durability of most building materials is longer than the function of the material which poses a bigger problem.

*Shearing layers of change* - The varying life spans for use of every building layer is theorized in the 'Shearing layers of change' by Brand (1994). The building has different rates of change, so they are decomposed into 5 layers, site, structure, skin, services, space plan and stuff, Brand (1994).

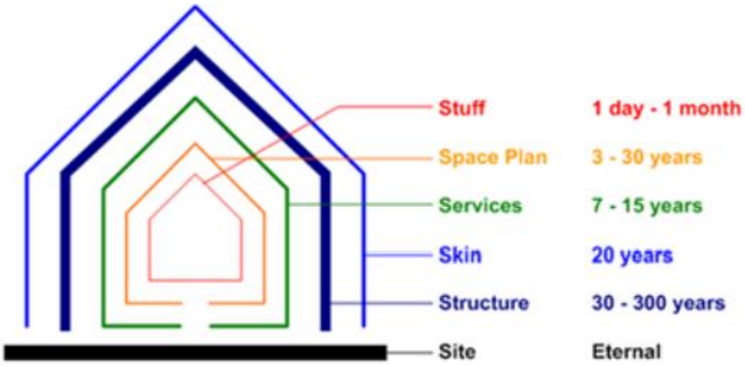


*Figure 8: The shearing layers of change* (Brand, 1994)

*Site*- Geographical setting, urban location and the legally defined lot, which is considered eternal.

*Structure*- refers to the foundation and load bearing elements that last between 30-300 years according to Brand (1994), however, an average of 50 years is considered for this research as per standards.

*Skin*- refers to the external façade/envelope of the building, with a life span of 20 years

*Services*– The mechanical, electrical or plumbing installations are considered under services and they have a functional life between 7 to 15 years

*Space plan*- refers to the external finishes for walls or floors or ceiling and it includes doors too. These change every 3 years however it could extend to 30 years.

*Stuff*- This layer refers to furniture and fittings and these range between a day to a month

El. Durmisevic (2016) states that flexible design of buildings must adopt a dynamic approach which considers these different service life spans of building layers for a given overall building life-span, as illustrated in the

Figure 9. Accounting for a dynamic thinking will ensure regular maintenance and will prolong the buildings durability.

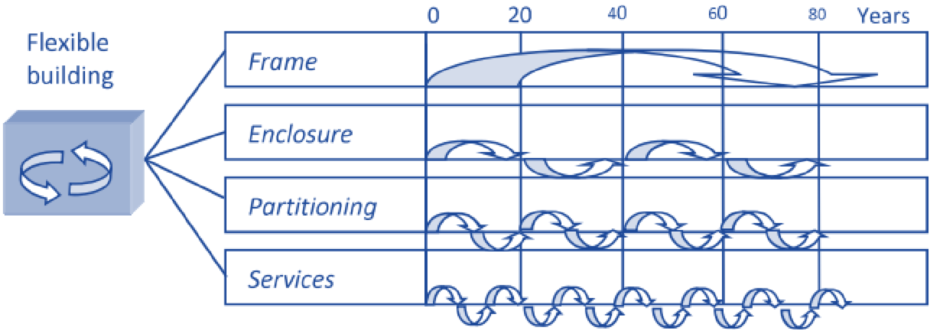


*Figure 9: A dynamic approach towards flexible building design based on changing durability of building layers* (Durmisevic, 2016)

### *3.2.4 Material levels*

Durmisevic (2006), defines buildings as, ''a multidimensional system that can be represented through different layers''. Buildings are a configuration of multiple materials, every material can be associated with a specific function. Industrialization or prefabrication methods in building construction offer a control over use of resources and reduce waste of materials. Additionally, it offers the opportunity of clustering parts into modules that determine the assembly (Elma Durmisevic, 2016). Decomposition of a building into its industrialized parts not only in building layers but to its smallest unit of materials offers a systems approach to tackle disassembly. The Figure 18, illustrates the hierarchy of material, component, sub-system and system levels in a completely transformable building and shows the integration of these levels in a building's configuration.

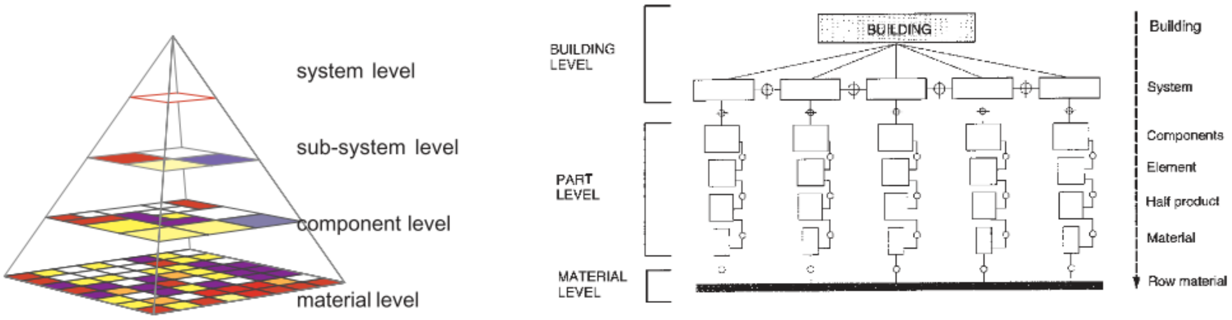


*Figure 10: Systematic approach towards Material level hierarchy(left) and integration of the levels in the building (right) Source:* (Durmisevic, 2006)

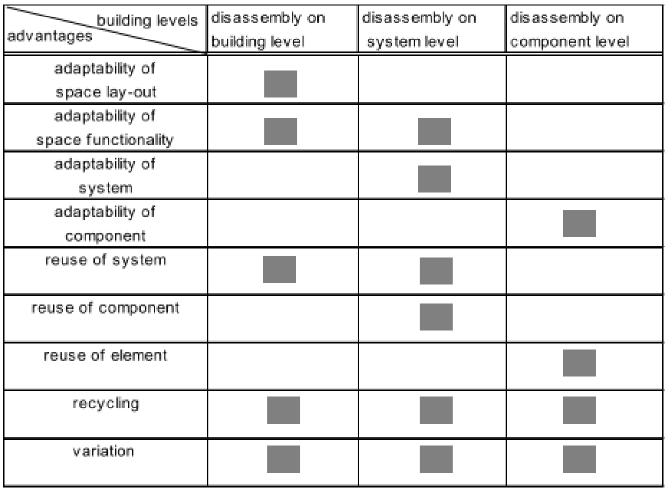
Designation of levels in buildings can be relative and therefore Dumisevic (2006), explains,

1. Building level – is a configuration of the fundamental buildings systems, such as structural system, façade (skin), partitioning (space plan) and services.
2. System level – a composition of components that cater to secondary functions of the building systems, for example, in the case of floor-systems, structural floor slab, insulation, raised floors and suspended ceilings.
3. Component level – is an assemblage of elements or materials that facilitate tertiary component related functions, such as the ducts, silencers, exhaust and supply vents that form the mechanical air ventilation distribution in the building tertiary to the secondary function of overall air treatment/ ventilation system.

The disassembly at varying building levels offers different advantages towards transformation, this is summarized in the table 5.

The disassembly at a component level ensures adaptability of the component and reuse of the elements. While disassembly at a system level ensures adaptability of space functionality and the system itself, thereby also enabling reuse of the system and component. Disassembly on a building level ensures adaptability of the space layout, space functionality and reuse of the system. A total transformable building with highest degree of adaptability is when disassembly is possible at all levels. However, with either one of the approaches there is always an advantage of recycling or variation.

*Table 5: The advantages of transformation shown at varying levels in a building by Dumisevic* (2006)



| building levels<br>advantages | disassembly on building level | disassembly on system level | disassembly on component level |
|---|---|---|---|
| adaptability of space lay-out | ■ | | |
| adaptability of space functionality | ■ | ■ | |
| adaptability of system | | ■ | |
| adaptability of component | | | ■ |
| reuse of system | ■ | ■ | |
| reuse of component | | ■ | |
| reuse of element | | | ■ |
| recycling | ■ | ■ | ■ |
| variation | ■ | ■ | ■ |

## 3.3 Conclusion

Circularity is a subset to sustainability as it is a concept that is beneficial to attain sustainability, that aims at resource efficiency, reducing energy consumption and generating zero waste. The essence lies in retaining resources at its highest value. Designing out waste, keeping materials and products in use and regenerating natural systems are the three main principals of circular economy. Separating materials into technological and biological cycles is effective for creating value within their individual loops. The three main circular design goals are narrowing, slowing and closing the loop. The strategies proposed to visualize the design goals are value retention options for circular flows and Design for X (DfX) approach. These strategies work in synergy to achieve circular design solutions. The commonly used DfX strategy in the built environment is Design for Disassembly. DfD creates value in two circular design goals, slowing and closing the loop through re-use, refurish, remanufacture or recycling, thereby prolonging the life of the product/material. Design for upgradability or adaptability can create the highest level of circularity by facilitating long product/material life. Design for Adaptability especially, shows opportunity of flexible spaces and proves feasible for prefabricated building solutions and not for traditional buildings.

Flexibility is a prominent problem in office buildings compared to residential buildings in the Netherlands, due to the higher rate of change in user and market demands. In order to provide flexibility in buildings, design for adaptability is key. The drivers for adaptability are technical (relates to technical flexibility) and economical obsolescence (relates to spatial flexibility). In order to achieve spatial flexibility, technical flexibility must be achieved. Therefore the strategies for technical flexibility are layering of building elements, indeterminacy, interchangeable components and design for deconstruction. For a building to be reversible or transformable, design for disassembly is the main criteria. However, the varying durability periods of the building layers (shearing layers of change by Brand) and materials create a significant impact on disassembly. Disassembly at different material levels i.e. Component, System and Building level, impacts the degree of adaptability and value retention. However, it guarantees recycling of resources in a circular flow and flexibility in buildings.

# 4. Measuring degree of circularity

From the previous chapter two key aspects towards circularity are identified, first in relation to circular material flow and second in relation to flexibility i.e. disassembly potential of material levels in buildings. However, to measure the extent of circularity for building configurations and gain clarity on its indicators, this chapter will cover assessment metrics or frameworks found in literature for measuring the degree of circularity.

For the material flow assessment of products, Material Circularity Indicator (MCI) by Ellen Macarthur Foundation (2019) is discussed in a stepwise manner with formulae used in calculation. For assessing flexibility, transformation capacity by E.Durmisevic (2006) and Detachability Index by Alba Concepts (2019) are studied. Furthermore, to understand the relationship between different indicators and an aggregated score towards measuring circularity, the building circularity indicator (BCI) developed by Alba concepts and the CB'23 core measurement scheme are studied. Finally comparisons are drawn and a selection towards assessment methods are reasoned.

## 4.1. Material Circularity Indicator

The Material Circularity Indicator (MCI) is developed by the Ellen Macarthur foundation (2019), and has gained worldwide recognition for assessment at product level and company/organizational level. The MCI for a product measures the degree of minimization of linear resource flow, maximization of a restorative flow of its components and measures the utilization (length and intensity of use) of the product compared to the industry average of a similar product. Figure 11 illustrates the MCI assessment. The framework is designed for both technical and biological cycles of resource flow. The outcome is a value for MCI that ranges between 0.1 to 1, where 0.1 is the measure for a fully linear product, while 1 is for a fully circular product.

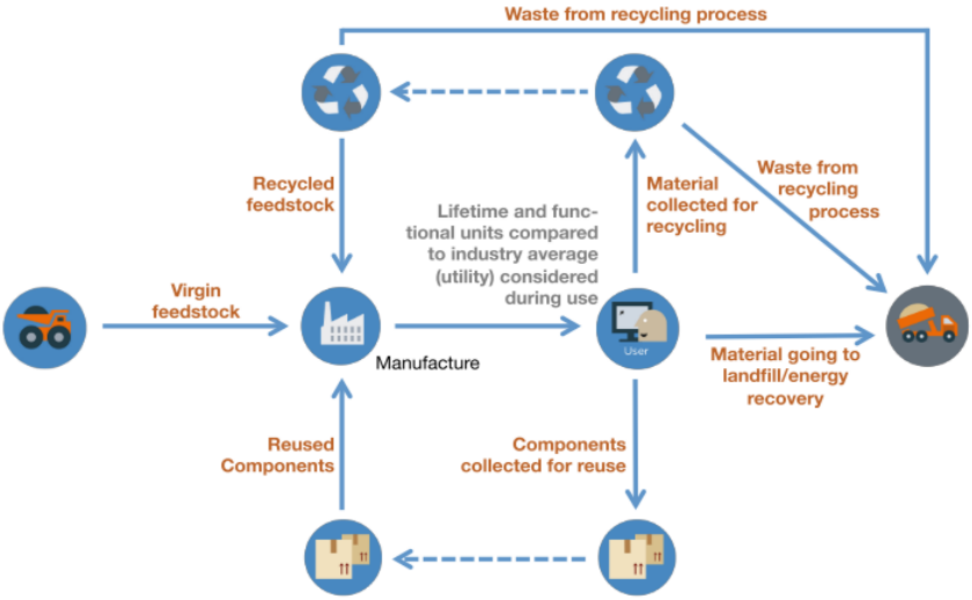


*Figure 11: A representation of the MCI by Ellen Macarthur foundation* (Measuring Circularity, 2019)

The three main attributes of MCI are;

1. The amount of Virgin material (V)
2. The product's utility factor (X)
3. The amount of unrecoverable waste material (W)

The *amount of Virgin material* (V) is calculated by the formula

$V= M*(1-F_r-F_u-F_S)$

Where;

M = Mass of the finished product

$F_r$ = fraction of feedstock derived from recycled sources

$F_u$ = fraction from reused sources

$F_S$ = fraction of biological material processed from sustained production

The *product's ultility factor* (X) is given by the formula

$X = (L/L_{av})*(U/U_{av})$

L = Life span of the product

$L_{av}$ = Average Industrial life span of similar product

U = Intensity of use per year

$U_{av}$ = Intensity of use per (Market average)

Note; either Intensity or life span can be used as factors and not both.

The *amount of waste* material going to landfill or energy recovery ($W_0$) from linear flow

$W_0= M*(1-C_r-C_u-C_c-C_E)$

Where;

M = Mass of the finished product

$C_r$ = fraction of the mass of the product being collected for recycling at the end of its use phase

$C_u$ = fraction of the mass of the product going into component reuse

$C_C$ = mass of the product comprising uncontaminated biological materials that are being composted

$C_E$ = mass of the product comprising biological materials from Sustained Production being used for Energy Recovery

The *amount of unrecoverable waste* material (W)

$W = W_0 + ((W_F + W_C)/2)$

Where;

$W_0$ = waste from linear flow

$W_C$ = waste from collection process

$W_F$ = waste from recycling process

From these mentioned attributes the *Linear flow index (LFI)* can be computed

$LFI = (V+W)/(2M+((W_F+W_C)/2))$ ;however, when $W_F=0$ and $W_C=0$

LFI = (V+W)/2M

Therefore, MCI can be calculated by

MCI = 1-LFI*(a/X) where a is a constant = 0.9

The constant value of 0.9 derived by EMF, is to balance the impact of increase in utility of a product and the reuse of the components to ensure the same reduction in virgin material use and unrecoverable waste for a given time period. Therefore, the MCI of a fully linear product (LFI=1) with a utility value X=1, is always 0.1 and not 0.

The performance of MCI for with respect to product utility in three scenarios of fully linear, 50% restorative and 100% restorative is shown in the chart Figure 12. Increasing product utility in case of linear and 50% restorative increases the MCI performance, however makes no difference to the 100% restorative.

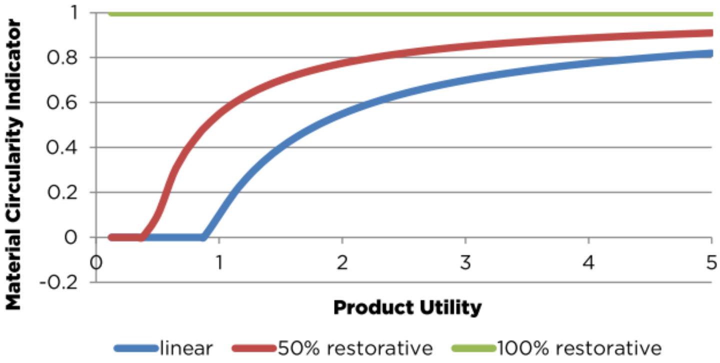


*Figure 12: Chart representing the MCI performance to product utility in three scenarios* (Measuring Circularity, 2019)

Limitations of this assessment framework include;

1. Comparison between two fully linear products cannot be carried out with this tool
2. It does not favor closed loops, for instance the material recovered for recycling does not return to the manufacturer. (e.g.; Product as a service model)
3. It lacks the capacity to measure the impact of the product design.

Assumptions of the assessment are;

1. The fraction of non-virgin materials recovered at the end of life can be processed to a similar quality as the original virgin material
2. products collected for reuse experience no loss of material during preparation
3. the mass of the product is constant throughout the life cycle

## 4.2. Transformation Capacity of Flexible Buildings

From the previous chapters, we have identified Design for disassembly as one of the circular DfX strategies that not only enables prolonging the products life span by reuse/refurbish (slowing the loop) but also enables recycling (closing the loop). Design for disassembly (DfD) is instrumental for low environmental impact and facilitates structural transformation. It is one of the key criteria for adaptability and transformation in buildings. This section discusses the design aspects that drive the decision making process towards DfD in buildings that will contribute towards high transformation capacity.

The two key performance indicators of transformation are Independence and Exchangeability. The disassembly aspects for building configuration are categorized into physical, technical and functional design domains as illustrated in Figure. Independence is largely determined by functional design domain of the configuration, while exchangeability is defined by technical and physical design domains. The eight different design aspects to consider for disassembly can be broadly categorized into the three design domains. However each of the design aspects influence the both Independence and exchangeability.

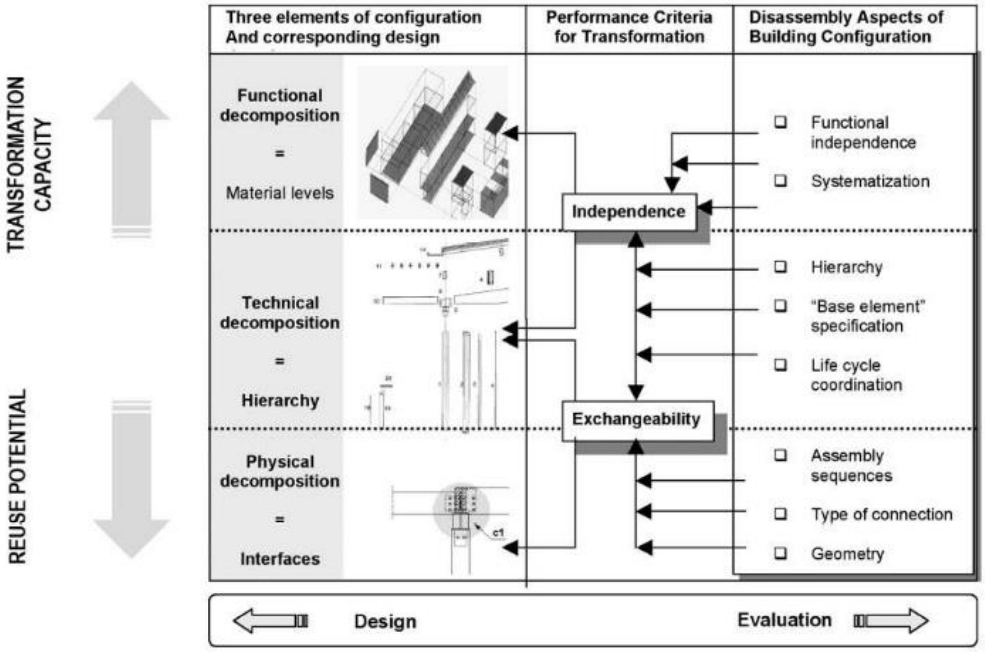


*Figure 21: Illustrates the relation between disassembly aspects and design domain by highlighting the performance criteria of transformation. It also indicates increase in reuse potential with physical decomposition while a higher transformation capacity with better functional independence* (Durmisevic, 2016)

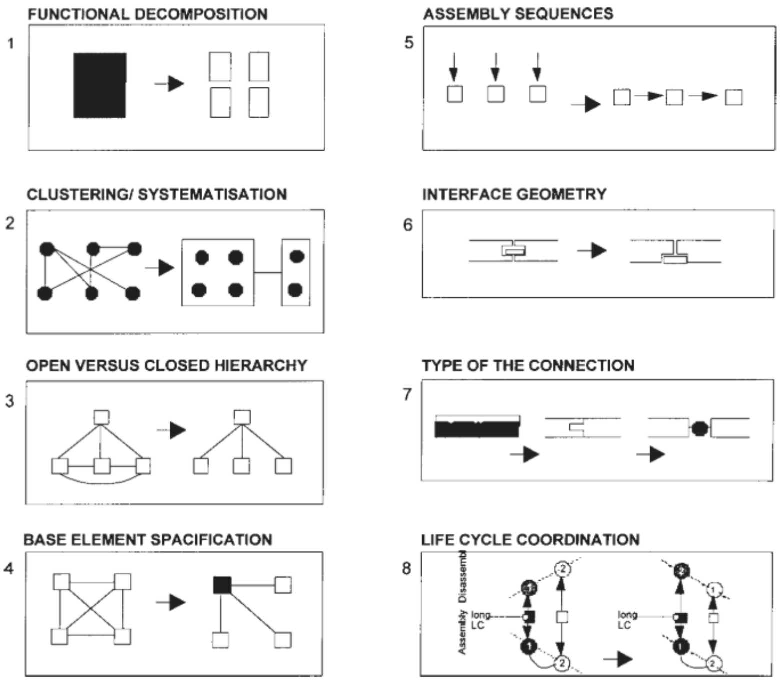


*Figure 22: Illustrates the 8 distinct design for disassembly aspects (Elma Durmisevic, 2016)*

1. Functional decomposition – refers grouping building materials/components/sub-system and system into their respective functional use to ensure independence.
    a. Functional independence – level of autonomy and separation of the different functions in a configuration
    b. Systemization – Clustering/grouping of functions based on life cycle and integration of materials

2. Technical decomposition – refers to arranging the materials/components/subsystems according to the base element specification and technical life spans. The main aspects are
    a. Relational pattern – is dictated by the number of relations one element in a component or in a component within a sub-system, that determines the level of integration
    b. Type and position of relations (hierarchy) – Type of relations can be classified in 6, i.e. closed, layered, stuck, table, open or shared as illustrated in figure 23. Closed, layered and stuck categorize as closed hierarchies while table, open or shared are partially or fully open hierarchies. The position of relations represent horizontal or vertical configuration, horizontal being seen as static and vertical seen as dynamic.

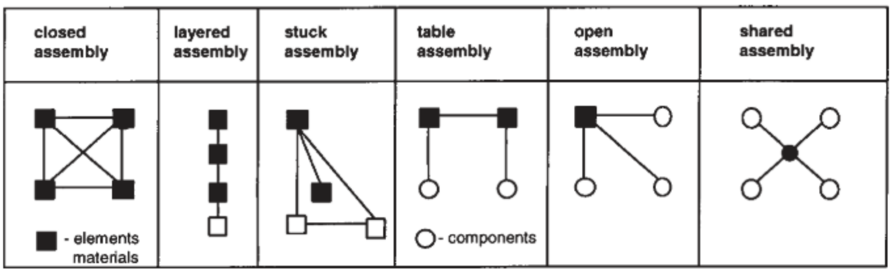


*Figure 23: Illustrates the types of relations or hierarchies between elements (Elma Durmisevic, 2016)*

    c. Base element specification – identification of the one main functional element that carries the rest, as they are primary elements that connects components
    d. Life cycle coordination – determines the assembly based on the life span of building materials, that ranges between 5 to 75 years. The materials that have shorter lifespan are usually assembled first to facilitate replaceability.

3. Physical decomposition – refers to the assembly/disassembly of the materials/component/ subsystems/ systems in terms of sequence, especially focusing on the geometry edge and connection type to enable exchangeability.
    a. Geometry of component edges – as the name suggest this criteria is largely dictating the assembly and disassembly of the system, examples are a linear edge or an overlap edge or an integral edge.
    b. Assembly sequences – depends on the assembly direction and sequence in which the elements/components are configured which highly influences the disassembly potential at end of life.
    c. Type of connections – determines the degree of freedom between the elements or components connected together, the main type of connections are direct (integral), indirect (accessory) and filled (Chemically).

The decision making process of a design for disassembly model is not linear but a conditional cyclic process (Durmisevic, 2006). This implies that every aspect influences the other and therefore, decisions made are only conditional until the overall picture is defined. The main design aspects and additional decision making aspects that have to be considered at every level in the building are illustrated in Figure .

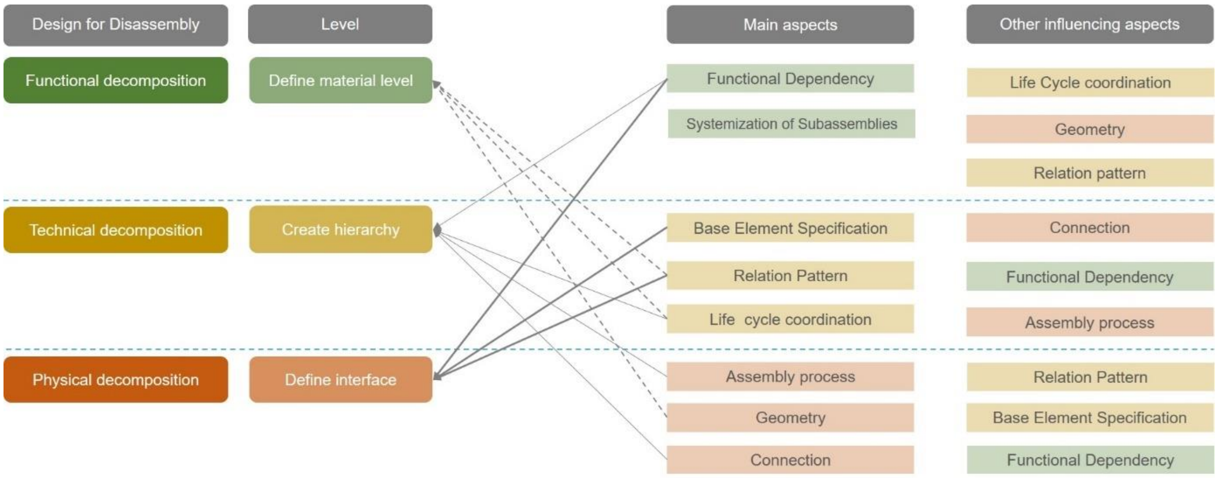


*Figure 24: Illustrates the main aspects and the influencing aspects at every design level* (Durmisevic, 2006)

### *3.3.1 Service life planning*

Main consideration before the assessment of DfD aspects is service life planning. It means to establish the use life scenarios for when and what to disassemble. This depends on the relation between the use life cycle (ULC) and the technical life cycle (TLC) of the building and the its products levels for every building layer. Service life planning enables efficient designing of buildings and use of resources, thereby controlling environmental impact.

Service life planning can be categorized into long-term and short-term scenarios which relate to the respective transformation strategy for building and materials. Short-term transformation strategies relate to maintaining the value of the material/product/system, either by replacing it or maintaining it or reusing for other purposes. However, a long term transformation strategy informs the transformation of the systems/products for reconfiguration or reuse in case of re-materialization of used buildings and their materials (Durmisevic, 2006). Furthermore, short-term scenario prove valuable in extending the life/value of the material and slowing the loop, however, long term scenario ensure extending the value for a longer duration thereby having a significant impact on the keeping material in constant use and reducing resource exploitation.

Therefore, to identify these scenarios, a comparison is drawn between the expected use life span to the technical life span of the building and its materials. The table 6 shows the three possible comparisons and the associated long and short-term scenario as listed by Durmisevic (2006). Office buildings are categorized under the long term scenario of time independent buildings as they are subject to frequent change. For the definitions of long term scenarios for use of configurations refer appendix 1.

*Table 6: Categorizes long term and short term scenarios for building configurations and materials based on the relationship between use life cycle and technical life cycle* (Durmisevic, 2006)

| Case | Long term scenarios for use of configurations | Short term scenarios for use of configurations | Long term strategy for materials | Short term strategy for materials |
|---|---|---|---|---|
| ULC< TLC | Time dependent building | - Free partitioning<br>- Reconfiguration<br>-Internal rearrangement<br>- Extendibility | -Disassembly on material level<br>-Recycling | -Disassembly on building and system level<br>- Reuse of variable components<br>- Reconfiguration |
| ULC >TLC | Specific building | - Internal<br>- rearrangement | -Disassembly on material level<br>- Recycling | -Disassembly on component level<br>-Replace for maintenance<br>-Reuse, recycling |

| | | | | |
|---|---|---|---|---|
| ULC = TLC | Temporary buildings | - Internal<br>- rearrangement | - Disassembly on material level<br>- Recycling | - Disassembly on material level<br>- Recycling |

### *3.3.2 Assessment based on a Knowledge Model*

Durmisevic (2006) explains, transformation capacity of components can be graded by the typology of the configurations i.e. ranging from static (0) to dynamic (1). The decisions taken for each disassembly aspect listed in the previous section influences the configuration type. For this, a knowledge model is developed based on acquired building data and the main performance criteria for disassembly. The knowledge model is structured in five levels of data as shown in figure. 25, from 0 to 4 and table 7 expands the abbreviations of independent and dependent variables as illustrated.

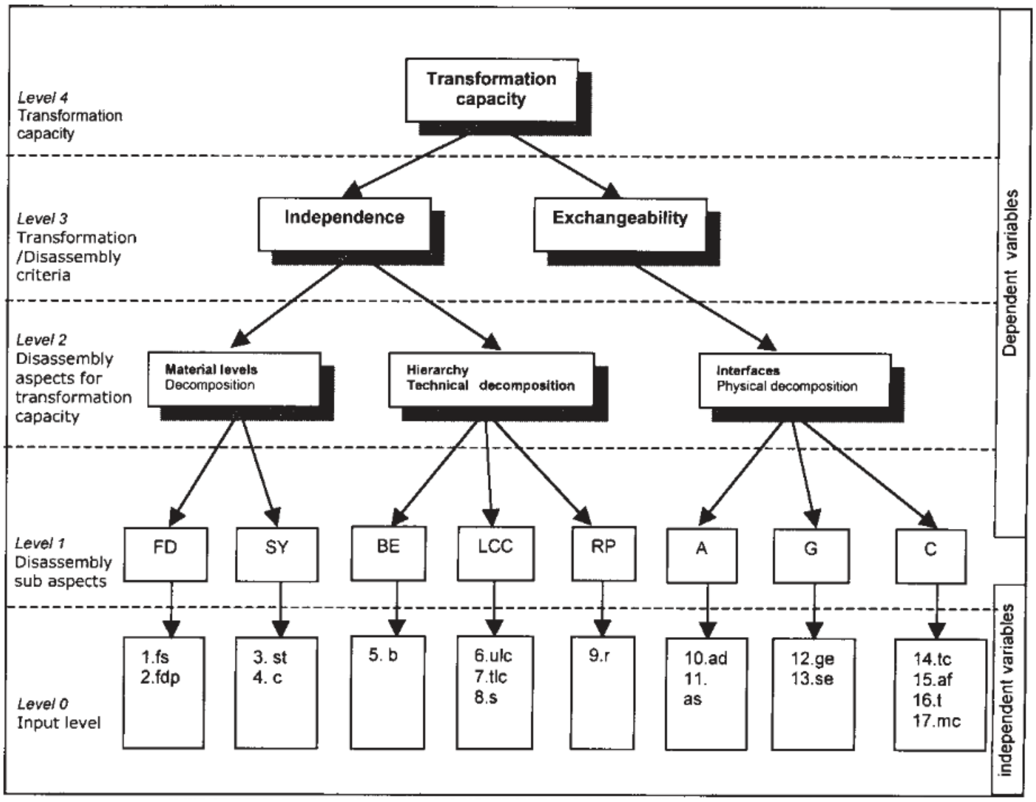


*Figure 25: Assessment model for determining transformation capacity illustrating the 5 data levels* (Durmisevic, 2006)

The zero level consists of independent variables that is unique for each project case. These variables are categorized under the eight sub-aspects of disassembly. This level impacts the weight/importance given to the sub-aspects. For this a list of weighted options per variable is used and this can be referred to in appendix 1.

The first level establishes the level of importance of each of the main aspects based on the sub-aspects values derived from level zero. The second level represents the impact on the main aspects of the building configuration i.e. functional, technical and physical decomposition. The third level then determines the impact on the two key performance criteria of Transformance capacity, i.e. Independence and exchangeability. Finally, the fourth level, determines the transformation capacity of the building configuration.

The framework can be used as decision support model for the design of transformable buildings and also as an evaluation model for assessing the transformation capacity of a building configuration (Durmisevic, 2006).

*Table 7: Expands the labels of the dependent and independent variables as illustrated in the figure 25.*

| LEVEL 2 | LEVEL 1 | | LEVEL 0 | |
|---|---|---|---|---|
| Disassembly level and main design aspect | Sub-aspects | Abbv. | Independent Variables | Abbv. |
| Material level (Functional decomposition) | Functional decomposition | (FD) | Functional separation | (fs) |
| | | | Functional dependence | (fdp) |
| | Systemization | (SY) | Structure of material level | (st) |
| | | | Type of clustering | (c) |
| Hierarchy (Technical decomposition) | Base element | (BE) | Type of base element | (b) |
| | Life cycle coordination | (LCC) | Use life cycle | (ulc) |
| | | | Technical life cycle | (tlc) |
| | | | Coordination of life cycle and size | (s) |
| | Relation pattern | (RP) | Type of relation pattern | (r) |
| Interfaces (Physical decomposition) | Assembly process | (A) | Assembly direction | (ad) |
| | | | Assembly sequence | (as) |
| | Geometry | (G) | Geometry of product edge | (gp) |
| | Connection | (C) | Type of connection | (tc) |
| | | | Accessibility of connection | (af) |
| | | | Tolerance | (t) |
| | | | Morphology of Joints | (mc) |

From studies, Dumisevic (2006) relates Transformation capacity (TC) to efficient use of materials and categorizes the TC value into three groups based on end of life scenario during disassembly i.e. Demolition; Partial-disassembly/demolition; and Reuse, recycle and reconfiguration;

Values less than 0.33 are configurations that require demolition at end of use life. Values from 0.33 to 0.67, are partially disassemble-able, leading to demolition waste in range 20-80%. And lastly, for highest disassembly potential, TC value must be greater than 0.67, contributing to only 25% waste during deconstruction.

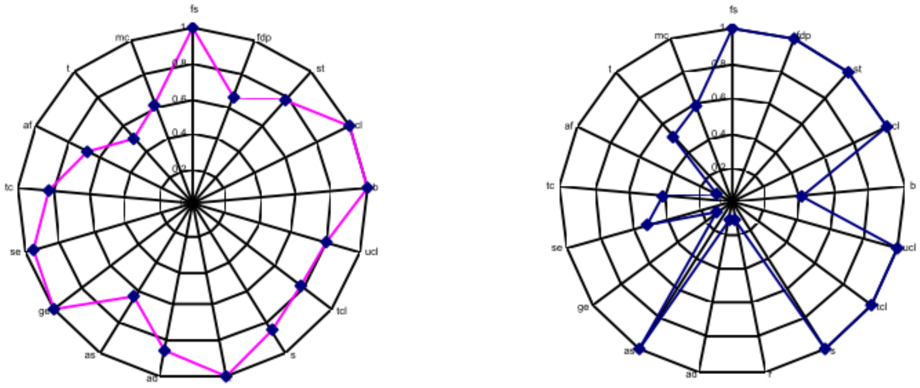


*Figure 26: Radial/Spider graphs representing the scores per disassembly aspect* (Durmisevic, 2006)

## 4.4. Detachability Index

The recent development reported in '*Measurement methodology detachability for GPR building and BREEAM-NL'* (Alba Concepts, 2019) by Alba concepts includes environmental impact through the use of Environmental Performance of the building (MPG) in the calculation towards the detachability index (LI).

Detachability is defined as the degree to which objects can be disassembled at all levels of scale within buildings so that the object can retain its function and high-quality reuse is feasible (Alba Concepts, 2019). The quality of reuse is determined by future scenario of the product which is directly related to the degree to which a product is detachable. The building configuration largely determines the degree of detachability or disassembly and the complexity of configuration depends on the building levels involved. (El. Durmisevic, 2006; Alba Concepts, 2019)

The factors that contribute towards detachability are categorized into technical, process-based and financial-based aspects (Van Vliet, 2018; Alba Concepts, 2019). The technical aspects largely relate to the sub-aspects under transformation capacity proposed by Durmisevic. While the process based aspects focus on factors such as disassembly instructions to be considered during the design, realization, use and disassembly stages of the building for highest reusability at end of use cycle. Lastly, the financial aspects consider the disassembly time, cost and residual value.

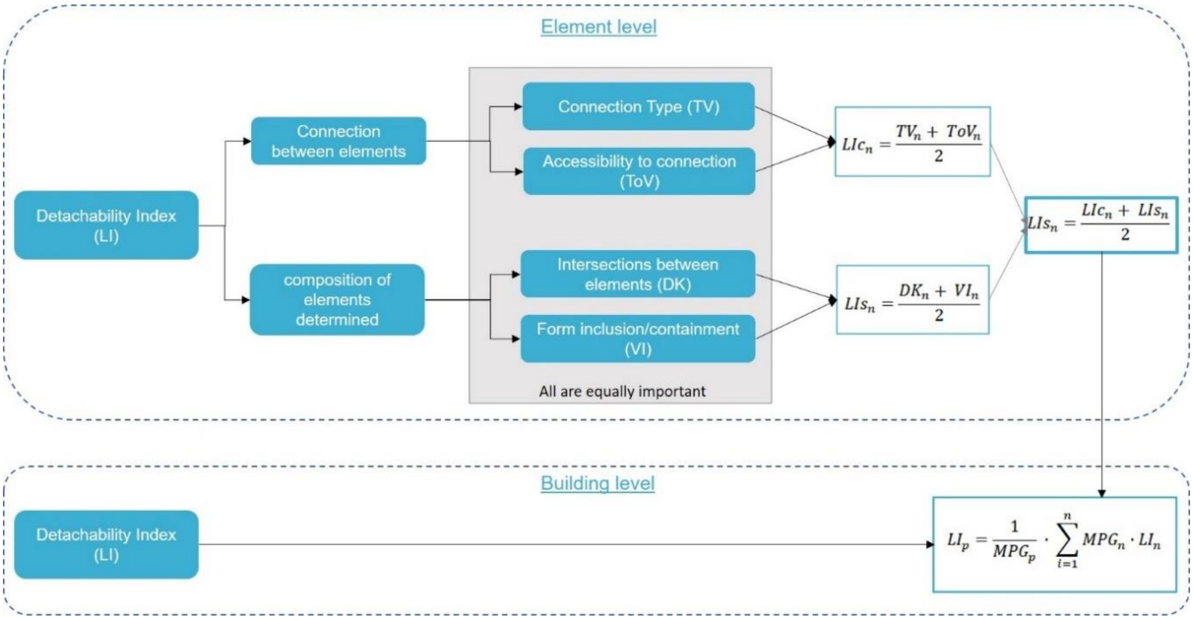


*Figure 27: Illustrates the determination of the detachability index at element and building level (Alba Concepts, 2019)*

The proposed conceptual scheme is shown in figure 27; wherein only four main sub-aspects are adopted from Durmisevic's framework mentioned in section 3.3.1. These aspects are selected on the basis of a survey carried out with 122 respondents (Van Vliet, 2018; Alba Concepts, 2019). These are classified into two main aspects and the two respective sub-aspects for evaluating the detachability at element level; i.e.

1. the connection between elements (LIc) - connection type (TV) and accessibility to connection (ToV)
2. the composition of elements (LIs) – intersections (DK) and form containment (VI) between elements

The average of (1) and (2) of all elements leads to the resulting detachability index for the system. And summation of all system values factored by their respective MPG (environmental performance factor) leads to the overall building level detachability Index. Inclusion of MPG as a normalizing factor to attain the overall result, attempts to create a direct dependency between detachability and environmental impact of the system. This helps in comparing one system to another. However, this approach lacks portraying which particular choice of system/element greatly influences to the final score.

### *4.4.1. Systemization and Clustering (NL/Sfb classification)*

One important aspect towards detachability is systemization and clustering material levels and building layers as mentioned in 3.2.2 and 3.2.3. For this, the construction industry, since years, in the Netherlands, uses multiple ways such as STABU specification and NL/SfB (BNA) element classification methods. These methods are also used to identify unique codes for building products to determine the environmental performance of buildings (MPG) (Van Vliet, 2018; Alba Concepts, 2019).

A common building product coding system contributes towards standardization of building products in the industry. It helps draw better relational dependencies between products/element in a building configuration and better estimate degree of detachability.

The NL/SfB classification system has existed in the construction industry for 70 years. It is used widely in the construction industry and has seen integration in a NEN standards. This classification method benefits digitization of data especially with reference to BIM (Building Information Modelling) (Bimloket, 2021).

The classification structure of the NL/SfB method is illustrated in the figure 28. It has 4 levels of data classification relating to a numerical digit (represented as X below) in the code, every two levels separated by a period;

1. Elements (X) – this level can be related to the Building layers by Stewart Brand of Site; Structure; Skin; Services; Space layout and Stuff
2. Element group (XX) – this level can by re-termed as systems, as it consists of element groups under each of the building layers; such as floor and building frames under primary element also referred to as Structure
3. Element variant group (XX.X) – this level can also be called the sub-systems; which further branches into system types; i.e. Load-bearing or non-load bearing in case of floors.
4. Element variants (XX.XX) – refers to the variants within a sub-system; this identifies the variants within the family of load-bearing; i.e. general, suspended, balcony, etc.

Therefore, each entity level can be identified by the unique number and position assigned in the overall code, this aids in evaluating detachability at the correct level, and draw relations between these entities. Towards the evaluation of detachability index, van Vliet (2018), proposes to add 4 new levels to this standard for better estimation. The additional levels refer to

5. Product (XX.XX.XX)
6. Component
7. Material
8. Raw material

Furthermore, the recommendation towards evaluating detachability is to consider atleast 5 levels for the following reasons (Alba concepts, 2019);

1. The availability of data at lower levels is limited, depending on the elaboration level of the design
2. The number of connections to be considered multiplied exponentially at a lower level. This costs more time to assess
3. The connections at element level are fundamental in the technical development of a building
4. Detachability is a relatively new concept in the market. Due to the lack of experience with the measurement method, complex relationships at lower levels are difficult to estimate by the market

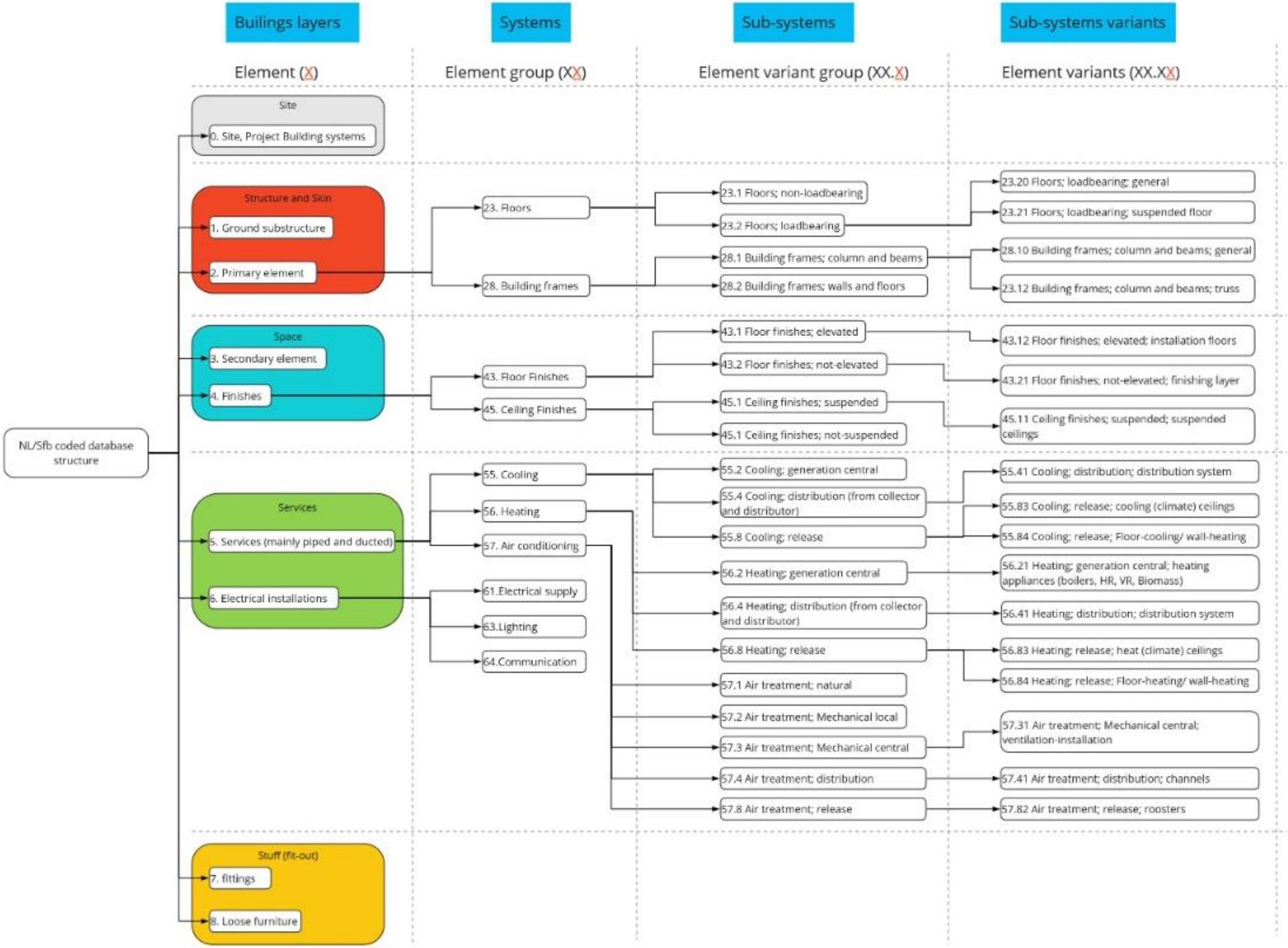


*Figure 28: The NL/SfB database structure showing the coding sequence and its relation to the material levels in the building. Adapted from NL/SfB database 2019 (Bimloket, 2021)*

## 4.2. Building Circularity Indicator

Building Circularity Indicator (BCI) is a metric to assess degree of circularity at a building level. This metric was developed by J.H.H Verberne (2016a), M. van Vliet (2018) and further developed to adopt it in the building industry by Alba Concepts. Alba concepts is a consultancy company established in the Netherlands that promotes sustainable construction practices by assessing the degree of circularity for buildings.

The metric uses the material circularity indicator's concept to measure the Material Index (M) to gain the degree of circularity of the intrinsic properties. While, it adopts selected design for disassembly sub-aspects proposed by Durmisevic (2006) to obtain the detachability index (LI) to gain the degree of circularity for relational properties. Finally, the two M and LI are normalized to obtain a single quantitative value that determines the degree of circularity at product level, element level and building level as shown in the figure 29.

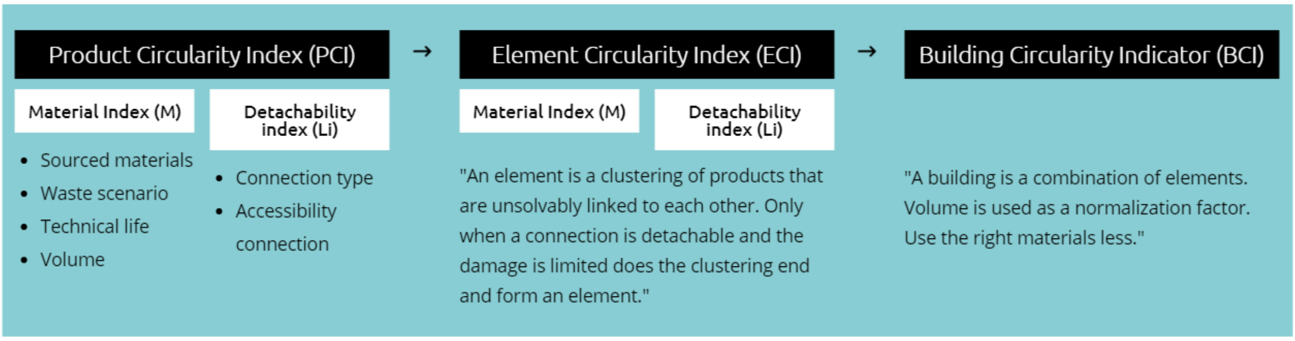


*Figure 13: Illustrates the conceptual assessment framework for the Building Circularity Indicator (BCI) from Alba Concepts (2019)*

For in-depth understanding the assessment method is elaborated using Verbene and van Vliet's research, which can be referred to in the Appendix 2. However, a conceptual overview, the figure 30 illustrates a step-wise process towards assessment using the BCI metric.

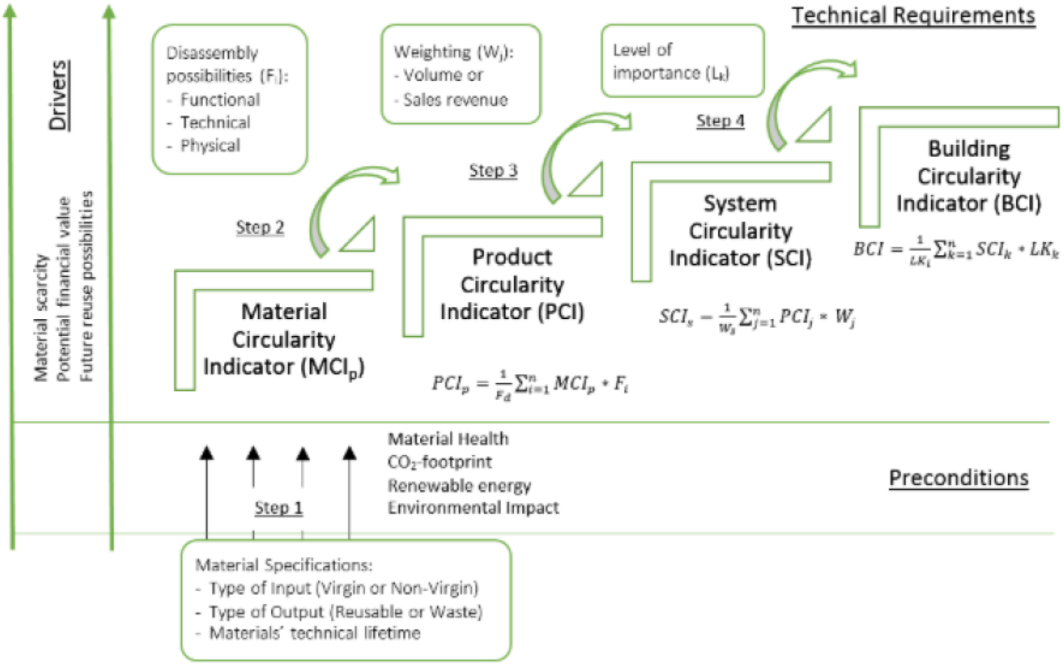


*Figure 30: A step-wise illustration of the BCI assessment framework* (Verberne, 2016b)

The BCI model considers the factors that cause environmental impact as preconditions and states that these give insight into analyzing the impact created by changing circularity levels, the three considered are;

1. Material Health – the level of toxicity of the material and risk associated with the material
2. $CO_2$ footprint – total amount of carbon emissions caused by material/product
3. Renewable energy -ratio of renewable energy to fossil fuel energy used in production of material/product

However, the final score does not include these into the assessment metric.

## 4.5. CB'23 core measurement scheme

The Platform CB'23, proposes core indicators and determination methods for measuring degree of circularity in construction. From extensive stakeholder interviews on topics that affect design with respect to circular construction, the platform has identified three core objectives that cover different criteria of decisions (*Measuring Circularity*, 2020);

1. Protecting material stocks
2. Protecting the environment
3. Protecting existing value

This assessment method focuses on applying to all circular strategies, that include demountable construction, minimizing the total amount of material, maximizing lifespan and the value retention options (R-values), at any Brand's shearing layers in a building.

Platform CB'23 argues that the existing measurement methods do not incorporate these three objectives together in one aggregated assessment for two reasons.

1. the relative weighting and prioritizing of certain indicators over the other is not sufficiently proven
2. An aggregated score, reduces possibilities to learn from the assessment and understand which choice influences the final scoring

The advantage of not aggregating the results into one score, opens the avenue of assessing the trade-offs between the three main objectives. For example; a particular circular strategy that ensures to protect material stocks and existing value of the object, does not necessarily create less impact on the environment.

Therefore, figure 31, illustrates the steps covered by the proposed core measurement method for evaluating circularity. It is important to note that the data collection, assessment towards the relative importance of these scores and finally decision making are not covered by this method.

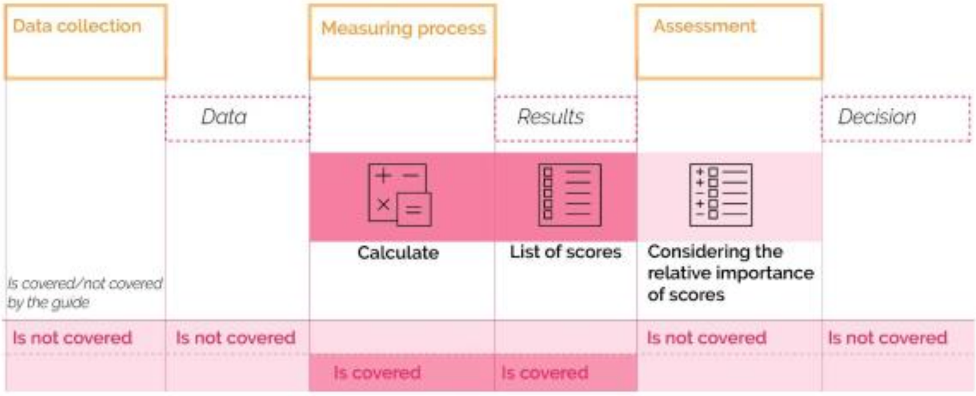


*Figure 31: Steps in circular decision-making that are part of the core measurement method CB'23 (*Measuring Circularity*, 2020)*

The core objectives emphasize on protection of material stocks, value and environment. However, the principle of protection can be categorized into two main branches of limiting loss (slowing and closing the loop) and limiting use (narrowing the loop). The indicators to measure the objectives are based on assessing the impact of these strategies and informs the extent to which the strategy is adhered.

The main measurement scheme is illustrated in the figure 32, it highlights the included parts and future development parts within this framework. For the calculation, this method recommends to inventorize all the materials throughout the life cycle of the building before obtaining the individual indicator results. The seven categories of indicators considered under the three core objectives are listed in table 8.

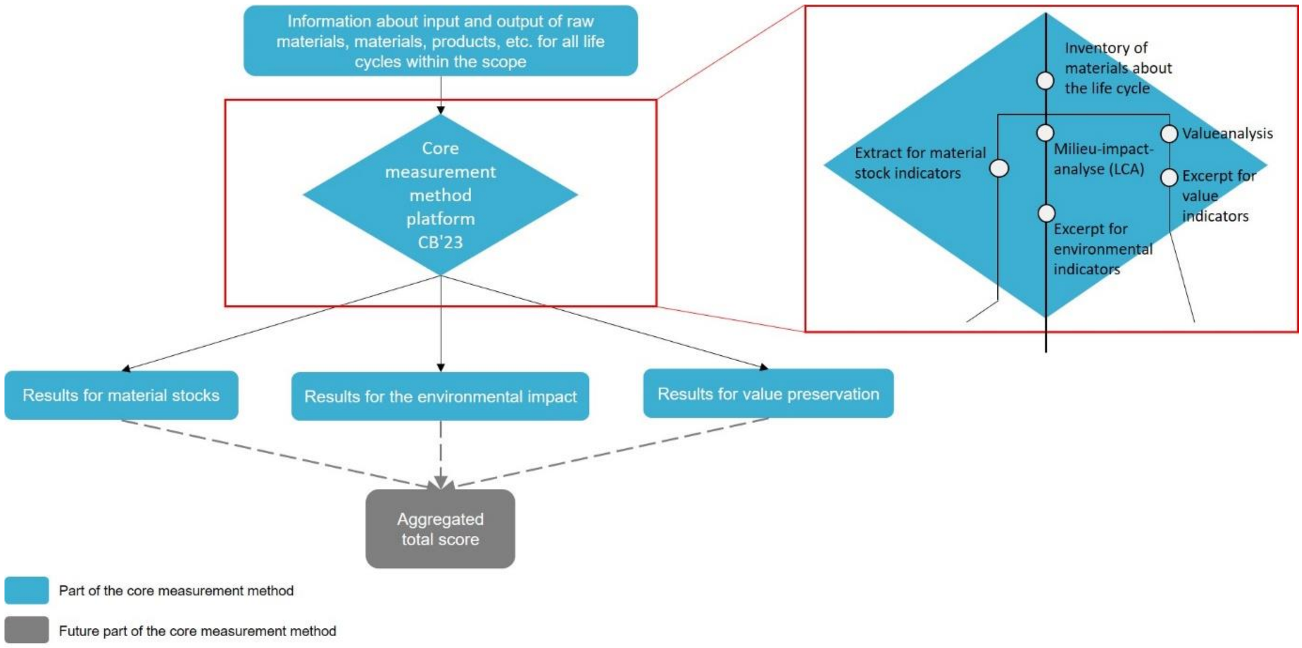


*Figure 32: The CB'23 core measurement scheme* (Measuring Circularity, *2020)*

*Table 8: List of seven indicator categories under the three core objectives of this scheme* (Measuring Circularity, *2020)*

| Protection of material stocks | | |
|---|---|---|
| 1 | Amount of material used (input flows) | Amount of primary material (non-renewable OR renewable & sustainable produced OR renewable & non-sustainably produced) |
| | | Amount of secondary material (from reuse OR from recycling) |
| | | Amount of physically scarce material |
| | | Quantity of socio-economically scarce raw materials |
| | | Quantity of socio-economically non-scarce raw materials |
| 2 | Amount of available material for next cycle (output flows) | Amount of material for reuse |
| | | Amount of material for recycling |
| 3 | Amount of lost material (output flows) | Quantity of material by energy recovery |
| | | Amount of material to landfill |
| Protection of the environment | | |
| 4 | Impact on environment | Climate change - total |
| | | Climate change - fossil |

| | | |
|---|---|---|
| | | Climate change - biogenic |
| | | Climate change - land use and land use change |
| | | Ozone layer degradation |
| | | Acidification |
| | | Eutrophication of freshwater |
| | | Eutrophication of seawater |
| | | Fertilization of land |
| | | Smog formation |
| | | Depletion of abiotic resources - minerals and metals |
| | | Depletion of abiotic resources - fossil energy carriers |
| | | Water use |
| | | Particulate matter emission |
| | | Ionizing radiation |
| | | Ecotoxicity (freshwater) |
| | | Human toxicity, carcinogenic |
| | | Human toxicity, non-carcinogenic |
| | | Land use-related impact / soil quality |
| Protection of existing value | | |
| 5 | Amount of initial value (input) | Technical functional value |
| | | Economic value |
| 6 | Amount of value available for next cycle (output) | Technical functional value |
| | | Economic value |
| 7 | Amount of existing value lost (output) | Technical functional value |
| | | Economic value |

*Protection of material stocks* can be related back to the Material Circularity indicator, which evaluates the intrinsic properties of a material and informs better selection. This includes the material input/source, material output/waste and also the material left for the next cycle, informing the material balance as illustrated in figure 33. The calculation method for these indicators are expanded upon in Appendix 3.

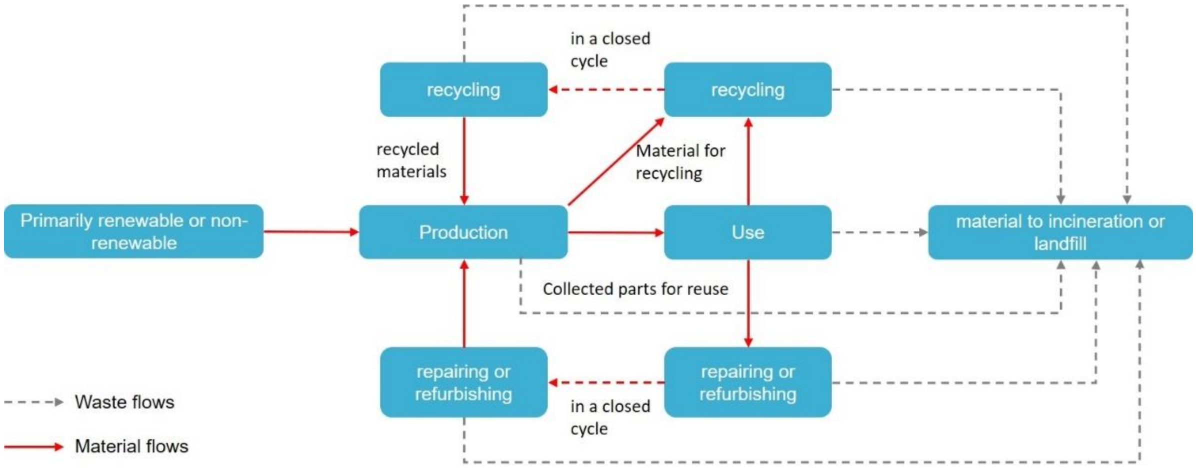


*Figure 33: Material Balance for assessing circular material flows* (Measuring Circularity, *2020)*

*Protection of environment* largely encompasses all aspects that lead towards creating an environmental impact. These aspects were adopted from the Determination method for evaluating the environmental performance of buildings (Bepalingsmethode MilieuPrestatie Gebouw -MPG) (*Measuring Circularity*, 2020).

Environmental impact of products throughout the life cycle can be compared based on the environmental cost indicator (ECI or MKI) value. ECI is a standardized method to convert the Life cycle analysis (LCA) environmental profile of a product to a single score. This allows easy comparison of LCA of products with the similar function (Stichting Nationale Milieudatabase, 2020).

ECI is determined by multiplying the environmental impacts from the LCA calculations with a financial value. The financial value for each environmental impact category represents the weighting factor or the shadow price. These have been identified for each environmental impact and include the expected social costs incurred by society, to avoid causing environmental impact through the currently known and used solutions.

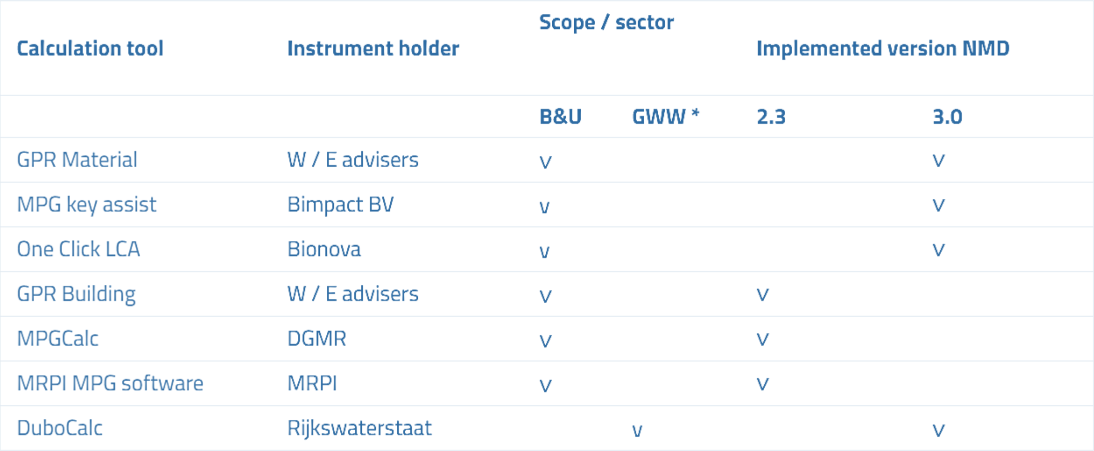
The sum of all the shadow cost per environmental effect gives the ECI of a product. Therefore, the ECI (per unit of product) refers to the environmental impact during the life cycle of one unit of product. The unit of measure associated to the value is euros per $m^2$. The lesser the value lessens the impact (Stichting Nationale Milieudatabase, 2020).

The environmental performance of buildings (MPG) is similar to environmental cost indicator (ECI), as they both indicate the total environmental impact. However, MPG (per unit building) refers to the environmental impact during the life cycle of one unit building.

The two indicators differ on the product/building level at which they represent the shadow costs respectively. However as both are based on the underlying method of Life cycle analysis (LCA) for evaluating environmental impact the ECI is used to determine MPG. The functional unit building consists of the total “ECI building”, per $m^2$ GFA (gross floor area), per year for the intended life span. Therefore MPG is determined by the ECI (building) divided by the gross floor area (GFA) and the intended life span years of the building. The unit of measure is euros per $m^2$ per year (Stichting Nationale Milieudatabase, 2020).

$$MPG = \frac{ECI\ bldg\ (euros)}{(Gross\ floor\ area\ (m^2) \times intended\ life\ (years))}$$

Furthermore, an MPG calculation should always be made with validated software instruments such as MPG calc, one click LCA or GPR building as listed in table below. After the calculation has been completed using one of the software, the results can be analyzed per building element which can inform the extent to which the different materials in the building are environmentally harmful (Stichting Nationale Milieudatabase, 2020).



| Calculation tool | Instrument holder | Scope / sector | | Implemented version NMD | |
|---|---|---|---|---|---|
| | | B&U | GWW * | 2.3 | 3.0 |
| GPR Material | W / E advisers | V | | | V |
| MPG key assist | Bimpact BV | V | | | V |
| One Click LCA | Bionova | V | | | V |
| GPR Building | W / E advisers | V | | V | |
| MPGCalc | DGMR | V | | V | |
| MRPI MPG software | MRPI | V | | V | |
| DuboCalc | Rijkswaterstaat | | V | | V |

*Figure 34: List of validated software instruments to calculate MPG* (Stichting Nationale Milieudatabase, 2020)

*Protection of existing value* of material and product determines its capability to

1. either last long for a certain function or
2. reused for the same function or

3. refurbished to maintain the same use function or
4. recycled to another function

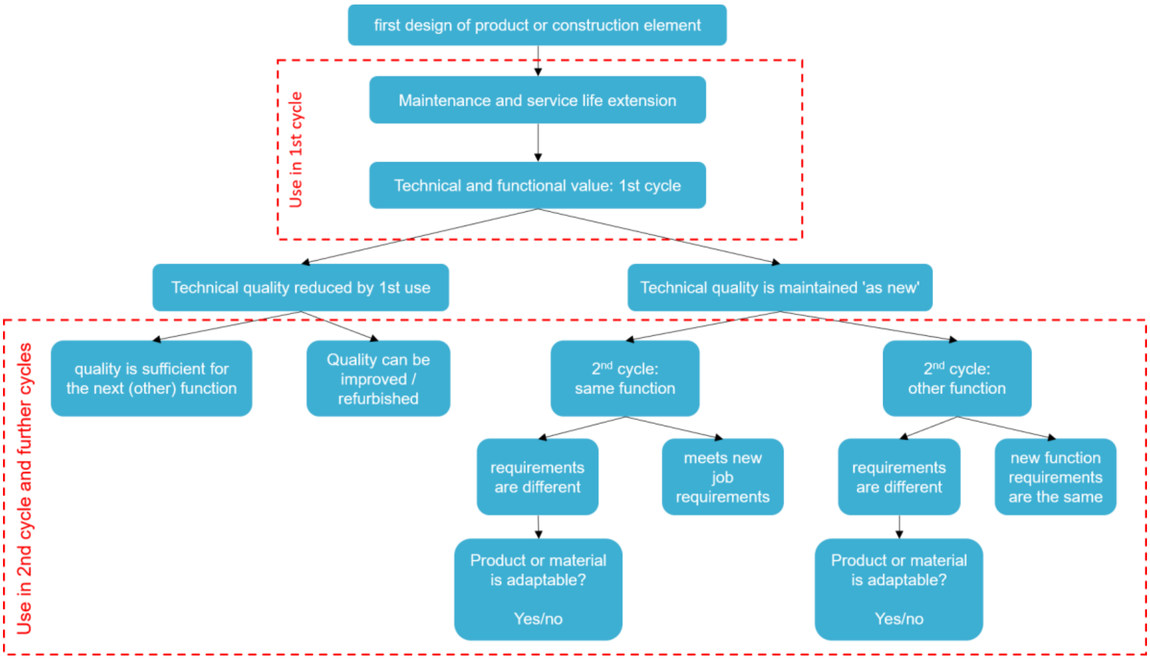


*Figure 35: Steps for determining the value of the product or material based on technical and functional quality after first cycle (Measuring Circularity, 2020)*

However, the value is unique to the level of scale it indicates i.e. element or product or material or raw material. The most important points for assessing value is at the beginning of the life cycle and during the use life cycle. In case of the beginning it is important know the service life of the structure, the degradation information, and possibilities of reuse/recycle for the next life cycle. However, during the use life cycle, information on technical quality is essential to predict reuse/recycle possibilities in the next cycle as shown in figure 35 (*Measuring Circularity*, 2020).

The two indicators for protection of initial, existing value lost and available value for the next cycle of a product/element are techno-functional value and economical value. However, the indicators for the techno-functional value are yet under development in this measurement scheme.

Techno-functional value is the degree to which the value of a product/element can be retained in multiple life cycles. The relevant aspect under this indicator are the parts that play an important role in estimating the current and future value of a product/element i.e. Functional quality, Technical quality, Degradation, Spatio-functional capacity at time x, technical adaptive capacity at time x, as covered in table (*Measuring Circularity*, 2020).

*Table 8: Description of the current and future value indicators (Measuring Circularity, 2020)*

| Name | Description | Type of information |
|---|---|---|
| Functional quality | The degree to which the product/element satisfies the requirements for the current function, determined by a set of technical performance requirements | Current value |
| Technical quality | The degree to which an product/element satisfies the performance requirement | Current value |
| Degradation | The degree to which the product/element has defects | Current value |

| | | |
|---|---|---|
| Spatio-functional adaptive capacity (overcapacity/ dimensioning) | Capacity of the product/element to cope with changes in functions and space requirements | Future value |
| Technical adaptive capacity (detachability) | Degree to which connections in and of the product/element can be detached and parts are accessible and physically independent of each other | Future value |

The most important information is the function of a product or element as it determines the technical performance. The technical requirement for floor systems changes from an office building to a residential building as per regulations. Another observation is, the spatio-functional adaptive capacity can be related to the spatial flexibility and the technical adaptive capacity can be related to technical flexibility as covered in section 3.2.1. However, in this context it emphasizes on the degree to which they perform for the required function.

*Adaptive capacity*

Apart from the three core objectives the scheme also highlights consideration of the adaptive capacity of the product/element/building. The two types of adaptive capacity addressed are spatio-functional and technical as covered in the table above. However, interesting to note is the similarity with the three dimensional model for transformation proposed by Durmisevic mentioned in section 3.2.1. Where disassembly is given the highest priority when the structure needs to be demountable to escape demolition which makes it one of the circular design strategy. However, the core method broadens the approach towards adaptive capacity, wherein it not only accounts for demount-ability (structural transformation) but includes adaptive (spatial transformation). Therefore, referring to two dimensions of transformation from Durmisevic's model (*Measuring Circularity*, 2020).

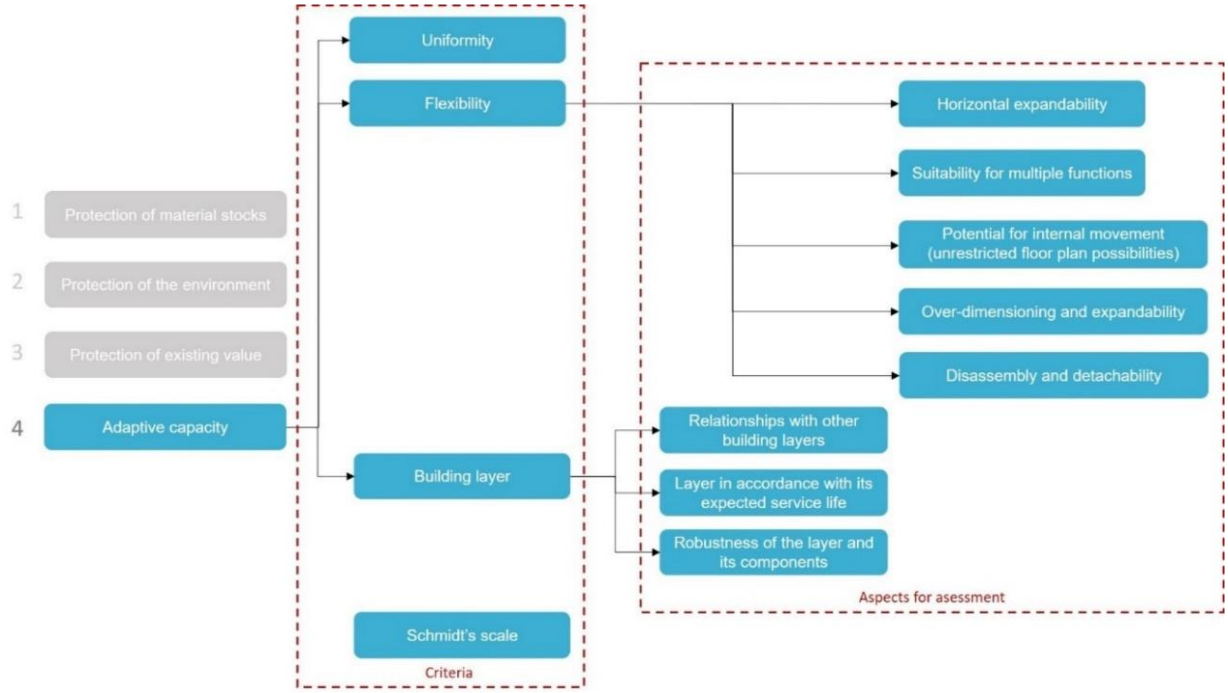


*Figure 36: Criteria for Adaptive capacity and respective aspects for assessment (*Measuring Circularity*, 2020)*

Currently the measurement method recommends a qualitative approach towards adaptive capacity addressing aspects under four main criteria for each building layer, during development of design brief or requirements, i.e.

1. Uniformity – refers to same shape or modular approach towards form, i.e. dimensions
2. Flexibility – refers to the degree to which the system can adapt to change, i.e. over-dimensioning, detachability or horizontal expansion
3. Building layer – relation between different building Brand's layers, life cycle coordination between the layers in a configuration and the layers expected service life.
4. Schmidt's scale – refers to the Schmidt's scale of adaptability based on 6 measures; adjustable, versatile, refitable, convertible, scalable and movable.

Appendix 4 further explains the aspects to be considered for assessment under the four criteria for each building layer. It is developed in the context of this research using the Adaptive capacity criteria and aspects.

## 4.8. Discussion and Conclusion

From the studied literature a comprehensive metric to assess degree of circularity is still under exploration and development, especially for its application in the field of Architecture, Engineering and Construction (AEC). Measuring degree of circularity is a relatively new topic and has daily contributions towards improvements or additions for existing methods with new knowledge generation.

The reviewed evaluation metrics and frameworks in this chapter are;

1. Material Circularity Indicator (MCI) (Measuring Circularity, 2019)
2. Knowledge model of Transformation Capacity (TC) (Durmisevic, 2006)
3. Detachability Index (LI) (Alba Concepts, 2019)
4. Building Circularity Indicator (BCI) (Van Vliet, 2018; Verberne, 2016b)
5. CB'23 Core measurement scheme (*Measuring Circularity*, 2020)

All the metrics are applicable for assessing individual or all aspects of circularity for entire buildings or part building configurations.

Material Circularity indicator can be used only to evaluate the degree of circular material flow of a building product from its source to end of life. Aspects such as amount of virgin material used, amount of unrecoverable waste, the product utility factor and the mass of the product can help achieve an overall MCI score for the product ranging between 0 to 1, where 0.1 indicates linear flow and 1 indicates a complete circular material flow in a product.

The knowledge model based evaluation framework for transformation capacity (TC) proves helpful to guide decisions based on demountability and short-term or long-term scenarios of material or building configurations. The first step towards disassembly is service life planning i.e. comparing the use life span of the building to the technical life span of the materials/products to know the long-term and short-term scenarios for spatial flexibility of the configuration and the retaining value of the material.

Next is to assess the main performance criteria of transformation i.e. independence and exchangeability. This can be determined by three main aspects of functional and technical decomposition for independence and physical decomposition for exchangeability. These main aspects are assessed based on 8 sub-aspects under each category which are determined by independent variables which have pre-determined weighted scores between 0.1 to 1 (Appendix 1), unique to each design configuration. Here, 0.1 indicates least flexibility while 1 indicates the highest score towards flexibility for each sub-aspect. An aggregation towards a final score is based on a fuzzy logic of averages for each level of data, i.e. from three main aspects to the two performance indicators and finally for a TC score.

Inspired by the Transformation capacity model, the detachability Index (LI) is developed by Alba concepts (2019). The detachability index includes only two sub-aspects of connection type and composition of the elements. Each sub-aspect is determined by an average of two independent variables as mentioned in the section 4.4. The detachability index can be used at an element/product level and a building level. For assessment at building level the element level score is normalized using summation of MPG value. This attempts to create a direct link between detachability and environmental impact, wherein higher the environmental impact (MPG) value of an element higher is its share towards the detachability index for the building. However, this method of assessment is new and needs further validation by applying it in multiple projects to understand variation in the results before accepting it as a standard towards evaluation of detachability index at a building level. Therefore, not a suitable method of evaluation for this research.

However, an important learning from the study on detachability index is the emphasis given to systemization and clustering of building products and systems by adopting the NL/SfB coding system standard that can be used to determine the material level of an element in a configuration. Such a numeric code can act as a unique identification for clear distinction between products belonging to different building layers. This code can be helpful to associate product specifications related to technical performance. Furthermore, it brings more clarity while assessing relations and connections between elements belonging to different building layers.

Building Circularity Indicator is a metric to assess building level circularity that includes assessing material index and the detachability index to achieve an overall aggregated score using normalization factors such as mass/volume of elements. The assessment for material index is developed on the basis of the Material Circularity indicator, whilst the detachability index is based on the transformation capacity model. This method will not be used for this research as the aggregation of all factors into one score makes the assessment less transparent, and there is an ambiguity towards the reason behind a lower or a higher score.

The CB'23 Core measurement scheme framework does not aggregate all indicators into one score. Instead it encourages to assess them individually, thereby ensuring complete transparency in the assessment. The three main objectives identified in this scheme towards measuring degree of circularity are; Protection of material stock (i.e. Material Balance/Material Circularity Indicator); Protection of the environment (MPG); Protection of existing value (Retaining option or strategy of reuse/recycle/repurpose after use life cycle) still in development and as a recommendation qualitative assessment towards adaptive capacity. This measurement scheme allows for independent assessment of the four indicators.

Therefore, this research will use CB'23 framework to assess only material balance and MPG value (shadow cost). Furthermore, in combination with the material balance (percentage of primary material used and percentage of material available for next cycle), that measures all material flow related aspects independently, the MCI will be used to create a overall score that will help rank options. As for the MPG value, these will be sourced from the validated software MPG calc. V1.2 based on the National Milieu (environmental) Database (DGMR BV., 2019). To gain insight into the retaining value of the product/element after the first life cycle the service life planning approach will be adopted by comparing the ULC of the building and TLC of the element. Finally to assess the disassembly aspects towards the integration of pipes and ducts in the floor-system the weighted scores per disassembly factor (appendix 1) will be used to inform functional decomposition and physical decomposition. As for the technical decomposition the NL/Sfb systemization and clustering scheme can be utilized to identify the products as per their respective building layers and therefore draw relations.

# 5. Role of an Integrated Floor-system

In a building floors contribute towards more than 50% of the total material mass, thereby contributing to more than 50% of the environmental impact and overall waste in times of demolition. However, to make floor-systems flexible and circular by reuse or recycle, it is essential to understand its role in a building and its relationships with other building components, especially services (Mechanical, electrical and plumbing) installations. The integration of building components of varying life spans within the structural floor-system not only impacts the circularity related indicators but also the functional and technical aspects.

This chapter contributes to an overall understanding of the functional and technical criteria and its impact on the choice of floor-system and services integration strategy; first by identifying the different building layers and material levels that are involved in an integrated floor-system configuration and second by studying the performance criteria that influence the system choice and configuration.

## 5.1. Building layers and product levels in an Integrated floor-system

A building can be categorized into different layers based on their durability life span as mentioned in section 3.2.2. It is simple to perceive each of these layer independently, however, the complexity begins at the intersection and interdependence of these layers to perform a function or satisfy the design requirement. A floor-system at a building level largely belongs to the structural layer, however, it shares a great deal of interaction with components from the services and space-plan layer. Furthermore, as established in the last chapter for an adaptable building it is of paramount importance to account for technical and spatial flexibility, i.e. disassembly and overcapacity/expandability. Therefore, this research focuses not only on the structural floor-system, also its integration with components from other layers especially service ducts/pipes/electrical cables and space-plan floor/ceiling finishes as shown in figure 40, making an interesting argument to study especially in the context of adaptable office buildings. Additionally, in a building floor-systems can cater to either ground or intermediate levels, this research will only focus on floor-systems for upper or intermediate levels.

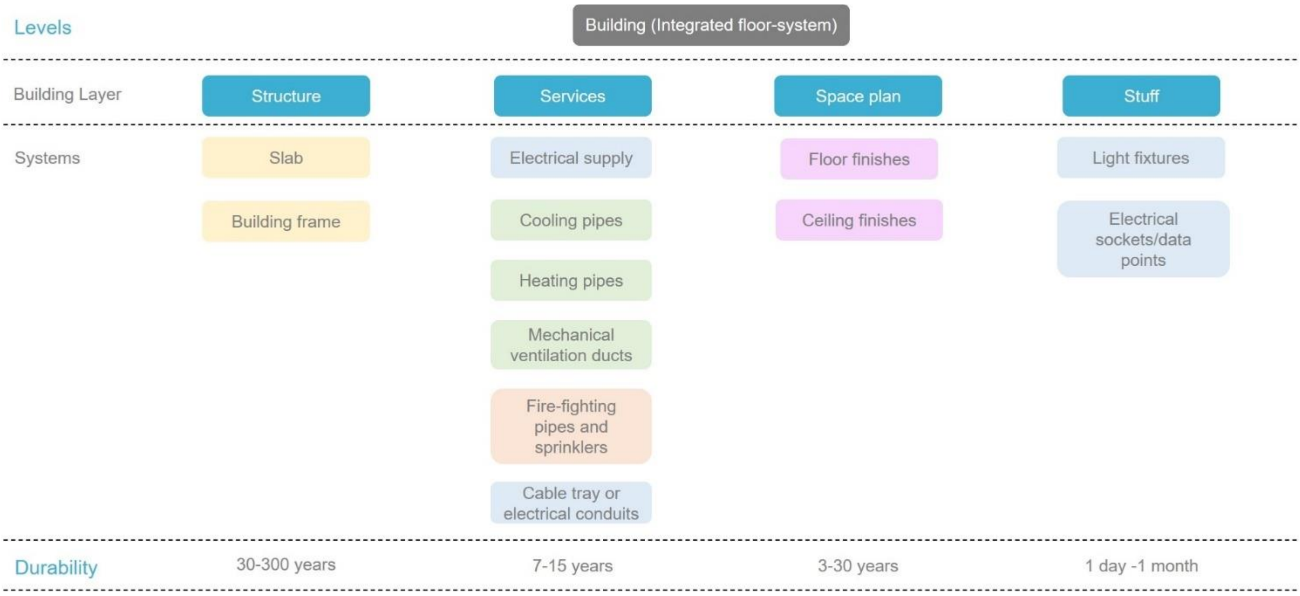


*Figure 38: A systematic breakdown and clustering of the building components in an integrated floor-system*

The component and sub-system level break down of the floor-system are as mentioned and summarized in the table 10.

Building layer: Structure, Services, Space layout (Surface treatment) and Stuff(fixtures)

Sub-system: slab, beam, acoustic insulation, Mechanical Electrical and Plumbing (MEP) installations, fixtures, raised/access floor system and a suspended ceiling are the most common included. They are dependent on the specifications, requirements that are set and material choice, therefore components will vary for each case scenario.

*Table 10: Summary of commonly incorporated components in the sub-systems of floor-systems from literature review, it is does not exhaust all special cases.*

| Building layer | Function | Sub-System | Brief description |
|---|---|---|---|
| Structure | Part of the Structural frame | Slab | • Spans over beams<br>• transfers vertical service and permanent loads to beams and then columns or façade and central core<br>• act as rigid diaphragms and transfer horizontal loads to stabilizing elements |
| | | Beams | • Spans over columns<br>• transfers vertical loads from slabs to columns |
| | | Integrated beam and slab | • As one system function together to cater both functional requirements of slab and beam. |
| Installations | Fire safety | Firefighting pipes and sprinklers | • To channel water through the pipes and sprinklers in case of fire |
| | Electrical | Cable Tray- Electrical cable wires | • Cables for electrical power supply |
| | Mechanical | Mechanical Ventilation duct | • To provide for fresh air ventilation and take out stale air through ducts |
| | | Cooling pipes | • To maintain comfortable indoor temperature by cooling in hot months of the year |
| | | Heating pipes | • To maintain comfortable indoor temperature by heating in cold months of the year |
| Surface treatment | External finish | Acoustic barrier | • For sound insulation and absorb vibrations |
| | | Raised/sub floor | • To conceal floor installations such as heating pipes and offer accessibility for maintenance<br>• Provide a flat floor for space layout |
| | | Concrete topping/screed | ▪ Used to finish the floor evenly<br>▪ Provides horizontal stability to the slab |
| | | Suspended ceiling | ▪ To conceal the ceiling installations such as mechanical duct and cable trays, and absorb sound |
| Fixtures | Power/data supply | Electrical sockets/data points | ▪ Often fixed in floors for electric power/data supply to user's devices |
| | Indoor artificial lighting | Light fixtures | ▪ Installed often in ceiling for indoor artificial lightings |

## 5.2. Product typologies/categorization per building layer

### *5.2.1 Structural layer - existing intermediate floors*

Distinguishing floors as per structural behavior categorizes them into one-way and two-way slabs. One-way slabs transfer loads only in one direction to the stabilizing system, while two way slabs work in both direction to transfer loads. Hegger (2006), classifies solid intermediate floors into the constructability categories of cast in-site, extent of prefabrication and materials employed, illustrated in Figure.

Relevant intermediate floors that are assessed based their performance towards, span, loads, integration of installations, fire, ease of constructability, integration of beams, structural topping and concrete core activation using information found in literature, Table 11.

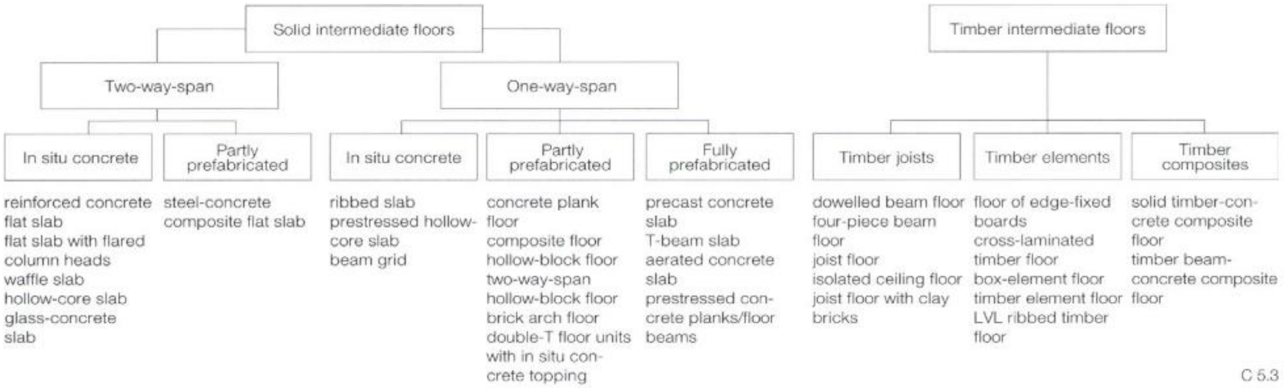
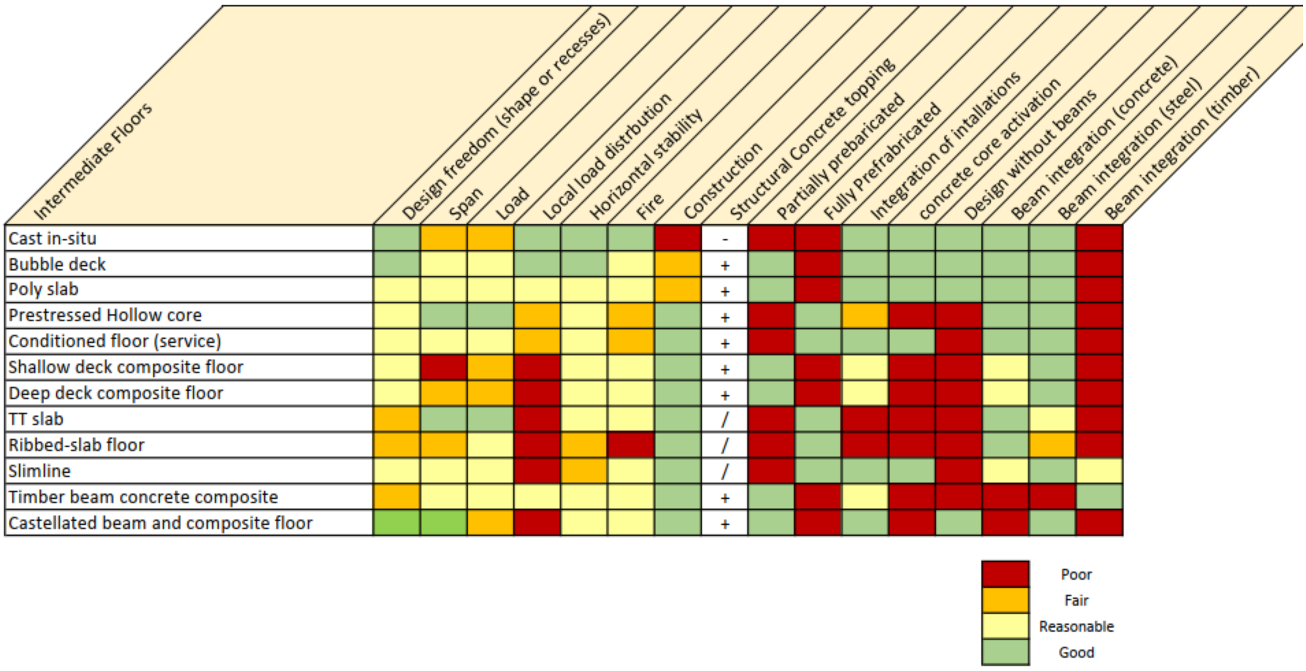


*Figure 39: Chart categorizing the different types of floor slabs (Hegger, 2006)*

Concrete core activation is an essential functional aspect that can distinguish intermediate floor slabs. It refers to the integration of heating/cooling pipes in the structural floor mass for thermal activation to provide a comfortable indoor temperature in rooms further explained in next section under services layer. The table 11, highlights in-situ concrete and prefabricated floor slabs that allow for this functional criteria.

The assessment shows prefabrication as a vital factor of intermediate floors to ease construction, as it provides quality control, saves construction time and environmentally reduces waste. Most assessed options are either partially or fully prefabricated elements. Another observation is that most floors have a better integration of concrete or steel beams. However, in case of lesser environmental impact timber is an ideal option, as it consumes less energy in its production process compared to concrete. This is proved by Hegger (2006), in an Life Cycle Analysis calculation of a solid reinforced concrete floor and an edge nailed timber floor, shown in table 12.

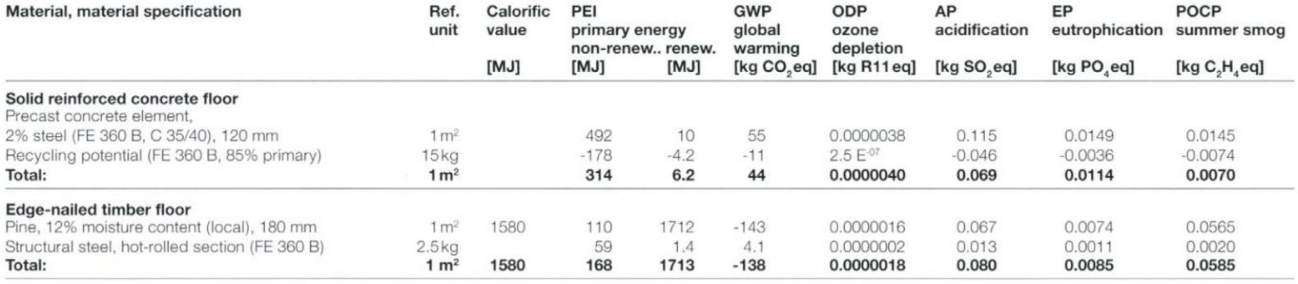
*Table 11: Assessment of some intermediate floors based on performance (Cie, 2016; Heggar 2006)*



| Intermediate Floors | Design freedom (shape or recesses) | Span | Load | Local load distrbution | Horizontal stability | Fire | Construction | Structural Concrete topping | Partially prebaricated | Fully Prefrabricated | Integration of intallations | concrete core activation | Design without beams | Beam integration (concrete) | Beam integration (steel) | Beam integration (timber) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cast in-situ | 🟩 | 🟧 | 🟧 | 🟩 | 🟩 | 🟩 | 🟥 | - | 🟥 | 🟥 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 |
| Bubble deck | 🟩 | 🟨 | 🟨 | 🟩 | 🟩 | 🟨 | 🟧 | + | 🟩 | 🟥 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 |
| Poly slab | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟧 | + | 🟩 | 🟥 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟥 |
| Prestressed Hollow core | 🟨 | 🟩 | 🟩 | 🟧 | 🟨 | 🟧 | 🟩 | + | 🟥 | 🟩 | 🟧 | 🟥 | 🟥 | 🟩 | 🟩 | 🟥 |
| Conditioned floor (service) | 🟨 | 🟨 | 🟨 | 🟧 | 🟨 | 🟧 | 🟩 | + | 🟥 | 🟩 | 🟩 | 🟩 | 🟥 | 🟩 | 🟩 | 🟥 |
| Shallow deck composite floor | 🟨 | 🟥 | 🟧 | 🟥 | 🟨 | 🟨 | 🟩 | + | 🟩 | 🟥 | 🟨 | 🟥 | 🟥 | 🟨 | 🟩 | 🟥 |
| Deep deck composite floor | 🟨 | 🟧 | 🟧 | 🟥 | 🟨 | 🟨 | 🟩 | + | 🟩 | 🟥 | 🟨 | 🟥 | 🟥 | 🟨 | 🟩 | 🟥 |
| TT slab | 🟧 | 🟩 | 🟩 | 🟥 | 🟨 | 🟨 | 🟩 | / | 🟥 | 🟩 | 🟥 | 🟥 | 🟥 | 🟩 | 🟨 | 🟥 |
| Ribbed-slab floor | 🟧 | 🟧 | 🟨 | 🟥 | 🟧 | 🟥 | 🟩 | / | 🟥 | 🟩 | 🟥 | 🟥 | 🟥 | 🟩 | 🟧 | 🟥 |
| Slimline | 🟨 | 🟨 | 🟨 | 🟥 | 🟧 | 🟨 | 🟩 | / | 🟥 | 🟩 | 🟩 | 🟩 | 🟥 | 🟨 | 🟩 | 🟨 |
| Timber beam concrete composite | 🟧 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | + | 🟩 | 🟥 | 🟨 | 🟥 | 🟥 | 🟥 | 🟥 | 🟩 |
| Castellated beam and composite floor | 🟩 | 🟩 | 🟧 | 🟥 | 🟨 | 🟨 | 🟩 | + | 🟩 | 🟥 | 🟩 | 🟥 | 🟩 | 🟥 | 🟩 | 🟥 |

🟥 Poor
🟧 Fair
🟨 Reasonable
🟩 Good

*Table 12: LCA assessment of two floor scenarios (Hegger,2006)*



| Material, material specification | Ref. unit | Calorific value [MJ] | PEI primary energy non-renew.. [MJ] | renew. [MJ] | GWP global warming [kg $CO_2$eq] | ODP ozone depletion [kg R11 eq] | AP acidification [kg $SO_2$eq] | EP eutrophication [kg $PO_4$eq] | POCP summer smog [kg $C_2H_4$eq] |
|---|---|---|---|---|---|---|---|---|---|
| **Solid reinforced concrete floor** | | | | | | | | | |
| Precast concrete element, 2% steel (FE 360 B, C 35/40), 120 mm | 1 $m^2$ | | 492 | 10 | 55 | 0.0000038 | 0.115 | 0.0149 | 0.0145 |
| Recycling potential (FE 360 B, 85% primary) | 15 kg | | -178 | -4.2 | -11 | 2.5 $E^{-07}$ | -0.046 | -0.0036 | -0.0074 |
| **Total:** | **1 $m^2$** | | **314** | **6.2** | **44** | **0.0000040** | **0.069** | **0.0114** | **0.0070** |
| **Edge-nailed timber floor** | | | | | | | | | |
| Pine, 12% moisture content (local), 180 mm | 1 $m^2$ | 1580 | 110 | 1712 | -143 | 0.0000016 | 0.067 | 0.0074 | 0.0565 |
| Structural steel, hot-rolled section (FE 360 B) | 2.5 kg | | 59 | 1.4 | 4.1 | 0.0000002 | 0.013 | 0.0011 | 0.0020 |
| **Total:** | **1 $m^2$** | **1580** | **168** | **1713** | **-138** | **0.0000018** | **0.080** | **0.0085** | **0.0585** |

### *5.2.2 Services layer*

Building services incorporated within or onto a floor-system are mechanical ventilation ducts, electrical conduiting, heating/cooling pipes and fire sprinklers. The components function to let fresh air into the room, heat or cool the rooms, ensure safety in case of fire and electrical supply. The main challenge of integrating building services into a floor-system is of disposal and recycling as they have a shorter service life than the structural layer. Therefore, prior planning and organization of the service installations is essential to facilitate easy replacement and maintenance.

Some important considerations towards design are grouping of ducts horizontally, ensuring short runs of heating pipes. Placing the services behind suspended ceiling instead of in-built/cast-in solutions as it offers accessibility for short-term repairs extending the durability of the system. It also provides an option of reuse or recycle of the material. The effective sizing of the components is an important factor as it impacts the overall thickness of the floor-system package.

The main considerations highlighted by Hegger (2006) for selection of type and material of installation are

1. Maintenance options
2. Adaptable to user demands (demountable and detachable)
3. Environmental or health impacts during the production, usage and disposal stage
4. Sound insulation and fire protection
5. Susceptibility to corrosion/decay/furring

#### *Material categorization in service pipes and ducts*

Hegger (2006), documented all the materials largely used in cold water pipes (example, firefighting) and materials used for heating systems. These are tabulated in Table , showing the type of connection, recyclability and durability. It is observed that the material group of metals pipes are more durable than plastics or composites, however it is vulnerable to corrosion. Plastics pipes are easier to install and offer low weight, however they are less rigid and need to be supported close to the structure. Connections such as spigot & socket, compression, screw and clamped are demountable which is not possible in glued, welded and soldered connections. With respect to combustion plastics perform poorly compared to metals. Recyclability of metal pipes is more likely compared to plastics.

In case of mechanical ventilation, the ducts have to be airtight to prevent any pressure losses and have vibration dampers/silencers to prevent sound transmission. The materials and components used are sheet steel ducts or plastic ducts.

Galvanized steel ducts resist corrosion are easy to clean and come in large sections. While it is incombustible it is not fire-resistant. In some cases stainless steel and aluminum ducts are used in case of intense exhaust air. Plastic ducts on the other hand are made of PVC, PE or PP, which are combustible come in small cross-sections and used only in case of fire-compartments in smaller buildings.

*Table 13: Material used for pipes in services for cold water and heating systems (Hegger,2006)*

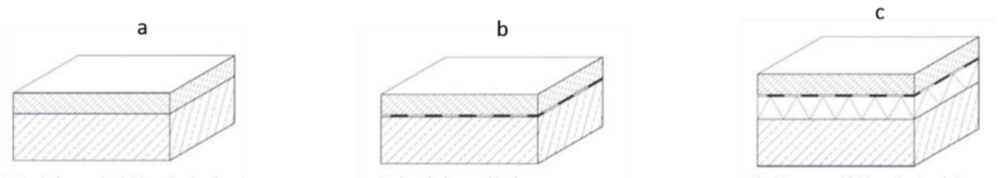
| Components | Material | Type of connection | | | | | | | Durability | Recyclability |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Spigot & Socket | compression | screw | clamped | welded | soldered | glued | | |
| cold water pipes | Metals | | | | | | | | | |
| | Stainless steel | | 🟩 | 🟩 | 🟩 | 🟩 | | | 80 - 100 | ● |
| | steel, hot dip galvanized | | 🟩 | 🟩 | 🟩 | | 🟩 | 🟩 | 40-60 | ● |
| | copper | | 🟩 | 🟩 | 🟩 | | 🟩 | | 40-60 | ● |
| | Plastics | | | | | | | | | |
| | PVC | 🟩 | 🟩 | | | | | 🟩 | 70-90 | ○ |
| | cross-linked polyethylene | | 🟩 | | 🟩 | 🟩 | | | 70-90 | ○ |
| | unplasticised polyethylene | 🟩 | | | 🟩 | 🟩 | | | 40-60 | ○ |
| | polypropylene | 🟩 | 🟩 | | | 🟩 | | | 60-80 | ○ |
| | Composites | | | | | | | | | |
| | composite pipes | 🟩 | 🟩 | 🟩 | 🟩 | | | | 40-60 | - |
| Heating system | Metals | | | | | | | | | |
| | Copper | | 🟩 | 🟩 | 🟩 | | 🟩 | | 60-80 | ● |
| | Plastics | | | | | | | | | |
| | polypropylene | 🟩 | 🟩 | | 🟩 | | | | 50-70 | ○ |
| | polybutylene | 🟩 | 🟩 | | 🟩 | | | | 50-71 | ○ |
| | cross-linked polyethylene | | 🟩 | | 🟩 | 🟩 | | | 50-72 | ○ |
| | Composite | | | | | | | | | |
| | composite pipes | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | | | 60-80 | - |

### 5.2.3 Space-plan layer

The space plan layer comprises of ceilings and floor screed types.

*Ceilings:* Due to the technical advancements in building services, ceilings function to hide the service layers from the interior space mainly for aesthetic purposes keeping with the fire safety regulations. Additionally, for better acoustic performance, sound absorption measures are commonly implemented on the ceiling due to the vast area expanse. For this suspended ceilings, island ceiling or free-hanging vertical elements also termed as baffles are used (ISSO, 24). However, in case of concrete core activation suspended ceiling should not be installed, due to the energy transfer that must take place between the floor slab and the space.

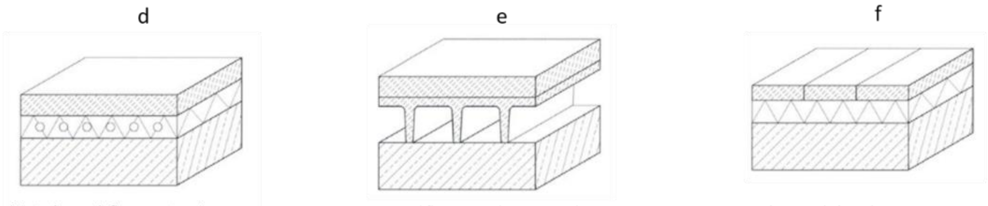
*Floors* have a multiple role within the floor-system, which often is dependent on the design requirements. The diverse functions range from sound insulation, thermal insulation, fire protection to moisture control. Therefore, there are multiple layer above the first layer of the structural slab such as a leveling layer, waterproof layer or a insulation layer. The main floor finish depends on the type of sub floor construction which include different screed forms. Hegger (2006), categorizes the different screeds forms as bonded, unbonded, floating, heated screed, raised floor and floor-grade boards, illustrated in figure. Screed types can be classified as wet and dry based on the material selection. Cement based screeds are considered wet, while wooden floor panels or particle boards are considered dry construction screed.



Bonded screed is laid on the load bearing layer such that a good bond develops between the two

Unbonded screed laid over a separating layer of plastic sheeting to avoid deformations in the underlying structure

Floating screed laid on the insulating layer and so remains movable on its substrate, hence the term "floating"



Heated screed- floor construction with heating pipes laid in the screed

Raised floor is used to accomodate services and are easily replaceable

Floor-grade boards

*Figure 40: Illustrates different screed forms (Hegger,2006)*

### *5.2.4 Interaction of service pipes with structure or space layer*

Concrete core activation involves thermal activation of the structural floor mass. It is different strategy from underfloor heating and floor cooling, see figure 41, where the pipes are included in the structural floor instead of the screed.

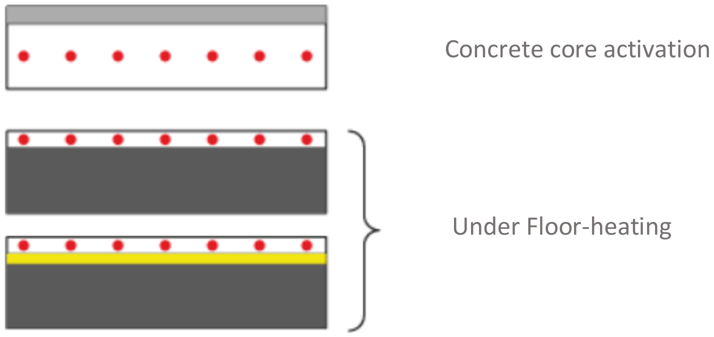


*Figure 41: Integration types of pipes in structure or space layer for heating/cooling(ISSO,85)*

## 5.3. Functional and Technical Performance Requirements

A floor-system (including beams and floors) functionally spans over the interior spaces of the buildings while forming the ceiling and the floor for the storey above (Hegger, 2006).

Structurally, a floor system functions to transfer the service and permanent loads through beams, girders and columns that finally transfer to the foundations (Paik & Na, 2019) as shown in figure 43. It also offers horizontal stability by acting as a rigid floor diaphragm to transfer horizontal loads to the stabilizing elements (Cie, 2016).

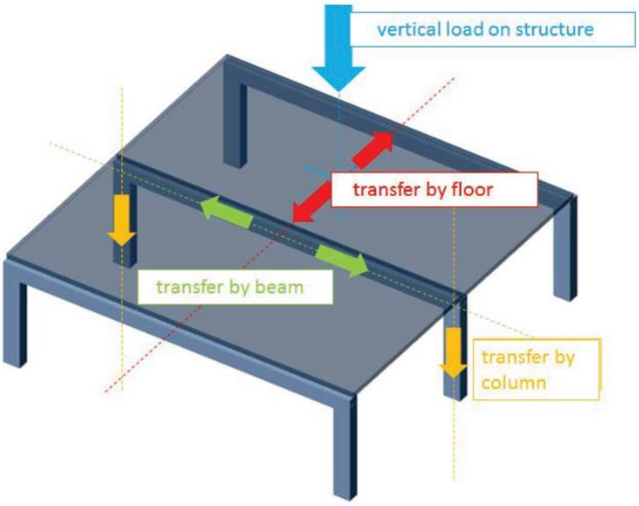


*Figure 43:Illustrates the transfer of vertical load by the floor slab and structural frame i.e. column and beams* (Cie, 2016)

Furthermore, in the event of fire, floor-systems are required to resist fire for a given time period until the occupants have vacated the building. Additionally, for comfort of occupants in case of floors with human traffic movement, such as offices, are required to insulate contact sound transfer.

At a building level these are technical requirements for floor-systems categorized under structural and building physics performance (SBR 542.05, 2005).

The most important aspect to be known before defining the technical requirements for a floor-system, is the function of the building i.e. residential or utility, in this research the focus is only on office buildings. Therefore, essential performance requirements applicable to offices are covered.

### 5.3.1 Structural Performance Criteria from regulations

*Basic structural design*

The NEN-EN 1990, covers the basics of structural design requirements and highlights the fundamental ones that are also applicable for floor-systems in buildings.

It states that, a structure shall be designed and calculated to ensure constructive resistance, usability and durability. In the event of a fire, the structural resistance must be sufficient during the prescribed time period. The basic requirements should be met by, the choice of suitable materials, efficient design and detailing, and by laying down methods of control for the design and calculation, production, execution and use, where applicable for a given project.

*Durability Criteria (Design life span)*

According to NEN-EN 1990, the first step towards structural design is to choose the appropriate construction method i.e. temporary or permanent based on the design life span of the structure. The design life span are also dependent on the building function. For most ordinary buildings the durability period considered is at least 50 years. The same applies for office buildings. The structure when designed to be reused should not be considered as temporary i.e. design life of 10 years.

In order to obtain a sufficiently durable construction for expected design life span, the following should be taken into account:

- the planned or foreseeable use of the structure;
- the required design and calculation criteria;

- the expected environmental conditions;
- the composition, properties and performance of the materials and products;
- the choice of the constructive system;
- the shape of the elements and their constructive detailing;
- the quality of craftsmanship and the level of supervision and control;
- the special protective measures;
- planned maintenance during the design life

*Usability Criteria*

The limit states relating to the functioning of the structure or parts thereof, under normal use (i.e. strength), the comfort of people (i.e. vibrations) and the appearance of the structures (i.e. deflection and cracking) are classified as usability criteria.

In order to ensure usability criteria are met and not exceeded, the design and calculations of the structure must include applicable values for loads, material properties, product properties and geometric properties.

The Eurocode 0, covers the idea of safety behind structures by covering all criteria under the branches of strength and deformations.

*Strength* relates to the extent of external loads a structure can withstand before complete collapse. This accounts the applied loads and factors of safety, which is identified by the three consequence class (CC 1, CC2 or CC3) associated to the product or structure. The higher a consequence class the higher the load factors assumed for the structural design and calculation towards a product/structure. The applicable load factors vary based on the load type, i.e. permanent or variable. The load factors associated to permanent (dead) loads are usually lower than for variable (live) loads. The sum of the permanent and variable loads factored by their respective load factors based on the consequence class, results in the design load for structural calculation (Cie, 2016). Refer appendix 5 for an overview on consequence classes. The consequence class of a structure is categorized based on the type of building function i.e. Office, residence, school or hospital, and the number of floors in the building i.e. building height. In the context of this research the structure must satisfy at least CC2 group as the focus in one Office buildings.

*Deformations* relate to the sag/deflection in a structure due to time dependent loading on the structure. Therefore, it is dependent on the durability of the structure, as the structure should not exceed the expected deformations for the entire design life span. The deflection limit or criteria can be set under the design brief of a project by the client depending on the use function.

There are three different forms of deformations that occur in structures, vertical, dynamic, and horizontal. In the context of floors, the most important forms considered are vertical and dynamic deformations, however, at a building level horizontal deformations are a must to be considered and criteria for the same must be met.

1. The vertical deformations are a cumulative of all sag (w) components as shown in figure 44, given by,

   $W_{tot} = W_1 + W_2 + W_3$ OR

   $W_{max} = W_1 + W_2 + W_3 – W_C$ (including the camber)

   Where;

   $W_C$ is the camber in the structure/product before loading

$W_1$ is the sag caused due to quasi-permanent loading determined based on the short-term properties of the structure. This includes the permanent dead load and the quasi-permanent include a part of the live load.

$W_2$ is the sag caused due to quasi-permanent loading determined based on the long-term properties of the structure, excluding the part included in the short term properties.

$W_3$ refers to the sag caused by part of variable actions that are not included in previous components, but based on short-term properties.

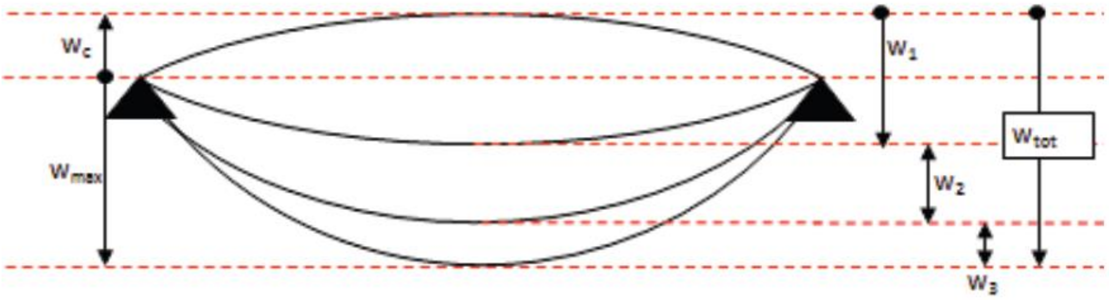


*Figure 44: Illustrates the sag components that are considered for determining vertical deformation in floor slabs* (Cie, 2016)

*Table 14: Categorizes the standard deformation requirements for floors and roofs (NEN-EN 1990, Annex A1.4.3)*

| | Additional sag $w_2 + w_3$ | Total sag $w_{max}$ |
|---|---|---|
| Floors without crack-sensitive walls or roofs used extensively by persons | $\leq {}^{l_{rep}}/_{333}$ | $\leq {}^{l_{rep}}/_{250}$ |
| Floors with crack-sensitive walls | $\leq {}^{l_{rep}}/_{500}$ | $\leq {}^{l_{rep}}/_{250}$ |
| Other roofs (only accessible for maintenance) | $\leq {}^{l_{rep}}/_{250}$ | $\leq {}^{l_{rep}}/_{250}$ |
| $l_{rep}$ Length of the span or twice the length of the cantilever | | |

2. Dynamic deformations are caused due to dynamic loads unlike static loads in case of vertical deformations. These dynamic loads are associated to actions such as walking or jumping on the structure. The floors often walked on such as in houses or offices the limit state will not be exceeded if the first natural frequency of the floor is atleast 3Hz (Cie, 2016). Which relates to 34mm under permanent load, without considering the span.

   To better estimate the vibrations and class of the structure (a to f) incurred due to walking HIVOSS diagrams as seen in figure 45 can be used, it consider model mass (kgs) of the structure, the natural frequency of the floor and the damping percentage.

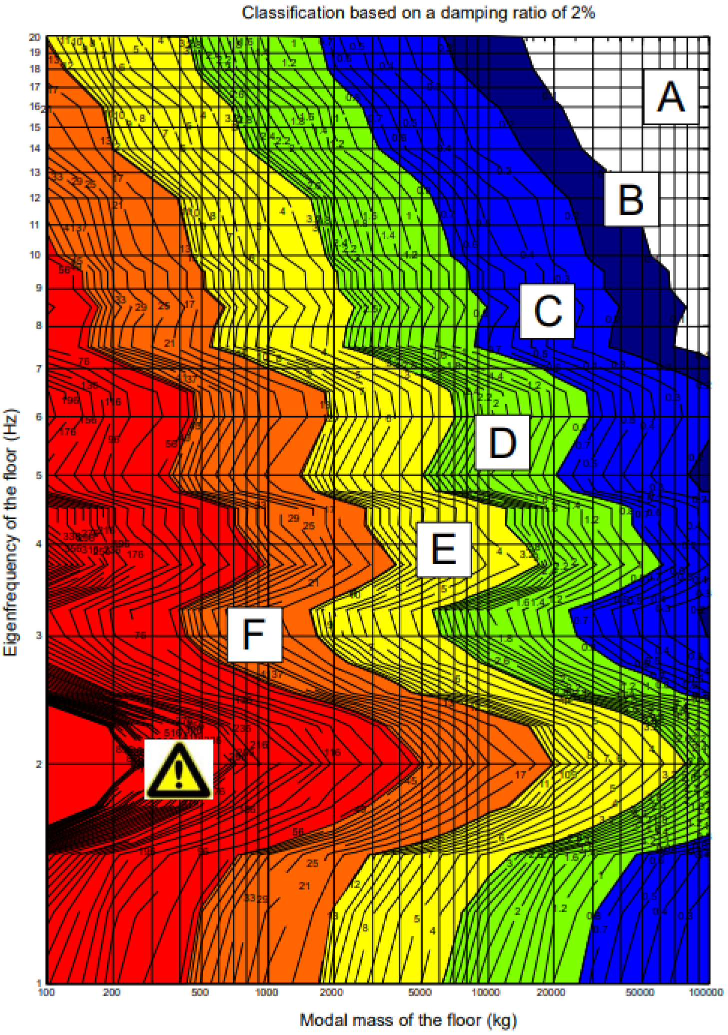


*Figure 45: Shows the HIVOSS diagram for dynamic vibrations caused by walking, for structure with 2% damping* (Feldmann et al., 2009)

### 5.3.2 Building Physics Performance

At a building level, Building Physics performance criteria that influence all building layers and building products/materials are fire resistance/propagation safety and sound insulation requirements. While thermal insulation is also essential to be considered for most opaque building materials, it was found in literature and through interviews (Chapter 7) this criteria is not determining in deciding for a floor system in office buildings.

#### Fire resistance and safety

Depending on the function of a (part of a) building, the Building Decree imposes requirements on the fire resistance with regard to structural collapse, fire penetration and smoke passage between rooms and building products. A standardized national testing method has been developed for each of these properties: NEN 6069 (fire resistance of building parts and construction products), NEN 6068 (fire penetration and fire transfer between rooms), NEN 6075 (smoke passage between rooms), and NEN 6069 (Determination of fire load). Furthermore, the requirements of resistance for load-bearing structural components (floors/beams/columns) and installation (ventilation ducts/cabling) vary. The structural design calculations in the event of fire for concrete, steel, steel-concrete and timber structures are different and highlighted in Eurocode 2-5.

Fire resistance can largely be described as the amount of time a structure can resist the fire load before collapse. This is usually expressed in minutes internationally. According to the Building Decree 2012, the requirement is dependent on the service function of the floor and its height from the adjacent ground level.

The first requirement is that all floors and escape routes (stairs/ramps) must comply to 30 minutes of resistance. The second is dependent on the height of the floor and the associated service function that determines the time period as shown in the table 15.

*Table 15: Fire resistance requirements of the structure (Soucre:Cie,2016, based on the 2012 Building Decree, tables 2.10.1 and 2.10.2)*

| Service function | Highest residential area compared to adjacent grounds | Fire-resistant period in terms of structural failure |
|---|---|---|
| Residential function | | |
| | ≤ 7 metres | 60 minutes |
| | Between 7 metres and 13 metres | 90 minutes |
| | > 13 metres | 120 minutes |
| Childcare function with sleeping area, detention cell function, healthcare function with beds, accommodation function | | |
| | ≤ 5 metres | 60 minutes |
| | Between 5 metres and 13 metres | 90 minutes |
| | > 13 metres | 120 minutes |
| Healthcare function without beds, office function, manufacturing function, educational function, sports function, retail function, other service functions related to the transport of persons or garaging of motor vehicles | | |
| | ≤ 5 metres | No requirement |
| | > 5 metres | 90 minutes |

*Fire resistance against structural collapse*

The time at which the structure collapses determines the fire resistance. All building products are lab tested for fire resistance and it is determined at load according to the 'standard fire', as shown in figure 47.

The determination of fire resistance with regard to structural collapse/succumbing depend on the following aspects of the structure; the type of structural component (column, beam, floor); the dimensions; the load present (usually depending on the type of building); the location of the structural component in the building (the number of heated sides) and the material (SBR, 2012).

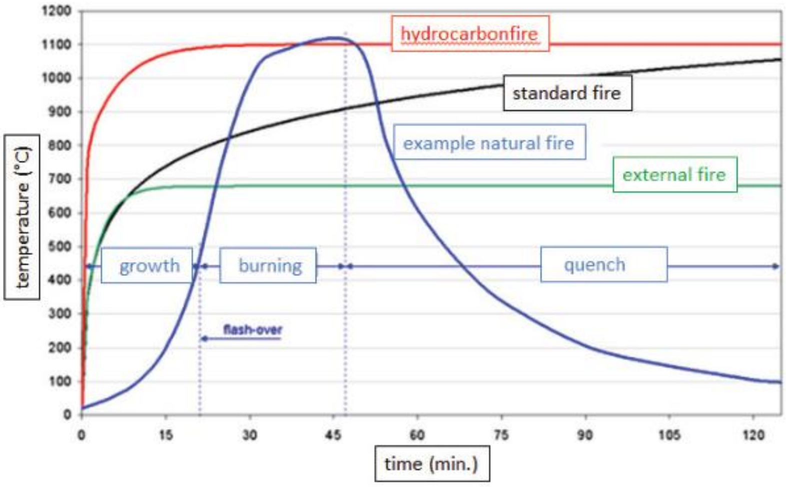


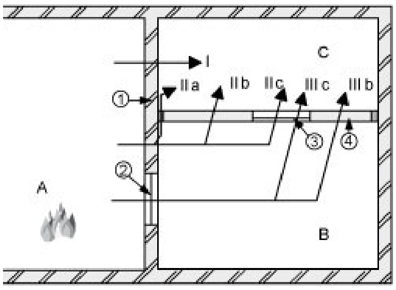
*Figure 46: Graph showing the standard fire curve used for testing building products (infosteel.be)*

### *Fire resistance with regard to separating function*

An exception is made for structural components that are loaded by fire from the outside in. In these cases, the temperature load on the structural component will be lower. These structural components are therefore entrusted with the so-called reduced standard fire curve when determining. In assessing fire resistance, two or more of the five assessment criteria broadly defined in appendix 5 are important, depending on the nature of the structural components and the situation in which they are applied (SBR 443D.12, 2012).

### *Fire resistance for fire penetration and transfer (wbdbo)*

The resistance to fire penetration and fire transfer (wbdbo) between two rooms is the shortest time a fire needs to spread from one room to another. This time is the sum of the resistances to fire penetration and the resistances to fire transfer that the fire encounters on the fastest fire expansion trajectory as shown in figure 47 (SBR 443D.12,2012).



*Wall: fire resistance (without door): 65 min Door-frame construction: fire resistance: 30 min Door-frame construction: fire resistance: 20 min Wall: fire resistance (without door but examined with connections): 25 min*

*Resistance to fire penetration from A to C:*

| | | |
|---|---|---|
| *case I.* | | *65 min* |
| *case Iia* | *65 + 25 =* | *90 min* |
| *case IIb* | *65 + 25 =* | *90 min* |
| *case Fil* | *65 + 20 =* | *85 min* |
| *case IIIc* | *30 + 20 =* | *50 min (Measuring)* |
| *case IIIb* | *30 + 25 =* | *55 min* |

*Figure 47: Demonstrates an example case for estimating fire resistance of material due to fire transfer and penetration (SBR 443D.12,2012)*

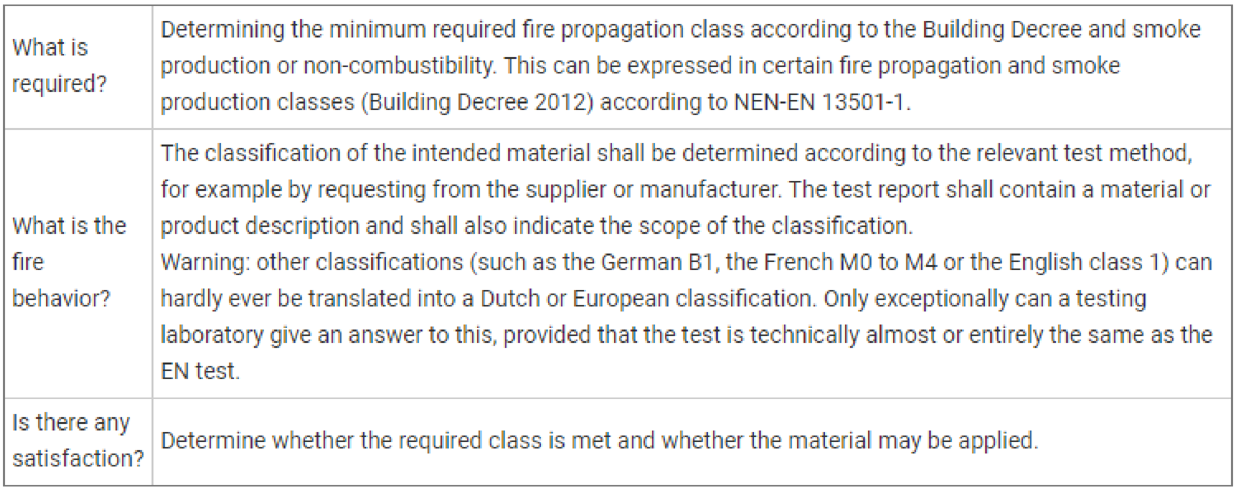
Penetrations through a separation structure should be assessed experimentally using NEN 6069. There are two exceptions to this:

ventilation ducts without fire dampers passing through a separation structure; ventilation ducts equipped with fire dampers through a separation structure. These ventilation ducts are assessed with the experimental determination in NEN 6076 and NEN 6077 or NEN-EN 13501-3 respectively). The air volume flow and pressure, which are often present in ventilation ducts, play an important role in these assessments.

European standard NEN-EN 1366-3 is often used for the assessment of the fire resistance of cable and pipe penetrations. This standard prescribes a standard configuration of cable ducts and cable bundles that covers most of the possible configurations in practice.

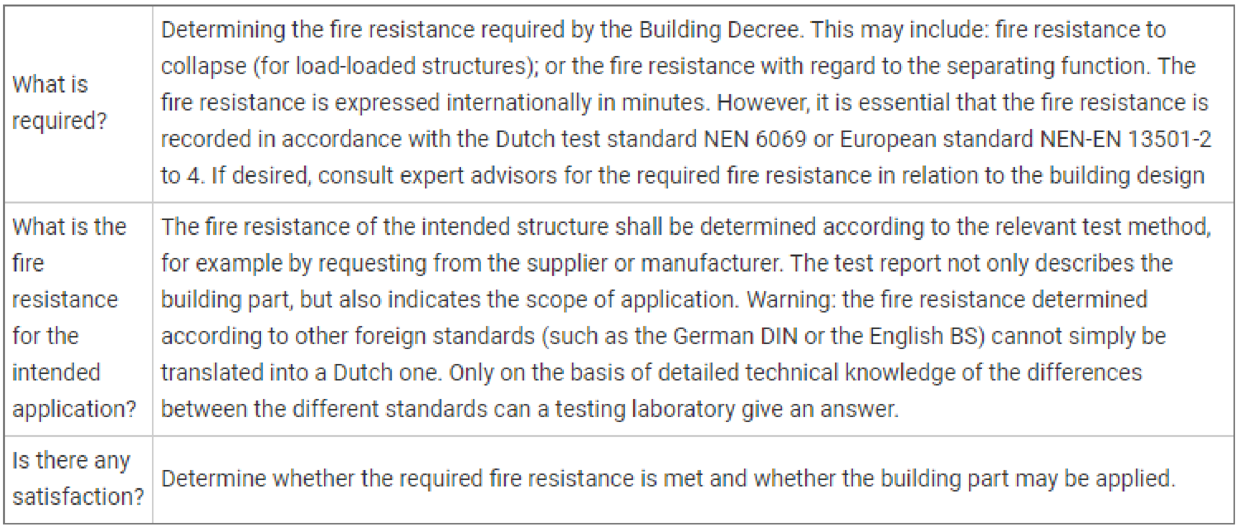
Therefore, a step-wise method towards choosing the suitable building products and construction is summarized by the ISSO-SBR publication ‘Fire safety: Design and testing - Part D’ (2012), in the following table 16 and 17 respectively, to resist fire propagation and structural collapse.

*Table 16: Step-wise method for choosing suitable building products (ISSO,SBR 2012)*



| | |
|---|---|
| What is required? | Determining the minimum required fire propagation class according to the Building Decree and smoke production or non-combustibility. This can be expressed in certain fire propagation and smoke production classes (Building Decree 2012) according to NEN-EN 13501-1. |
| What is the fire behavior? | The classification of the intended material shall be determined according to the relevant test method, for example by requesting from the supplier or manufacturer. The test report shall contain a material or product description and shall also indicate the scope of the classification.<br>Warning: other classifications (such as the German B1, the French M0 to M4 or the English class 1) can hardly ever be translated into a Dutch or European classification. Only exceptionally can a testing laboratory give an answer to this, provided that the test is technically almost or entirely the same as the EN test. |
| Is there any satisfaction? | Determine whether the required class is met and whether the material may be applied. |

*Table 17: Step-wise method for choosing suitable building construction method (ISSO,SBR 2012)*



| | |
|---|---|
| What is required? | Determining the fire resistance required by the Building Decree. This may include: fire resistance to collapse (for load-loaded structures); or the fire resistance with regard to the separating function. The fire resistance is expressed internationally in minutes. However, it is essential that the fire resistance is recorded in accordance with the Dutch test standard NEN 6069 or European standard NEN-EN 13501-2 to 4. If desired, consult expert advisors for the required fire resistance in relation to the building design |
| What is the fire resistance for the intended application? | The fire resistance of the intended structure shall be determined according to the relevant test method, for example by requesting from the supplier or manufacturer. The test report not only describes the building part, but also indicates the scope of application. Warning: the fire resistance determined according to other foreign standards (such as the German DIN or the English BS) cannot simply be translated into a Dutch one. Only on the basis of detailed technical knowledge of the differences between the different standards can a testing laboratory give an answer. |
| Is there any satisfaction? | Determine whether the required fire resistance is met and whether the building part may be applied. |

### *Sound insulation and absorption*

The sound insulation of building products and materials are crucial in determining the acoustic performance in a space/room/building. The requirements for a given space is dependent on the functional use of the space, i.e. requirements for housing versus utility (office) building varies.

To briefly summarize the basics, sound propagates in a wave form via solid, liquid and air mediums, however, in the context of a built space, air and structure are the most important mediums. They are classified as air-borne sound and structure-borne sound transmission in literature, as illustrated in the figure 48.

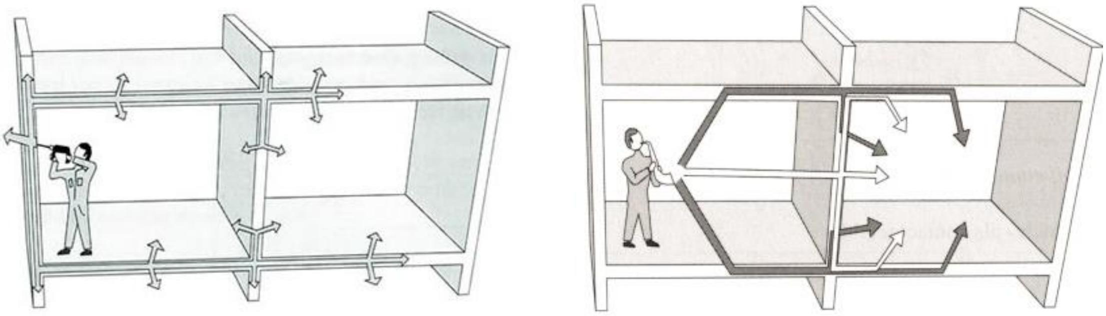


*Figure 48: (left) transmission through structure (right) transmission through air (ISSO, 24)*

### *Airborne sound insulation*

In case of air-borne transmission, caused by playing music or talking loudly, the sound from the source travels through the medium of air to the receiver through walls and floors. However, the extent to which the receiver hears this as noise can be controlled or reduced by the right selection of wall partitions or floor finishes.

The airborne sound insulation also termed as sound insulation value denoted by R for building products or construction is tested in a controlled laboratory setting. The measurements are taken in accordance with NEN-EN-ISO standards as mentioned in NEN 5077:2019. Furthermore, sound insulation is associated to a material/product property that is measured in Decibels [dB]. The general sound insulation of a structure is calculated by given formula, when in a lab setting, with a transmission and receiving room including measuring devices.

$$R = L_{pzend} - L_{pontv.} + 10\log\frac{S}{A_{ontv.}} \qquad [dB]$$

wherein:

$R.$ = direct sound insulation [dB]

$L_{.pressing}$ = the noise level $L_P$ in the transmission room [dB]

$L_{.Pontv.}$ = the noise level $L_P$ in the receiving room [dB]

$S.$ = surface of the separation structure to be examined [m²]

$A_{.ontv.}$ = the total sound absorption in the receiving room [m² open window]

A.ontv. can be calculated by measuring the reverberation time T(s) in the receiving room and entered in the general formula as given below:

$$T_{ontv.} = \frac{1}{6}\frac{V_{ontv.}}{A_{ontv}}, \text{ met } V_{ontv.} = \text{volume ontvangvertrek in } m^3 \qquad [s]$$

The total sound absorption Aontv. in the receiving room can be calculated by measuring the reverberation time and determining the volume of the receiving room. The area S of a structure to be examined/measured. By measuring the noise level LP. in the transmission and receiving room, the sound insulation value R can then be calculated in each frequency band.

However, in a situation where sound is travelling between rooms, and the receiving room has high absorption value due to very soft furniture it caters to reduced noise levels. Therefore, sound absorption of structures/finishing materials is crucial in dampening and reducing the sound.

*Sound absorption* is dependent on the type of material and their mechanism towards absorption. According to ISSO 24 the classified into porous, membranes (non-perforated), resonator (perforated), as illustrated into a graph with sound absorption with varying frequency in the figure 49.

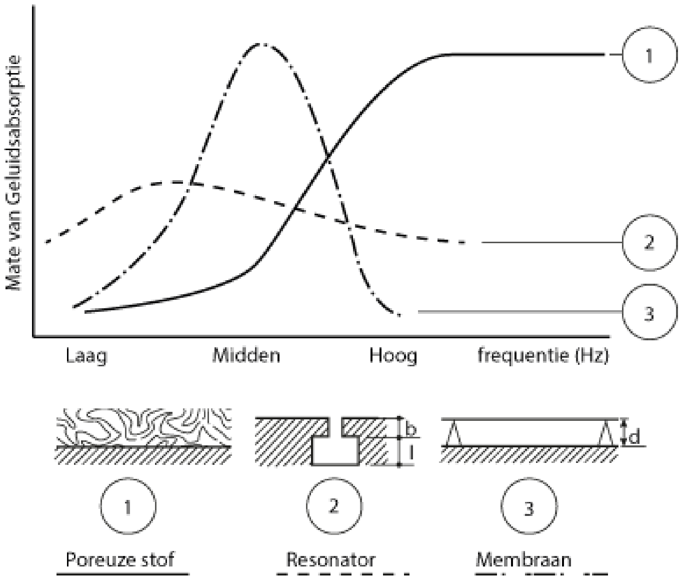


*Figure 49: Characteristic absorption spectra of different absorption mechanisms (ISSO, 24)*

In practice these measures are adding either on the ceiling or walls of a space, explained in the next section. It closely related to the finishing materials used in a space. Sound absorption is determined in the laboratory using a reverberation chamber. Sound absorption coefficient values are usually found in the manufacturer or supplier data/specification sheets for materials. Refer appendix 5 for values of some structure and finishing materials.

### Structure-borne sound insulation

In the case of structure-borne, caused by hammering or water pipes or air ducts or walking that involves direct contact with the surface/structure, the sound travels through the structure via vibrations, this in turn radiates in the form of air-borne noise through walls or floors. In other words, sound emitted by the structure ends up on the receivers ears in the form of airborne noise through transmission by air.

A healthy human ear can detect sound at frequencies between 20 and 20,000 Hz. Vibrations can generally be felt (with the feet) when the frequency(s) of these are in the frequency range below approximately 100 Hz. Above 100 Hz, the vibrations are experienced as sound (and therefore no longer felt as vibrations) (ISSO 24).

Therefore, heavy constructions are less likely to vibrate compared to lighter constructions.

Structure-borne noise is differentiated into contact and construction noise in literature,

- contact noise refers to temporary actions of acts of walking, jumping on the floor or slamming the door
- construction noise refers to permanent contact of vibrating machines with the structure or ventilation ducts or pipes.

For sound caused due to vibrations it is essential to dampen them using the appropriate material. In case of contact noise, such as walking, is largely dependent on the floor finish of the space/room. The use of carpets and softer materials improves the acoustic performance, in comparison to hard floor finishes such as hard wood flooring. Additionally, a floating screed often greatly improves contact sound insulation, while improving air noise insulation is limited to a few decibels.

Floating screed is further categorized in three types wet, dry and improved dry.

The 'dry' floating screed is light and has a relatively low height compared to the other two types. Acoustically, the 'dry' screed provides limited contact sound insulation, with no underfloor heating possible. If the 'dry' screed with underfloor heating is carried out, it does not improve the contact sound insulation (SBR, 2005).

For high contact sound insulation in combination with underfloor heating, both the 'wet' and the 'improved dry' floating screed can be used; the 'improved dry' floating screed is lighter than the 'wet' system (SBR, 2005).

Therefore, the improvement is largely dependent on the thickness (m), mass per area (kg/sqm) and the type of insulating material used, refer appendix 5 for a table of the characteristics of each category.

In the case of construction or installation noise created by ventilation ducts or pipes are addressed by similar vibration damping measures to reduce the effect. For example, ventilation duct systems not only produce noise but also silences them naturally. However, this is done through:

- Uncoated straight duct pieces;
- Uncoated bends;
- Branches and splits;
- Cross-sectional changes;
- Outlet openings (channel outlets);
- Installation parts (filters, humidifiers, batteries)

If the natural damping in an air duct system is not sufficient, additional damping must be built into the air duct system. The additional damping can be achieved by:

- Installing in the air duct system of silencers in various forms

The attenuation of sound in straight air ducts is determined by several factors, some essential aspects are:

- The channel dimensions and shape;
- The material and wall thickness of this;
- The stiffness of the duct and the method of suspension

Furthermore, in most ventilation system sufficient dampening cannot be achieved naturally, therefore adding silencers to the channels is essential. These damper are standard manufactured products and they can be categorized as per shape, rectangular, round dampers or flexible sound absorbing hoses as illustrated in figure 50.

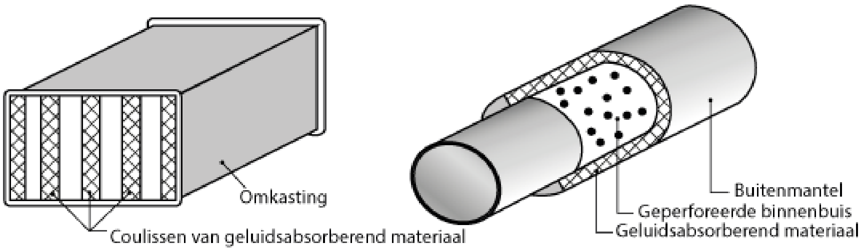


*Figure 50: Standard ventilation duct silencer (rectangular and round) (ISSO, 24)*

### *5.3.3 Product standardization and unique identifications/certificates*

To ensure all building products comply by the building regulations and quality standards at a European level, the European Construction Products Regulation (CPR) promotes a common technical language of CE marking and Declaration of performance (DoP) to be used by the manufacturers for expressing the technical performance of their products. It facilitates free movement of products in the EU by associating harmonized technical specifications to the products. This helps regulators ensure product quality in terms of safety, health and environment (Standards & Market, 2020).

In Netherlands, suppliers/products have long had the possibility to provide a product with a KOMO certificate, to indicate a material or product meets the performance requirements of the Building Decree. A KOMO certificate shows that a product or service meets the performance requirements of the Building Decree and the contemporary quality requirements of the market. It is only valid in the Netherland and indicates that the products have been tested in accordance with the appropriate testing standards and mentions where they may be applied (SBR publication, 2012).

Therefore, such a form of quality assurance of building products incentivizes standardization and prefabrication in the industry. Thereby, promoting efficient use of products and materials. However, the selection of products is still carried out based on project specific functional, technical requirements, cost and its appearance.

## 5.4. State of the art Integrated floor-systems in the Netherlands

### *5.4.1 Integrated design for floor-systems*

Integrated design deals with a building scale that incorporates materials at multiple levels that perform independent functions but have a close relationship between each other (van Herwijnen & Jorissen, 2006). Integrated design can be related to the functional decomposition aspect of Design for disassembly approach. Under this aspect, the functional autonomy criteria of integrating independent functions is illustrated using an example of floor-system (figure 51), by integrating structure and service installations in four different scenarios (Durmisevic, 2006);

1. Total integration refers to a scenario where the structural elements have more than one primary function. Here, they are used also to integrate service installation within the material, acting as insulation for sound, or storing heat for equal dissipation (core activation), etc.
2. Planned interpenetration that incorporates preassigned voids and holes for installations within the structural elements
3. Unplanned interpenetration of structural elements and installations
4. Total separation, ensuring every function is completely in its own zone

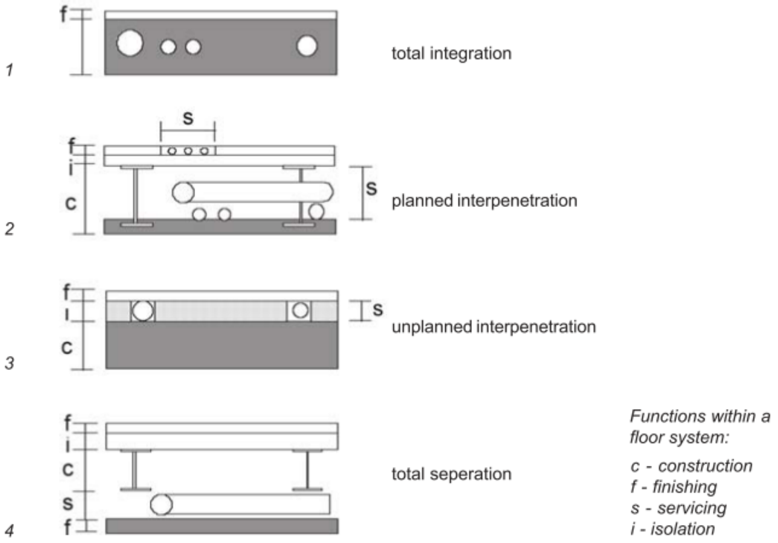
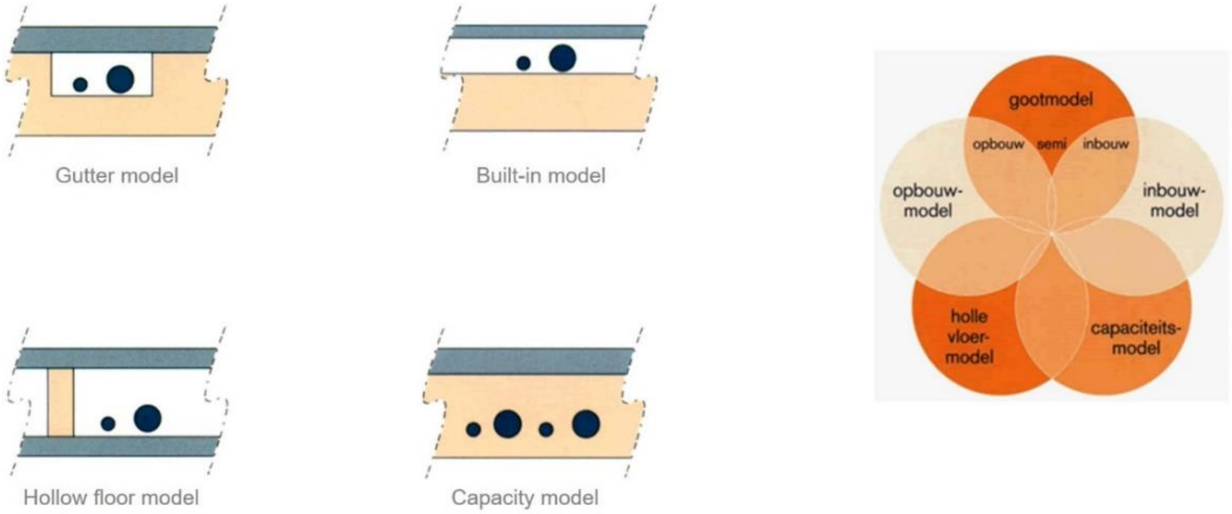


*Figure 51: Illustrating four scenarios demonstrating functional integration within floor-systems*(Durmisevic, 2006)

### *5.4.2 Pipe integration typologies in floor-systems*


Gutter model

Built-in model

Hollow floor model

Capacity model

2005, SBR publication

*Figure 52:Four pipe integration typologies illustrated as flexible concept models (SBR, 2005)*

The integration of service installations such as pipes in floors has been categorized into four flexible concept models (IFD Pogramme & SBR 2005)

- *Gutter model*
- *Built-in or Raised floor model*
- *Hollow floor model*
- *Capacity model*

These can be identified as typologies of the integrated floor-systems that are existing in practice.

*Gutter model* is a further developed version of a duct slab floor, where additional slots or pipe zones can accommodate pipes. These slots are later filled and covered with a demountable plating or a traditional screed, either with or without a foil layer. The use of these floors is determined by the number and location of the slots. Pipes with large diameters cannot be accommodated.

*Hollow floor model* consists of a beamed floor with a subfloor (also ceiling) and an upper cladding or screed. There are examples of all-steel floors, combinations of steel and concrete, entirely concrete floors and wooden floors. The degree of flexibility depends on being able to implement and have pipes crossed in the hollow space of the floor. Furthermore, it is important for later accessibility that the screed (or ceiling) is demountable.

*Capacity model* is mainly used in prefabricated concrete construction. Additional pipes are already accommodated during manufacturing in the factory, creating an overcapacity of connection options. During the assembly on site, one chooses which connection is used in relation to the customer's wishes. This model can be used in prefabricated floors and for cast in-situ floors, such as a wide slab floor.

*The built-in and superstructure model* are rare in residential floors, with the exception of the renovation sector. In non-residential construction these are very common models. A wide range of suspended ceiling systems and raised computer floors are available for non-residential construction. An advantage of these additional facilities is that the pipes remain easily accessible for subsequent maintenance or replacement.

### *5.4.3 Identifying existing typologies and criterion of decision making*

As part of Industrial, Flexible and Demountable (IFD) Building programme, a survey study carried out by SBR and SEV through telephonic interviews gives an overview on

- existing floor systems under the mentioned typologies and
- the decision making reasons for its implementation in reference projects in Netherlands

The table 18 summarizes the survey study as published in SBR 2005 ‘Flexible floors in practice’. Some floor systems mentioned in the table and others widely available in the Netherlands are also studied and included in the appendix 5.

*Table 18:Shows the results of the survey and highlights the criteria to choose an integrated floor-system in practice for diverse building functions categorized by three integration typologies (SBR,2005)*

| Typology | System choice | Building function | Decision maker (DM) | Decision making criteria |
|---|---|---|---|---|
| Gutter model | VBI pipe floor | Housing and apartments | Client or architect | - increase *process flexibility, span* and the *slender floor* as main reasons<br>- Other reasons *construction speed* and *cost reduction* |
| | Betonson's Wing+floor | non-residential | consultants | - *concrete core activation* and *process flexibility*<br>- *low floor height* without the need for a suspended ceiling or computer floor |
| Hollow floor model | Infra+ floor of Prefab Limburg | Housing and offices | Clients | - *process and use flexibility*<br>- *low weight* is an important criterion |
| | Corus Star-Frame floor | Housing and hostel | Architects | - *construction site logistics* and *construction process*<br>- Fast construction by prefabricated elements in combination with the *low weight* |
| | Sadef Staalvloer | Housing and supermarket | unknown | - *fast construction* by prefabricated elements in combination with the *low mass* |
| Capacity model | Bestcon 60 floor of Heijmans | apartment complexes and an office | Client and contractor | - *cost, construction speed* and the complete *integration of pipes and electrical lines* |

The decision making criterion for flexible floor systems largely depend on the type of building frame, the construction process and project requirements. Some of the important criteria gathered from this study are listed as follows (SBR, 2005)

- Price (direct cost and indirect process costs)
- Fast construction method (reduction of construction interest and direct construction costs)
- Supplier and its conditions of delivery speed
- Concrete core activation in combination with higher net floor height
- Finishing of the ceiling
- Weight; a lower weight works directly into the foundation and indirectly less heavy equipment is needed
- Process flexibility in execution phase, which allows (as yet to decide) buyers and users to postpone their choices for the installations
- Process flexibility in design phase
- User flexibility
- Independence of the supplier
- Clear phasing of the construction process as opposed to a continuous construction process
- Feasibility Building physical properties
- Preparation time
- Free layout due to a large span
- Constructional properties

## 5.5. Conclusion

An integrated floor-system constitutes of three building layers i.e. Structure, Services and Space. The type of interaction between the layers is largely determined by the position of the services such as pipes and ducts. This interaction impacts functional, technical and circularity (read flexibility) related aspects of the configuration. The main challenge of integration of the three building layers in one system, in the circularity perspective is the varying technical life spans of the components. In functional perspective it impacts the overall thickness of the floor-system package and in technical perspective it is impacts the building physics properties. The two discussed technical criteria that impact the choice of products used in the configuration are structural and building physics performance.

Structural performance criteria for floor-systems can be branched in durability and usability criteria. Here, durability is expressed by the technical life span of the structure in number of years. This indicates that structure is guaranteed for use with assured safety (strength) for given life time. While usability criteria is largely informed by

- strength of the structure i.e. the extent of external loads it can carry. It is determined by the Consequence Class group that is based on the building function and number of floors. Office buildings of 5 floors and above lie in the CC2 group.
- deformations in the structure due to static (sag due to applied loads) or dynamic (vibrations induced due to walking or jumping) loading. The sag in floors are dependent on the span length and the vibrations in floors is dependent on mass.

Building Physics related performance criteria applicable for integrated floor-systems are fire resistance properties, sound insulation and sound absorption properties of the buildings products used in the configuration.

Furthermore, it is also found that all building construction products that are manufactured (prefabricated) are regulated at an EU level to meet standards by certifications such as CE marking and Declaration of Performance

(DoP).This is especially to ensure the products technical performance meets the standard requirements and has been tested in regulated environments. This promotes standardization by quality control and performance assurance for all prefabricated/ manufactured building products. This ensures specified performance for mentioned technical life span of these products is guaranteed thereby facilitating better service life planning of the floor-system configuration. Inturn facilitating better possibilities of flexible and adaptable buildings.

The review form the survey study carried out by the industrial, flexible and demountable programme in the Netherlands (SBR, 2005) has identified four pipe integration typologies in floor-systems, i.e. Gutter model, Capacity model, built-in model, and hollow-floor model. These are categorized based on their concept of pipe integration into the floor slab (i.e. concrete core activation) or in the screed or raised floor determines the flexibility of the system. However, for ducts integration its position in-between the beams, below the beam or the raised and if covered by suspended ceiling determine flexibility. Finally, the study also shows, the criteria to select integrated floor-system is most importantly based on flexibility, construction time and increased net floor-height. However, the literature review does not help understand the interaction between the multi-disciplinary stakeholders (i.e. Architects, Structural Engineer and MEP consultant) and their values or perspectives when deciding for an integrated floor-system for office buildings. For this reason interviews were carried out with 10 participants from different disciplines and the results are discussed in Chapter 7.

# 6. State of the art computational decision support approaches

*“….. we cannot solve present day major political and organizational problems simply by grinding through a mathematical model or computer algorithm. What we require besides is the design of better deliberation and judgement.’’*

*- C.W. Churchman & H.B. Eisenber*

Design decision made in the early/preliminary stages of design have a huge impact on circularity and cost related aspects in a project. To ensure minimal impact on costs and the environment, the decision makers (DM) must be supported with information or insights on their decisions, especially when driven by complex multi-disciplinary criteria. Computational tools that support preliminary design are mostly smaller in number compared to tools that support decisions in the later stages of design (Wang et al, 2002).

Therefore, to understand how best such a support system can be developed for early stages of design and what existing state of the art approaches and applications are used in the scientific field; this chapter reviews the literature of Decision Support Systems, the novel approach of Dashboard based tools and discusses the advantages and challenges of service oriented DSS in cloud (Analytics-as-a-service).

## 6.1. Decision Support Systems

### *6.1.1 Theoretical foundation*

A definition of Decision Support System (DSS) that best suits the context of this research is, DSS is a computer-based system that supports the decision makers (DMs) in the process towards framing and exploring the implications of their judgements, and therefore making informed decision based on understanding (French et al., 2010).

DSS are mostly either classified as model driven (i.e. linear programming or decision trees) or data driven (based on a database). However, they are almost always a combination of both with slightly more emphasis on either one of the categories (French et al., 2010).

Another form of categorizing DSS tools is based on the level of support they offer the DMs and its relation to the managerial activity it performs, this is highlighted by French et al. (2010) in the context of business decision making, illustrated in the graph, figure 53..

| | |
|---|---|
| **Level 0:** | Acquisition, checking and presentation of data, directly or with minimal analysis, to DMs. |
| **Level 1:** | Analysis and forecasting of the current and future environment. |
| **Level 2:** | Simulation and analysis of the consequences of potential strategies; determination of their feasibility and quantification of their benefits and disadvantages. |
| **Level 3:** | Evaluation and ranking of alternative strategies in the face of uncertainty by balancing their respective benefits and disadvantages. |

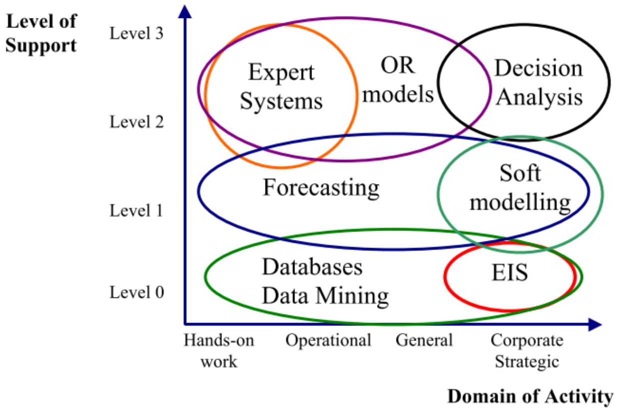


*Figure 53: Illustrates the different levels of support offered by decision support systems* (French et al., 2010)

There are four levels of classification based on the support type, as shown in figure 53. The level 0 can be associated to only providing the information as is to the DMs with no insight into analysis of the data, relating to databases or data mining. Level 1 supports the analysis of the data towards forecasting the performance through one or more decision models, however, it does not share the consequence of the DM’s actions or set inputs. To address this drawback, the level 2 stage of support is beneficial, however, this level does not prompt or suggest alternative options that possibly performs better for a given problem. Therefore, for support towards prescriptive decision making level 3 stage proves valuable (French et al., 2010).

### *6.1.2 Development of a Decision Support System*

To understand the development of a computational decision support system and steps involved a case example of the Environmental Decision Support System (EDSS) is studied.

#### *Environmental Decision support system*

An Environmental Decision support system, is an expert system that assists the decision makers in the environmental domain with increased quality and consistency of decisions in reduced time. The general development framework of an environmental decision support system is illustrated in the flow diagram as shown in figure 54. The development is initiated with a problem analysis followed by acquiring data and knowledge into a database. The relevant data and knowledge is then converted into the selected Artificial Intelligence or statistical or numerical models which could be rule-based, case-based or based on neural networks genetic algorithms or simulation models. These models are then implemented and integrated into an environmental decision support system that provides decision making assistance based on the data and knowledge fed into the system (Poch et al., 2004).

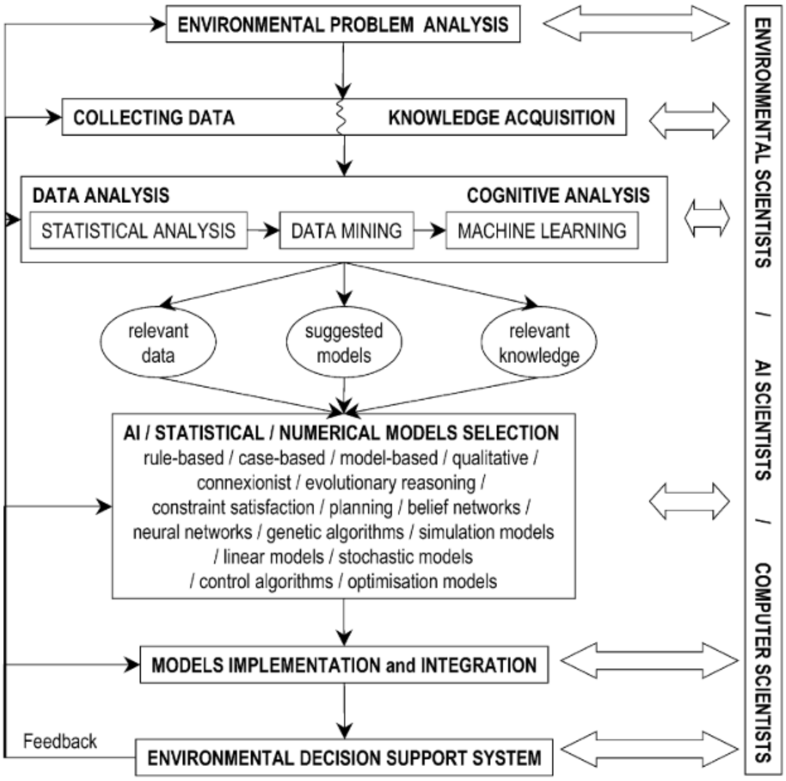


*Figure 54: Illustrates the flow diagram for the development of a EDSS* (Poch et al., 2004)

An application of the EDSS architecture can be understood through the Waste water treatment plant (WWTP) supervision example. A WWTP is a complex system as it involves multi-disciplinary fields of knowledge from chemical and biological processes, which demands expertise from different scientific fields. The WWTP control systems often face limitation when problems require acquired qualitative information and heuristic reasoning to resolve them. Therefore, a EDSS approach proves beneficial to adopt for better level and quality control actions especially that meet prescribed environmental specifications (Poch et al., 2004). The diagram in figure

55 shows the stages involved in developing a decision support system for waste water treatment which aligns with the EDSS flow diagram figure 54.

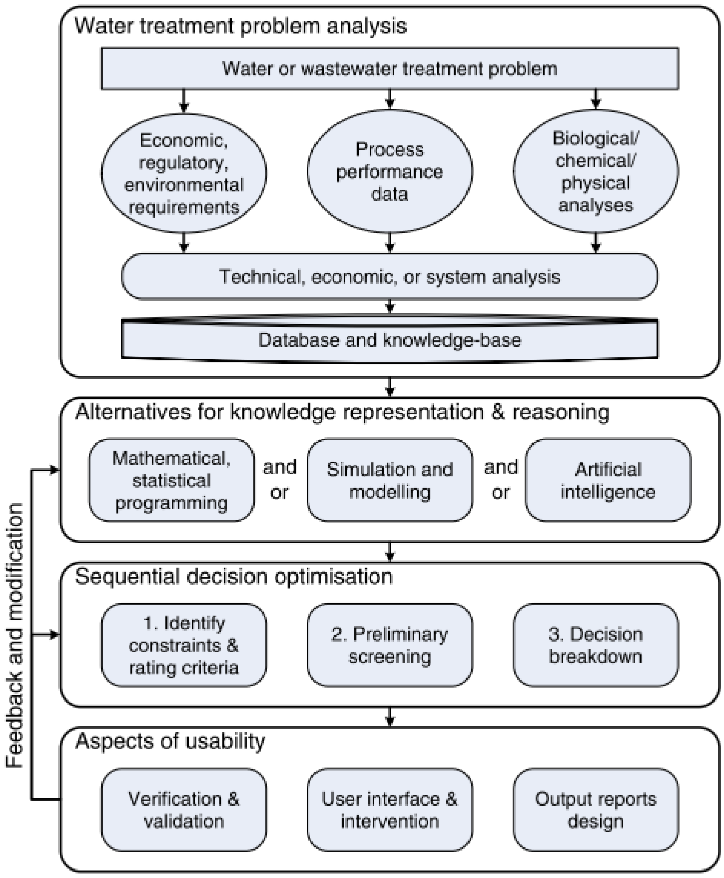


*Figure 55: The stages involved in development of a waste water treatment Decision support system* (Hamouda et al., 2009).

Once the first stage of problem is well defined and analyzed the next step to acquire the necessary knowledge form source such as, literature review, expert interviews or data mined from databases. This informs the data classification into specific and general knowledge that makes the Database/knowledge base.

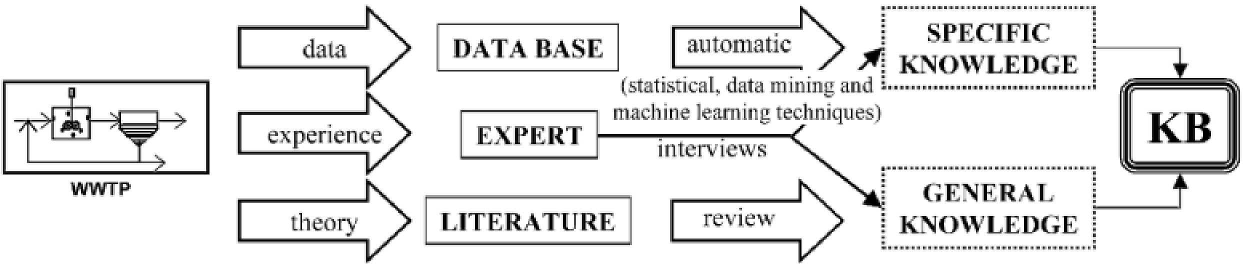


*Figure 56: The sources of knowledge acquisition* (Poch et al., 2004)

The next phase is to select the model of representation of all the acquired knowledge and reasoning to automate the process of selection of a waste water treatment system. For this there are multiple approaches, i.e. based on mathematical programming, simulation and modelling and Artificial intelligence, as explained in the table 18 (Hamouda et al., 2009).

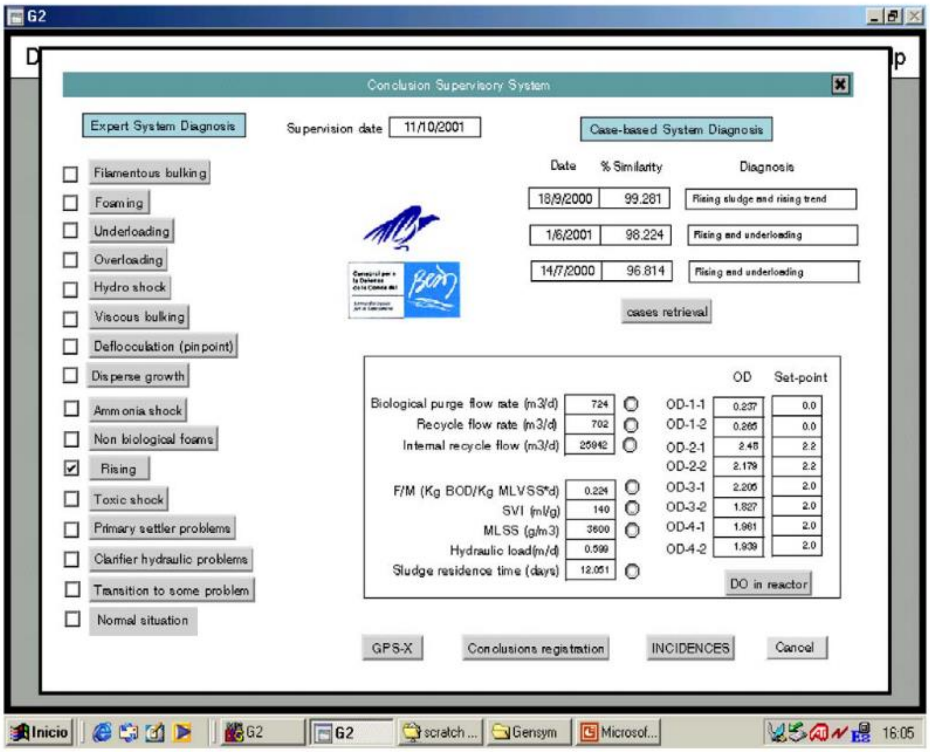
*Table 18: The different methods of knowledge representation and reasoning reviewed by Hamouda et al.* (2009)

| Knowledge representation method | | Description |
|---|---|---|
| Mathematical programming | | *The approach focuses largely on the technical aspects of the design and is mainly concerned with optimising the solution.* |
| Simulation and modelling | | *Process simulation and modelling helps to define and quantify relationships between the process performance and design variables in the form of a mathematical relationship. Simulation plays an important role in generating design alternatives and estimating their performance under various conditions* |
| Artificial Intelligence | Knowledge-based systems (KBS) | *emulate human reasoning using knowledge within a particular discipline based on Heuristic rules. Knowledge is usually organized and documented in the form of decision trees as a precursor to developing the KBS.*<br>*Rules extracted from decision trees can be codified to discard, favor, or disadvantage alternatives based on their characteristics.* |
| | Issue-based information systems | *a natural framework to record information as argumentation in a deliberation process and are used to map the rationale of alternative selection and design as a process of argumentation. These IBIS networks take the shape of a tree-view. The issue or question related to the design is shown at the top, the possible alternative solutions to the issue raised branch from it, and the arguments or reasons behind the selection of an alternative complete the tree-view.* |
| | Case-based reasoning | *estimates the problem solution based on the successful solutions for previous similar problems.* |
| | Neural networks | *mimic human brain functioning by learning how to deal with certain problems from experience, and then applying this learning to new but similar problems. Much like the human brain, their structure includes interconnected neurons that generate an output based on input signals. The number of neurons and the way they are connected influences the output.* |
| | Bayesian probability networks | are probabilistic graphical networks that represent a set of variables and the extent to which they are conditionally independent. |
| | Fuzzy logic | is not a stand-alone method; rather it is a technique to manipulate incomplete, imprecise, or unreliable information and improve the representation of relationships that are not well defined in the problem under analysis |

After having chosen a method for the representation of the knowledge and reasoning, the next step is to screen alternative solutions and propose the optimum. The optimization of solutions towards a pareto - optimal helps in case of conflicting objectives. However, this step is often not used in this specific example of waste water treatment plants (Hamouda et al., 2009).

To sequentially optimize decision, there are two methods, i.e. Screening methods and decision breakdown. Screening analysis can be based on either elimination of alternatives that do not satisfy a certain value, or by generating fitting alternative and only isolated the best solutions. When multiple criteria are used to evaluate alternatives, relative weighted importance can be assigned to the criteria and an aggregated score can help rank all alternatives for making a decision (Hamouda et al., 2009). There are multiple methods based on the multi-criteria decision making (MCDM) that can be adopted(Abraham et al., 2014). However, these will not be covered as part of this research.

The last stage concerns the aspects of usability of the developed Decision Support System, which is informed by the user interface and verification/validation steps. Here, validity refers to testing the system to know whether the outputs help the user resolve the formulated problem. The objective towards validation to assess the quality of results and note further improvements. The best form of validation is to test it with a real world case scenario, however it is often not feasible. Finally, the main aspects to consider for usability of a user interface are the level of interaction and quality of design. The interface must consist of the user input, the decision reasoning and show results of the DSS calculations and allow the user to change input variables (Hamouda et al., 2009).



Supervision date 11/10/2001

☐ Filamentous bulking
☐ Foaming
☐ Underloading
☐ Overloading
☐ Hydro shock
☐ Viscous bulking
☐ Deflocculation (pinpoint)
☐ Disperse growth
☐ Ammonia shock
☐ Non biological foams
☑ Rising
☐ Toxic shock
☐ Primary settler problems
☐ Clarifier hydraulic problems
☐ Transition to some problem
☐ Normal situation

| Date | % Similarity | Diagnosis |
|---|---|---|
| 18/9/2000 | 99.281 | Rising sludge and rising trend |
| 1/6/2001 | 98.224 | Rising and underloading |
| 14/7/2000 | 96.814 | Rising and underloading |

Biological purge flow rate (m3/d) 724 ○
Recycle flow rate (m3/d) 702 ○
Internal recycle flow (m3/d) 25942 ○
F/M (Kg BOD/Kg MLVSS*d) 0.224 ○
SVI (ml/g) 140 ○
MLSS (g/m3) 3600 ○
Hydraulic load(m/d) 0.599
Sludge residence time (days) 12.051 ○

| | OD | Set-point |
|---|---|---|
| OD-1-1 | 0.237 | 0.0 |
| OD-1-2 | 0.265 | 0.0 |
| OD-2-1 | 2.48 | 2.2 |
| OD-2-2 | 2.179 | 2.2 |
| OD-3-1 | 2.206 | 2.0 |
| OD-3-2 | 1.827 | 2.0 |
| OD-4-1 | 1.981 | 2.0 |
| OD-4-2 | 1.939 | 2.0 |

*Figure 57: A User-interface example developed based on EDSS flow for a WWTP supervision* (Poch et al., 2004)

This case example gives an overview of the different steps towards development of a DSS. However, to further explore the application of workflow that are similar to DSS in the Architecture, Engineering and Construction (AEC) field, two state of the art computational tools are highlighted and discussed in the next section.

## 6.2. Applications in AEC

The Architecture, Engineering and Construction industry has always been slower in the process of adopting automation and advance technology towards design or decision making assistance, in comparison to automotive or aerospace industry. It still often depends on the knowledge and experience of experts in the process towards collective decision making for a given design problem.

The extensive experiential knowledge within the field cannot be replaced by technology but it can be harnessed to use technology to develop essential assistance that can drive innovation. This thesis therefore positions itself at the center of this argument. There have been multiple applications found in literature that can be used as inspiration.

*StructuralComponents* (Rolvink et al., 2010) is a software tool developed for the use of a structural engineer. It is designed to support the architects and engineers in the early design stages of a tall building to generate and evaluate structural model behaviour. The concept for this tool is to adapt the model to changes and evaluate alternate design options in (near) real time. The tool comprises of two components a modular software architecture and a dashboard presentation, as shown in the figure 58.

The version 2.0 of the structural components is a framework that is implementable in any parametric modelling software and was developed as a plug-in for Grasshopper (*Rhino - About McNeel*, 2021). To apply the framework a parametric modelling software is used only for user-interaction, analysis and visualization of the result (Coenders, 2011).

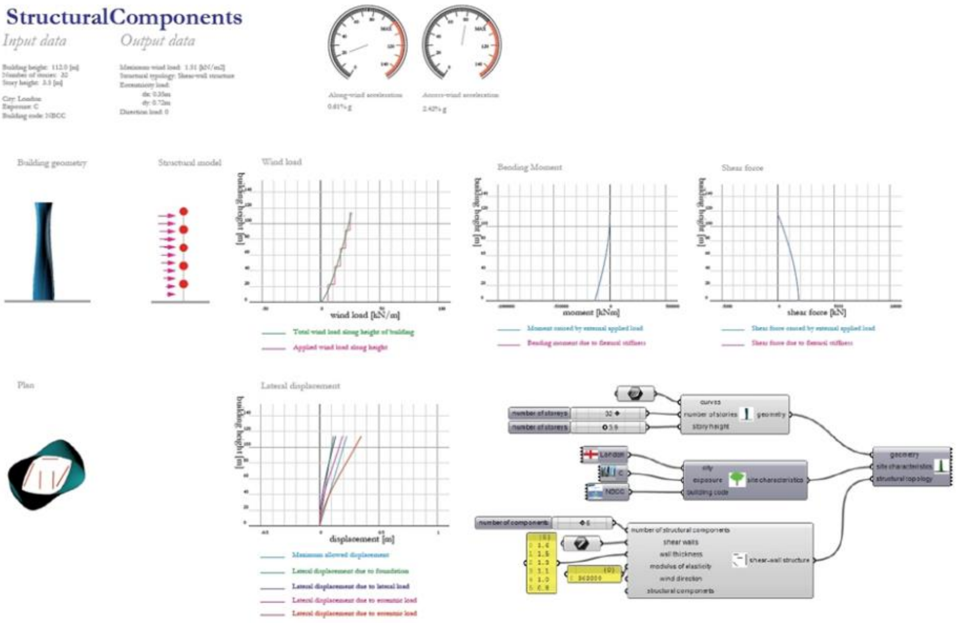
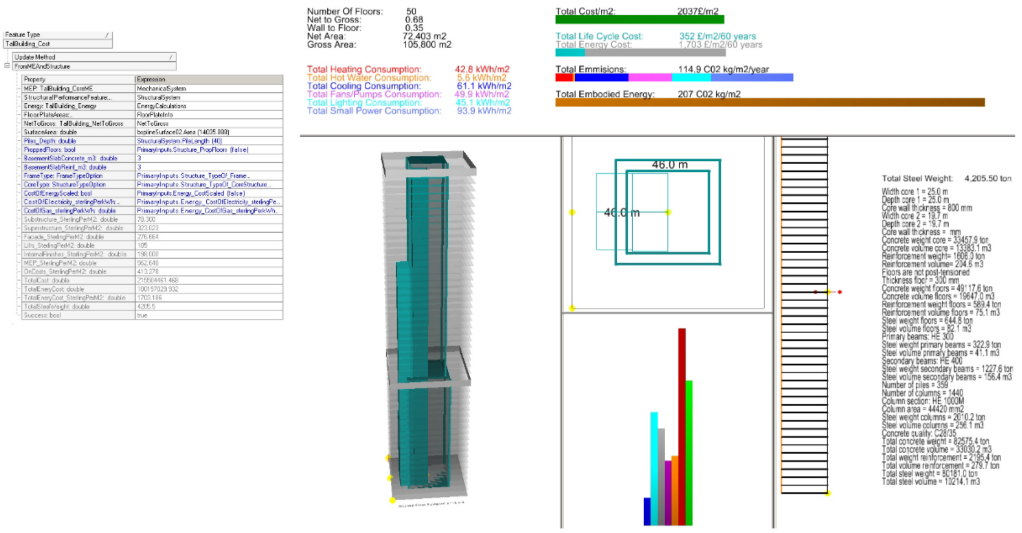


*Figure 58: StructuralComponents dashboard interface* (Coenders, 2011)

Tall Building Simulation Tool (Kimpian et al., 2009) is a communication and education tool that helps optioneering for the early design stages of the a tall building design and supports the development of design brief for the clients. Its main features are of a dashboard and automated design, as shown in the figure 59. The highlighting aspect is utilization of knowledge into a logic and coded to support automated design of the building structure to evaluate quantities, dimensions and design feasibility. Furthermore, the use of dashboard to communicate and educate by visualizing the results for not only engineers but clients with minimal technical skills (Coenders, 2011).



Feature Type
TallBuilding_Cost

Update Method
FromMEAndStructure

| Property | Expression |
|---|---|
| MEP: TallBuilding_CoreME | MechanicalSystem |
| StructuralPerformanceFeature:.. | StructuralSystem |
| Energy: TallBuilding_Energy | EnergyCalculations |
| FloorPlateAreas:.. | FloorPlateInfo |
| NetToGross: TallBuilding_NetToGross | NetToGross |
| SurfaceArea: double | bsplineSurface02.Area (14035.888) |
| Piles_Depth: double | StructuralSystem.PileLength (40) |
| ProppedFloors: bool | PrimaryInputs.Structure_PropFloors (false) |
| BasementSlabConcrete_m3: double | 3 |
| BasementSlabReinf_m3: double | 3 |
| FrameType: FrameTypeOption | PrimaryInputs.Structure_TypeOf_Frame.. |
| CoreType: StructureTypeOption | PrimaryInputs.Structure_TypeOf_CoreStructure... |
| CostOfEnergyScaled: bool | PrimaryInputs.Energy_CostScaled (false) |
| CostOfElectricity_sterlingPerkWh:.. | PrimaryInputs.Energy_CostOfElectricity_sterlingPe.. |
| CostOfGas_sterlingPerkWh: double | PrimaryInputs.Energy_CostOfGas_sterlingPerkWh.. |
| Substructure_SterlingPerM2: double | 78.300 |
| Superstructure_SterlingPerM2: double | 323.023 |
| Facade_SterlingPerM2: double | 276.664 |
| Lifts_SterlingPerM2: double | 105 |
| InternalFinishes_SterlingPerM2: double | 198.000 |
| MEP_SterlingPerM2: double | 562.640 |
| OnCosts_SterlingPerM2: double | 413.278 |
| TotalCost: double | 215504461.468 |
| TotalEneryCost: double | 180197029.932 |
| TotalEneryCost_SterlingPerM2: double | 1703.186 |
| TotalSteelWeight: double | 4205.5 |
| Success: bool | true |

| | |
|---|---|
| Number Of Floors: | 50 |
| Net to Gross: | 0.68 |
| Wall to Floor: | 0.35 |
| Net Area: | 72,403 m2 |
| Gross Area: | 105,800 m2 |

| | |
|---|---|
| Total Heating Consumption: | 42.8 kWh/m2 |
| Total Hot Water Consumption: | 5.6 kWh/m2 |
| Total Cooling Consumption: | 61.1 kWh/m2 |
| Total Fans/Pumps Consumption: | 49.9 kWh/m2 |
| Total Lighting Consumption: | 45.1 kWh/m2 |
| Total Small Power Consumption: | 93.9 kWh/m2 |

| | |
|---|---|
| Total Cost/m2: | 2037£/m2 |
| Total Life Cycle Cost: | 352 £/m2/60 years |
| Total Energy Cost: | 1,703 £/m2/60 years |
| Total Emmisions: | 114.9 C02 kg/m2/year |
| Total Embodied Energy: | 207 C02 kg/m2 |

Total Steel Weight: 4,205.50 ton

Width core 1 = 25.0 m
Depth core 1 = 25.0 m
Core wall thickness = 800 mm
Width core 2 = 19.7 m
Depth core 2 = 19.7 m
Core wall thickness = mm
Concrete weight core = 33457.9 ton
Concrete volume core = 13383.1 m3
Reinforcement weight= 1606.0 ton
Reinforcement volume= 204.6 m3
Floors are not post-tensioned
Thickness floor = 300 mm
Concrete weight floors = 49117.6 ton
Concrete volume floors = 19647.0 m3
Reinforcement weight floors = 589.4 ton
Reinforcement volume floors = 75.1 m3
Steel weight floors = 644.8 ton
Steel volume floors = 82.1 m3
Primary beams: HE 300
Steel weight primary beams = 322.9 ton
Steel volume primary beams = 41.1 m3
Secondary beams: HE 400
Steel weight secondary beams = 1227.6 ton
Steel volume secondary beams = 156.4 m3
Number of piles = 359
Number of columns = 1440
Column section: HE 1000M
Column area = 44420 mm2
Steel weight columns = 2010.2 ton
Steel volume columns = 256.1 m3
Concrete quality: C28/35
Total concrete weight = 82575.4 ton
Total concrete volume = 33030.2 m3
Total weight reinforcement = 2195.4 ton
Total volume reinforcement = 279.7 ton
Total steel weight = 80181.0 ton
Total steel volume = 10214.1 m3

*Figure59: showing the Tall Building Simulation Tool dashboard interface* (Coenders, 2011)

Relating the decision support system theory to these tools, it can be said that the StructuralComponents tool supports the DM at level 1 while the Tall Building Simulation Tool ensures level 2 support by analyzing the consequences and relationships between design aspects.

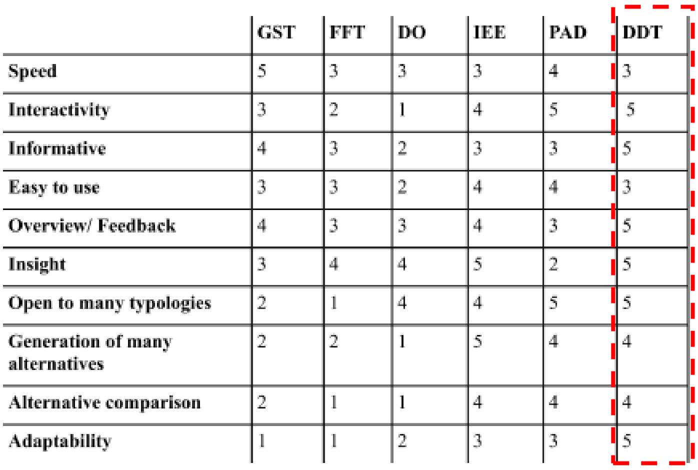
## 6.3 Novelty of Dashboard based Design Tool (DDT)

As seen from the applications Dashboard based design tools are an approach to support decision making in the early stages of the design process. It can be used to configure and evaluate models in real-time. It is important to note that this approach is not technology driven, but it is derived by understanding and studying the design process itself. Furthermore, it closely knits design and technology by adapting to the existing or modified design strategies (Rolvink et al., 2014).

A comparison can be drawn among some significant state of the art computational tools used within the AEC industry at early stages of design with the dashboard based design tool, to further understand its novelty.

Rolvink et al. (2014), give an overview of these state of the art tools used for conceptual design phases in the context of structural design. The table below summarizes and scores them out of 5 based on the criteria of speed, interactivity, informative, easy utilization, overview/feedback, insight, open to many typologies, generation of many alternatives and finally adaptability.

*Table 19: Drawing comparisons and evaluating the different computational approaches in AEC* (Rolvink et al., 2014)



| | GST | FFT | DO | IEE | PAD | DDT |
|---|---|---|---|---|---|---|
| **Speed** | 5 | 3 | 3 | 3 | 4 | 3 |
| **Interactivity** | 3 | 2 | 1 | 4 | 5 | 5 |
| **Informative** | 4 | 3 | 2 | 3 | 3 | 5 |
| **Easy to use** | 3 | 3 | 2 | 4 | 4 | 3 |
| **Overview/ Feedback** | 4 | 3 | 3 | 4 | 3 | 5 |
| **Insight** | 3 | 4 | 4 | 5 | 2 | 5 |
| **Open to many typologies** | 2 | 1 | 4 | 4 | 5 | 5 |
| **Generation of many alternatives** | 2 | 2 | 1 | 5 | 4 | 4 |
| **Alternative comparison** | 2 | 1 | 1 | 4 | 4 | 4 |
| **Adaptability** | 1 | 1 | 2 | 3 | 3 | 5 |

**Legend**:

**GST**- Graphic Static Tools

**FFT**- Form Finding Tools

**DO** - Design Optimisation

**IEE**- Interactive Evolutionary exploration

**PAD**- Parametric and Associative Design,

**DBD**- Dashboard-based Design Tools

From the evaluation overview, it can be assimilated that dashboard based design tools do outweigh most other in terms of interactivity, informative, feedback, insight, openness to many typologies and adaptability. Additionally it also fairs well on the criteria of generating many options and comparing them.

### *Analytics-as-a-Service (AaaS)*

Dashboard based design tools in AEC can be related to the growing trend of Analytics-as-a-Service (AaaS) which is a service oriented decision support system (DSS in cloud) for businesses. Analytics based solutions are applications that probe data to solve problems or provide decision support or help in business planning. The concept is often referred to as Agile Analytics, which means it is not a standalone database/software but a shared service that can be used by different stakeholders to visualize analytics. It is a way of converting utility computing into an analytics service model(Demirkan & Delen, 2013).

Dermirkan and Delen (2013) state this approach especially outperforms the discipline specific stove-pipe applications, and supports integration of complex Key Performance Indicators (KPIs), metrics and dashboards. Furthermore, with the explosion of front-end analytics tools and back-end Business Intelligence (BI) tools, platforms, and data marts, the hardship of managing, maintaining, and creating the "raw data to insights" business model has increased dramatically. It's becoming increasingly important to reorganize the silos and stovepipes of platforms or tools or information into much more centralized but flexible analytical systems.

However, in the case of mined knowledge it also important to recognize that its value is significantly connected to its richness (i.e. quality and quantity) for good insights or better decision support. Furthermore, such an approach of data mining/knowledge acquisition requires enormous capital and is very resource intensive (Demirkan & Delen, 2013).

## 6.3. Conclusion

To support the multi-disciplinary fields of knowledge and the complex relationships between them and make better decision towards integrated floor-systems driven by circularity, a decision support system (DSS) approach is selected.

A DSS is computer based system that assists decision makers in formulating and exploring the impact of their inputs and judgements, therefore supporting informed decision making. DSS are data-driven and model based approaches that store acquired data and knowledge from literature research and interviews into a knowledge base/database. It further uses knowledge representation and reasoning models to process the data and therefore suggest solution alternatives to the Decision Maker (DM). The model selection can be based on mathematical programming, simulation models or Artificial Intelligence. To develop a good DSS one must, follow a system analysis approach, acquire relevant data and knowledge related to the problem, be flexible incase of missing/uncertain data, create a user friendly interactive interface, and show relevant justified results that aid the user in making better decisions.

The AEC industry has examples that the novel approach of Dashboard based Design Tools are the most interactive, insightful, informative, adaptable and open to many typologies, when compared to other commonly used approaches. It is also found that the DDT has a better scalability and scope when developed as a service oriented analytics tool (DSS in cloud). The benefits are it is easily shared between stakeholders to gain quick insights into a problem or decisions and it helps connect different disciplines in one platform.

For this research a DSS based on a data-driven database and a model-driven by heuristic knowledge based (KBS) using decision trees will be developed. This method can best translate human reasoning and acquired expert knowledge from literature review and interviews into decision trees. Another advantage is decision trees can be easily codified as conditional statements to filter the solution alternatives of floor-systems and display its circularity related performance based on the material and integration typology. Finally, the interface will be based on a DDT approach to facilitate user interactivity, share information and gain insights.

# III

# INTERVIEWS AND DATA ANALYSIS

In this section of the report the analysis from the interview responses gathered from 10 experts in the field and enlists all the multi-disciplinary factors that influence the integrated floor-system design and lastly draws important relationships between all the factors from literature and interviews are discussed.

The significance of this section in this research can be related to the DSS development stage that refers to completion of acquiring data and knowledge and the stage that refers to data and cognitive analysis.

# 7. Multi-disciplinary influences on integrated circular floor-system

Durmisevic (2006) states, "Architecture is no longer independent, but relies on many different building specialists and partners during design and building processes."

There are multiple disciplines involved in a design process to implement mere concepts desk to site. An integrated circular design approach involves a collaborative team work towards a project. In the context of an integrated circular floor-system design process, involves multiple stakeholders i.e. clients, architects, engineers, consultants and contractors. This chapter highlights the finding from the interviews with the stakeholders and summarizes the multi-disciplinary influences.

## 7.1. Understanding decision making within the integrated design process through expert interviews

To gain insight further insight into who and what questions on decision-making criteria and aspects that influence the design of an integrated floor-system in the context of circularity; A qualitative approach of one to one interviews was adopted. The aim of the interview was to cover the following broader topics with the stakeholders that largely form the interdisciplinary design team in the early stages of the project. The goal was to;

- understand the *interaction between different stakeholders* involved in the process, i.e. Structural engineer, MEP (Mechanical, electrical and plumbing) consultant, Architect and Client, who largely influence the design of the floor-system.
- understand *integration of the different design aspects* that takes priority for each stakeholder
- understand the state of *incorporating circular design strategies* in the design process and who drives/initiates it
- find out if efforts are taken to *evaluate the degree of circularity or environmental impact* of the different design solutions in order to make a decision
- Lastly, knowing the *wishes or expectations of the stakeholders for a decision support system* to assist the decision making process for a circular integrated floor-system

For the purpose of this research a questionnaire was prepared prior to the interviews and some pilot tests were carried out with peers to ensure the time and delivery of the questions are satisfactory. Refer appendix 6 for the complete questionnaire with respondent answers analyzed for each discipline.

A total of 10 participants were interviewed each representing one of the design domains i.e. Architecture, Structural Design and Building Physics, there was also one client interviewed to gain a broader perspective other than the design disciplines. The participant distribution and generic information is as illustrated in the charts in figure 60. The participation selection was based on years of experience in two brackets i.e. between 5 to 20 years and more than 20 years. This was important to acquire credible knowledge and to strengthen the understanding between criteria and its influences on the decision making processes. The type and size of firms the participants work in, gives an generic idea of the working dynamic and collaborations between them and other stakeholders.

Under this section the findings of the interview process are categorized into the four sections of interaction between stakeholder disciplines, interaction between components, incorporation of circularity and assessment towards circularity in current practice.

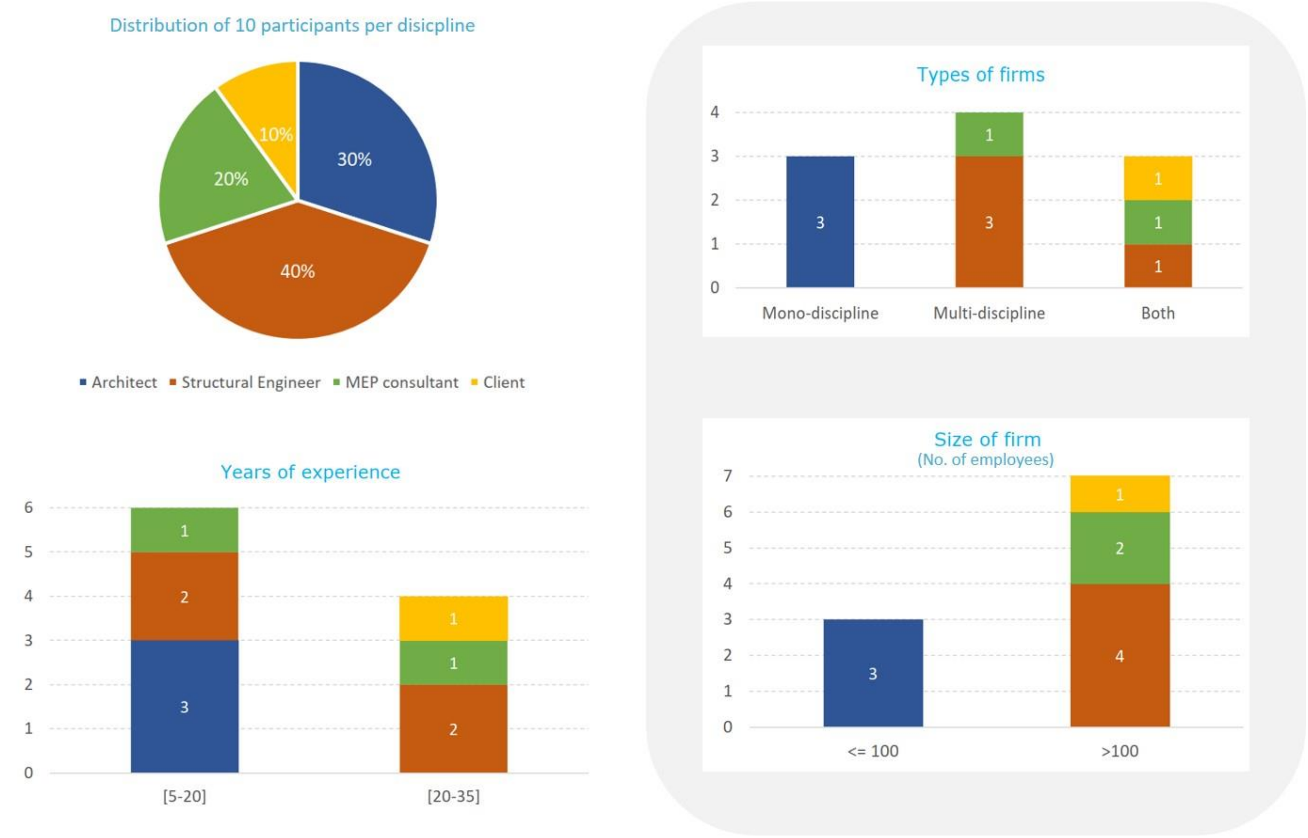


*Figure 60:Charts illustrating the participant distribution, years of experience, and type and size of firm*

### *7.1.1 Interaction between stakeholders and disciplines*

A project's design phase is typically divided into sketch design, preliminary design, definitive and execution phase. Each phase marks a certain level of detail to be achieved within the project. It was essential to find out in which stage of an office building design process do the multi-disciplinary stakeholders interact.

From the interviewed stakeholder, clients and most architects are involved from the sketch design phase where the design requirements (building type, functions and areas) and the architectural concept sketch/plan are defined respectively. The structural engineer and the MEP consultant mostly are involved after this phase, i.e. in the preliminary design phase. The information exchanged in this phase are largely regarding the technical requirements such as, fire resistance, materialization, sound insulation, size and weight of the structure and the installation placement or integration concept. This information is exchanged through preliminary plan and sections options and the selection of the desired option takes place on the basis of satisfying budget, sustainability, project related and regulation/standards specified requirements. In the context of this research this phase is of prime importance, as most decisions that influence towards a floor system are taken here. The discussions during this phase are carried out by holding meetings, or in some cases workshops, however, the most effective way of collaboration pointed out by the interviewees is through workshop sessions, where all disciplines work together in one space.

During the preliminary phase there are multiple challenges that are debated and discussed before the selection and finalization of one option towards an integrated floor-system to make definitive in the next phase.

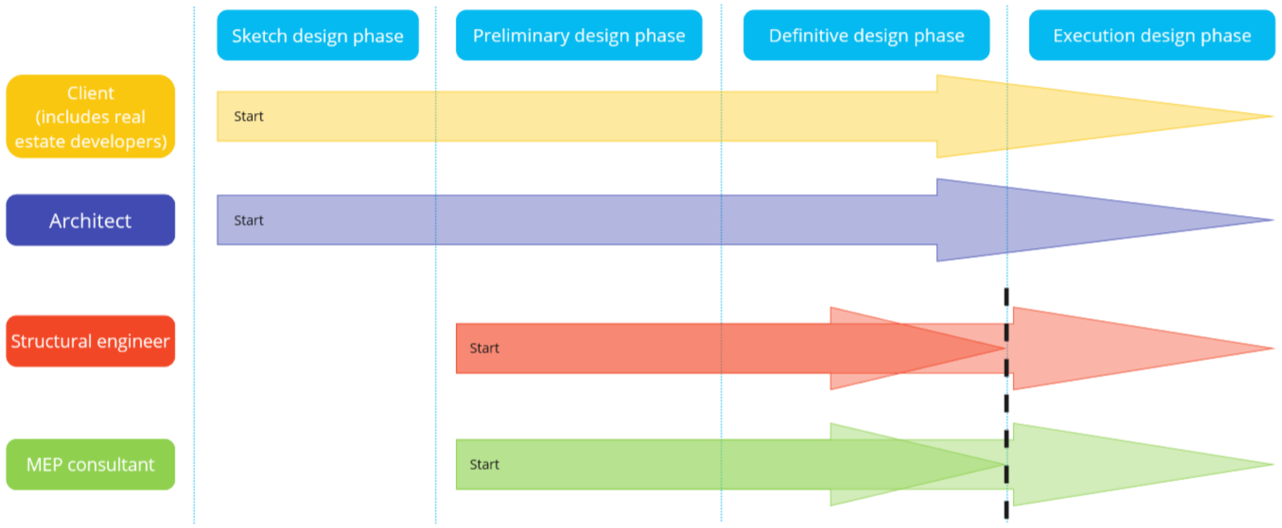
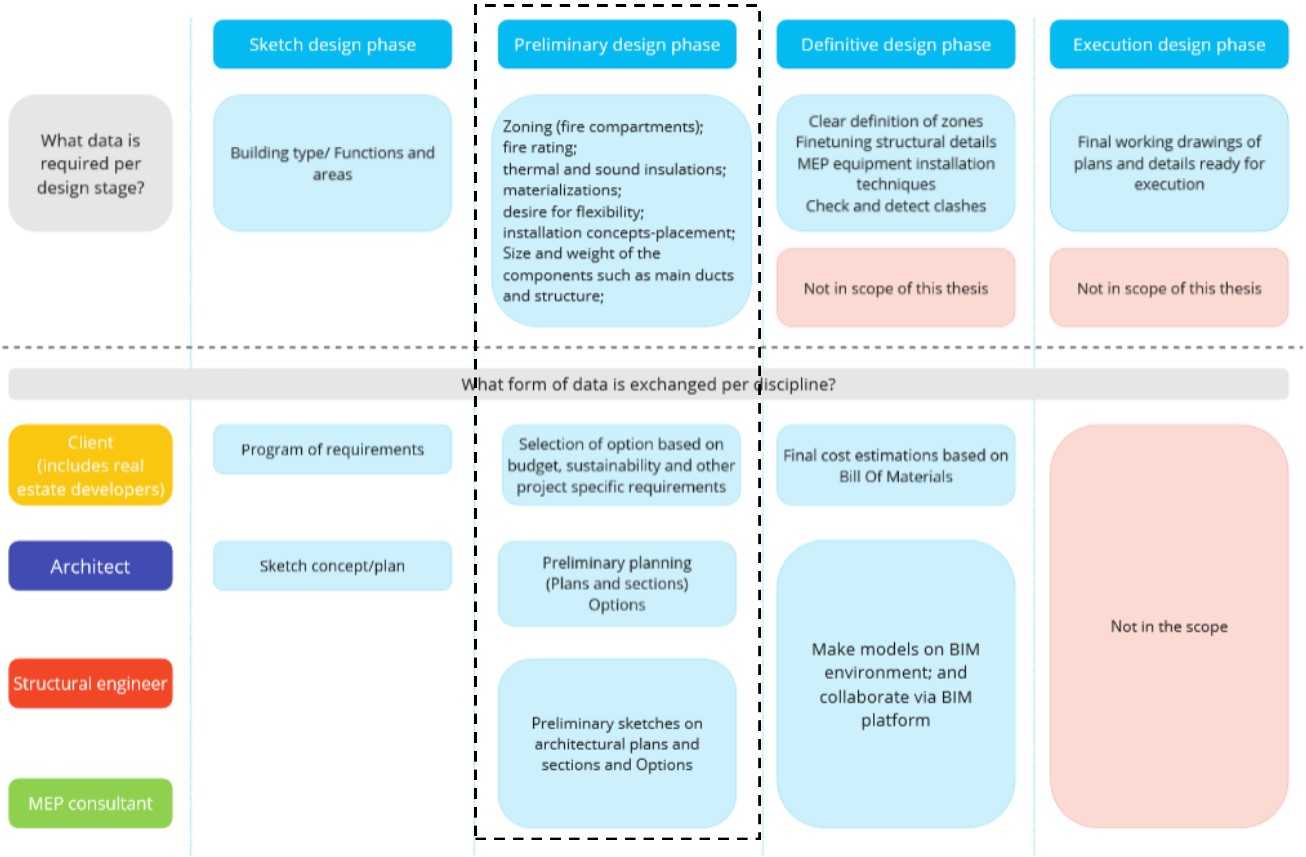


*Figure 61: Illustrating the design phases in which the different disciplines are first involved*



| | Sketch design phase | Preliminary design phase | Definitive design phase | Execution design phase |
|---|---|---|---|---|
| What data is required per design stage? | Building type/ Functions and areas | Zoning (fire compartments);<br>fire rating;<br>thermal and sound insulations;<br>materializations;<br>desire for flexibility;<br>installation concepts-placement;<br>Size and weight of the components such as main ducts and structure; | Clear definition of zones<br>Finetuning structural details<br>MEP equipment installation techniques<br>Check and detect clashes | Final working drawings of plans and details ready for execution |
| | | | Not in scope of this thesis | Not in scope of this thesis |
| What form of data is exchanged per discipline? | | | | |
| Client (includes real estate developers) | Program of requirements | Selection of option based on budget, sustainability and other project specific requirements | Final cost estimations based on Bill Of Materials | Not in the scope |
| Architect | Sketch concept/plan | Preliminary planning (Plans and sections) Options | Make models on BIM environment; and collaborate via BIM platform | |
| Structural engineer | | Preliminary sketches on architectural plans and sections and Options | | |
| MEP consultant | | | | |

*Figure 62: Details the data required and exchanged per design phase by the disciplines and highlights the preliminary design stage as the decision towards floor-system is taken here*

The figure on the right illustrates the challenges listed by the interviewees in a ranked order (by the number of times it was mentioned).

One of the most mentioned challenge was that of cost and not exceeded a budgeted target. However, this largely dependent on certain (material or installation selection or construction method) and uncertain (i.e. time) factors. The next most discussed topic is the MEP integration into the structure. Whether to integrate or not is always a debate, as this impacts the thickness of the overall floor-system. The thickness comes third followed by span. However, it is crucial as they impact the floor to floor height which then influences the cost.

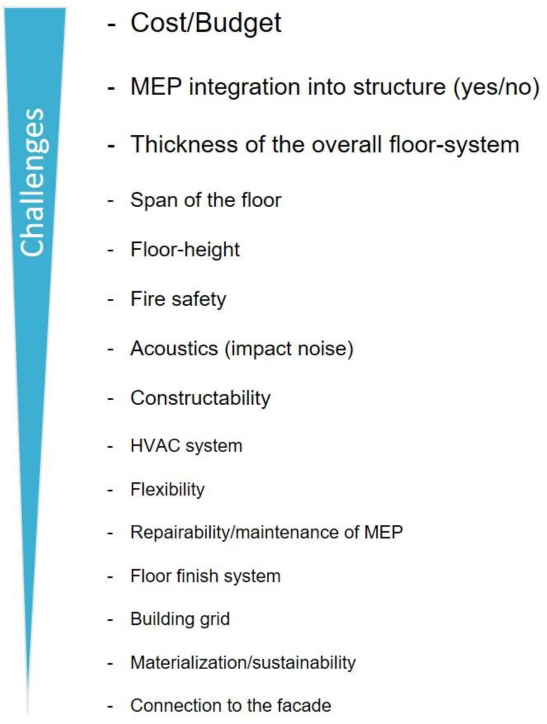


*Figure 63: Challenges ordered in the descending order based on the responses*

### *7.1.2 Integration of different components*

These listed challenges are faced when certain design requirements are to be met such as fire safety or sound insulation. For this there are multiple factors that influence the integration of the components in a floor-system such as flexibility. Some of these aspects are highlighted in the diagram, and these are also covered in the literature review in previous sections.

With respect to who largely influences the decision towards the optioneering and choice, it was found that the structural engineer usually drives it, however, the final decision-making veto is always with the client.

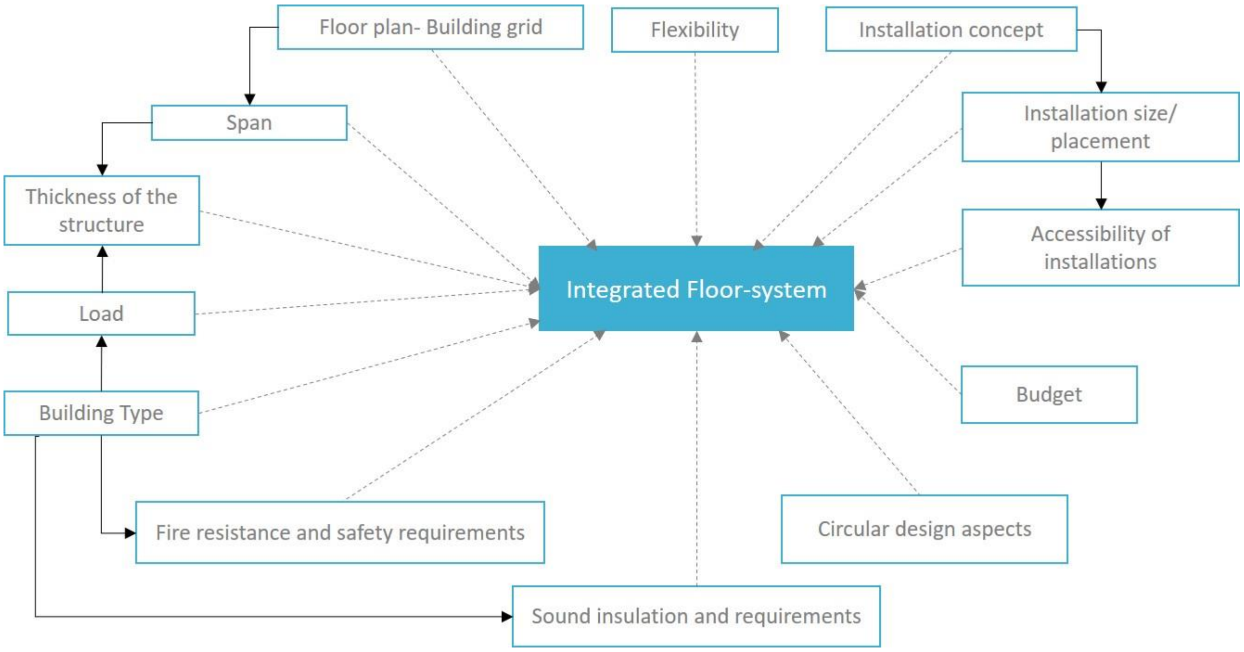


*Figure 64: Influence chart showing the different factors that influence the integrated floor-system*

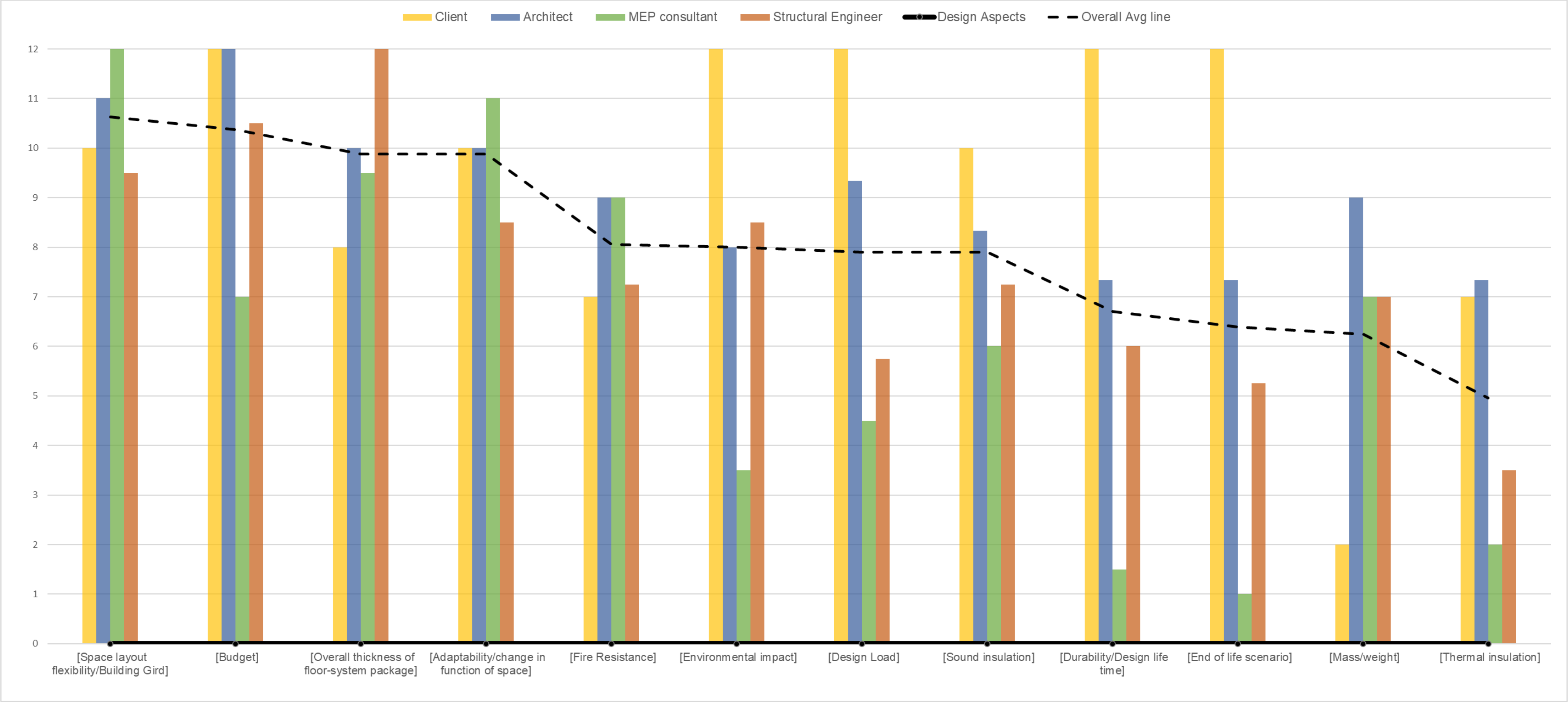


*Figure 65: Chart showing the design aspects that influence the integration of different components in a floor-system ordered in high-low priority based on responses*

Finally, to further understand which design aspect (criteria) takes the highest priority towards an integrated floor-system, with a multiple choice between, flexibility, budget, overall thickness of the floor-package, adaptability (change of function), fire safety, environmental impact, load, sound insulation, design life time, end of life scenario, mass, and thermal insulation. The highest ranked was flexibility, and the order follows the sequence of mention, as shown in graph.

### *5.1.3 Incorporation of circular design aspects in practice*

Majority of disciplines agree towards incorporating circular design strategies early in the design process while only a little more than half have actually implemented them in projects. The most used circular strategy in practice towards configuration of a floor-system is 'Design for maintenance'.

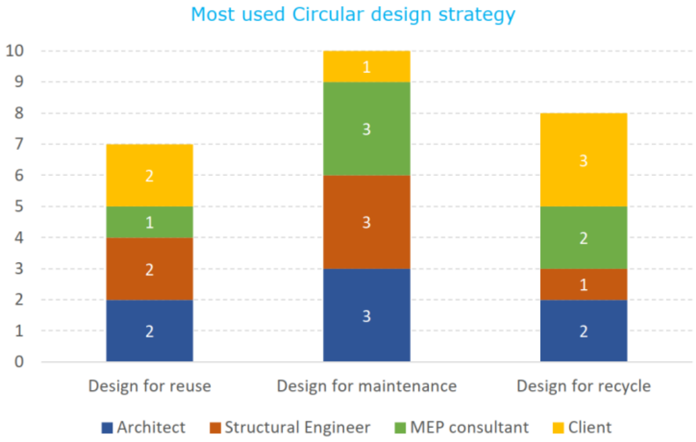


*Figure 66: Chart showing responses towards most circular strategy used in the context of integrated floor-system*

While the commonly considered life cycle scenario for office building design is where, the use life span of the building is lesser than technical life span of the building itself. To compare this with literature found, it holds true, as the rate of change of use is much higher which demands flexibility and adaptability of the structure.

Furthermore, among the stakeholders, it can be derived that the clients largely drives or initiates circular strategy or thinking approaches within a project. However, each discipline has a different view on who initiates which is illustrated in appendix 6, under section 4 of analyzed answers.

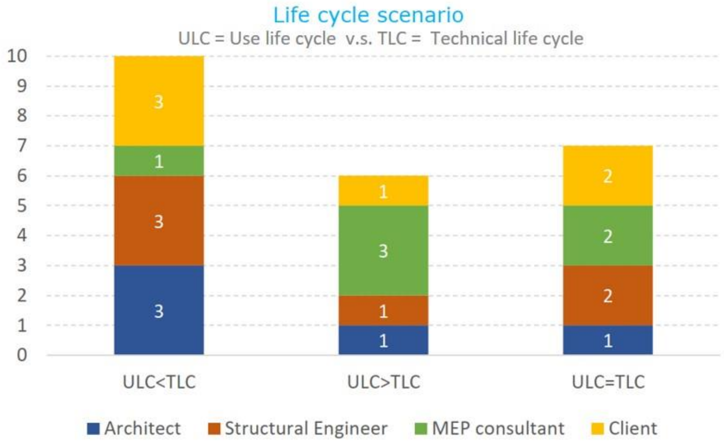


*Figure 67: Chart showing responses for the life cycle scenario assumed in practice for office buildings*

### *5.1.4 Assessment towards environmental impact, material circularity and disassembly*

Inventorying materials is key to estimate environmental impact in terms of shadow costs and for project budgeting

Assessing environmental impact is mostly done using validated MPG determination software by the NMD foundation, such as MPG calc. tool (DGMR, 2019) during the preliminary design phases.

Assessing circularity is still a gray area in practice, not much is known in relation to a score, however, it is integrated in the form of design aspects (such as disassembly) to add value towards circularity without really associating a number to it.

However, the most important criteria that takes priority, based on the responses, to reduce the environmental impact is materialization (mass and locally sourced), followed by carbon impact caused due to transportation, flexibility (demountable/disassembly), endless reuse, span of floor, budget (economical, environmental and societal) and finally insulation and energy consumption.

### *5.1.5 Wishes and expectations of the stakeholders for a decision support system*

From the responses the main aspects highlighted for the development of a decision support system are,

- it offers multiple options to compare
- it is informative (educated choice) and helps better integration/collaboration between disciplines
- Reduce Time and effort (quick evaluations to know impact on key performance indicators)
- Flexible (reversible) and transparent towards decision support

## 7.2. Multi-discipline criteria and choice influence mapping using existing literature and interview

### *7.2.1 Overview of factors influencing a circular integrated floor-system*

1. Building function – determines the usability criteria of structural performance (deformations, and applied loads) and building physics performance (fire resistance and sound insulation)
2. Building life span – determines the durability criteria under the structural performance and informs the long-term/short-term scenarios for service life planning
3. Building area (length and depth) – determines the total MPG – shadow costs for buildings products based on its functional unit measure.
4. Number of floors/ building height – informs the fire safety regulations and determines consequence class that apply to the structure
5. Floor to floor height –limits overall floor thickness package to ensure a comfortable usable volume, furthermore, it is a crucial estimator to building cost based on façade area and additional steps between floors.
6. Building grid – greatly influences the floor-plan flexibility and determines floor spans. It works in synergy with the building frame choice
7. Building frame choice – refers to the stabilizing system i.e. column beam or outrigger core, which largely influences the structural floor type and informs floor spans
8. Floor span – influences the thickness of the structural floor slab and is informed by the building grid
9. Load applied – depends on the program function and informs the thickness of the floor slab
10. Climate installation concept – informs the placement of the services (integration strategy) and the thickness of the ducts, which is crucial for determining overall thickness of floor-package
11. Integration strategy of services (MEP) – this largely influences the position or placement of the services and its interaction with other layers i.e. structure and space. Thereby influencing the flexibility of overall system i.e. adaptive capacity and disassembly aspects
12. Type of screed – influences the performance of the space layer, in terms of sound insulation and fire safety, furthermore it also impacts the thickness and accessibility to the services layer if integrated into the screed. The choice of wet or dry screed establish the connection type between layers that influence the disassembly aspects
13. Fire resistance – the lab tested fire resistance of products and materials influence the choice and selection to cater to the project specifications/ requirements

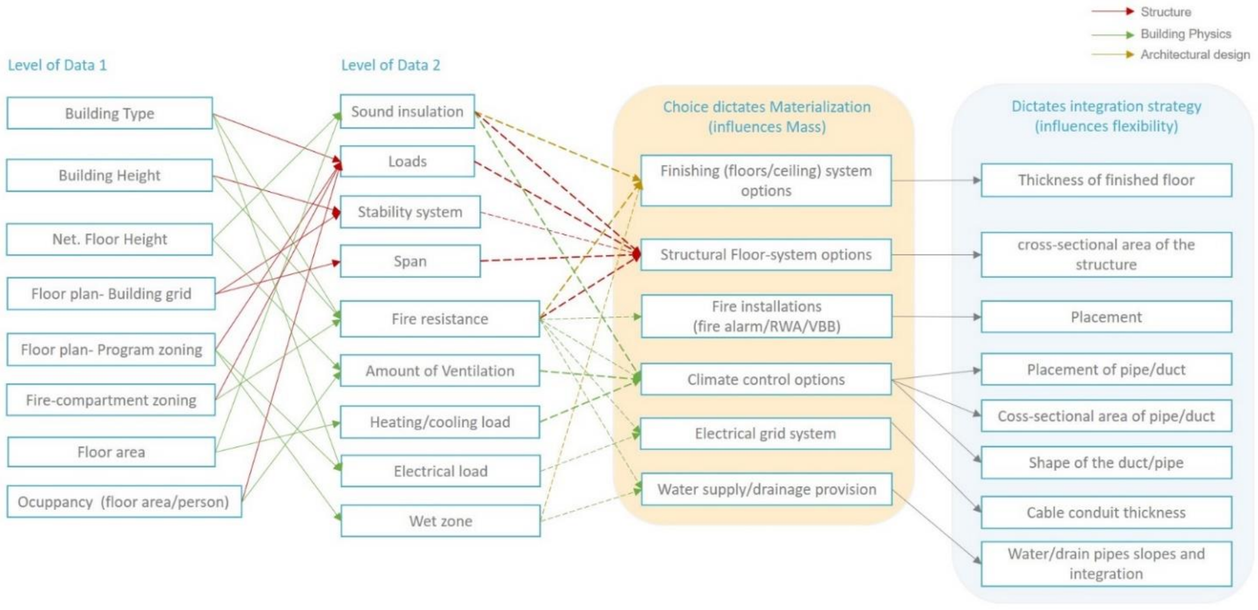
14. Sound insulation/absorption – the lab tested sound absorption of materials especially for the space layer (ceilings and floor screed/finishes) influences the choice and selection to cater to project specifications/requirements
15. Thickness of the package – The overall thickness of the package as mentioned in previous
16. Mass – the mass of the structural floor influences the contact sound performance and the vibrations caused by dynamic loads. It also impacts the material efficiency.
17. Flexibility – largely categorized into technical and spatial flexibility impacts the integration strategy of the overall configuration; it influences retaining the value of the products and materials in a scenario of change.
18. Material/Product choice – this is plays one the most important role and influences the environmental impact and material flow/balance in light of circularity.
19. Service life planning- comparing the use life span of the building to the technical life span for all building layers influences the value of the material usage for multiple life cycles and determines reusability, recyclability and maintenance/repurpose.

While all factors covered cater to either technical or functional aspects of the design, there are some aesthetic aspects such as the architectural look and feel of a product/material that sometimes drive certain choices. These are subjective and case dependent. However, highlights the need of visualizing the basic geometry of configurations.

### *5.2.2 Mapping influential relationships*

From the understanding through extensive literature study and interviews, a nearly comprehensive relation mapping is attempted to further inform a sequence to the influences, as illustrated in the figure 68.

While the sequence cannot be set in concrete, as this largely depends from project to project. The sequence is driven by requirements set by the design team (mostly clients and architects but sometimes with consultants too), which act as the starting points to approach the design problem. Therefore, the interview was valuable to set a starting point to approach the sequence for the design of an integrated floor-system. Flexibility, was the most mentioned/prioritized design aspect on an average by all disciplines.



(NEN, ISSO, Kennisbank)

*Figure 68: Influence diagram showing all the factors that influence the integrated floor-system in 4 levels (adopted from sources: NEN standards, ISSO, Kennisbank)*

*Flexibility as the most important criteria*

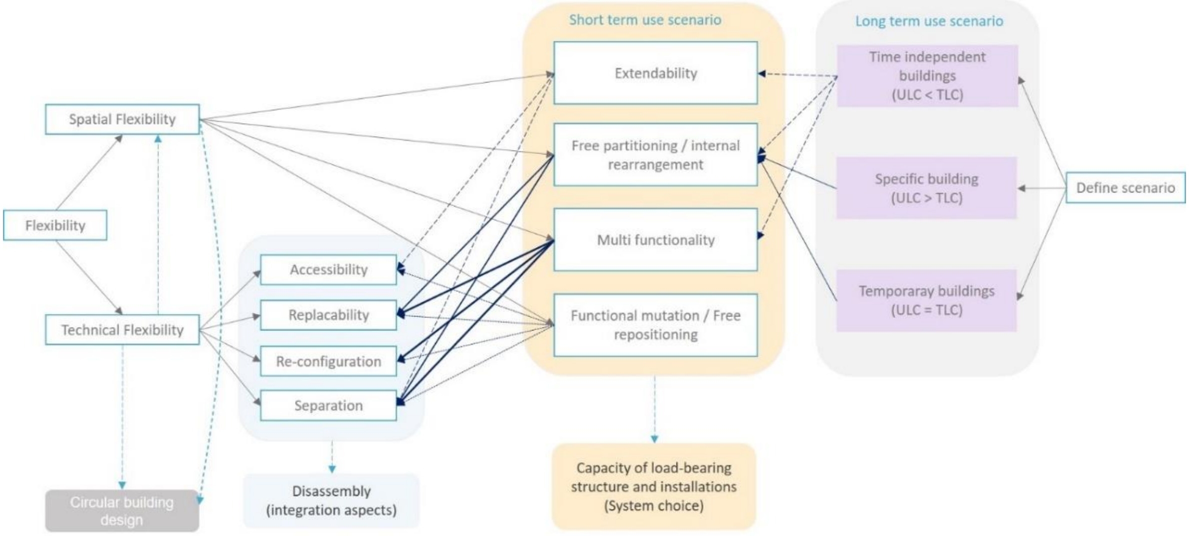
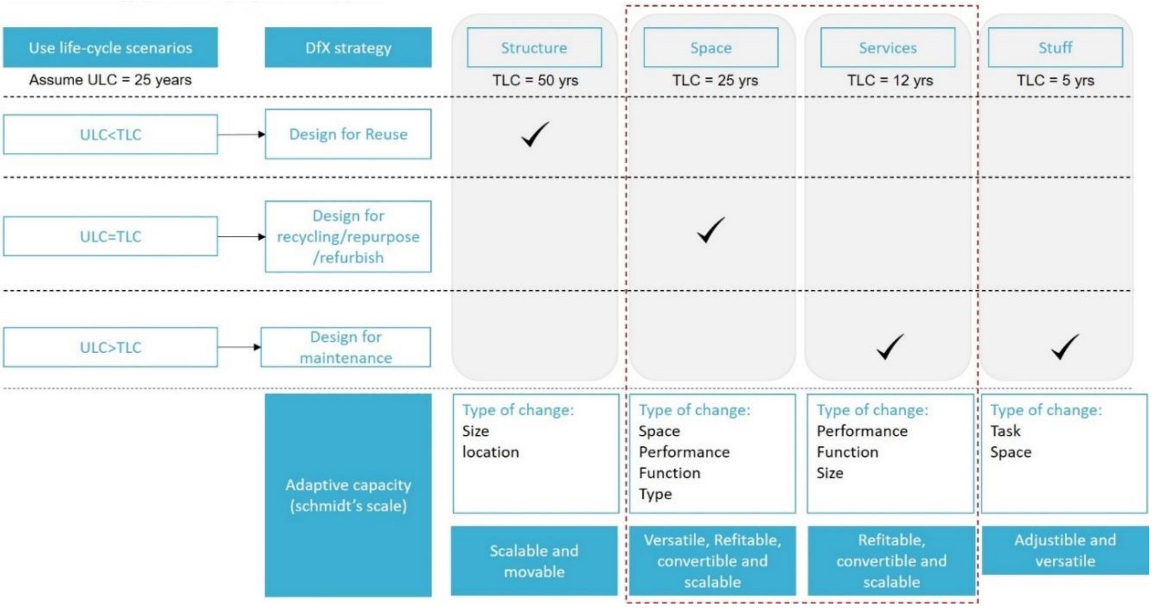


*Figure 68: The influence diagram showing the relations between the service life planning and flexibility (Adopted from E.Durmisevic, 2006)*

The figure 68, refreshes flexibility categorization mentioned by Durmisevic (2006), and relations between spatial flexibility and technical flexibility. However, these are largely dependent on the service life planning, determined by the long term and short term scenarios as mentioned in section 3.3.1. The use life cycle and technical life cycle is compared for each building layer involved in the floor-system which helps determine the circular design strategy to be applied as illustrated in figure 69. For example, if the use life cycle of the building is 25 years, and comparing it to the overall service layer of an average 12 years. The design strategy to be applied is that of maintenance. However, this also draws a close relation with the Schmidt's scale of adaptive capacity (appendix 4), on the type of change the building layers experience and their respective frequency.



| Use life-cycle scenarios<br>Assume ULC = 25 years | DfX strategy | Structure<br>TLC = 50 yrs | Space<br>TLC = 25 yrs | Services<br>TLC = 12 yrs | Stuff<br>TLC = 5 yrs |
|---|---|---|---|---|---|
| ULC<TLC | Design for Reuse | ✓ | | | |
| ULC=TLC | Design for recycling/repurpose /refurbish | | ✓ | | |
| ULC>TLC | Design for maintenance | | | ✓ | ✓ |
| | Adaptive capacity (schmidt's scale) | Type of change:<br>Size<br>location | Type of change:<br>Space<br>Performance<br>Function<br>Type | Type of change:<br>Performance<br>Function<br>Size | Type of change:<br>Task<br>Space |
| | | Scalable and movable | Versatile, Refitable, convertible and scalable | Refitable, convertible and scalable | Adjustible and versatile |

*Figure 69: Chart showing the relation between service life planning, the retaining value / DfX strategy applied and the associated type of change based on Schmidt's scale for each building layer (adopted from E.Durmisevic,2006; Measuring Circularity, 2020)*

From Schmidt's scale one can derive that space and services layer are highly susceptible to change after the stuff layer. Due, to the number of changes that affect them and frequency scale they change lies in, it can be marked crucial that the layer of space and services require to be more flexible compared to structural layer. Especially as change in space, performance, function and size affect these layers as shown in figure 69. Therefore, the integration of services such as pipes and ducts within the structure or the space layer greatly impacts the flexibility of the floor-system configuration.

*Systemization and clustering into building layer and material levels*

The next most important step to be addressed in the context of flexibility is the systemization and clustering of the products/materials into the building layers as mentioned in section 4.4.1. This largely supports the configuration process by distinguishing the building layers and its respective products/materials into their durability cycles. Therefore, highlighting the possible challenges during integration with respect to flexibility.

For this the products can be classified using the NL-Sfb coding system as illustrated in figure 28, categorizing them into the respective building layer and the product/material level.

*Environmental impact and material balance/flow*

The key towards environmental impact and knowing the material flow of the building products selected, is inventorying and cataloguing. Especially in case of environmental impact, the NMD foundation encourages the use of the validated databases as mentioned in section 4.5, to source the weighted shadow costs per functional unit of a material/product. While the material source and end of life information is still not available for all materials on a database, foundations of NMD and Nibe are in the constant process of development.

*Product and Material dependent properties*

Product and material dependent properties or specifications are usually available on manufacturers data/technical sheets. As mentioned inventorying material and product specific information can prove valuable not only for measuring material flow and environmental impact, but for material/product based performance. Therefore, pushing for a standard database such as the National Milieu Database, however, not only for environmental impact, also technical performance attributes such as lab tested certified, fire resistance, sound insulation/absorption of materials/products.

## 7.3 Conclusion

From the interview response analysis it is found that the decision towards the floor-system is done in the preliminary stages of design. The challenges faced towards the design of an integrated floor-system is cost, the MEP integration strategy and the overall thickness of the floor package. The most important design aspect regarding integration of different building layers in on configuration is flexibility. This is also highlighted in the literature review on the state of the art of integrated floor-systems.

However, measuring circularity seems to be a gray area in practice, as not all are very well aware of the concept and the indicators that contribute to the assessment. Circularity is associated to practices of designing for disassembly, however, no measurement is associated towards any indicators. Therefore, this shows there is a need for the design team of Structural engineers, Architects, MEP consultant for better support in relation to circularity related indicators while designing an integrated floor-system. This is largely owning to the close relation of integrated floor system and the topic of circularity to flexibility and demountability.

The relations drawn between the service life planning to the DfX strategy or retaining existing value highlights the need to begin the design with first setting the required building use lifespan before deciding on the integration strategy. This is largely to ensure the protection of the existing value the building layer specific product at the end of the first use life span. Finally, systemization and categorization of materials/products is key to assess environmental and material circularity related impacts.

# IV

# DSS DEVELOPMENT

# 8. Decision-support system for circular integrated floor-systems

## 8.1. Overview

*Purpose:* The need for a knowledge-based decision support system is to assist the Structural Engineers, Architects or the MEP consultants in the early stages of an office building project. It must help them make informed decisions regarding the floor-system choice and the service integration strategy especially in relation to circularity. The aim of the system is to show the impact of design criteria input on the circularity related objectives of protecting material stock, protecting the environment and the amount of flexibility due to services integration strategy (based on disassembly factor). Therefore to create such a system, the steps of development as illustrated in figure 70 are followed.

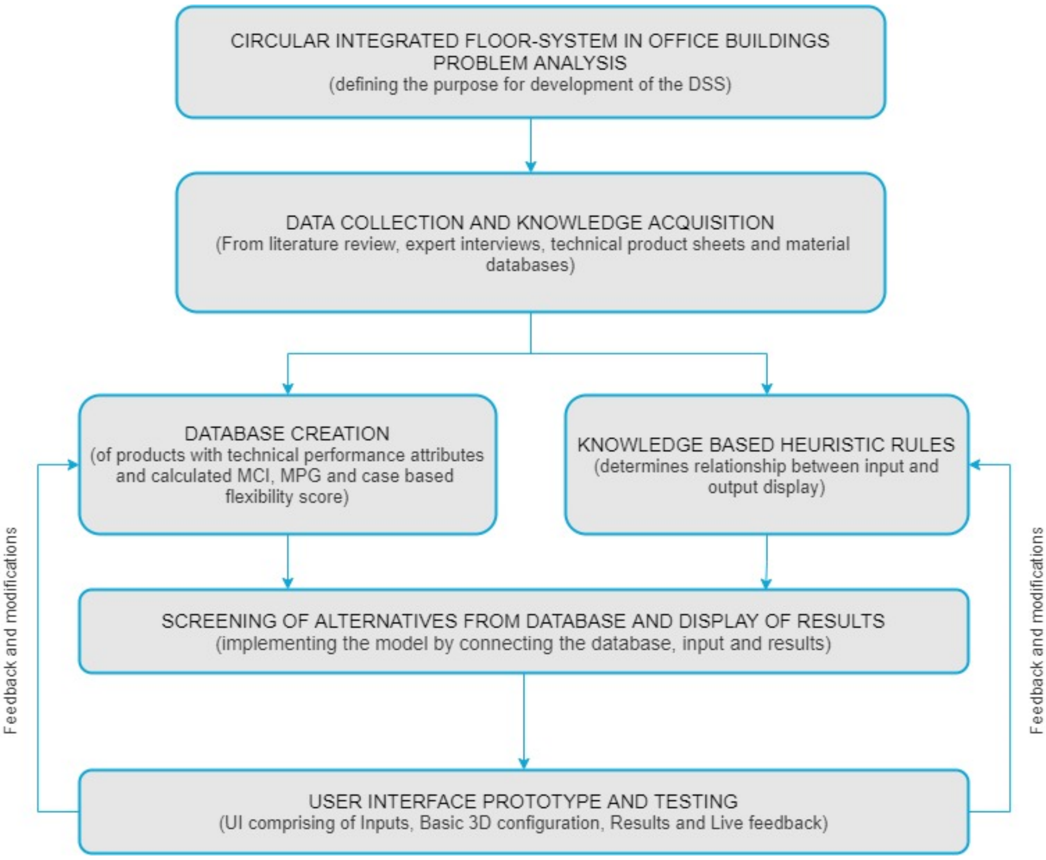


*Figure 70: Steps followed for the development of a Decision Support System for circular integrated floor-system in office buildings*

Step 1: First the problem was formulated by research to understand why such a system is essential and how it can contribute towards better decision in the preliminary design stages of the integrated floor-system design as mentioned in the previous paragraph.

Step 2: The extensive literature review and expert interviews contributed towards the development of a DSS that is a combination of data-driven and model-driven systems which is a common characteristic of a DSS as mentioned in section 6.1.1.

Step 3: The data gathered from technical data sheets, literature review, databases such as NMD, CES and Nibe contributed to populating the database with prefabricated/premanufactured building products categorized into respective building layers to create a centralized Knowledge Base. The knowledge gathered from understanding the relationships between the design aspects and integration strategy on the circularity indicators defines the model based on heuristic rules represented in the form of decision trees.

Step 4: Integration of the database and coding the conditional decision trees into one platform to define relevant inputs, a basic 3d model configuration and visualize results.

Step 5: Finally, creating a User interface prototype to test with the users and then implement feedback to improve it.

## 8.2 Development

### *8.2.1. Database*

The database is the knowledge engine of the proposed DSS development. A database approach is chosen to centralize all the data acquired from different sources to ensure better product level categorization and inventorying of materials into different building layers, as shown in the figure 71.

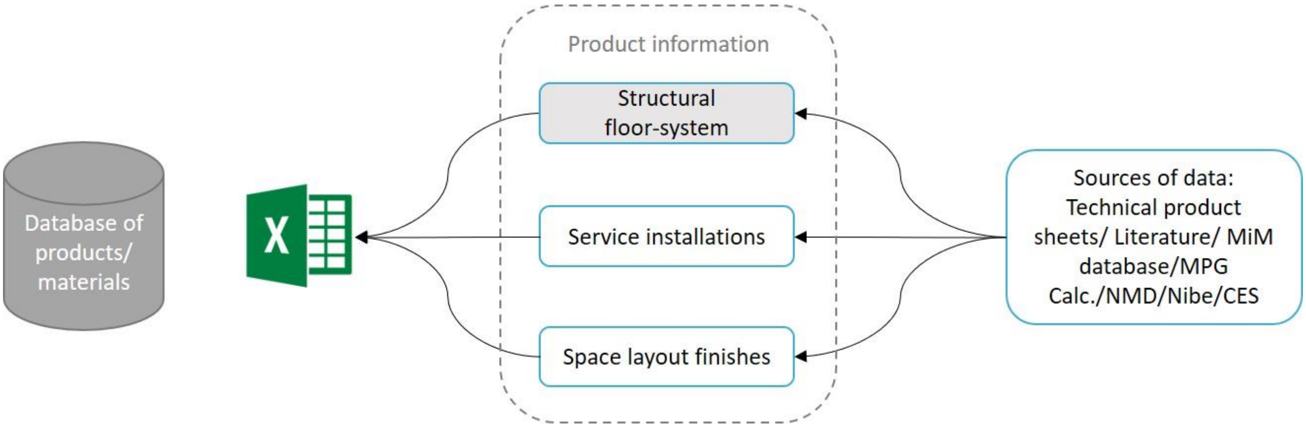


*Figure 71: Illustrating the building layer wise distinction of products and multi-disciplinary data storage into an Microsoft excel based database*

A database is beneficial as it can be used to store knowledge not only from one but multiple domains. In the case of circular integrated floor-systems, it allows for

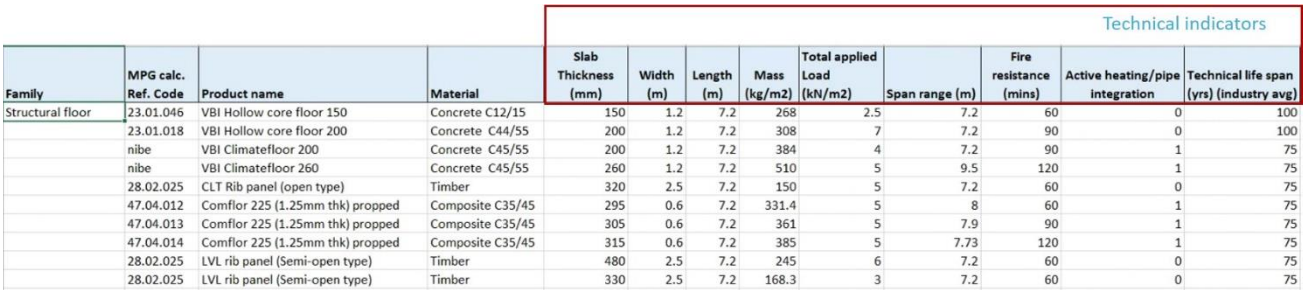
- Efficient categorization and systemization of products belonging to different building layer, i.e. Structure, Space or Services and provides the opportunity to associate them with a unique NL-Sfb based coding system for better standardization and identification
- storing multi-disciplinary quantitative information related to the technical performance attributes specific to the product based on function of the building layer from technical data sheets, figure 72. For example;

  *Structural layer (floor-slabs; loadbearing)* - Total applied load (kN/sqm), span (m), mass (kg/sqm), material (name), slab thickness (mm), fire resistance (mins), technical life span (years)

  *Services layer (air treatment; distribution channels)* – shape, cross-sectional diameter (mm), operating temperature (deg), technical life span (years), material (name), fire rating/coating (mins or yes/no)

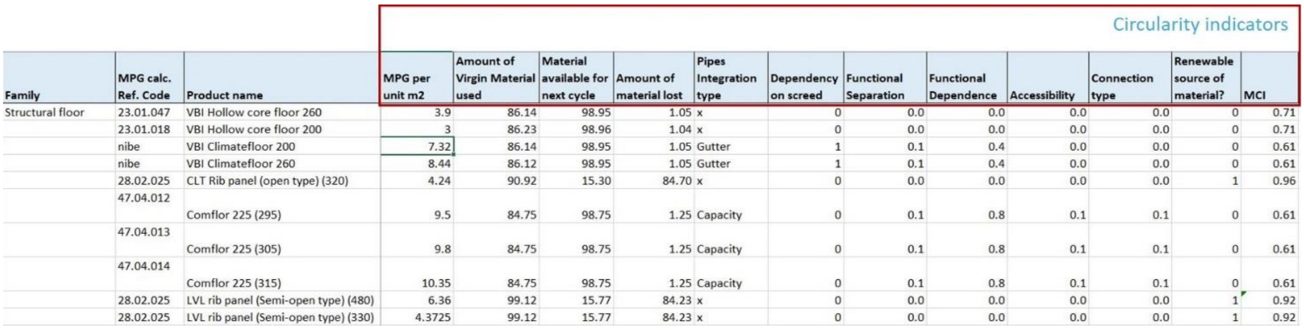
  *Space layer (floor finish; elevated; installation floor)* – thickness (mm), material (name), sound absorption/insulation value; fire resistance (mins)

  And at the same time information related to the circularity indicators such as MCI and MPG value per product as manually precalculated values and sourced values from databases such as NMD/Nibe/CES or isolated software application such as MPG calc, respectively.



Technical indicators

| Family | MPG calc. Ref. Code | Product name | Material | Slab Thickness (mm) | Width (m) | Length (m) | Mass (kg/m2) | Total applied Load (kN/m2) | Span range (m) | Fire resistance (mins) | Active heating/pipe integration | Technical life span (yrs) (industry avg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Structural floor | 23.01.046 | VBI Hollow core floor 150 | Concrete C12/15 | 150 | 1.2 | 7.2 | 268 | 2.5 | 7.2 | 60 | 0 | 100 |
| | 23.01.018 | VBI Hollow core floor 200 | Concrete C44/55 | 200 | 1.2 | 7.2 | 308 | 7 | 7.2 | 90 | 0 | 100 |
| | nibe | VBI Climatefloor 200 | Concrete C45/55 | 200 | 1.2 | 7.2 | 384 | 4 | 7.2 | 90 | 1 | 75 |
| | nibe | VBI Climatefloor 260 | Concrete C45/55 | 260 | 1.2 | 7.2 | 510 | 5 | 9.5 | 120 | 1 | 75 |
| | 28.02.025 | CLT Rib panel (open type) | Timber | 320 | 2.5 | 7.2 | 150 | 5 | 7.2 | 60 | 0 | 75 |
| | 47.04.012 | Comflor 225 (1.25mm thk) propped | Composite C35/45 | 295 | 0.6 | 7.2 | 331.4 | 5 | 8 | 60 | 1 | 75 |
| | 47.04.013 | Comflor 225 (1.25mm thk) propped | Composite C35/45 | 305 | 0.6 | 7.2 | 361 | 5 | 7.9 | 90 | 1 | 75 |
| | 47.04.014 | Comflor 225 (1.25mm thk) propped | Composite C35/45 | 315 | 0.6 | 7.2 | 385 | 5 | 7.73 | 120 | 1 | 75 |
| | 28.02.025 | LVL rib panel (Semi-open type) | Timber | 480 | 2.5 | 7.2 | 245 | 6 | 7.2 | 60 | 0 | 75 |
| | 28.02.025 | LVL rib panel (Semi-open type) | Timber | 330 | 2.5 | 7.2 | 168.3 | 3 | 7.2 | 60 | 0 | 75 |



Circularity indicators

| Family | MPG calc. Ref. Code | Product name | MPG per unit m2 | Amount of Virgin Material used | Material available for next cycle | Amount of material lost | Pipes Integration type | Dependency on screed | Functional Separation | Functional Dependence | Accessibility | Connection type | Renewable source of material? | MCI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Structural floor | 23.01.047 | VBI Hollow core floor 260 | 3.9 | 86.14 | 98.95 | 1.05 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.71 |
| | 23.01.018 | VBI Hollow core floor 200 | 3 | 86.23 | 98.96 | 1.04 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.71 |
| | nibe | VBI Climatefloor 200 | 7.32 | 86.14 | 98.95 | 1.05 | Gutter | 1 | 0.1 | 0.4 | 0.0 | 0.0 | 0 | 0.61 |
| | nibe | VBI Climatefloor 260 | 8.44 | 86.12 | 98.95 | 1.05 | Gutter | 1 | 0.1 | 0.4 | 0.0 | 0.0 | 0 | 0.61 |
| | 28.02.025 | CLT Rib panel (open type) (320) | 4.24 | 90.92 | 15.30 | 84.70 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | 0.96 |
| | 47.04.012 | Comflor 225 (295) | 9.5 | 84.75 | 98.75 | 1.25 | Capacity | 0 | 0.1 | 0.8 | 0.1 | 0.1 | 0 | 0.61 |
| | 47.04.013 | Comflor 225 (305) | 9.8 | 84.75 | 98.75 | 1.25 | Capacity | 0 | 0.1 | 0.8 | 0.1 | 0.1 | 0 | 0.61 |
| | 47.04.014 | Comflor 225 (315) | 10.35 | 84.75 | 98.75 | 1.25 | Capacity | 0 | 0.1 | 0.8 | 0.1 | 0.1 | 0 | 0.61 |
| | 28.02.025 | LVL rib panel (Semi-open type) (480) | 6.36 | 99.12 | 15.77 | 84.23 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | 0.92 |
| | 28.02.025 | LVL rib panel (Semi-open type) (330) | 4.3725 | 99.12 | 15.77 | 84.23 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | 0.92 |

*Figure 72: Showing the database populated with structural floor systems with associated technical and circularity related indicators*

- storing other qualitative knowledge related data based on yes or no (Boolean values) for example in case of structural layer aspects such as concrete core activation and fully prefabricated or partial prefabricated. It could also store information based on applicable integration typology indicating whether the product follows a capacity model or gutter model typology.

Therefore, it offers flexibility towards the kind of data stored whilst posing the opportunity to scale it or expand when necessary.

### 8.2.2. Input and Output

Deciding the inputs and the outputs for this DSS is an important aspect, especially to ensure it supports the user make informed decision in choosing the appropriate floor-system and integration strategy, by quick demonstration of impact caused by the set input criteria on the circularity indicators.

The ***inputs*** for this system can be broadly categorized as building specific parameters, technical criteria and Integration choice for services.

1. *Building specific parameters* cater to the general inputs of building function, building area, use life span, floor-to floor height and overall building height, these are specific to the project
2. *Technical Criteria* are parameters that are specific to building layers of structure, services or space that help screen/filter out the products form the database. There is a direct relationship of these criteria with the technical performance attributes populated in the database; for example the technical input criteria per layer are,

    (Structural layer; floor slabs) – floor span (m), total load applied (kN/m2), Mass/self-weight (kg/m2) and fire resistance (mins)

    (Services; air-treatment) – duct shape (round/rectangular/oval), and diameter/cross-sectional width or height (mm), fire rating (mins)

    (Space; screed) – thickness (mm), sound absorption/insulation value; fire resistance (mins)

3. *Integration choice for services* contain yes/no or qualitative inputs towards integration scheme of pipes in screed or floor slab and ducts in the beams or below the beams, these choices directly impact the flexibility (DfD factors) and the typology of integration. For example;

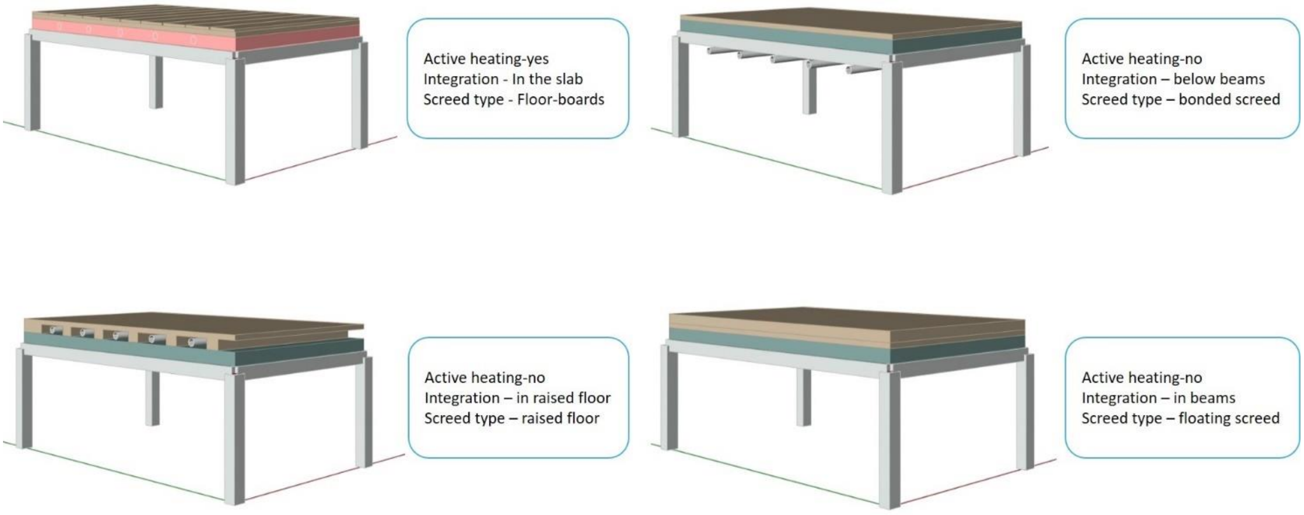
    For integration of pipe in floor-slab or screed, inputs are Concrete core activation or floor-heating determining the integration typology. Which impacts the input choices of screed typologies that can be applied i.e. bonded, unbonded, floating, raised floor, or floor boards.

    For integration of ducts into the floor-system, the input are integration choice of below the beams or in-between the beams and the choice of covering the ducts with a suspended ceiling.

The ***outputs*** for this system can be categorized into the display of *applicable products* remaining from the database (filtered by the technical criteria limits set in the inputs) and the corresponding assessment on circularity indicators of *material balance, MCI, MPG and flexibility* (based on the weighted DfD factors). The results can be displayed in the form of tables and graphs. Furthermore, the *existing value of the product* is an additional output that highlights if the product can be reused/recycled/maintained after its first use cycle (based on service life planning).

Another additional aspect to the output is the option of *analyzing the input/ live feedback*. This is an important part of the outputs especially as it educates the user regarding the eliminated options by highlighting which technical criteria input it does not satisfy/satisfy.

Lastly, a *basic 3D configuration* is another output component that helps the user understand the implications of their integration choices set on the visual configuration of the integrated floor-system, as shown in the figure 72.



Active heating-yes
Integration - In the slab
Screed type - Floor-boards

Active heating-no
Integration – below beams
Screed type – bonded screed

Active heating-no
Integration – in raised floor
Screed type – raised floor

Active heating-no
Integration – in beams
Screed type – floating screed

*Figure 72: Demonstrating the basic 3D visualization of the configuration based on integration choice inputs*

### *8.2.3. Heuristic rule based decision tree and data flow model*

To connect the separate components of the inputs, outputs and the centralized database of data/knowledge, a heuristic rule based decision tree is developed based on simple mathematical logic and knowledge gathered from the literature research/expert interviews.

The decision tree follows a conditional logic for data flow that is initiated when the inputs are set which interacts with the database to filter products, share live feedback, create a basic 3d configuration and display the corresponding circularity related results.

The following figure 73 illustrates the decision tree and indicates the data flow model governed by heuristic rules for the development of a DSS to assist decisions towards integrated floor-system while showing the impacts on the circularity indicators. The model can be read from left to right, starting from the different kinds of data input that used to directly compare with the product attributes from the database and therefore process results based on some conditional decision nodes that either is a yes/no input or comparing numeric values to finally display the mentioned results.

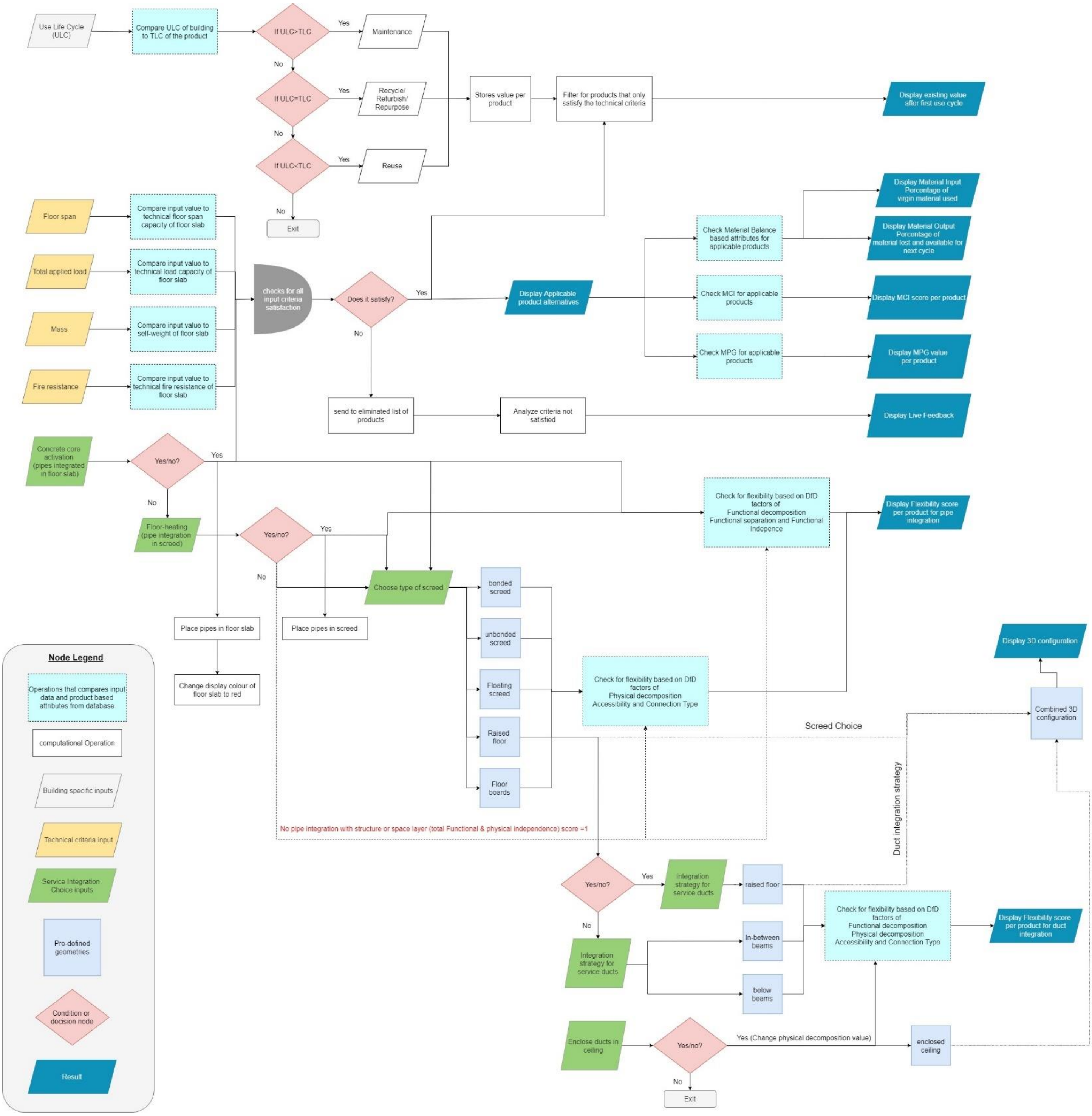


*Figure 73: Decision Tree and data flow model for a DSS to support circular integrated floor-system decisions*

### 8.2.4. Implementation

To implement this heuristic logic and develop/demonstrate the potential of the proposed DSS scheme for circular integrated floor-systems, a Dashboard based design tool (DDT) approach is adopted. A DDT approach form literature proves to be interactive, insightful, informative, adaptable, open to many typologies and fast. This aligns with the wishes/expectations of the users as discussed in section 5.1.5. To make it more collaborative between the different users, such an approach can be translated to a service oriented DSS (in cloud) providing Analytics-as-a-Service(AaaS). Furthering possibilities of scalability and scope in relation to usability of this system.

To provide a prototype level demonstration of the proposed DSS system, the AEC industry wide used software of Rhinoceros and plugin of Grasshopper (McNeel, 2021) is adopted. This decision is made based on the potential demonstrated by state of the art applications in AEC discussed in section 6.2.

The workflow therefore is structured as illustrated in the figure 74, and shows the interaction between the different programs and the grasshopper plugins utilized for implementation.

The grasshopper environment aid in the transferring the decision tree into a codified representation model, with its versatile interaction with;

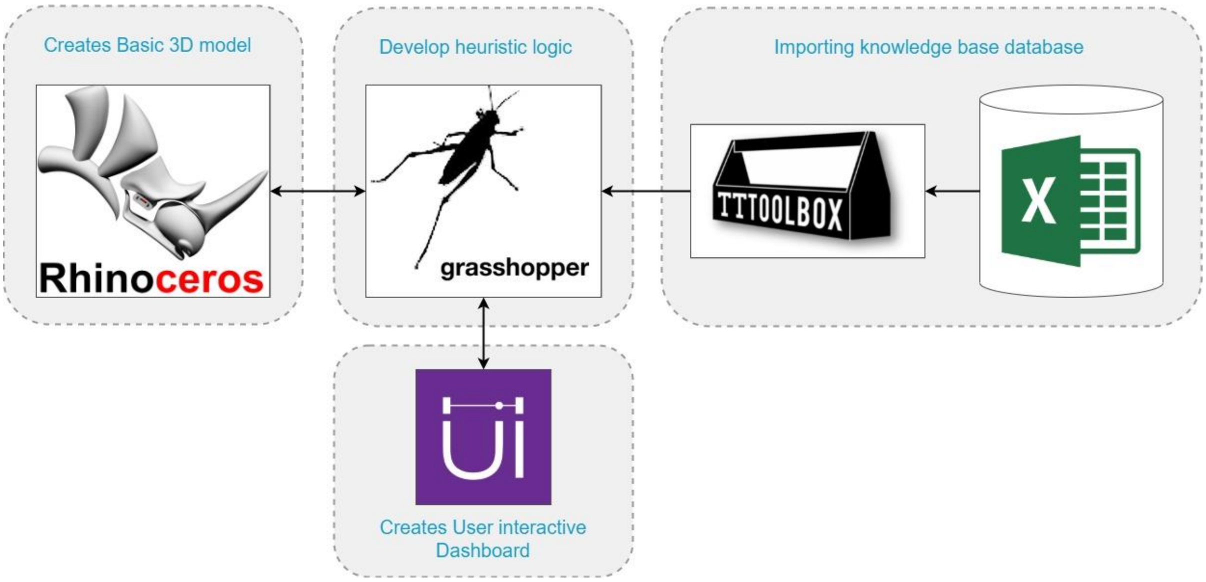


Figure 74: Demonstrating the workflow used to implement the DSS as a DDT

- Excel powered by TT Toolbox (*TT Toolbox - Addon for Grasshopper | Grasshopper Docs*, n.d.), enables importing all information fields from the database that can be processed using grasshopper based on the heuristic logic
- Rhinoceros (*Rhino - About McNeel*, 2021), is instrumental in creating a basic 3D configuration of the integrated floor-system which can be generated in the grasshopper environment and linked to the dashboard
- Human UI (*Human UI - Addon for Grasshopper | Grasshopper Docs*, n.d.), facilitates the creation of a dashboard based design tool with interactive user interface, that interacts with user to input data on the dashboard, returns values to the grasshopper interface which inturn delivers the results to display

### *8.2.5. Dashboard based design tool - User Interface concept*

An interactive dashboard on the front-end is conceptualized as illustrated in the figure 75, it facilitates a centralized platform to set input and visually display 3D configuration, share live feedback and results in the form of tables and graphs.

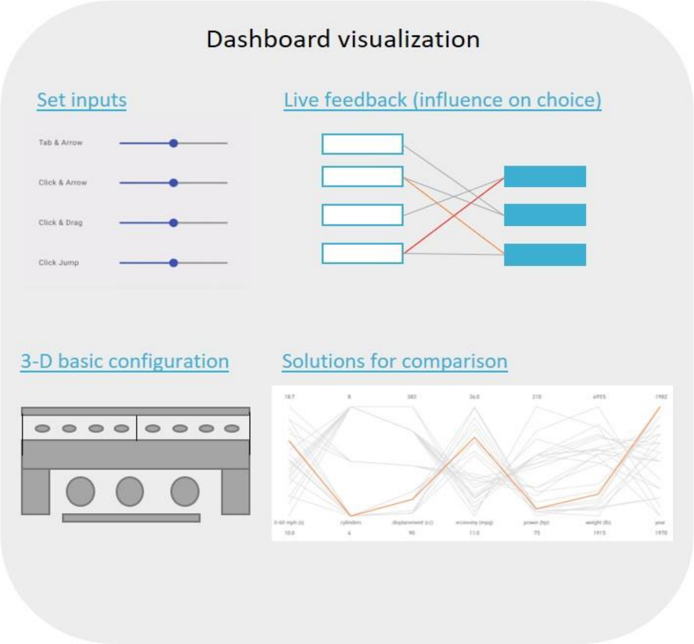


*Figure 75: Illustrating a conceptual representation constituting of all the components in an interactive DDT*

To materialize the DSS development based on a DDT, a prototype is developed to implement the framework and test with the users the extent to which such a system assists them in making informed decision towards a circular integrated floor-system.

# V

# DSS Prototype & Testing

# 9. DSS Prototype

To implement the proposed DSS model as a Dashboard based Design tool (DDT), a prototype of the same is developed on the Rhinoceros plugin of Grasshopper. This prototype is the medium for testing the overall DSS model to check the extent of support such a framework provides for users to make better decisions for floor-systems choices and pipe integration strategy in early/preliminary design stages of a project.

## 9.1 Demonstration of working prototype using the Dashboard Interface

### *9.1.1 Assumptions, Boundary conditions and general information of data sourcing*

The prototype is developed keeping certain assumptions and boundary conditions towards development to ensure the overall potential of this DSS system can be portrayed.

The assumptions made for this model is that it is facilitates alternatives of floor-system options only for office spaces where round duct pipes of 300 millimeters diameter is to be installed. It also is developed assuming that the building framing system follows a column and beam structure with floor slabs spanning at least 7.2 meters.

The boundary condition is that the development of database is restricted to only structural layer products of floor slabs, with prefabricated or partially prefabricated options of 10 numbers in total. The material options distribution within the 10 products alternatives are 2 concrete hollow core floor slabs, 2 concrete climate floor slabs (with provision to integrate service pipes), 3 steel concrete composite floors, 1 CLT ribbed panel and 2 LVL rib panel. These numbers represent the different variation in the slab thicknesses.

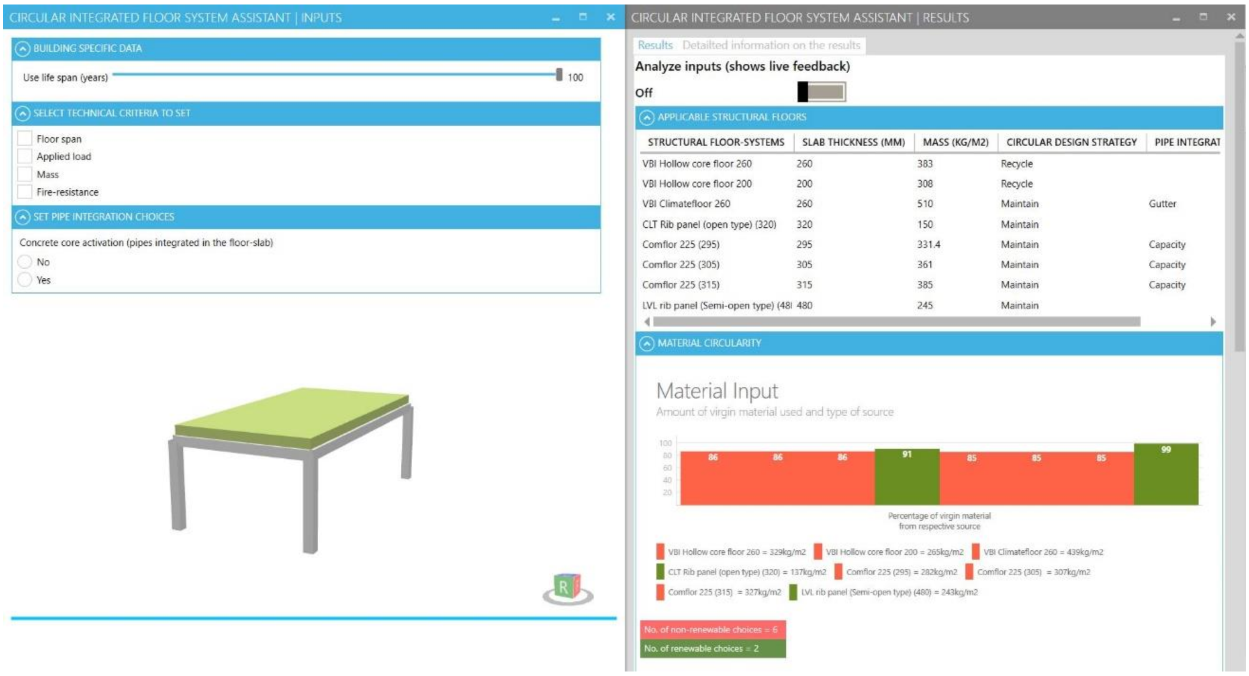
The assessment of circularity indicators of Material balance, MCI, MPG and the Flexibility aspects is being pre-calculated and manually entered into the database for the reasons mentioned in section 8.2.1. To reinstate it provide a direct relational link with the unique product code and centralizes are product specification in one platform. However, the units assumed for MPG values are per functional unit area of the product which is a standardized unit of measurement found in MPG calc. (DGMR, 2019) and all product codes are taken form the same source, if not mentioned otherwise. To assess material balance values of percentage of virgin material, percentage of material lost and percentage of material available for the next cycle; material input related factors were sourced from Nibe database (*Nibe Database on Environmental and Health Data of Construction Products*, 2019) or CES material database (*Ansys (CES) Granta EduPack | Software for Materials Education*, n.d.). To calculate the MCI, the formulae reviewed in literature were implemented. For the flexibility related aspects based on disassembly factors, only Functional decomposition and Physical decomposition were considered. This is largely due to the inferences from literature, that an integrated floor-system typologies dictate the functional dependency and separation variables under functional decomposition. Furthermore, in terms of maintenance or disassembly of the integrated services, accessibility and connection type are determining that dictate the physical decomposition aspects.

Finally, all the other technical performance attributes have been sourced from technical data sheets as provided on manufacturers websites. And for the qualitative aspects of integration typology type and renewable and non-renewable or dependency on screed for integration in case of climate floors (gutter model), these are an inference from reviewed literature. For detailed overview of the values used refer to appendix.

### *9.1.2 Walk-through of the Dashboard based design tool*

#### *Configuration*

The dashboard is controlled by the running Grasshopper script at the back end, which is connected to the data in the Excel based database. The Dashboard shown in figure 76, is the first preview of the design tool. It has been divided into two windows, the inputs window (left) and outputs window (right)



Use life span (years) 100

☐ Floor span
☐ Applied load
☐ Mass
☐ Fire-resistance

Concrete core activation (pipes integrated in the floor-slab)

○ No
○ Yes

Analyze inputs (shows live feedback)

Off

| STRUCTURAL FLOOR-SYSTEMS | SLAB THICKNESS (MM) | MASS (KG/M2) | CIRCULAR DESIGN STRATEGY | PIPE INTEGRAT |
|---|---|---|---|---|
| VBI Hollow core floor 260 | 260 | 383 | Recycle | |
| VBI Hollow core floor 200 | 200 | 308 | Recycle | |
| VBI Climatefloor 260 | 260 | 510 | Maintain | Gutter |
| CLT Rib panel (open type) (320) | 320 | 150 | Maintain | |
| Comflor 225 (295) | 295 | 331.4 | Maintain | Capacity |
| Comflor 225 (305) | 305 | 361 | Maintain | Capacity |
| Comflor 225 (315) | 315 | 385 | Maintain | Capacity |
| LVL rib panel (Semi-open type) (48 | 480 | 245 | Maintain | |

🟥 VBI Hollow core floor 260 = 329kg/m2
🟥 VBI Hollow core floor 200 = 265kg/m2
🟥 VBI Climatefloor 260 = 439kg/m2
🟩 CLT Rib panel (open type) (320) = 137kg/m2
🟥 Comflor 225 (295) = 282kg/m2
🟥 Comflor 225 (305) = 307kg/m2
🟥 Comflor 225 (315) = 327kg/m2
🟩 LVL rib panel (Semi-open type) (480) = 243kg/m2

No. of non-renewable choices = 6
No. of renewable choices = 2

*Figure 76: The first preview of the Dashboard User interface when launched.*

- *Inputs Window*: the one on the left is the inputs window that comprises of all the necessary inputs in the order from top starting with building specific data, technical criteria (set as per user preference), and service integration choices. The 3D basic configuration is the last component at the bottom, displaying the integration typology based on inputs.
- *Outputs Window:* the second one on the right is the outputs window, comprising of three tabs, results, live feedback and detailed information on results. The main tab of results displays the applicable floor-system alternatives in a tabular representation and displays all the circularity related indicators (Material circularity, MPG and Flexibility). The toggle of analyze inputs when enabled shows the live feedback tab where eliminated floor-system options are assigned a satisfactory (ok) or not satisfactory (x) mark under each technical criteria to educate the user of the impact due to input. Finally the last tab highlights all the result related information, such as, service life planning scenarios, description on the integration typology models, the flexibility score table depicting the significance of the DfD factor score.

*Single Case based working demonstration*

A single case based step-wise demonstration is discussed to demonstrate the usage of this tool. However, multiple cases are possible with developed prototype, that shows the potential of this approach.

*Steps for setting inputs*

Step 1: The user starts by setting the building layer specific input of Use life span, this impacts the service life planning scenario after end of first life cycle i.e. if the product is reused, recycled or maintained. (let's assume user sets it to 100 years)

Step 2: The next step is for the user to select the technical criteria for their design case, this filters the applicable structural floors systems alternatives based on the step 3. (let's assume floor-span, applied load, and fire resistance criteria are to be set by the user)

Step 3: The slider for the selected criteria appear and the slider can be adjusted to the preferable value or changed by double-click and entering the desired value. (Assume: Floor-span is 7.2m, total Applied load is 5kN, and fire resistance is set to 60 mins)

Step 4: Pipe integration choices are to be set, starting with concrete core activation, if set to NO, followed by pipe integration in the screed, and choice of screed type. (Assume: concrete-core activation is NO, pipes are integrated in screed is YES, and choice of screed is raised floor)

Step 5: User must select duct integration strategy, here the default will be raised floor, as this particular screed type provides for integration of not only pipes but also other service installation, in this case ducts.

The figure 77 displays the results of the steps taken so far in setting the inputs.

BUILDING SPECIFIC DATA

Use life span (years) 100

SELECT TECHNICAL CRITERIA TO SET

☑ Floor span
☑ Applied load
☐ Mass
☑ Fire-resistance

SET TECHNICAL CRITERIA LIMIT

Floor Span 7.2
Total applied load (kN/m2) 5
Fire resistance (mins) 60

SET PIPE INTEGRATION CHOICES

Concrete core activation (pipes integrated in the floor-slab)
● No
○ Yes

Pipes integrated in the screed
○ No
● Yes

Choose type of screed: raised floor

SET DUCT INTEGRATION CHOICES

Choose duct integration strategy: in raised floor

*Figure 77: Showing all the assumed values/choices in the inputs window with the configured 3D model*

Having set the inputs, the user can see the results in the outputs window, however, with a dashboard based approach this can be viewed parallelly in real-time while setting them. Below will be a step wise display of all the results based on this input case.

Result 1: Applicable structural floors, this displays all the applicable floor-systems alternatives based on the technical criteria set. It also shows other related information such as slab thickness, mass (self-weight), existing retaining value (termed as the circular design strategy) after its first use life span of 100 years and lastly, it also displays the pipe integration typology the configuration follows, in this case of a built-in model (due to the services integration into a raised floor).

APPLICABLE STRUCTURAL FLOORS

| STRUCTURAL FLOOR-SYSTEMS | SLAB THICKNESS (MM) | MASS (KG/M2) | CIRCULAR DESIGN | PIPE INTEGRATION TYPOI |
|---|---|---|---|---|
| VBI Hollow core floor 260 | 260 | 383 | Recycle | Built-in model |
| VBI Hollow core floor 200 | 200 | 308 | Recycle | Built-in model |
| CLT Rib panel (open type) (320) | 320 | 150 | Maintain | Built-in model |
| LVL rib panel (Semi-open type) (48 | 480 | 245 | Maintain | Built-in model |

*Figure 78: Resulting applicable structural floor systems based on the inputs set as displayed in figure 77.*

Result 2: Material Circularity displays, as shown in figure 79;

- the material input (percentage of virgin material, i.e. the amount of material sourced from primary sources; and shows the number of renewable choices as green and number of non-renewable choices as red)
- the material output (percentage of material lost to landfill or incineration and percentage of material available for the next cycle by reuse or recycle)
- the material circularity indicator, scores the product by a number between 0 to 1, where 1 denotes the highest circularity and 0 the least
- And displays the best alternative in terms of material circularity, in this case CLT rib panel (open type 320)

No. of non-renewable choices = 2

No. of renewable choices = 2

The best choice: CLT Rib panel (open type) (320)

Reason: lowest percentage/amount of virgin material used from a renewable resource;
High percentage/amount of material can be incinerated and least lost due to landfill.

*Figure 79: Resulting material circularity related results, displaying the material input and output per product, and the overall aggregated material circularity score, with CLT option scoring best.*

Result 3: Flexibility due to integration typology of pipes and ducts, as shown in figure 80, displays scores based on DfD aspects weighted by E.Dumisevic transformation capacity model where, 1 is the most flexible and 0 the least flexible;

- The functional decomposition based disassembly factors of functional separation and functional dependency for pipes and ducts individually.
    - Functional separation for both pipes and ducts are scored the same at 0.1 as this signifies the integration of functions with different life cycles into one element. It holds true, as both pipes and ducts have a shorter life span compared to the raised floor-system they are enclosed in.
    - Functional dependency  as well for both pipes and ducts are the same at 0.8 as this signifies planned interpenetration for different solutions.
- The physical decomposition based disassembly factors of accessibility and connection type for pipes and ducts are also displayed individually.
    - Accessibility is scored 0.8 as it implies that the pipes and ducts are accessible however with additional operation but causing no damage.
    - Connection type is scored 1 as it signifies the pipes and ducts are integrated in the raised floor with accessorised external connection.

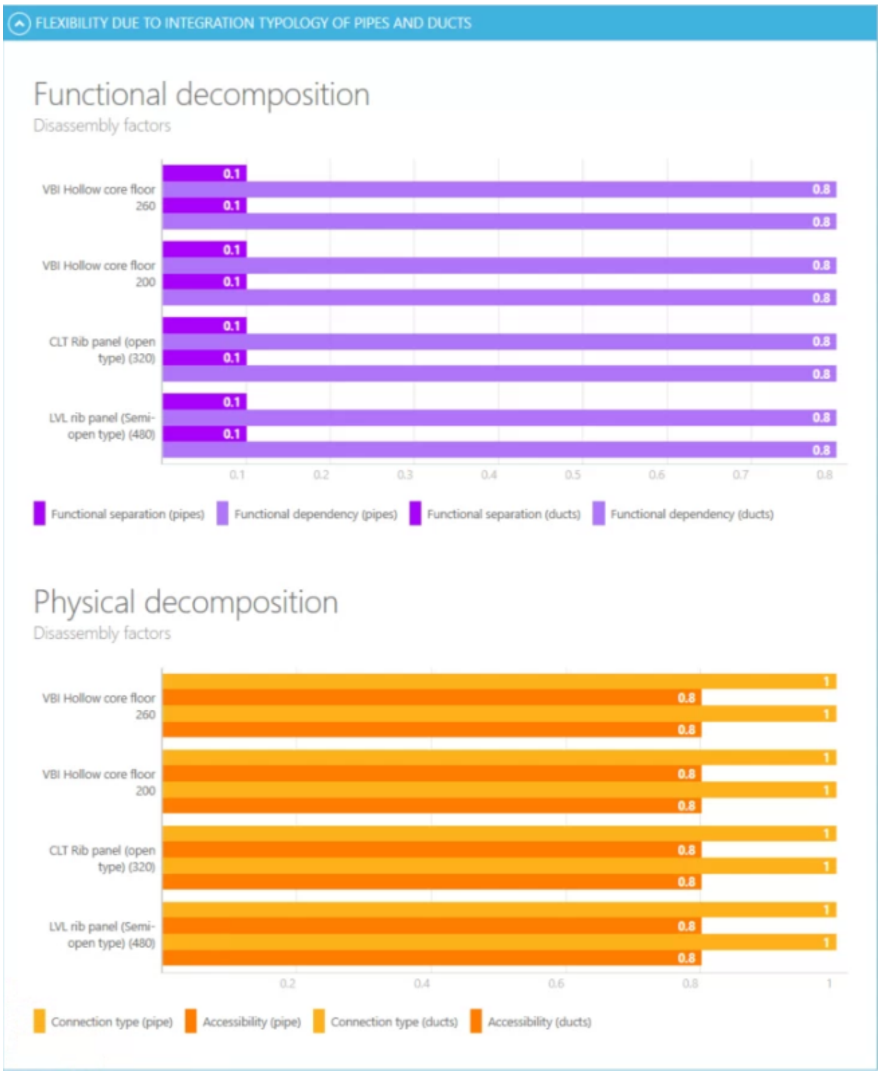


*Figure 80: Shows the display of the results under the flexibility due to integration typology of pipes and ducts*

Result 4: Displayes the MPG value per functional unit area of each product, as shown in figure 81.

Here, lower the score lower the environmental impact caused by the product.

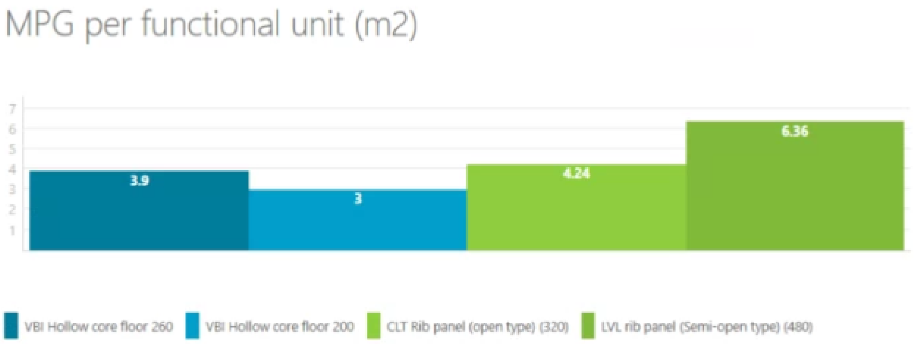
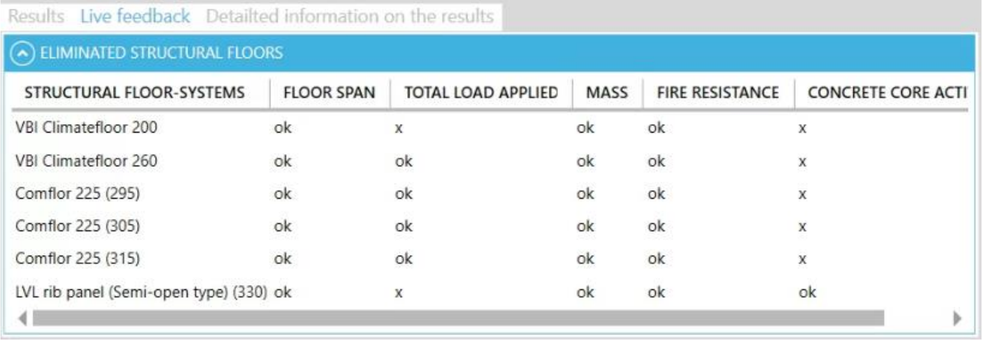


*Figure 81: Graph display for the MPG value of the applicable floor-system options*

Result 5: Live feedback on the inputs; shown by displaying the eliminated options and highlighting the technical criteria that have been satisfied (ok) and not satisfied (x), as shown in the figure 82.



| STRUCTURAL FLOOR-SYSTEMS | FLOOR SPAN | TOTAL LOAD APPLIED | MASS | FIRE RESISTANCE | CONCRETE CORE ACTI |
|---|---|---|---|---|---|
| VBI Climatefloor 200 | ok | x | ok | ok | x |
| VBI Climatefloor 260 | ok | ok | ok | ok | x |
| Comflor 225 (295) | ok | ok | ok | ok | x |
| Comflor 225 (305) | ok | ok | ok | ok | x |
| Comflor 225 (315) | ok | ok | ok | ok | x |
| LVL rib panel (Semi-open type) (330) | ok | x | ok | ok | ok |

*Figure 82: Shows the display result of live feedback that is enabled when analyze input toggle in ON.*

# 10. Prototype Testing and User Feedback

The tool was test with three users, two structural engineers and one MEP consultant, to gain insights into aspects such as usability, interactivity, informative and the users approach towards application of this dashboard in a real world situation (where there are multiple-criteria that play a role).

*Testing approach:*

The testing was conducted via a virtual (online) meeting. A brief explanation was shared regarding the goal or purpose of the Dashboard based tool and the participants were given access to control the tool via a screen sharing feature. The participants, took control one after the other while observing the changes in the results windows parallelly as they set the inputs. A good detailed feedback was shared while using the tool and the rest based on questions framed on earlier mentioned aspects.

*User feedback on the tool:*

During the testing the tool the most important points mentioned towards further improvements were:

1. The reversibility of the outputs into an input criteria to facilitate filtering of the applicable structural floor-systems when circularity goals are the starting points
2. The addition of a table that could show the solutions that have been eliminated; this feedback was addressed with the addition of the live feedback tab in the outputs window as mentioned in the earlier chapter
3. Addition of technical criteria for space layer, that consists of mass requirements to be set for screed and ceiling to determine overall mass of the system for better acoustic performance insights

4. For the results displayed showing the three different circularity related indicators (Material circularity, Flexibility and MPG), the users suggested it could be valuable to conclude the results by displaying the overall best system based on a aggregation or a scoring basis for better informative decision making
5. Finally, more fine-tuning of the graphs and visual representations of the good scoring vs the bad scoring alternatives could help the user; most suggestions with regards to this are implemented in the demonstrated example, as mentioned in the earlier chapter.

*To what extent was this tool user-friendly and interactive?*

All users found this approach very user-friendly and interactive, as they could very easily push slider or buttons to set their inputs and observe the results in the output window simultaneously.

*When and how do you envision using this tool in the a design of an office building project?*

All users agreed it is very helpful in the early or preliminary design stages of a project, where they can use this tool to gain quick insights into what possible integrated floor-systems options can be applicable for a given case scenario.

*In the situation of a real-time project where there are multiple-criteria that impact the design towards an integrated floor-system, how would you envision this tool to support you as a user?*

The MEP consultant, mentioned in such a case, while this tool gives an initial idea of the mass of the structural floor-system it still requires additional building layer such as screed and ceiling mass inputs to inform acoustic performance of the overall package. However, in addition to mass if other material related data regarding the sound insulation properties are also added to the database such that sound insulation becomes a input criteria to filter could add much more value to this tool in practice. In case of structural aspects, it was pointed out that the overall impact on the floor-to-floor height could be an added result that could act as a score towards selection of an integrated floor-system design.

# 11. Limitations and further recommendations

The Decision Support System developed using a Dashboard based design tool approach proves to be very useful to gain quick insights into the applicable integrated floor-system alternatives and learn the circularity related impacts, however, there are some limitations of this approach

1. The display of results and insights shared as outputs are only as good as the knowledge based database, the current prototype is only sharing insights for structural floor-system alternatives
2. The limitations of the platforms used for the prototype development such as the Human UI poses certain limitation with regard to the graphical representation of data, only select few type of graphs can be plotted such as vertical or horizontal bar charts. The possibility of visualizing better graphical representation such as spider charts or parallel coordinate charts are not possible using this plugin
3. It lacks an overall scoring system between the multiple circularity indicators to advise users and recommend best solutions

Further recommendations for this approach are

1. Development of a more exhaustive database of not only the structural layer, but also for services and space layer, that then better inform the user regarding other technical criteria especially the overall floor system thickness, the overall mass, and the sound insulation for the complete package
2. Developing an aggregated scoring system to rank alternatives based on multiple criteria analysis
3. Launching the dashboard on a cloud or make it a web-based platform to adopt service oriented DSS approach for better scalability and scope of use
4. Make it reversible by providing the flexibility to the user of choosing the input and output criteria to independently create reports for different situations

# VI

# CONCLUSIONS

# 12. Conclusions

The main objective of the research is to develop a decision support system for the stakeholders involved in the preliminary design stages of an integrated floor-system design by demonstrating the impact of the technical criteria on the circularity related indicators. This chapter answers the main research question by first discussing the answers to the sub-research questions. This format is followed to address the finer details that support the main answer.

*1. What are the main principles and strategies for circular design under a Circular economy in the built environment?*

Circularity is a subset to sustainability as it is a concept that is beneficial to attain sustainability, that aims at resource efficiency, reducing energy consumption and generating zero waste. The essence lies in retaining resources at its highest value. Designing out waste, keeping materials and products in use and regenerating natural systems are the three main principals of circular economy. Separating materials into technological and biological cycles is effective for creating value within their individual loops. The three main circular design goals are narrowing, slowing and closing the loop. The strategies proposed to visualize the design goals are value retention options for circular flows and Design for X (DfX) approach. These strategies work in synergy to achieve circular design solutions. The commonly used DfX strategy in the built environment is Design for Disassembly. DfD creates value in two circular design goals, slowing and closing the loop through re-use, refurish, remanufacture or recycling, thereby prolonging the life of the product/material. Design for upgradability or adaptability can create the highest level of circularity by facilitating long product/material life. Design for Adaptability especially, shows opportunity of flexible spaces and proves feasible for prefabricated building solutions and not for traditional buildings.

*2. Which design strategy can facilitate adaptability in office buildings and identify the key design aspects?*

Flexibility is a prominent problem in office buildings compared to residential buildings in the Netherlands, due to the higher rate of change in user and market demands. In order to provide flexibility in buildings, design for adaptability is key. The drivers for adaptability are technical (relates to technical flexibility) and economical obsolescence (relates to spatial flexibility). In order to achieve spatial flexibility, technical flexibility must be achieved. Therefore the strategies for technical flexibility are layering of building elements, indeterminacy, interchangeable components and design for deconstruction. For a building to be reversible or transformable, design for disassembly is the main criteria. However, the varying durability periods of the building layers (shearing layers of change by Brand) and materials create a significant impact on disassembly. Disassembly at different material levels i.e. Component, System and Building level, impacts the degree of adaptability and value retention. However, it guarantees recycling of resources in a circular flow and flexibility in buildings. The three-dimensional model of transformation proposed by Durmisevic (2006), i.e. structural transformation, spatial transformation and material/element transformation, highlights designing for disassembly facilitates transformation in all three dimensions.

*3. What are the circularity indicators and how can they be evaluated especially in case of building material and systems?*

From the literature review it was found that comprehensive metric to assess degree of circularity is still under exploration and development, especially for its application in the field of Architecture, Engineering and Construction (AEC). Measuring degree of circularity is a relatively new topic and has daily new contributions or knowledge generation towards improvements or additions to existing methods. However, from multiple assessment method and frameworks studied, the following are identified as the key circularity indicators

1. material balance (protection of material stock) - is largely dependent on amount of material used (primary/secondary source) and amount of material available for next cycle (reuse or recycle) and amount of material lost (landfill or incineration). Database sources of Nibe, NMD, and CES are used

to extract relevant data. These indicators are better supported with Material Circularity Indicator (MCI) by EMF, as it can help aggregate all the three mentioned indicators in one to rank the alternatives. Using a combination of both the formats assessment on non-aggregated and one aggregated, provides insights into why one aggregated score fairs better than the other

2. reducing environmental impact throughout the life cycle – can be informed by the MPG shadow cost from a validated calculation software by the NMD foundation, sourced from MPG calc. (DGMR, 2019)
3. retaining existing value – is crucial to determine the value of a product in the second life, however, as the CB'23 method is yet to be determined for the indicators, this is kept out of the scope. However, service planning by comparing use life cycle of the building to technical life cycle of the product, the retaining value or strategy can be informed after the first life cycle based on E.Durmisevic (2006) theory
4. designing for future adaptability – technical flexibility can be assessed using the weighted factors of the disassembly aspects (appendix 1)

*4. What is the role of an integrated floor-system in a building?*

*• What factors influence the design?*

*• What are the key technical performance criteria?*

*• What are the existing integrated floor systems or typologies commonly used in buildings?*

An integrated floor-system constitutes of three building layers i.e. Structure, Services and Space. The type of interaction between the layers is largely determined by the position of the services such as pipes and ducts. This interaction impacts functional, technical and circularity (read flexibility) related aspects of the configuration. The main challenge of integration of the three building layers in one system, in the circularity perspective is the varying technical life spans of the components. In functional perspective it impacts the overall thickness of the floor-system package and in technical perspective it is impacts the building physics properties. The two discussed technical criteria that impact the choice of products used in the configuration are structural and building physics performance.

Structural performance criteria for floor-systems can be branched into durability and usability criteria. Here, durability is expressed by the technical life span of the structure in number of years. This indicates that structure is guaranteed for use with assured safety (strength) for given life time. While usability criteria is largely informed by

- strength of the structure i.e. the extent of external loads it can carry. It is determined by the Consequence Class group that is based on the building function and number of floors. Office buildings of 5 floors and above lie in the CC2 group.
- deformations in the structure due to static (sag due to applied loads) or dynamic (vibrations induced due to walking or jumping) loading. The sag in floors are dependent on the span length and the vibrations in floors is dependent on mass.

Building physics performance criteria that are the most significant for integrated floor-system are

- sound insulation- caused by contact noise i.e. direct contact with the floor surface are the most significant and this depends on the mass per square meter of the structural floor, while for type of screed or ceiling, it is influenced by the absorption coefficients of the material. For the service installation especially mechanical air ducts, installation noise caused through fans etc are crucial, which can be silenced using dampers.
- fire-resistance- is a criteria that largely depend on, i.e. structural collapse due to succumbing to fire and penetration into a fire compartment.

The existing pipe integration typologies found in literature, are gutter, hollow floor, capacity and built-in model. This can further be simplified based on the component they intersect with, i.e. in floor slab, in screed, or no integration. There are some existing examples that follow the typologies such as Infra+foor, VBI pipe floor and slimline floor. For the ducts it is found they follow integration in beams, below beams, in raised floor or no integration. From literature and interviews it can also be concluded that pipes and ducts largely govern the integration strategies for floor-systems.

*5. Who are the stakeholders involved and what are the main considerations for a decision-making process for an integrated design approach in preliminary design stage for floor-systems?*

The stakeholders involved in the decision making process for a floor-system are clients, architects, structural engineers and MEP consultants.

From the interview response analysis it is found that the decision towards the floor-system is done in the preliminary stages of design. The challenges faced towards the design of an integrated floor-system is cost, the MEP integration strategy and the overall thickness of the floor package. The most important design aspect regarding integration of different building layers in on configuration is flexibility. This is also highlighted in the literature review on the state of the art of integrated floor-systems.

However, measuring circularity seems to be a gray area in practice, as not all are very well aware of the concept and the indicators that contribute to the assessment. Circularity is associated to practices of designing for disassembly, however, no measurement is associated towards any indicators. Therefore, this shows there is a need for the design team of Structural engineers, Architects, MEP consultant for better support in relation to circularity related indicators while designing an integrated floor-system. Based on their wishes and expectation they would like a system that offers multiple options to compare, is informative, reduces time and effort (quick evaluations to know impact on key performance indicators), flexible and transparent towards decision support and helps better integration/collaboration between disciplines.

*6. What is the suitable computational decision-making approach for preliminary design stage?*

A DSS is computer based system that assists decision makers in formulating and exploring the impact of their inputs and judgements, therefore supporting informed decision making. DSS are data-driven and model based approaches that store acquired data and knowledge from literature research and interviews into a knowledge base/database. It further uses knowledge representation and reasoning models to process the data and therefore suggest solution alternatives to the Decision Maker (DM). The model selection can be based on mathematical programming, simulation models or Artificial Intelligence. To develop a good DSS one must, follow a system analysis approach, acquire relevant data and knowledge related to the problem, be flexible in case of missing/uncertain data, create a user friendly interactive interface, and show relevant justified results that aid the user in making better decisions.

The AEC industry has examples that the novel approach of Dashboard based Design Tools are the most interactive, insightful, informative, adaptable and open to many typologies, when compared to other commonly used approaches. It is also found that the DDT has a better scalability and scope when developed as a service oriented analytics tool (DSS in cloud). The benefits are it is easily shared between stakeholders to gain quick insights into a problem or decisions and it helps connect different disciplines in one platform.

For this research a DSS based on a data-driven database and a model-driven by heuristic knowledge based (KBS) using decision trees will be developed. This method can best translate human reasoning and acquired expert knowledge from literature review and interviews into decision trees. Another advantage is decision trees can be easily codified as conditional statements to filter the solution alternatives of floor-systems and display its circularity related performance based on the material and integration typology. Finally, the interface will be based on a DDT approach to facilitate user interactivity, share information and gain insights.

*How can a **decision support system** assist the **stakeholders** involved in the preliminary design phase of an **integrated floor-system**, to compare design options based on **technical performance** and **degree of circularity** to make a suitable design choice to **facilitate adaptability** in office buildings?*

The aim of the research is to develop a decision support system to demonstrate the impact of design criteria input on the circularity related objectives of protecting material stock, protecting the environment and the amount of flexibility due to services integration strategy (based on disassembly factor) to facilitate adaptability in office buildings.

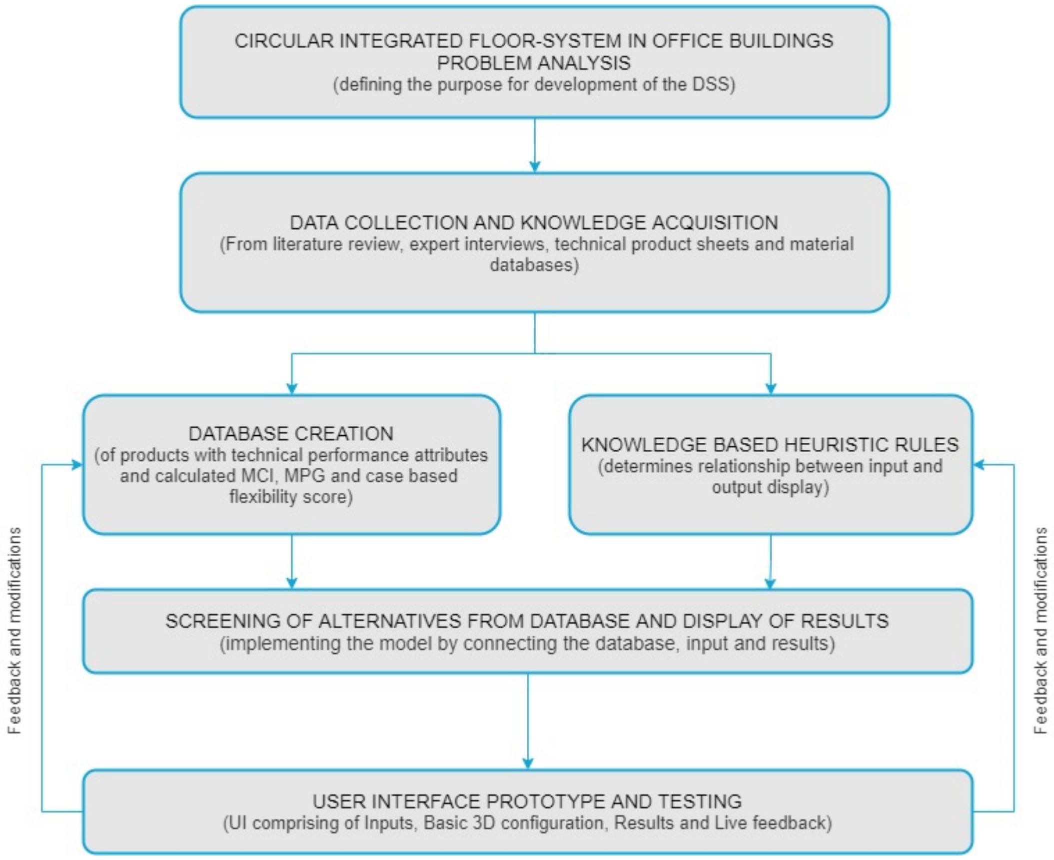


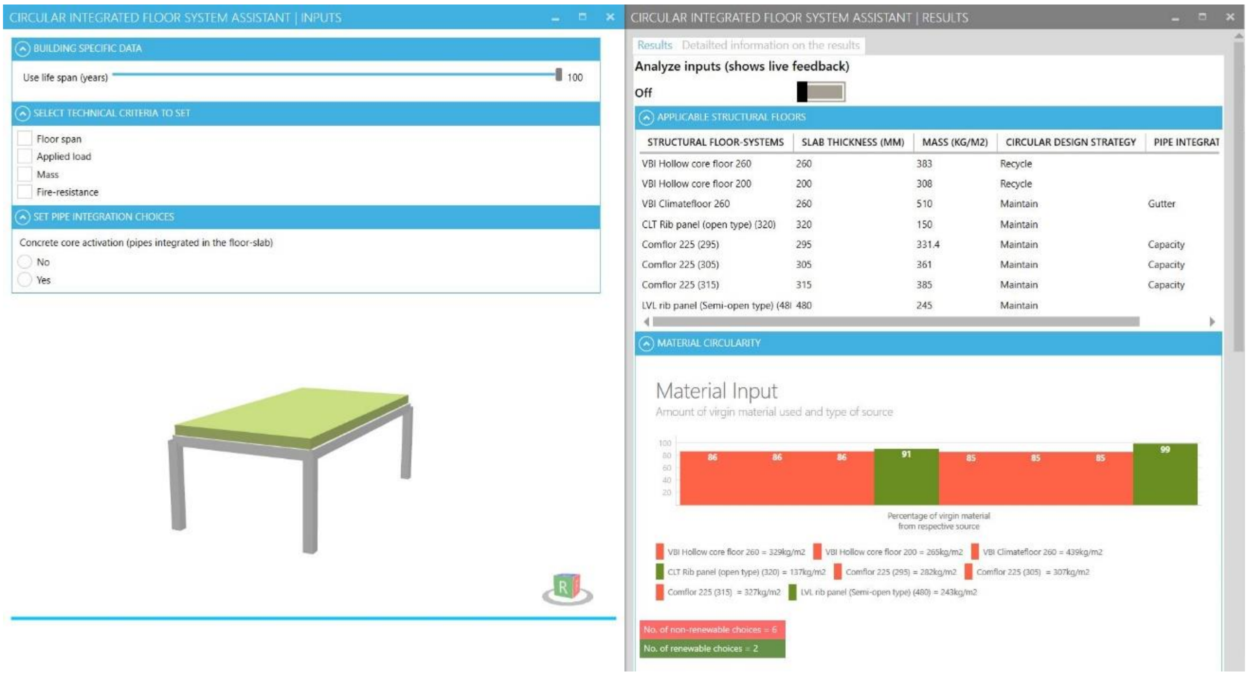
*Figure 83: Illustrating the DSS development flow diagram for circular integrated floor-system in office buildings*

For this a Decision Support System development as illustrated in the figure 83 was adopted, which followed the steps of first defining the problem and the need to inform the stakeholder making better decision pertaining to integrated floor-system keeping with circularity indicators. This was identified clearly where the stakeholder in practice find assessment towards circularity a gray area and therefore are not aware of the indicators that could inform better decisions. From their wishes it was understood they would value a system that could share quick insights, be interactive, informative and display multiple alternatives.

The extensive literature review and expert interviews contributed towards the next step of development of a DSS that is a combination of a data-driven and model-driven system. The data gathered from technical data sheets, literature review, databases such as NMD, CES and Nibe contributed to populating the database with prefabricated/premanufactured building products categorized into respective building layers to create a centralized Knowledge Base. The knowledge gathered from understanding the relationships between the design aspects and integration strategy on the circularity indicators defined the model based on heuristic rules represented in the form of decision trees.

Next the two data driven database and the heuristic knowledge based logic was integrated into one platform to define relevant inputs and outputs, a basic 3d model configuration and visualize results. Finally, the last step of development is creating a User interface prototype to test with the users and implement feedback to improve it.

To implement this approach a Dashboard based design tool approach was adopted as aligns with the demands of the user (stakeholders) expectations. And when coupled with a service oriented DSS in cloud approach it has better scalability and scope. To showcase the potential of this approach a prototype is developed, as shown in the figure 84. The user interface is configured with two parallel windows one for the input and the other for outputs, to instantly be aware of the change in results while setting the inputs criteria.



Use life span (years) 100

☐ Floor span
☐ Applied load
☐ Mass
☐ Fire-resistance

Concrete core activation (pipes integrated in the floor-slab)
○ No
○ Yes

Analyze inputs (shows live feedback)
Off

| STRUCTURAL FLOOR-SYSTEMS | SLAB THICKNESS (MM) | MASS (KG/M2) | CIRCULAR DESIGN STRATEGY | PIPE INTEGRAT |
|---|---|---|---|---|
| VBI Hollow core floor 260 | 260 | 383 | Recycle | |
| VBI Hollow core floor 200 | 200 | 308 | Recycle | |
| VBI Climatefloor 260 | 260 | 510 | Maintain | Gutter |
| CLT Rib panel (open type) (320) | 320 | 150 | Maintain | |
| Comflor 225 (295) | 295 | 331.4 | Maintain | Capacity |
| Comflor 225 (305) | 305 | 361 | Maintain | Capacity |
| Comflor 225 (315) | 315 | 385 | Maintain | Capacity |
| LVL rib panel (Semi-open type) (48 | 480 | 245 | Maintain | |

🟥 VBI Hollow core floor 260 = 329kg/m2
🟥 VBI Hollow core floor 200 = 265kg/m2
🟥 VBI Climatefloor 260 = 439kg/m2
🟩 CLT Rib panel (open type) (320) = 137kg/m2
🟥 Comflor 225 (295) = 282kg/m2
🟥 Comflor 225 (305) = 307kg/m2
🟥 Comflor 225 (315) = 327kg/m2
🟩 LVL rib panel (Semi-open type) (480) = 243kg/m2

No. of non-renewable choices = 6
No. of renewable choices = 2

Figure 84: the DDS developed based on the DDT computational approach

The prototype developed was tested with the users and found that a dashboard based design tool offers a very user-friendly and interactive experience. It supports the preliminary design stages of a project by giving quick insights into the possible alternatives for a given design case. Furthermore, the users testing the tool recognized the potential the proposed prototype when scaled up, with a bigger database of knowledge, as it could provide much deeper insights and could be a possible tool for future industry wide application.

The possibility to not only see results for the applicable alternatives per case but also learn what options are eliminated for which reason, is a valuable addition to this tool that can assist make better design decision.

An important finding is the results displaying the circularity indicators need to be aggregated in a scoring system to better rank alternatives based on all factors. However, by displaying the results of the indicators independently does keep better transparency towards decision making but lacks advising the user for the best choice.

Finally, this proposed decision support system holds immense potential for future applications in the AEC industry, however, testing this approach in a real-time project case can help find further insights in the possible pitfalls when considering all other aspects (feasibility, cost or subjective aesthetic appearances) that are to be considered in the decision making process of an office building design.

# 13. Future research directions

The research has explored the topic by covering an overview of multiple fields of knowledge. However, there is further scope of research in this topic,

1. To develop an aggregated scoring system that could weigh all the different circularity indicators in one scale. Especially complex, as the values of good and bad are not always represented in a low number (bad option) a higher number (good option). For example the MCI value of 1 represents the most circular material however, the MPG values that are closer to 0 represent better materials options with lesser impact.
2. To create a better database structure and organization that can relate between multiple building layer products attributes when designing in an integrated manner to achieve demount ability. This scope of research is related to the field of information modelling and data structures.
3. To build on this research and check for other integration challenges in building, such as façade and the structural frame.
4. Create a reversible DSS system that can allow the users to choose between the input criteria to be set and have the freedom to visualize the outputs that interests them (i.e. not only circularity indicators) for a given case scenario.

# 9. Reflection

## Graduation Position

*'The significance of seeking a scientific basis for design does not lie in the likelihood of reducing design to one or another of the sciences… Rather it lies in a concern to connect and integrate useful knowledge from the arts and sciences alike.'* - Richard Buchanan, "The wicked Problems in Design Thinking", in Margolin and Buchanan, eds., The idea of Design, 1995.

As rightly stated in the statement by Richard Buchanan, the science behind design is not one dimensional rather multidimensional, it is the art of combining and connecting multiple fields of knowledge. This master thesis titled 'Decision-making support framework for a circular integrated floor-system design', is positioned at the center of multiple scientific fields of knowledge. The knowledge from Architecture, Building Physics, Structures, Sustainability and Computational design are integrated to create a decision making framework. A framework that can assist the multi-disciplinary design team to consciously evaluate their decisions towards a circular integrated floor-system design.

The graduation studio within the Master track of Building Technology, strives to generate innovative methods and designs that can contribute positively towards technology, environment and society. In this context the thesis bridges between the technological and environmental aspects directly. The technological contribution is the development of a computational framework to assist in designing an integrated floor-system design. While the environmental contribution is using circular design aspects to drive the decision making process to achieve adaptable/flexible and reusable/recyclable solutions. And finally, the thesis draws indirect relations to the society by providing for buildings that are resilient to technical or economical changes with the ability to reuse and recycle the material in order to protect the existing stock and reducing the carbon impacts of the building sector. Thereby, progressing the society towards a healthier built environment.

The thesis is carried out in collaboration with the chair of Product innovation and Design informatics within the Architectural, Engineering and Technology department. Due to the topic's strong link with the building industry, it is also being carried out in collaboration with ABT BV, an engineering and building construction consultancy company in Delft.

## Graduation Process

The graduation thesis commenced by understanding the 'why' behind the need towards a circular integrated floor-system in an office building. This led the research towards understanding its position in the very broad subject of circularity and circular economy in the built environment at a Global, Continental (European union) and National (The Netherlands) level. One of the prominent problems found at all levels is the large resource footprint of the built environment. In addition to this, the construction industry in the Netherlands is one of the largest contributors to the waste production, which is counterproductive to the circularity goal of achieving zero waste and effective use of resources. Furthermore, it also contributes significantly to the carbon footprint.

Getting a good overview of circular design was essential to identify the value retentions strategies for the material flow and the design for 'X' strategies. This helped pinning the focus on long term strategies towards the built environment that caters to slowing the resource (material/product) flow by designing buildings for Adaptability, Maintenance, Re-use and those alike. Furthermore, the literature research on the current state of office building in the Netherlands led to draw a close relation in the need to design adaptable buildings, due to the high rate of change in user demands. However, to make buildings adaptable and ensure effective use of materials/products, literature states a life cycle design approach is essential to be integrate early in the design process.

In a building the most resource (material/product) intensive entity are that of the floor-systems. Floor-systems when observed as a total integrated package that includes not only the structure, but services, space and stuff layers from Stewart Brand's shearing layers of change, strikes a complexity of service life span coordination when integrated into the building, to ensure adaptability. Therefore demanding careful integration of the various layers into one Building level system.

Buildings are always a multi-discipline design problem, it involves multiple stakeholder in the design team striving towards a complete solution. In the context of deciding towards a floor-system design, an architect, structural engineer, building physics/MEP consultant and the client are involved. However their extent of involvement and influences especially in the light of incorporating circular design strategy is not found in literature. Therefore, the research included qualitative means of one-to-one interviews to collect more data and insight. The interview questionnaire was themed on multi-disciplinary collaboration, integration of components, incorporating circular design strategies and assessing environmental impact/degree of circularity of floor-systems. The results of the interview fed as inputs to the next step in the process.

The process then steered towards the 'what'-questions that identifies the multiple design requirements/criteria, design parameters and finally system choices within the disciplines of architecture, structural design and building physics. This helped grasp the multiple-attributes and decision making performance indicators that determine floor-system choice. Additionally, it was also important to identify the circularity indicators towards material balance and adaptable design. The interviews answered what data (criteria and design attributes) is shared when in the design process and in which phase the decision towards a floor-system is made, it also highlighted what challenges are faced in integration of components and what criteria take priority in decision-making.

Furthermore, the computational decision making theory and systems were studied for multi-disciplinary problems in the AEC industry. This informed the thesis on existing methods and frameworks to facilitate the final question on 'how' the gathered data must be organized.

Finally, the last step was to answer the 'how' question, that focused on creating the decision making framework itself that can assist the stakeholders towards making a circular decision for a floor-system design. This involved relating all the data found in the previous step to find correlations and relationships to inform the consequence of multiple-criteria based design decision.

To implement this understanding a test case is developed to further inform how the integration within a floor-system can work or not, when the goal is to obtain high circularity goals and identify the trade-offs.

The entire structured graduation process works in synergy with the graduation studio timeline, as framing the context through the 'why'- exploration phase aligns with P1-P2 stages of the studio. The 'what' phase is the time between P2-P3 and finally, the 'how' phase takes up the time period between P3-P4. This approach is planned accordingly in order to achieve good results by the P4 stage. And ensure enough time is devoted to draw out reflections and the final conclusions by P5.

The approach of 'why', 'what' and 'how', pushes the outcome of the results to be driven by substantial reasoning purely backed by literature and qualitative research sources. This helps in delivering an informed design outcome that has a strong foundational reasoning for its delivery. In other words, design when driven by research offers valuable contribution towards the scientific realm and influences best practices within the AEC industry.

## Societal Impact

Resource depletion and carbon emissions are one of the vital triggers towards transitioning into a circular economy. While circularity is not the only answer to achieving the sustainable development goals, it certainly is one of the contributors. The built environment (shelter) forms the first tire of basic needs in the Maslow's Pyramid, this demands it to gain high priority in the transition to attain sustainability goals. Therefore, transition towards a circular built economy has become a national level goal for multiple countries around the world. The Netherlands being one of them, has launched a nationwide programme with an aim to completely adopt circular economy by 2050. The context of this research topic was framed keeping this as one of the main considerations and attempts to aid this transition.

In order to contribute towards exploration of circular building practices, an integrated floor-system in the office building within the Netherlands is chosen as the main focus for implementing and showcasing the potential impact. The thesis does not simply focus on engineering the one innovative circular floor-system. However, it proposes a framework that can assist towards designing an integrated floor-system that has a certain degree of circularity, posing an opportunity to explore options. This in the future can become a tool to guide the designers to make informed decisions while selecting and integrating building level systems that are circular and contribute positively to the environment.

The ability of buildings to adapt throughout its design life span i.e. on an average of 50 years creates opportunity of reuse in multiple use scenarios and adds value to the investment made at the time of construction. Investing into an adaptable circular building strategy is an added asset as it starts with considering future scenarios of use and provides multiple opportunity to ensure long term return on investment. In the context of circular economy, buildings can be perceived as material/product banks/reserves, that not only keep the resources in use for a long time by slowing the resource loop, but also closing the loop by providing opportunity to refurbish and recycle. This reduces the resource intensive demand of the built environment on the planet, as it keeps the resources in constant use, thereby reducing construction waste due to demolitions. Finally, this offers people a healthier built environment as a service that can be utilized as per their desired wishes/demands with great deal of flexibility.

# 14. Bibliography

Abraham, K., Flager, F., Macedo, J., Gerber, D. J., & Lepech, M. (2014). Multi-attribute decision-making and data visualization for multi-disciplinary group building project decisions. *Proceedings of the Engineering Project Organization Conference, June 2015*. http://www.epossociety.org/EPOC2014/Papers/Abraham_Flager_Macedo_Gerber_Lepech.pdf

*Ansys (CES) Granta EduPack | Software for Materials Education*. (n.d.). Retrieved June 22, 2021, from https://www.ansys.com/products/materials/granta-edupack

Arnette, A. N., Brewer, B. L., & Choal, T. (2014). Design for sustainability (DFS): The intersection of supply chain and environment. *Journal of Cleaner Production*, *83*, 374–390. https://doi.org/10.1016/j.jclepro.2014.07.021

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bragança, L., Vieira, S. M., Andrade, J. B., Cui, H., & Lu, J. (2014). *Early Stage Design Decisions: The Way to Achieve Sustainable Buildings at Lower Costs*. https://doi.org/10.1155/2014/365364

Brand, S. (1994). *How Building Learn*. http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf

Cie, C. I. E. (2016). *Concrete Building Structures reader CIE3340 / CIE4281*. *November*.

Coenders, J. (2011). *Networked Design*.

Demirkan, H., & Delen, D. (2013). Leveraging the capabilities of service-oriented decision support systems: Putting analytics and big data in cloud. *Decision Support Systems*, *55*(1), 412–421. https://doi.org/10.1016/j.dss.2012.05.048

Durmisevic, E. (2016). Dynamic and Circular Buildings by High Transformation and Reuse Capacity -Elma Durmisevic. *Sustainable 2016*, 86–100.

Durmisevic, El. (2006). *Transformable Building Structures*.

Feldmann, M., Heinemeyer, C., Butz, C., Caetano, E., Cunha, Á., Galanti, F., & Goldack, A. (2009). *Design of floor structures for human induced vibrations* (Vol. 3).

French, S., Maule, J., & Papamichail, N. (2010). Artificial Intelligence and Decision Systems Course notes. *October*, *October*, 115–141.

Geldermans, R. J. (2016a). Design for Change and Circularity - Accommodating Circular Material & Product Flows in Construction. *Energy Procedia*, *96*(October), 301–311. https://doi.org/10.1016/j.egypro.2016.09.153

Geldermans, R. J. (2016b). Design for Change and Circularity - Accommodating Circular Material & Product Flows in Construction. *Energy Procedia*, *96*(October), 301–311. https://doi.org/10.1016/j.egypro.2016.09.153

Gosling, J., Sassi, P., Naim, M., & Lark, R. (2013). Adaptable buildings: A systems approach. *Sustainable Cities and Society*, *7*, 44–51. https://doi.org/10.1016/j.scs.2012.11.002

Hamouda, M. A., Anderson, W. B., & Huck, P. M. (2009). Decision support systems in water and wastewater treatment process selection and design: A review. *Water Science and Technology*, *60*(7), 1767–1770. https://doi.org/10.2166/wst.2009.538

*Human UI - Addon for Grasshopper | Grasshopper Docs*. (n.d.). Retrieved June 22, 2021, from http://grasshopperdocs.com/addons/human-ui.html

Israelsson, N., & Hansson, B. (2009). Factors influencing flexibility in buildings. *Structural Survey*, *27*(2), 138–147. https://doi.org/10.1108/02630800910956461

*ISSO*. (n.d.). Retrieved June 23, 2021, from https://open.isso.nl/publicatie/isso-publicatie-85-thermisch-actieve-vloeren-betonkernactivering/2011/algemeen/2/2.2

Kimpian, J., Mason, J., Coenders, J., Jestico, D., & Watts, S. (2009). Sustainably tall: Investment, energy, life cycle. *ACADIA 09: ReForm(): Building a Better Tomorrow - Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture*, 130–143.

*Measuring circularity*. (2020). *July*.

Measuring Circularity, E. M. F. (2019). *Ellen MacArthur Foundation Project Team (in alphabetical order)*. 1–64.

Minunno, R., O'Grady, T., Morrison, G. M., Gruner, R. L., & Colling, M. (2018). Strategies for applying the circular economy to prefabricated buildings. *Buildings*, *8*(9). https://doi.org/10.3390/buildings8090125

*Nibe Database on environmental and health data of construction products*. (2019). Nibe. https://www.nibe.info/nl/members#group-171-28

Paik, I., & Na, S. (2019). Evaluation of carbon dioxide emissions amongst alternative slab systems during the construction phase in a building project. *Applied Sciences (Switzerland)*, *9*(20), 1–17. https://doi.org/10.3390/app9204333

Poch, M., Comas, J., Rodríguez-Roda, I., Sànchez-Marrè, M., & Cortés, U. (2004). Designing and building real environmental decision support systems. *Environmental Modelling and Software*, *19*(9), 857–873. https://doi.org/10.1016/j.envsoft.2003.03.007

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resources, Conservation and Recycling*, *135*(November 2017), 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

*Rhino - About McNeel*. (2021). https://www.rhino3d.com/mcneel/about/

Rolvink, A., Breider, J., & Coenders, J. (2010). Structural Components - a parametric associative design toolbox for conceptual structural design. *Symposium of the International Association for Shell and Spatial Structures (50th. 2009. Valencia). Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures : Proceedings*, *October*, 1124–1135.

Rolvink, A., Mueller, C., & Coenders, J. (2014). State on the Art of Computational Tools for Conceptual Structural Design. *Proceedings of the IASS-SLTE 2014 Symposium "Shells, Membranes and Spatial Structures: Footprints," April 2017*, 1–8.

Saidani, M., Yannou, B., Leroy, Y., & Cluzel, F. (2017). How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. *Recycling*, *2*(1). https://doi.org/10.3390/recycling2010006

SBR publication. (2012). *Fire Safety: Design and Testing - Part D*. SBR. https://open.isso.nl/publicatie/brandveiligheid-ontwerpen-en-toetsen-deel-d/2012/2/2.2

Standards, S. B., & Market, I. (n.d.). *Discussion Paper The future of the standardisation system within the CPR*. 1–6.

Stichting Nationale Milieudatabase. (2020). *Inkopen met de milieuprestatie gebouwen ( MPG ), handreiking en stappenplan*. 61.

*TT Toolbox - Addon for Grasshopper | Grasshopper Docs*. (n.d.). Retrieved June 22, 2021, from https://grasshopperdocs.com/addons/tt-toolbox.html

van Herwijnen, F., & Jorissen, A. J. M. (2006). Development of an Integrated Timber Floor System. In *Proceedings from the International Conference on Advances in Engineering and Technology* (Issue i). Woodhead Publishing Limited. https://doi.org/10.1016/b978-008045312-5/50012-1

Van Vliet, M. (2018). *Disassembling the steps towards Building Circularity*. 1–185.

Verberne, J. J. H. (2016a). *Building circularity indicators - an approach for measuring circularity of a building*. 165.

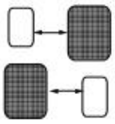
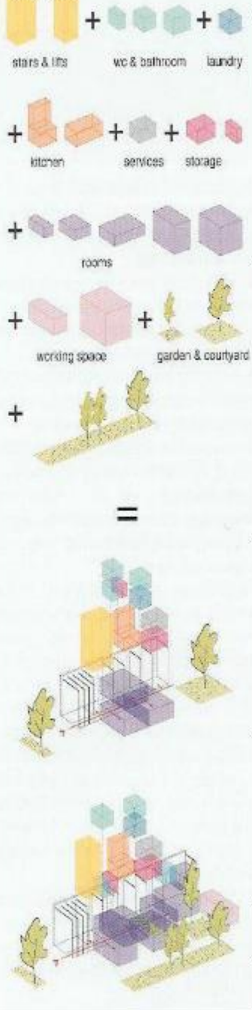
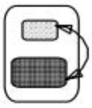
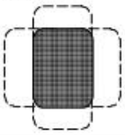
Verberne, J. J. H. (2016b). *Building circularity indicators - an approach for measuring circularity of a building*. 165.

# Appendix 1

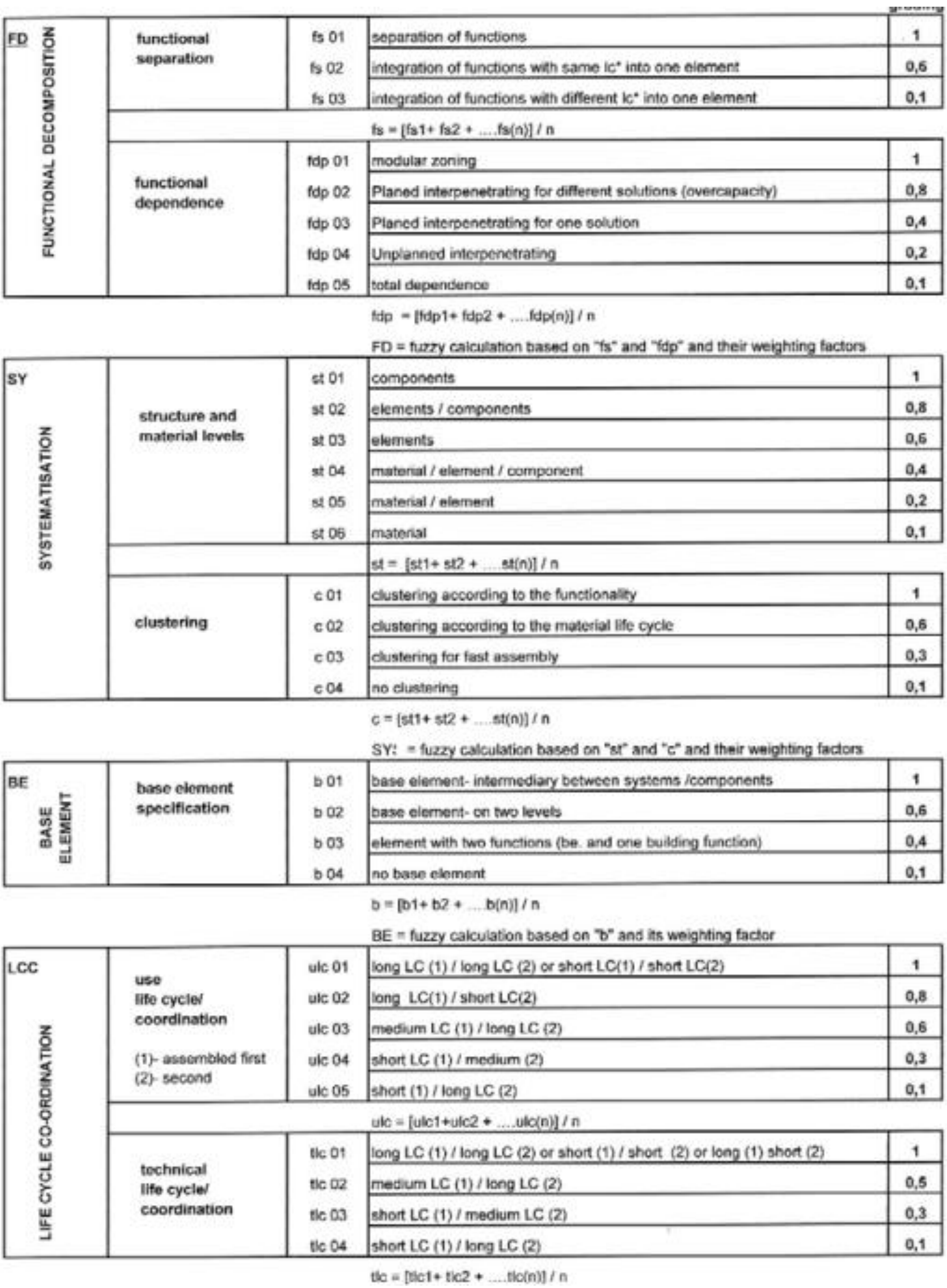
## *BUILDING USE TYPE AND ASSOCIATED LONG TERM STRATEGY (E.DURMISEVIC, 2006)*

| **Long term strategy** | | **Definition** | **Destination of the building** |
|---|---|---|---|
| 1 | Time independent buildings | buildings that are frequently subject to transformations due to the market changes, social economic or whether changes | housing<br>retail<br>office<br>schools<br>floating houses |
| 2 | Specific buildings | buildings that are of the long term strategic interest, and therefore are less sensitive to market, economic and social changes | Hospitals<br>Governmental buildings<br>Sport facilities<br>Banks<br>Manufacturing facilities |
| 3 | Temporally buildings | buildings that have dynamic interactions with society and the climate, these buildings can answer immediate needs of the society | Pavilions<br>Expositions<br>Information centres<br>Kiosks<br>Summer restaurants/cafés |
| 4 | Mobile buildings | buildings that are mobile because of climate conditions or life/work stile<br>Mobile buildings could have all perviously mentioned strategies | floating house<br>movable school<br>floating pavilion |

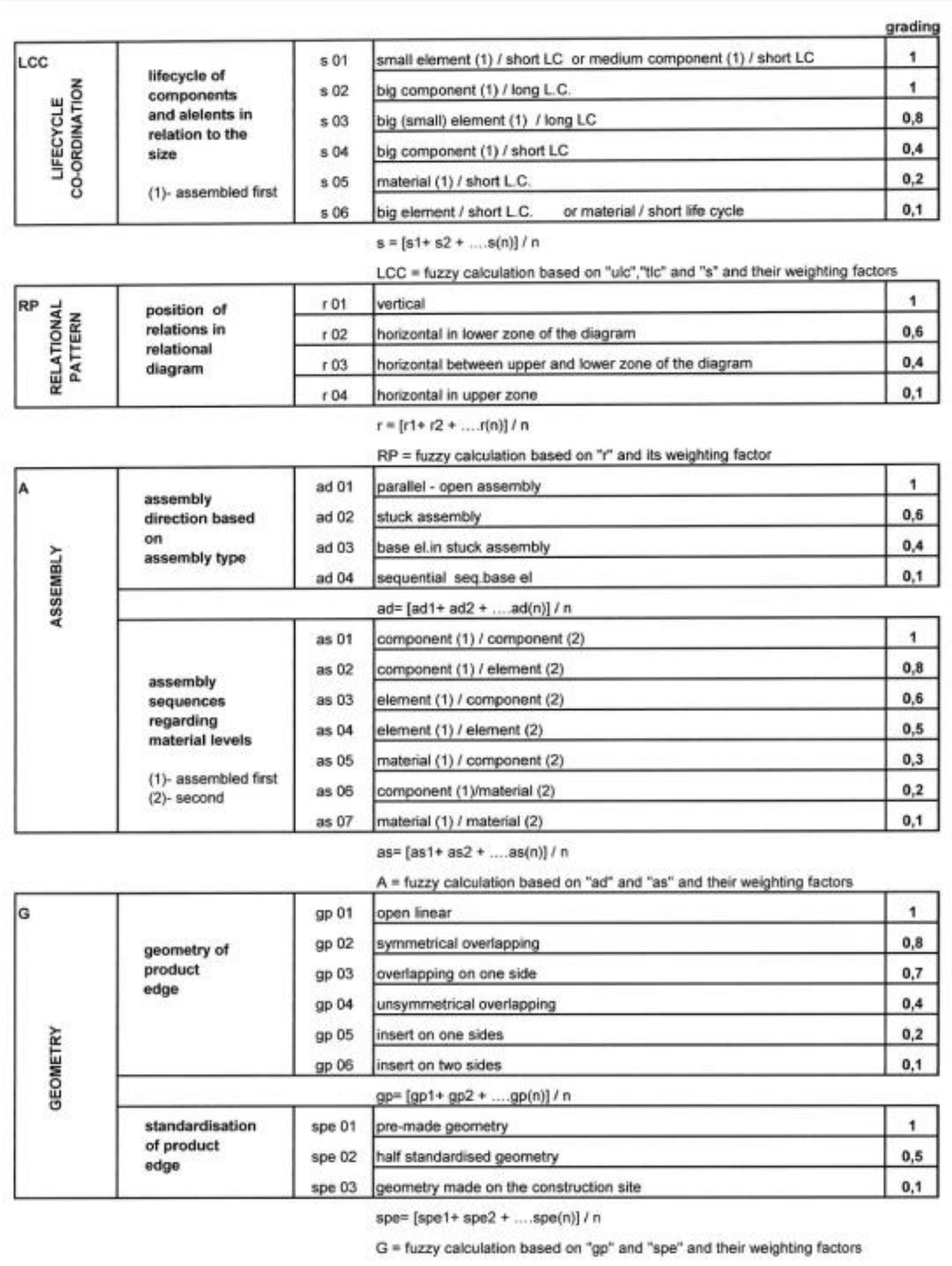
## *SHORT-TERM SCENARIO AND BUILDING/SYSTEM/COMPONENT LEVEL STRATEGY (E.DURMISEVIC, 2006)*

| | **Short term scenarios for the use of configurations** | **Building strategies** | **graphical representation of the scenarios** | **Systems / Components Strategies** |
|---|---|---|---|---|
| 1 | Free repositioning of the functional zones  | The ability to reposition different functional units within one building structure. This means that building function remains the same but its sub-functions can be moved from one location to another. bathroom units moved from one location to another |  | The ability to reposition different components within one system structure. This means that systems function remains the same but its components can be moved from one location to another.<br>electric components within the wall |
| 2 | Reconfiguration of one functional zone (partitioning into another within the sam structural constrains  | The ability to reconfigure one space from one function to another. That means that the space changes the function within the same structural constrains.<br>multyfunctionality | | The ability to reconfigure one function of the system into a new function. This means that the systems function is partly changed by insertion of some new components<br>Facade system that in place of closed section introduces and open section<br>Partitioning wall that in place of finishing panel introduces TV screen |
| 3 | Internal rearangment  | Free internal partitioning of one functional zone into sub-zones. For example, partitioning of office spaces. The main function is not changed, only the size of sub-zones is changed | | Free Internal partitioning of system into subsystems and components. Forr example facade system whose components can be replaced from one location to another as shown on the example of Next 21facade system (chapter 3) |
| 4 | extendibility  | The ability to extend the building horizontally or vertically | | The ability to extend the system by adding subsystems or components<br>to it horizontally or vertically |
| 5 | combination of two strateg | free repositioning and partitioning | | |
| 6 | combination of more that t scenarios | free repositioning, partitioning and extendibility | | |

## DESIGN FOR DISASSEMBLY ASPECTS (E.DURMISEVIC, 2006)



| | | | | |
|---|---|---|---|---|
| FD<br>FUNCTIONAL DECOMPOSITION | functional separation | fs 01 | separation of functions | 1 |
| | | fs 02 | integration of functions with same lc* into one element | 0,6 |
| | | fs 03 | integration of functions with different lc* into one element | 0,1 |
| | | | fs = [fs1+ fs2 + ....fs(n)] / n | |
| | functional dependence | fdp 01 | modular zoning | 1 |
| | | fdp 02 | Planed interpenetrating for different solutions (overcapacity) | 0,8 |
| | | fdp 03 | Planed interpenetrating for one solution | 0,4 |
| | | fdp 04 | Unplanned interpenetrating | 0,2 |
| | | fdp 05 | total dependence | 0,1 |
| | | | fdp = [fdp1+ fdp2 + ....fdp(n)] / n | |
| | | | FD = fuzzy calculation based on "fs" and "fdp" and their weighting factors | |
| SY<br>SYSTEMATISATION | structure and material levels | st 01 | components | 1 |
| | | st 02 | elements / components | 0,8 |
| | | st 03 | elements | 0,6 |
| | | st 04 | material / element / component | 0,4 |
| | | st 05 | material / element | 0,2 |
| | | st 06 | material | 0,1 |
| | | | st = [st1+ st2 + ....st(n)] / n | |
| | clustering | c 01 | clustering according to the functionality | 1 |
| | | c 02 | clustering according to the material life cycle | 0,6 |
| | | c 03 | clustering for fast assembly | 0,3 |
| | | c 04 | no clustering | 0,1 |
| | | | c = [st1+ st2 + ....st(n)] / n | |
| | | | SY: = fuzzy calculation based on "st" and "c" and their weighting factors | |
| BE<br>BASE ELEMENT | base element specification | b 01 | base element- intermediary between systems /components | 1 |
| | | b 02 | base element- on two levels | 0,6 |
| | | b 03 | element with two functions (be. and one building function) | 0,4 |
| | | b 04 | no base element | 0,1 |
| | | | b = [b1+ b2 + ....b(n)] / n | |
| | | | BE = fuzzy calculation based on "b" and its weighting factor | |
| LCC<br>LIFE CYCLE CO-ORDINATION | use life cycle/ coordination<br>(1)- assembled first<br>(2)- second | ulc 01 | long LC (1) / long LC (2) or short LC(1) / short LC(2) | 1 |
| | | ulc 02 | long LC(1) / short LC(2) | 0,8 |
| | | ulc 03 | medium LC (1) / long LC (2) | 0,6 |
| | | ulc 04 | short LC (1) / medium (2) | 0,3 |
| | | ulc 05 | short (1) / long LC (2) | 0,1 |
| | | | ulc = [ulc1+ulc2 + ....ulc(n)] / n | |
| | technical life cycle/ coordination | tlc 01 | long LC (1) / long LC (2) or short (1) / short (2) or long (1) short (2) | 1 |
| | | tlc 02 | medium LC (1) / long LC (2) | 0,5 |
| | | tlc 03 | short LC (1) / medium LC (2) | 0,3 |
| | | tlc 04 | short LC (1) / long LC (2) | 0,1 |
| | | | tlc = [tlc1+ tlc2 + ....tlc(n)] / n | |



| | | | | grading |
|---|---|---|---|---|
| LCC<br>LIFECYCLE CO-ORDINATION | lifecycle of components and alelents in relation to the size<br>(1)- assembled first | s 01 | small element (1) / short LC or medium component (1) / short LC | 1 |
| | | s 02 | big component (1) / long L.C. | 1 |
| | | s 03 | big (small) element (1) / long LC | 0,8 |
| | | s 04 | big component (1) / short LC | 0,4 |
| | | s 05 | material (1) / short L.C. | 0,2 |
| | | s 06 | big element / short L.C. or material / short life cycle | 0,1 |

s = [s1+ s2 + ….s(n)] / n

LCC = fuzzy calculation based on "ulc","tlc" and "s" and their weighting factors

| | | | | |
|---|---|---|---|---|
| RP<br>RELATIONAL PATTERN | position of relations in relational diagram | r 01 | vertical | 1 |
| | | r 02 | horizontal in lower zone of the diagram | 0,6 |
| | | r 03 | horizontal between upper and lower zone of the diagram | 0,4 |
| | | r 04 | horizontal in upper zone | 0,1 |

r = [r1+ r2 + ….r(n)] / n

RP = fuzzy calculation based on "r" and its weighting factor

| | | | | |
|---|---|---|---|---|
| A<br>ASSEMBLY | assembly direction based on assembly type | ad 01 | parallel - open assembly | 1 |
| | | ad 02 | stuck assembly | 0,6 |
| | | ad 03 | base el.in stuck assembly | 0,4 |
| | | ad 04 | sequential seq.base el | 0,1 |
| | ad= [ad1+ ad2 + ….ad(n)] / n | | | |
| | assembly sequences regarding material levels<br>(1)- assembled first<br>(2)- second | as 01 | component (1) / component (2) | 1 |
| | | as 02 | component (1) / element (2) | 0,8 |
| | | as 03 | element (1) / component (2) | 0,6 |
| | | as 04 | element (1) / element (2) | 0,5 |
| | | as 05 | material (1) / component (2) | 0,3 |
| | | as 06 | component (1)/material (2) | 0,2 |
| | | as 07 | material (1) / material (2) | 0,1 |

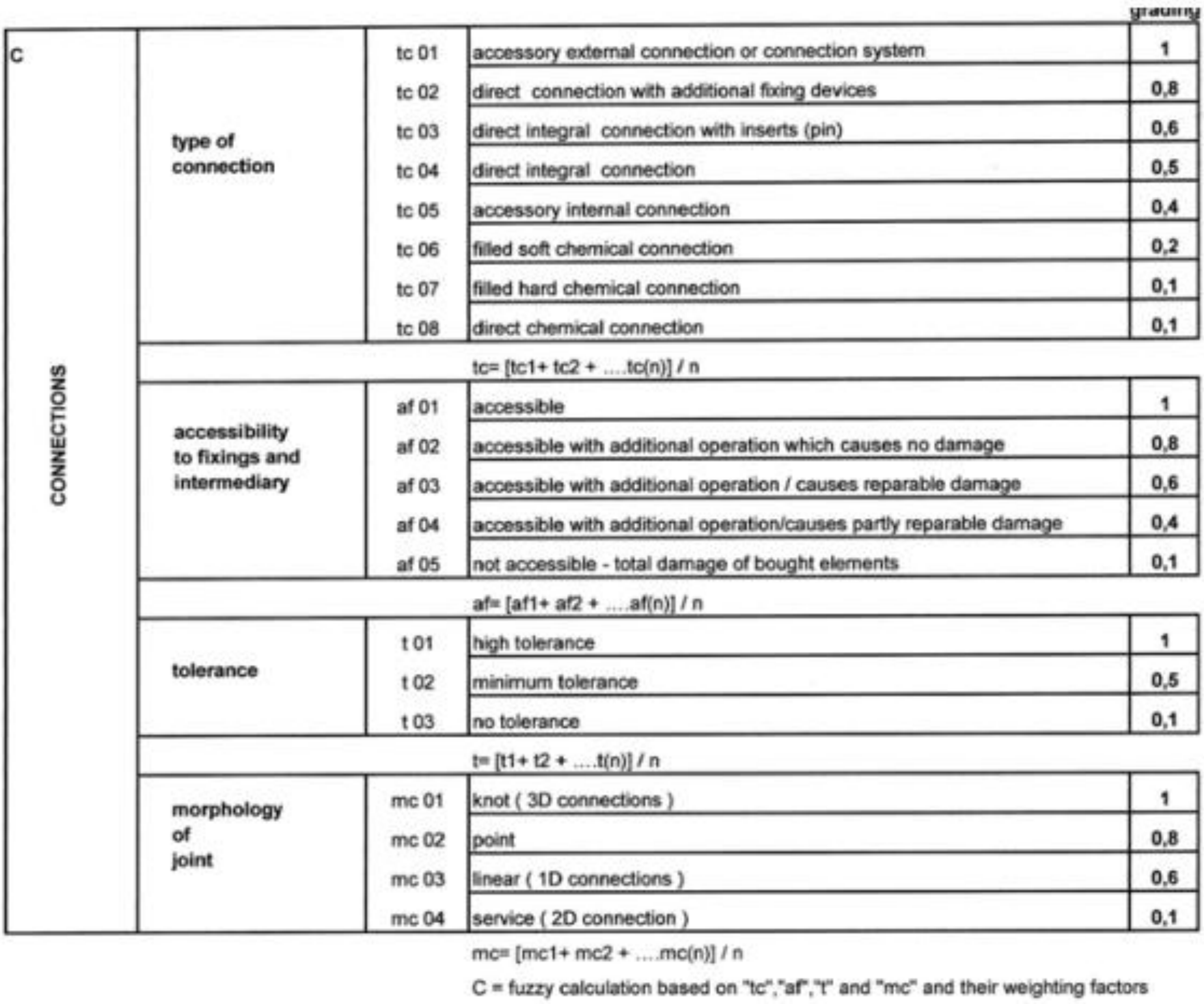
as= [as1+ as2 + ….as(n)] / n

A = fuzzy calculation based on "ad" and "as" and their weighting factors

| | | | | |
|---|---|---|---|---|
| G<br>GEOMETRY | geometry of product edge | gp 01 | open linear | 1 |
| | | gp 02 | symmetrical overlapping | 0,8 |
| | | gp 03 | overlapping on one side | 0,7 |
| | | gp 04 | unsymmetrical overlapping | 0,4 |
| | | gp 05 | insert on one sides | 0,2 |
| | | gp 06 | insert on two sides | 0,1 |
| | gp= [gp1+ gp2 + ….gp(n)] / n | | | |
| | standardisation of product edge | spe 01 | pre-made geometry | 1 |
| | | spe 02 | half standardised geometry | 0,5 |
| | | spe 03 | geometry made on the construction site | 0,1 |

spe= [spe1+ spe2 + ….spe(n)] / n

G = fuzzy calculation based on "gp" and "spe" and their weighting factors



| | | | | grading |
|---|---|---|---|---|
| C<br>CONNECTIONS | type of connection | tc 01 | accessory external connection or connection system | 1 |
| | | tc 02 | direct connection with additional fixing devices | 0,8 |
| | | tc 03 | direct integral connection with inserts (pin) | 0,6 |
| | | tc 04 | direct integral connection | 0,5 |
| | | tc 05 | accessory internal connection | 0,4 |
| | | tc 06 | filled soft chemical connection | 0,2 |
| | | tc 07 | filled hard chemical connection | 0,1 |
| | | tc 08 | direct chemical connection | 0,1 |
| | | | tc= [tc1+ tc2 + ….tc(n)] / n | |
| | accessibility to fixings and intermediary | af 01 | accessible | 1 |
| | | af 02 | accessible with additional operation which causes no damage | 0,8 |
| | | af 03 | accessible with additional operation / causes reparable damage | 0,6 |
| | | af 04 | accessible with additional operation/causes partly reparable damage | 0,4 |
| | | af 05 | not accessible - total damage of bought elements | 0,1 |
| | | | af= [af1+ af2 + ….af(n)] / n | |
| | tolerance | t 01 | high tolerance | 1 |
| | | t 02 | minimum tolerance | 0,5 |
| | | t 03 | no tolerance | 0,1 |
| | | | t= [t1+ t2 + ….t(n)] / n | |
| | morphology of joint | mc 01 | knot ( 3D connections ) | 1 |
| | | mc 02 | point | 0,8 |
| | | mc 03 | linear ( 1D connections ) | 0,6 |
| | | mc 04 | service ( 2D connection ) | 0,1 |

mc= [mc1+ mc2 + ….mc(n)] / n

C = fuzzy calculation based on "tc","af","t" and "mc" and their weighting factors

# APPENDIX 2

## *BUILDING CIRCULARITY INDICATOR*

Under this section three version of the Building circularity indicator framework are discussed. The first version proposed by J.H.H Verbene (2016a) is explained, a modified version by Van Vliet(2018) is briefly discussed and lastly the framework used by Alba concepts is covered. Alba concepts is a company established in the Netherlands that assess the degree of circularity for buildings in practice.

### *BCI by Verberne*

The Building Circularity Indicator (BCI) developed by Verbene (2016a), is an assessment tool for buildings at four levels, material (MCI), product (PCI), system (SCI) and building (BCI) as shown in Figure . The BCI incorporates two evaluation tools in its framework, Material Circularity indicator (MCI), developed by the Ellen Macarthur foundation and the Design for Disassembly (DFD) factors for connections proposed by El. Durmisevic (2006).

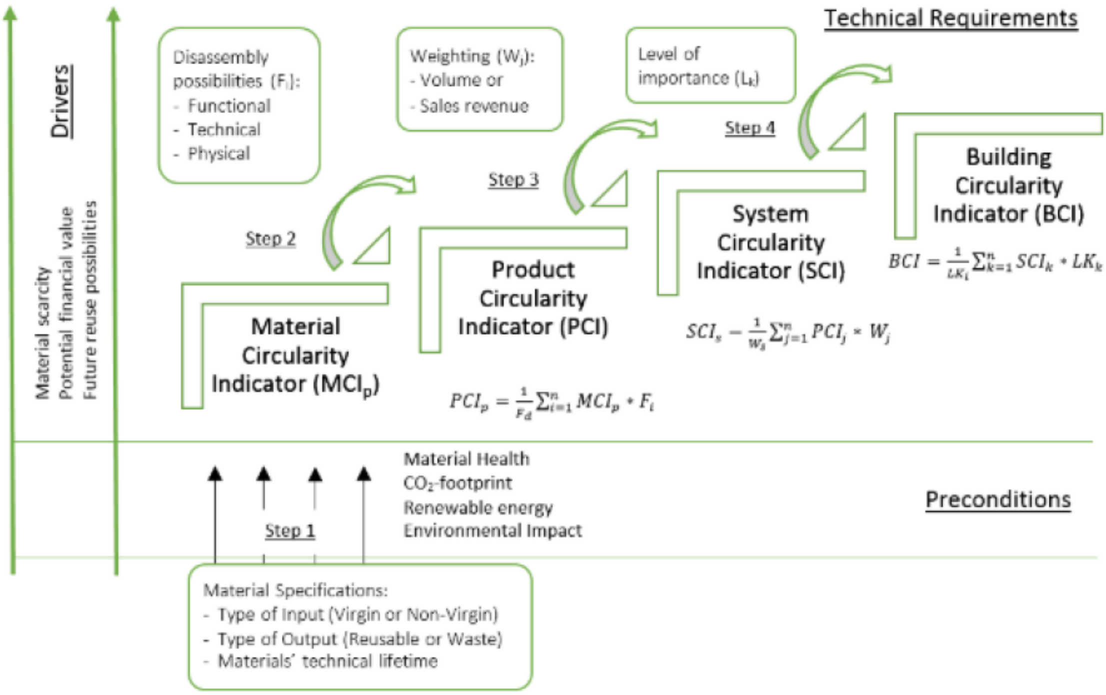


*Figure 1: A step-wise illustration of the BCI assessment framework* (Verberne, 2016b)

Verbene's (2016b) BCI focuses largely into material input, output and utility along with the connections and physical interfaces of the products assembly. It is vital to note, this framework is only applicable to technical cycles of resource flows as biological cycles demand a different assessment approach.

**Step 1 | MCI**

Verbene adapted Ellen Macarthur foundation's MCI for its use in the context of buildings, stating that building is an assemblage of materials connected to one another. While the whole workflow resembles the MCI, there are changes/assumptions that have been made, which are as follows;

1. A distinction is made between virgin and non-virgin material input and it is assumed that a 100% non-virgin material input for a product that has a 100% restorative material output at end of its life, Circularity is 100%. While a product made of 100% virgin material that ends up in landfill is 0%

circular. Therefore, the degree of circularity also quoted as the 'theoretical value' ranges between 0 to 1.

2. There is no distinction between the fraction of recycled content ($F_R$) and fraction of reused content ($F_U$). It is assumed that for CE the source of non-virgin material input doesn't hold much importance, as long as the total fraction of non-virgin material in feedstock is known. Therefore, a variable of $NV_{RC}$ is introduced to replace $F_R$ and $F_U$ for the calculating amount of virgin material. Material input, total amount of Virgin material (V) is given by;

   $V_x = M_x (1- NV_{RC(x)})$

   Where;

   M = Mass of the product

   $NV_{RC}$ = Faction of feedstock from non-virgin sources (recycled/reused content)

   However, a product is an assembly of materials therefore;

   $V= \sum_x V_x$

3. The same is assumed for material output i.e. amount of waste(W) produced by the product at end of life. Only the fraction of the product that is reused/recycled/refurbished/ remanufactured are considered together in the variable $F_{RU}$, to contribute towards a better circular degree. While the fraction of material that ends up in landfill or for energy recovery is not considered circular.

   $W= M (1-F_{RU})$

   Where;

   M = Mass of the product

   $F_{RU}$ = Fraction of waste material reused/recycled/refurbish/remanufacture

4. The Utility factor (X) is the ratio between the life of the product and the life of the system, as the building is comprised of system, product and material. The life of the product is given by the length of the products use phase ($L_p$). Life of the product has a direct impact of the waste stream and amount of virgin material while calculating the MCI. As doubling the product life time decreases the waste stream and virgin material by half. While the life of the system ($L_{sys}$) determines the products state in the used building system. Building systems have varying lifespan as mentioned earlier. Based on Steward Brands 'shearing layer of change', in years, Site = 500, structure=100, skin=20, services=15, space plan=10 and stuff =5. Therefore X is determines as

   $X = L_p/ L_{sys}$

   The difference between MCI by EMF and Verbene is in the denominator of the utility factor (X). While EMF's MCI considers the industry average per product ($L_{av}$), it varies from one product to another, however, Verbene's considers life time of the building's system ($L_{sys}$), which makes it a constant for the products used in a particular system, that helps indicate the performance of one product over the other at a system level. However, the disadvantage of using a constant value as the denominator will not indicate the industrial advancements.

5. Lastly, with the values of V, W and X the LFI (linear flow index) and MCI for a product 'b' can be calculated by;

   $LFI= (V+W)/2M$

   $MCI_{p(b)} = 1-(LFI_{p(b)}*F(X_{p(b)}))$,

   Where, $F(X)= a/X_{p(b)}$ and a=0.9, constant given by EMF(2019)

However, often the product life time is lesser than life of the system in buildings and incase the LFI=1, then MCI tends to a negative value, to avoid this Verbene rewrites the formula as;

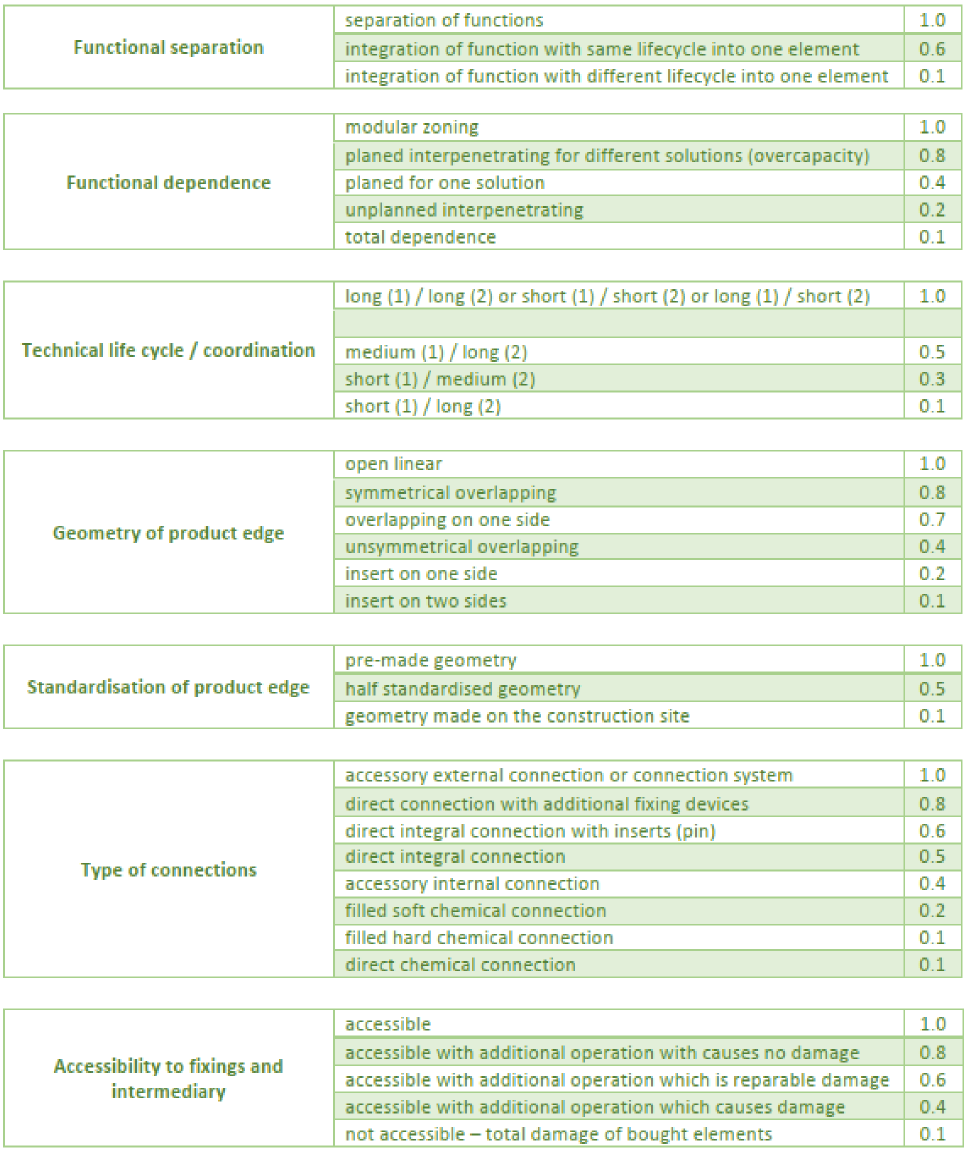
$$MCI_{p(b)} = Max\ (0;(1-(\ LFI_{p(b)}*F(X_{p(b)})))$$

This explains why MCI by Verberne ranges between 0 to 1.

**Step 2 | PCI**

The Product circularity Indicator is the next step, also quoted as the practical value for circularity. It accounts the physical connections between products using the disassembly factors as proposed by Durmisevic (2006). However, not all DfD factors proposed are included in the BCI model. The considered DfD variables are shown in Table .

*Table 1: DfD factors weighted by Durmisevic*(2006) *considered by Verberne*(2016b) *for PCI calculation*



| | | |
|---|---|---|
| **Functional separation** | separation of functions | 1.0 |
| | integration of function with same lifecycle into one element | 0.6 |
| | integration of function with different lifecycle into one element | 0.1 |
| **Functional dependence** | modular zoning | 1.0 |
| | planed interpenetrating for different solutions (overcapacity) | 0.8 |
| | planed for one solution | 0.4 |
| | unplanned interpenetrating | 0.2 |
| | total dependence | 0.1 |
| **Technical life cycle / coordination** | long (1) / long (2) or short (1) / short (2) or long (1) / short (2) | 1.0 |
| | | |
| | medium (1) / long (2) | 0.5 |
| | short (1) / medium (2) | 0.3 |
| | short (1) / long (2) | 0.1 |
| **Geometry of product edge** | open linear | 1.0 |
| | symmetrical overlapping | 0.8 |
| | overlapping on one side | 0.7 |
| | unsymmetrical overlapping | 0.4 |
| | insert on one side | 0.2 |
| | insert on two sides | 0.1 |
| **Standardisation of product edge** | pre-made geometry | 1.0 |
| | half standardised geometry | 0.5 |
| | geometry made on the construction site | 0.1 |
| **Type of connections** | accessory external connection or connection system | 1.0 |
| | direct connection with additional fixing devices | 0.8 |
| | direct integral connection with inserts (pin) | 0.6 |
| | direct integral connection | 0.5 |
| | accessory internal connection | 0.4 |
| | filled soft chemical connection | 0.2 |
| | filled hard chemical connection | 0.1 |
| | direct chemical connection | 0.1 |
| **Accessibility to fixings and intermediary** | accessible | 1.0 |
| | accessible with additional operation with causes no damage | 0.8 |
| | accessible with additional operation which is reparable damage | 0.6 |
| | accessible with additional operation which causes damage | 0.4 |
| | not accessible – total damage of bought elements | 0.1 |

The weightage of the factors range from 0.1 to 1, 0.1 implying the worst impact while 1 being the best connection.

PCI of a product is given by;

$$\mathrm{PCI_p} = \frac{1}{F_d}\sum_{i=1}^{n} MCI_P * F_i$$

Where;

$F_i$ = factor of one of DfD factors

And $F_d$ is the summation of all the DfD factors given by

$$\mathrm{F_d} = \sum_{i=1}^{n} F_i$$

A simplification is made by assuming that all DfD factors have the same impact on the PCI, however, this may not be the case in reality.

**Step 3 | SCI**

To determine the system circularity indicator, the MCIs (theoretical value) and PCI (practical value) of all products need to be aggregated. For this, a normalized factor of product mass is used to identify a weighted average of each product to calculate the SCI of a system s (Verberne, 2016b).

Theoretical value for a product j is given by

$$\mathrm{SCI_{S(t)}} = \frac{1}{W_s}\sum_{j=1}^{n} MCI_j \times W_j$$

Practical value for a product j is given by

$$\mathrm{SCI_{S(t)}} = \frac{1}{W_s}\sum_{j=1}^{n} PCI_j \times W_j$$

Where,

$W_j$ = mass of the product

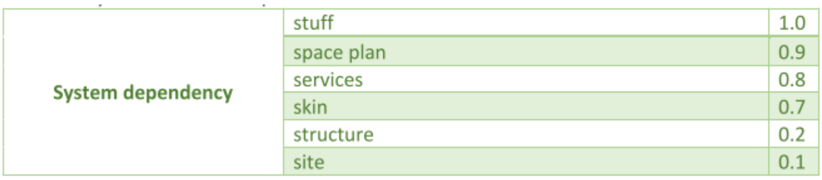
$W_S = \sum_{j=1}^{n} W_j$ , total product mass

SCI value also ranges between 0 to 1.

**Step 4 | BCI**

Similarly, **BCI** of a building is an aggregation of systems i.e. SCI theoretical and practical of system k, weighted by the factor of system dependency ($LK_k$) derived by fuzzy logic, as shown in table.

*Table 2:Weighted factors given to building systems as per level of importance stated by Stewart Brand* (Verberne, 2016b)



| | | |
|---|---|---|
| **System dependency** | stuff | 1.0 |
| | space plan | 0.9 |
| | services | 0.8 |
| | skin | 0.7 |
| | structure | 0.2 |
| | site | 0.1 |

Therefore BCI is given by;

$$\mathrm{BCI_{(t)}} = \frac{1}{LK}\sum_{k=1}^{n} SCI_{(t)k} \times LK_k$$

$$\mathrm{BCI_{(p)}} = \frac{1}{LK}\sum_{k=1}^{n} SCI_{(p)k} \times LK_k$$

Where $LK_k$ is a factor for system dependency and LK is the summation of all factors,

$$\mathrm{LK} = \sum_{k=1}^{n} LK_k$$

**Preconditions of BCI**

The BCI model considers the factors that cause environmental impact as preconditions and these give insight into analyzing the impact changing circularity levels create, the three included are;

1. Material Health – the level of toxicity of the material and risk associated with the material
2. $CO_2$ footprint – total amount of carbon emissions caused by material/product
3. Renewable energy - ratio of renewable energy to fossil fuel energy used in production of material/product

**Drivers of BCI**

The two main drivers of the BCI model are identified as the material value potential and safeguarding the future reuse possibilities (Verberne, 2016b).

1. Material Value Potential – refers to the financial value associated to a material/product that acts as an incentives for suppliers. The suppliers are then competing to produce maximum product/material quality to associate a financial value accounting end of life purpose i.e. reuse (higher value) an recycle (lower value).
2. Safeguarding the future reuse possibilities – refers to the Circular Business Models that can be adopted to facilitate the possible re-use of the products or materials and safeguarding these possibilities lies in the suppliers purview.

The BCI assessment model is comprehensive framework that can be used for decision making towards building design with quantitative circularity indicators for comparing scenarios, however, some limitations of the framework are

1. It only considers technological cycles, thereby not considering biological cycles that could include inputs for material such as wood and it lacks the potential to account energy recovery as material output at the end of life of the product (in case of wood burning as fuel).
2. A Bill of material (BOM) list is essential for the inputs to calculate the MCI.
3. The utility factor is based on product's length of lifetime in use-phase, however, a clear distinction is lacking between the technical and functional life time of the product to determine this factor.
4. The fraction of waste that is recovered is cumulated under one variable without addressing waste recovery potential (via reuse or recycling) and only an overall MCI value is indicated.
5. Only a selected 7 DfD factors are considered out the 25 factors proposed by Durmisevic, thereby narrowing the scope of practical evaluation on product design.
6. Lastly, inclusion of the two drivers mentioned earlier as indicators within the BCI could improve the tool towards guiding the decision making process.

### *Modified BCI by M. van Vliet*

The BCI assessment tool by Verberne was modified by M. van Vliet to address some limitations of the former.

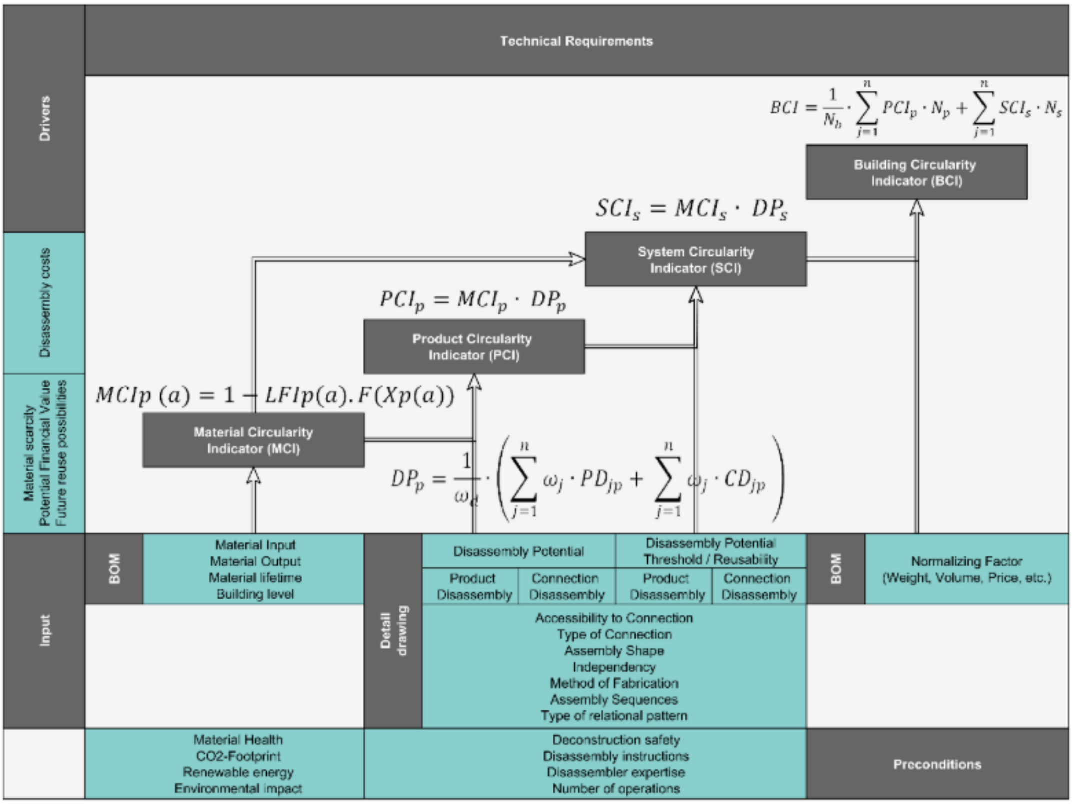


*Figure 2:Modified BCI assessment tool by Van Vliet* (2018)

The modified BCI assessment framework is illustrated in the Figure , the changes or additions are as listed;

1. MCI holds no changes in the formula itself, however, a coding system is proposed for the requirement of a BOM (Bill of material) list to gather material input data for calculation.
2. A framework based on creating relational patterns through detail drawings to assess disassembly potential is an extension to the PCI. The calculation for PCI for a product p is modified as;

   $PCI_p = MCI_p*DP_p$

   Where,

   $DP_p$ = disassembly potential of a product p

   $DP_P$ is distinguished into product DP and connection DP, calculated as

   $$DP_P = \frac{1}{W_d} * (\sum_{j=1}^{n} W_j * PD_{jp} + \sum_{j=1}^{n} W_j * CD_{jp})$$

   Where;

   $PD_{jp}$ = Product disassembly potential of factor j for product p

   $CD_{jp}$ = Connection disassembly potential of factor j for product p

   $W_j$ = Weight of the disassembly factors j

   $W_d$ = Total weight of the disassembly factors

3. A total of 12 DfD factors are considered in the calculation of Disassembly Potential.
4. Product grouping/clustering based on reusability and DP threshold is done to determine systems and their disassembly potential, therefore eliminating the use of system dependency factors. A DP threshold of 0.6 is set, for clustering products into systems.

5. The SCI is given by multiplying the MCI of the system s and the disassembly potential of a system s, written as;

   $$SCI_s = MCI_s * DP_s$$

   $MCI_s$ = the aggregation of the LFI (Linear flow index) and the utility factor (X) for all products in a system.

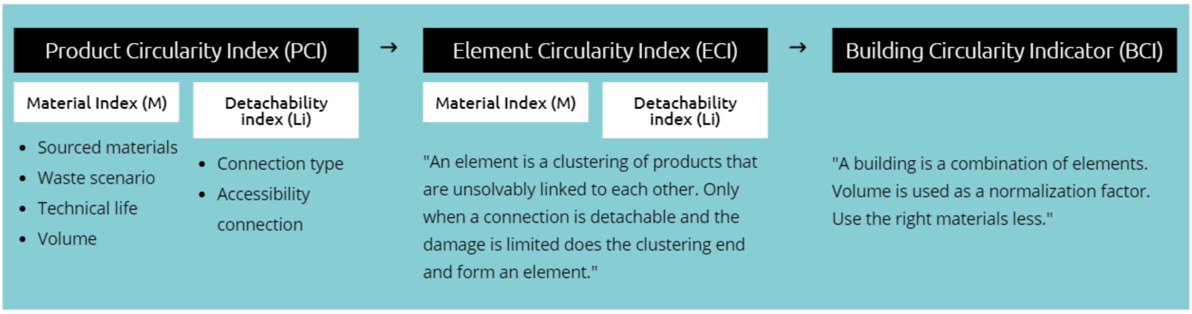
6. Finally the modified BCI is calculated by summation of the PCI and SCI using normalizing factors (not specified but either mass, volume or price).

   $$BCI = \frac{1}{N_b} * \sum_{j=1}^{n} PCI_P * N_P + \sum_{j=1}^{n} SCI_s * N_s$$

   Where,
   $N_b$ = Sum of normalizing factors for products p and systems s
   $N_s$ = Normalizing factor of systems s
   $N_p$ = Normalizing factor of systems p

*BCI by Alba Concepts*

The model of BCI used by Alba Concepts is a simplified version of the BCI framework developed by Verberne. The framework has three levels of assessment in a building, product, element and building circularity Index, as illustrated in the Figure .



"An element is a clustering of products that are unsolvably linked to each other. Only when a connection is detachable and the damage is limited does the clustering end and form an element."

"A building is a combination of elements. Volume is used as a normalization factor. Use the right materials less."

*Figure 3: The BCI conceptual framework by Alba Concepts*

The difference between this model of the BCI from Verberne and Vliet is the use of Element Circularity Index (ECI), instead of the System Circularity Indicator (SCI). The definition of element stated is as the clustering of products that are configured in a totally integrated manner with no room for detachment. Under ECI assessment the detachability index of such elements are measured and multiplied by the Material Index of products in the element.

From Vliet's (2018) research it is found that, the ECI here is calculated as;

ECI = Material Index (MI) * Detachability Index (LI)

The detachability index (LI) can also be termed as the disassembly potential (measures to what extent a element is detachable). The LI for a element is calculated as;

$LI_E = (TV + ToV)/2$

Where;

TV = connection type

ToV = Accessibility of the connection

Both these DfD factors are weighted fuzzy variables as used in Verberne's BCI.

For calculating the BCI a normalizing factor of element volume is considered instead of system dependency factors as used in case of Verberne. Thus, calculated as;

$$\text{BCI} = \frac{1}{total\ Volume} * (\sum m^3 * ECI)$$

*Summary*

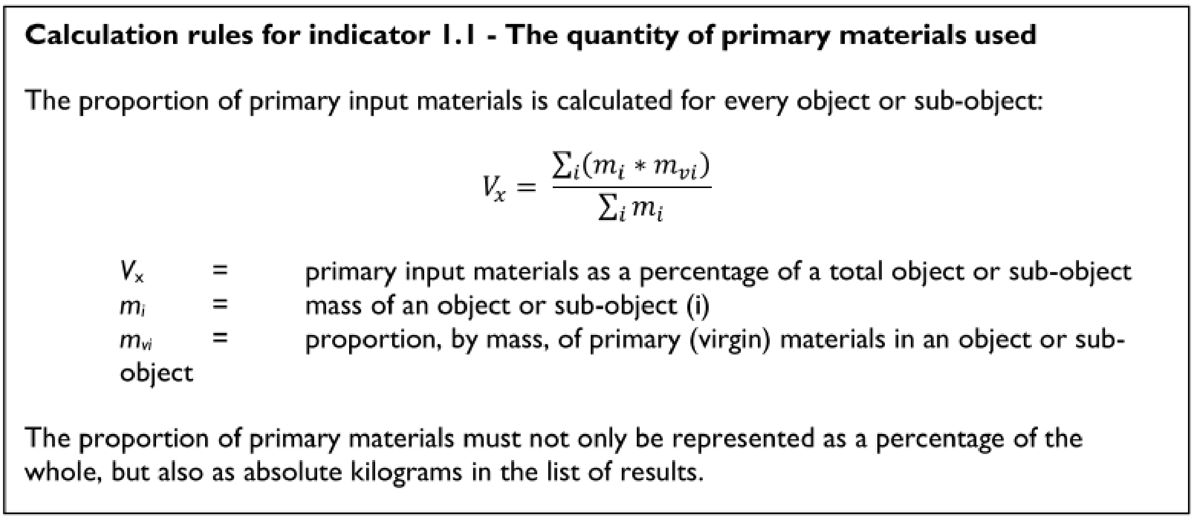
The three different BCI frameworks discussed are by Verberne, Vliet and Alba concepts. While Verberne and Vliet have created this framework as an output of their master graduation research, Alba concepts has adapted the academic findings into a simpler version to apply the same in practice. The computation and use of the framework is detailed in the sections above, however, the table below is created to assess the similarities (green) and differences (orange) between each of the framework.

| BCI Method | MCI | DfD factors | PCI | SCI | BCI |
|---|---|---|---|---|---|
| Verberne (2016b) | $\text{MCI}_{\text{p(b)}} = 1\text{-}(\text{LFI}_{\text{p(b)}}*\text{F}(\text{X}_{\text{p(b)}})$<br>Adaptation of the Ellen Macarthur's MCI framework, with modified LFI and X calculation | 7 | $\text{PCI}_{\text{p}} = \frac{1}{F_d} \sum_{i=1}^{n} MCI_P * F_i$<br>Summation of MCI of product multiplied by the factor of n DfD | Two values i.e. theoretical and practical are determined using mass as the normalizing factor. | Uses system dependency factors for normalizing the SCI |
| Van Vliet (2018) | Same as Verberne | 12 | $\text{PCIp} = \text{MCIp} * \text{DPp}$<br>The disassembly potential (DP) is calculated at product and connection level. | $\text{SCI}_{\text{s}} = \text{MCI}_{\text{s}} * \text{DP}_{\text{s}}$<br>Uses disassembly threshold to categorize products into systems. | Summation of PCI and SCI using normalizing factors of either weight, volume or price |
| Alba Concepts (2020) | It is an adaptation of Verberne's framework (calculation was not found in literature) | 4 | $\text{PCI} = \text{M}*\text{LI}$<br>The detachability index is calculated using connection type and accessibility connection factors | $\text{ECI} = \text{M} * \text{LI}$<br>Termed as ECI instead of SCI. Calculated using detachability index(Li) | Uses ECI and the normalizing factor of volume |

# APPENDIX 3

## CB23 CORE-MEASUREMENT METHOD

## PROTECTION OF MATERIAL (MEASURING CIRCULARITY, 2020)



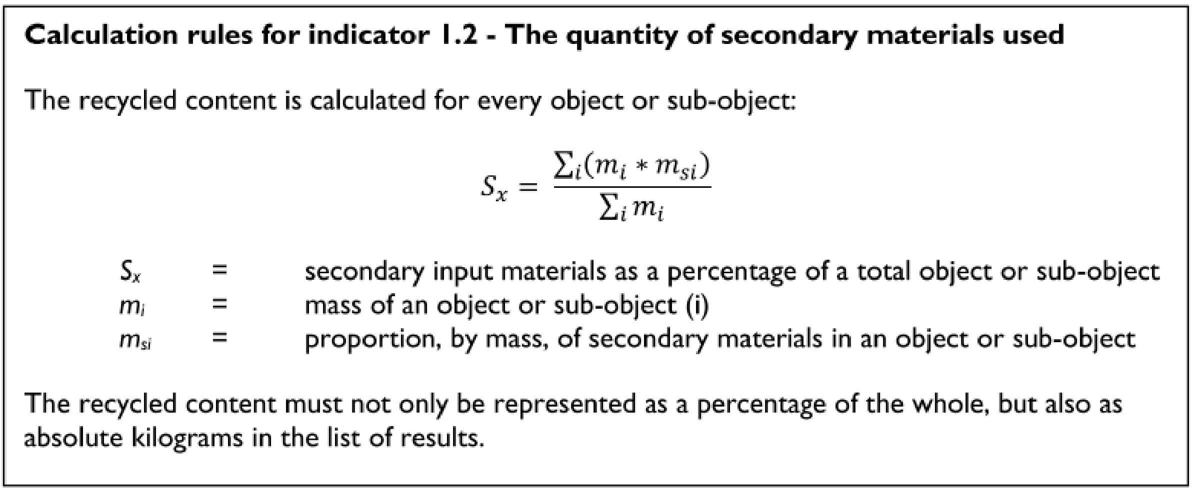
**Calculation rules for indicator 1.1 - The quantity of primary materials used**

The proportion of primary input materials is calculated for every object or sub-object:

$$V_x = \frac{\sum_i (m_i * m_{vi})}{\sum_i m_i}$$

$V_x$ = primary input materials as a percentage of a total object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_{vi}$ = proportion, by mass, of primary (virgin) materials in an object or sub-object

The proportion of primary materials must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.



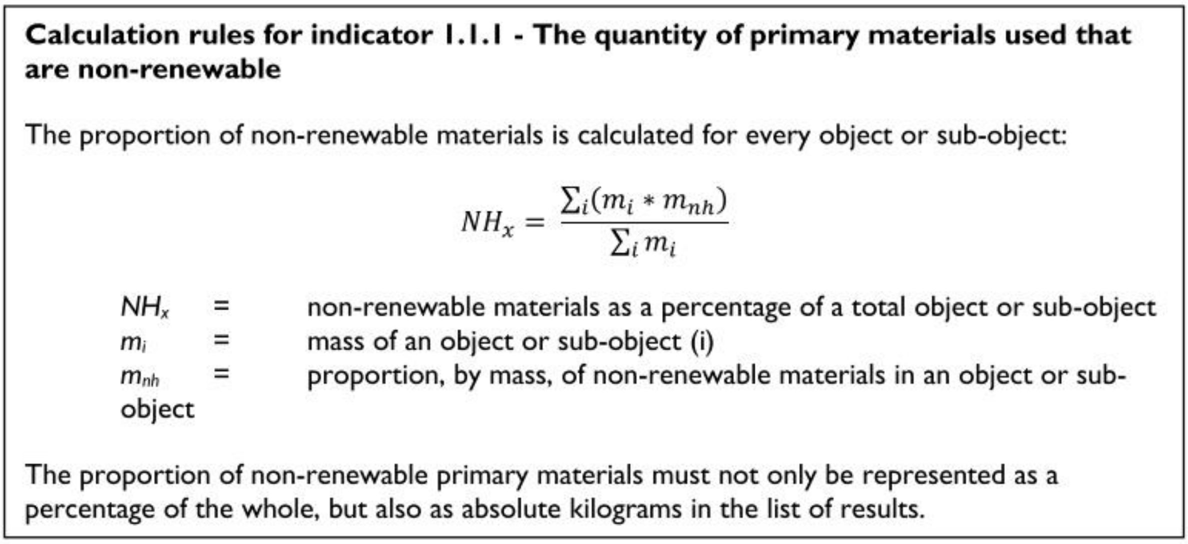
**Calculation rules for indicator 1.2 - The quantity of secondary materials used**

The recycled content is calculated for every object or sub-object:

$$S_x = \frac{\sum_i (m_i * m_{si})}{\sum_i m_i}$$

$S_x$ = secondary input materials as a percentage of a total object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_{si}$ = proportion, by mass, of secondary materials in an object or sub-object

The recycled content must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.



**Calculation rules for indicator 1.1.1 - The quantity of primary materials used that are non-renewable**

The proportion of non-renewable materials is calculated for every object or sub-object:

$$NH_x = \frac{\sum_i (m_i * m_{nh})}{\sum_i m_i}$$

$NH_x$ = non-renewable materials as a percentage of a total object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_{nh}$ = proportion, by mass, of non-renewable materials in an object or sub-object

The proportion of non-renewable primary materials must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.

**Calculation rules for indicator 1.1.2 - The quantity of primary materials used that are renewable**

The proportion of renewable materials is calculated for every object or sub:

$$H_x = \frac{\sum_i (m_i * m_h)}{\sum_i m_i}$$

$H_x$ = renewable materials as a percentage of a total object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_h$ = proportion, by mass, of renewable materials in an object or sub-object

The proportion of renewable primary materials must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.

**Calculation rules for indicator 1.1.2a – The quantity of primary materials used that are renewable and are sustainably produced**

The proportion of sustainably produced renewable materials is calculated for every object or sub-object:

$$N_x = \frac{\sum_i (m_i * m_{ni})}{\sum_i m_i}$$

$N_x$ = sustainably produced renewable materials as a percentage of a total object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_{ni}$ = proportion, by mass, of primary, sustainably produced renewable materials in an object or sub-object

The proportion of sustainably produced renewable primary materials must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.

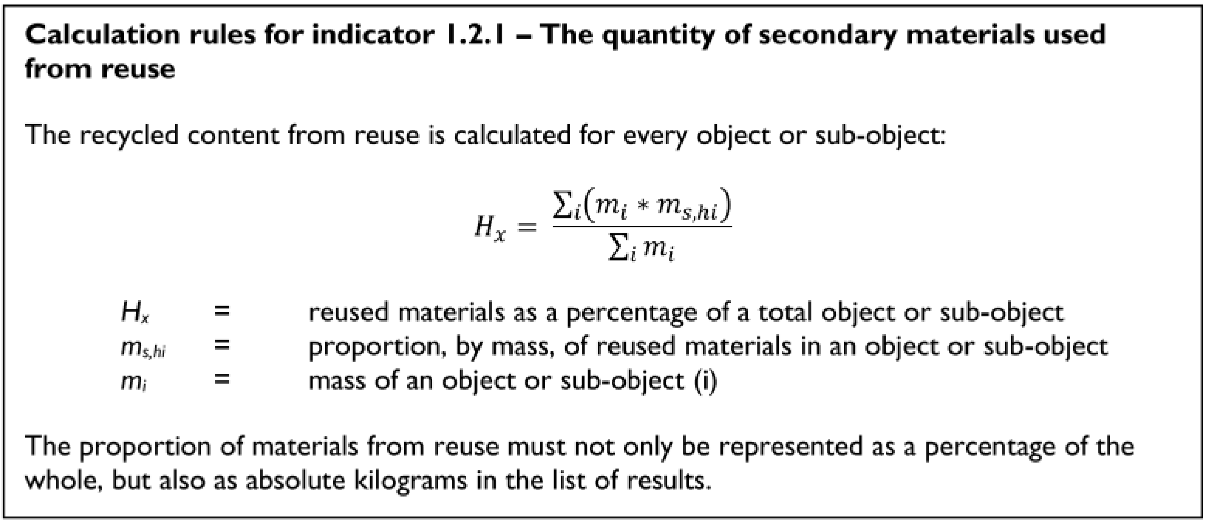
**Calculation rules for indicator 1.1.2b – The quantity of primary materials used that are renewable and are not sustainably produced**

The proportion of unsustainably produced renewable materials is calculated for every object or sub-object:

$$VN_x = \frac{\sum_i \left(m_i * (m_{vi} - m_{ni})\right)}{\sum_i m_i}$$

$VN_x$ = non-renewable or unsustainably produced renewable raw materials as a percentage of a total object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_{vi}$ = proportion, by mass, of primary (virgin) materials in an object or sub-object
$m_{ni}$ = proportion, by mass, of sustainably produced renewable materials in an object or sub-object

The proportion of unsustainably produced renewable primary materials must not only be represented as a percentage of the whole, but also as absolute kilos.



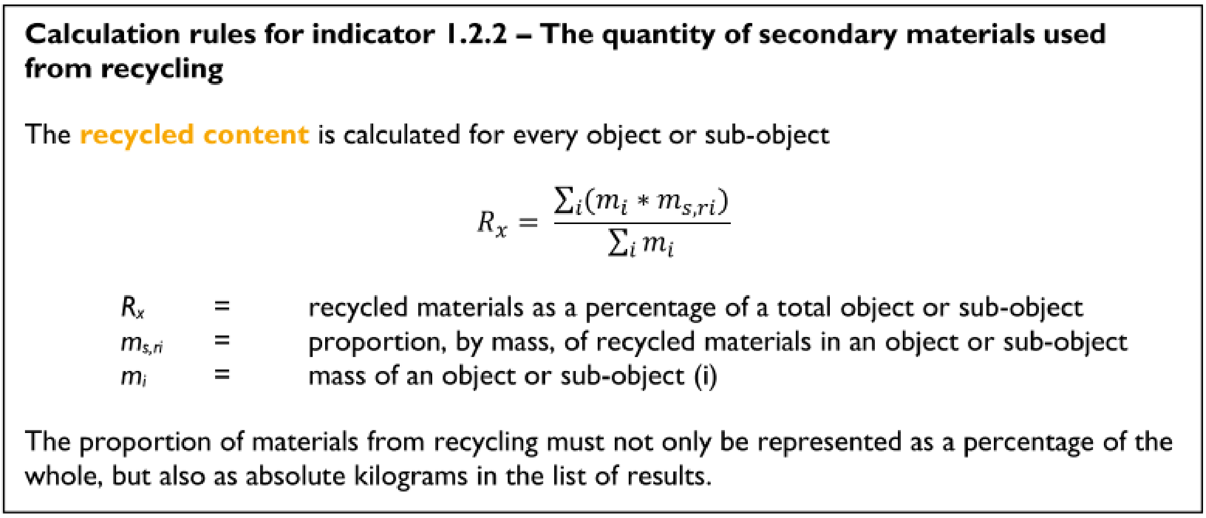
### Calculation rules for indicator 1.2.1 – The quantity of secondary materials used from reuse

The recycled content from reuse is calculated for every object or sub-object:

$$H_x = \frac{\sum_i (m_i * m_{s,hi})}{\sum_i m_i}$$

$H_x$ = reused materials as a percentage of a total object or sub-object
$m_{s,hi}$ = proportion, by mass, of reused materials in an object or sub-object
$m_i$ = mass of an object or sub-object (i)

The proportion of materials from reuse must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.



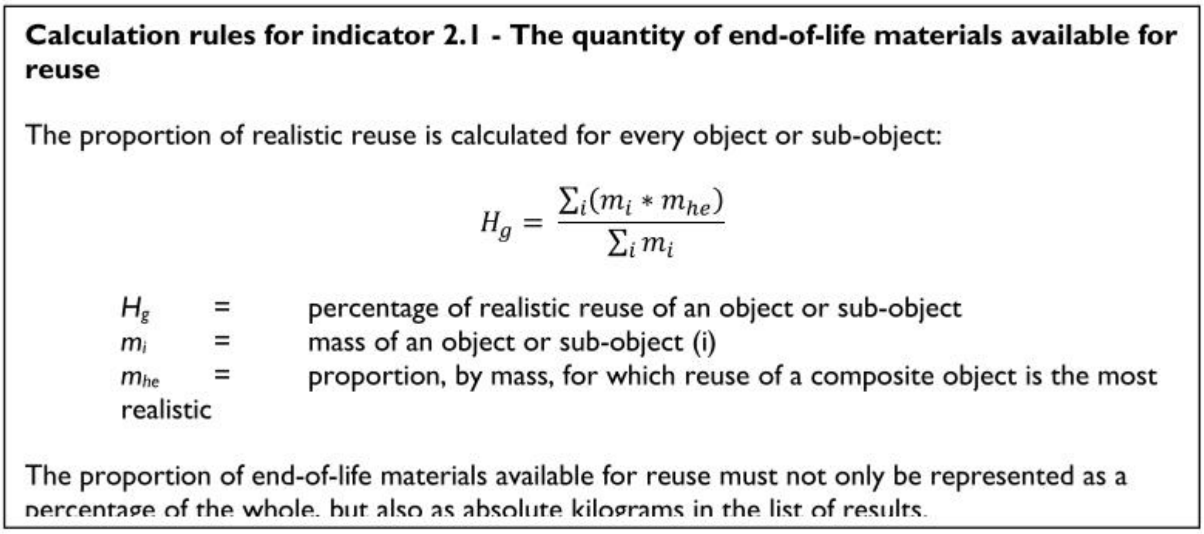
### Calculation rules for indicator 1.2.2 – The quantity of secondary materials used from recycling

The **recycled content** is calculated for every object or sub-object

$$R_x = \frac{\sum_i (m_i * m_{s,ri})}{\sum_i m_i}$$

$R_x$ = recycled materials as a percentage of a total object or sub-object
$m_{s,ri}$ = proportion, by mass, of recycled materials in an object or sub-object
$m_i$ = mass of an object or sub-object (i)

The proportion of materials from recycling must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.



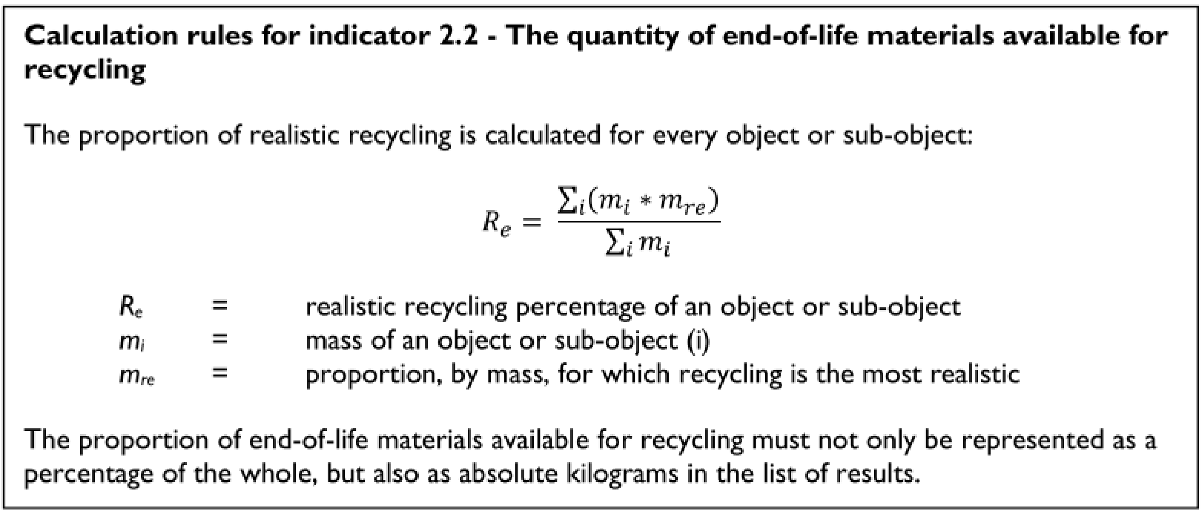
### Calculation rules for indicator 2.1 - The quantity of end-of-life materials available for reuse

The proportion of realistic reuse is calculated for every object or sub-object:

$$H_g = \frac{\sum_i (m_i * m_{he})}{\sum_i m_i}$$

$H_g$ = percentage of realistic reuse of an object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_{he}$ = proportion, by mass, for which reuse of a composite object is the most realistic

The proportion of end-of-life materials available for reuse must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.



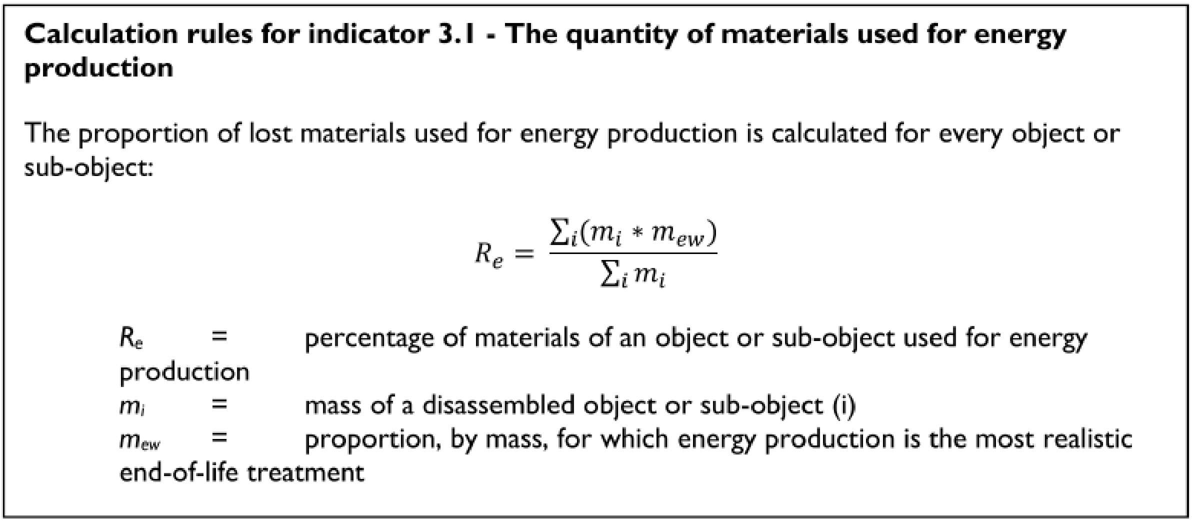
**Calculation rules for indicator 2.2 - The quantity of end-of-life materials available for recycling**

The proportion of realistic recycling is calculated for every object or sub-object:

$$R_e = \frac{\sum_i (m_i * m_{re})}{\sum_i m_i}$$

$R_e$ = realistic recycling percentage of an object or sub-object
$m_i$ = mass of an object or sub-object (i)
$m_{re}$ = proportion, by mass, for which recycling is the most realistic

The proportion of end-of-life materials available for recycling must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.

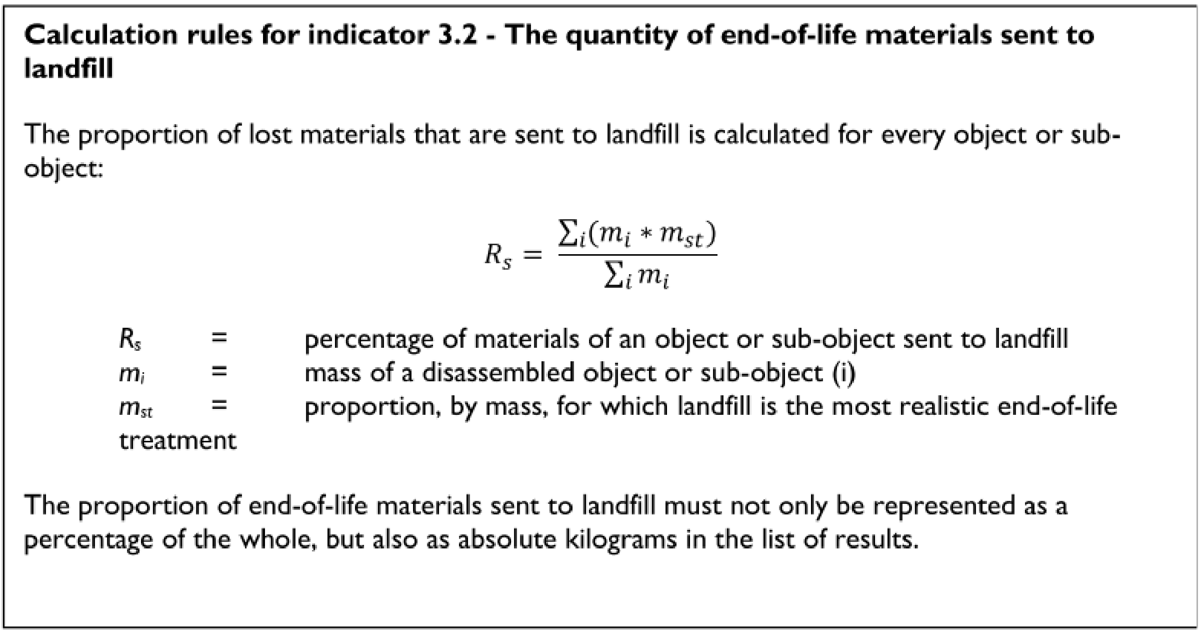


**Calculation rules for indicator 3.1 - The quantity of materials used for energy production**

The proportion of lost materials used for energy production is calculated for every object or sub-object:

$$R_e = \frac{\sum_i (m_i * m_{ew})}{\sum_i m_i}$$

$R_e$ = percentage of materials of an object or sub-object used for energy production
$m_i$ = mass of a disassembled object or sub-object (i)
$m_{ew}$ = proportion, by mass, for which energy production is the most realistic end-of-life treatment



**Calculation rules for indicator 3.2 - The quantity of end-of-life materials sent to landfill**

The proportion of lost materials that are sent to landfill is calculated for every object or sub-object:

$$R_s = \frac{\sum_i (m_i * m_{st})}{\sum_i m_i}$$

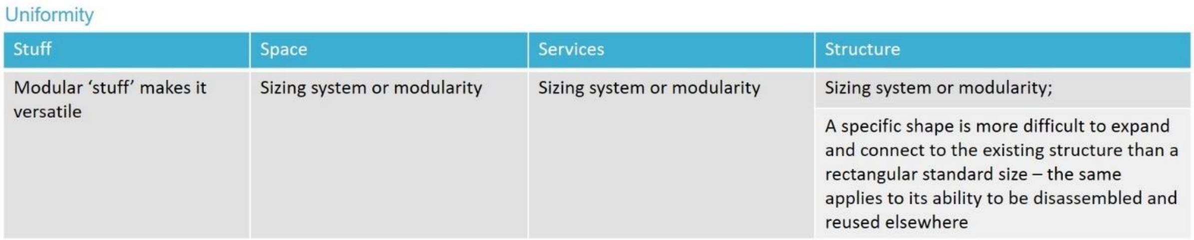
$R_s$ = percentage of materials of an object or sub-object sent to landfill
$m_i$ = mass of a disassembled object or sub-object (i)
$m_{st}$ = proportion, by mass, for which landfill is the most realistic end-of-life treatment

The proportion of end-of-life materials sent to landfill must not only be represented as a percentage of the whole, but also as absolute kilograms in the list of results.

# APPENDIX 4

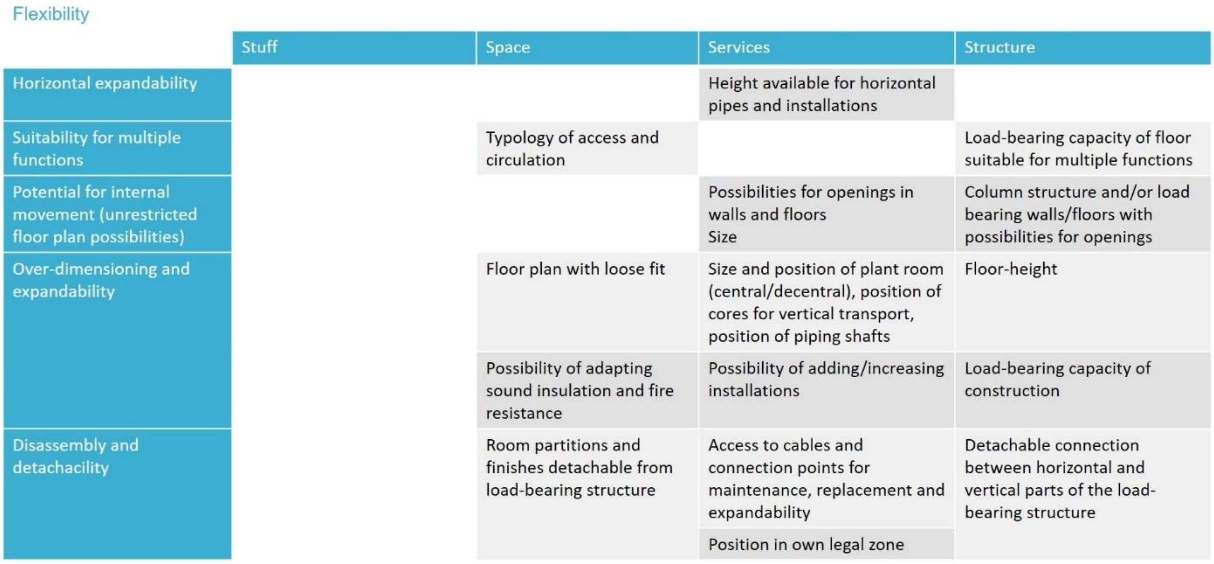
## *CB'23 CORE MEASUREMENT METHOD*

## ADAPTIVE CAPACITY



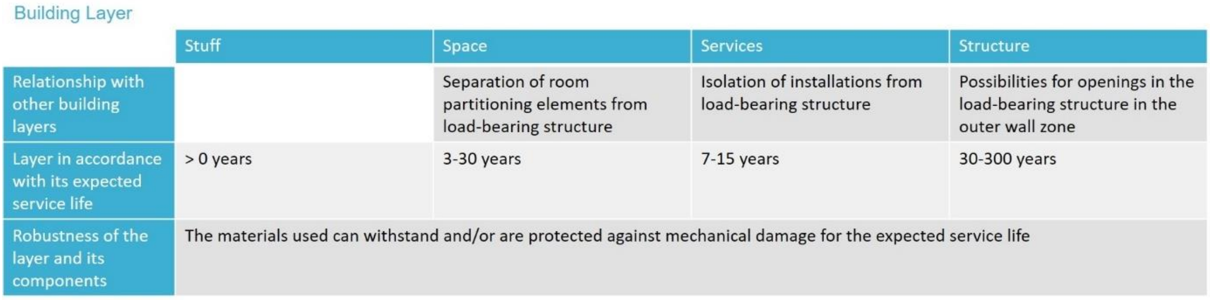
Uniformity

| Stuff | Space | Services | Structure |
|---|---|---|---|
| Modular 'stuff' makes it versatile | Sizing system or modularity | Sizing system or modularity | Sizing system or modularity;<br>A specific shape is more difficult to expand and connect to the existing structure than a rectangular standard size – the same applies to its ability to be disassembled and reused elsewhere |



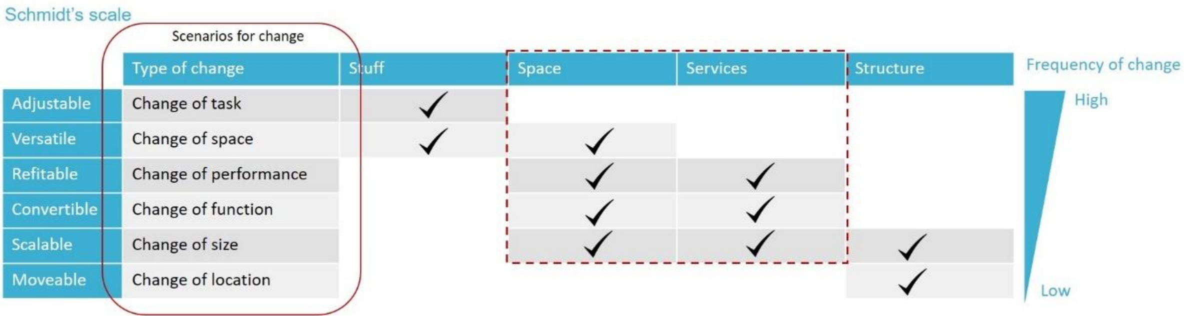
Flexibility

| | Stuff | Space | Services | Structure |
|---|---|---|---|---|
| Horizontal expandability | | | Height available for horizontal pipes and installations | |
| Suitability for multiple functions | | Typology of access and circulation | | Load-bearing capacity of floor suitable for multiple functions |
| Potential for internal movement (unrestricted floor plan possibilities) | | | Possibilities for openings in walls and floors<br>Size | Column structure and/or load bearing walls/floors with possibilities for openings |
| Over-dimensioning and expandability | | Floor plan with loose fit | Size and position of plant room (central/decentral), position of cores for vertical transport, position of piping shafts | Floor-height |
| | | Possibility of adapting sound insulation and fire resistance | Possibility of adding/increasing installations | Load-bearing capacity of construction |
| Disassembly and detachacility | | Room partitions and finishes detachable from load-bearing structure | Access to cables and connection points for maintenance, replacement and expandability<br>Position in own legal zone | Detachable connection between horizontal and vertical parts of the load-bearing structure |



Building Layer

| | Stuff | Space | Services | Structure |
|---|---|---|---|---|
| Relationship with other building layers | | Separation of room partitioning elements from load-bearing structure | Isolation of installations from load-bearing structure | Possibilities for openings in the load-bearing structure in the outer wall zone |
| Layer in accordance with its expected service life | > 0 years | 3-30 years | 7-15 years | 30-300 years |
| Robustness of the layer and its components | The materials used can withstand and/or are protected against mechanical damage for the expected service life | | | |



Schmidt's scale

Scenarios for change

| | Type of change | Stuff | Space | Services | Structure |
|---|---|---|---|---|---|
| Adjustable | Change of task | ✓ | | | |
| Versatile | Change of space | ✓ | ✓ | | |
| Refitable | Change of performance | | ✓ | ✓ | |
| Convertible | Change of function | | ✓ | ✓ | |
| Scalable | Change of size | | ✓ | ✓ | ✓ |
| Moveable | Change of location | | | | ✓ |

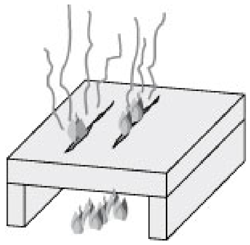
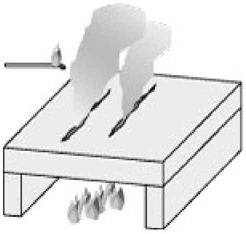
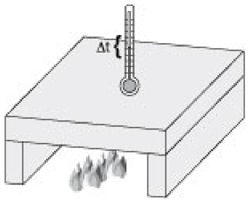
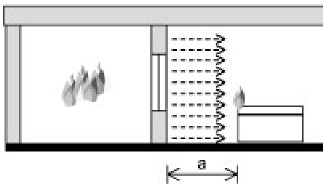
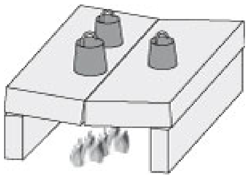
# APPENDIX 5

## OVERVIEW OF CONSEQUENCE CLASSES (IN CONFORMITY WITH NEN-EN 1990, NEN-EN 1991-1-7 AND NEN 8700)

| CC | Description |
|---|---|
| 1a | Limited or negligible economic, social or environmental consequences (excluding loss of human life) |
| 1b | Limited consequences in terms of loss of human life and/or limited or negligible economic, social or environmental consequences - Examples: single family residences with maximum 3 floors, farm buildings, industrial buildings with maximum 2 floors occupied by only a limited number of people, horticultural greenhouses |
| 2 | Moderate consequences in terms of loss of human life and/or substantial economic, social or environmental consequences |
| 2a<br>Risk group Low | Insofar as not included in CC1 or CC2b or CC3:<br>Examples: single family residences with 4 or more floors, residential buildings, hotels and office buildings with maximum 4 floors, educational buildings with 1 floor, shops with maximum 2 floors, public buildings with a floor area < 2000 m$^2$ per floor, industrial buildings with maximum 2 floors, car parks with maximum 2 floors |
| 2b<br>Risk group High | Insofar as not included in CC1 or CC2a or CC3:<br>Examples: residential buildings, hotels and office buildings with 5 or more floors, educational buildings with 2 or more floors, shops with 3 or more floors, hospitals with maximum 3 floors, public buildings with a floor area < 2000 m$^2$ per floor, industrial buildings with 3 or more floors, car parks with 3 or more floors |
| 3 | Major consequences in terms of loss of human life and/ or very significant economic, social or environmental consequences. Examples: tall buildings that reach more than 70 metres above the adjacent ground surface; buildings where the span of the structure in a spanning direction is greater than 50 metres and where, in case of failure, more than 500 persons are simultaneously at risk (such as, large exhibition and station halls; structures that serve a public function (such as, educational buildings, stadiums, concert halls, galleried stands, etc.) where, in case of failure, more than 500 persons are simultaneously at risk; buildings occupied by persons with reduced self-reliance, such as hospitals, detention centres, nursing homes with 4 or more floors, etc.; buildings from where highly crucial processes are managed, e.g. air traffic control towers at international airports, traffic control building, etc.; industrial buildings for hazardous materials and/or processes for which an environmental permit is required |

### *FIRE RESISTANCE WITH REGARD TO THE SEPARATING FUNCTION*

### *CRITERIA ASSOCIATED WITH THE DETERMINATION OF FIRE RESISTANCE OF BUILDING PARTS IN ACCORDANCE WITH NEN 6069*

<table>
<tr><th colspan="2">FLAME DENSITY INVOLVED IN THE SEAL</th></tr>
<tr><td></td><td>THE BUILDING PART ALLOWS HOT GASES AND/OR FLAMES TO PASS THROUGH OVERSIZED OPENINGS (> 25 MM OR A 6 MM WIDE AND 150 MM LONG GAP); FLAMES ARE VISIBLE CONTINUOUSLY ON THE UNHEATED SIDE FOR AT LEAST 10 SECONDS; OR DRIED WATTS IGNITE ON THE UNHEATED SIDE</td></tr>
<tr><th colspan="2">FLAME DENSITY INVOLVED IN FLAMMABILITY</th></tr>
<tr><td></td><td>COMBUSTIBLE GASES ARE PRODUCED ON THE NON-HEATED SIDE OF THE BUILDING PART, WHICH CAN BE IGNITED BY MEANS OF A DECOY FLAME AND CONTINUE TO BURN CONTINUOUSLY FOR AT LEAST 30 SECONDS.</td></tr>
<tr><th colspan="2">THERMAL INSULATION INVOLVED IN TEMPERATURE</th></tr>
<tr><td> </td><td>THE BUILDING PART UNDERGOES A CERTAIN, CRITICALLY ASSUMED TEMPERATURE INCREASE ON THE NON-HEATED SIDE<br>ON AVERAGE OVER THE SURFACE UP TO 140 °C; OR LOCALLY UP TO 180 °C</td></tr>
<tr><th colspan="2">THERMAL INSULATION INVOLVED IN HEAT RADIATION</th></tr>
<tr><td> </td><td>THE HEAT RADIATION ON THE NON-HEATED SIDE OF THE BUILDING PART EXCEEDS A CERTAIN CRITICALLY ASSUMED VALUE<br>15 KW/M² AT A DISTANCE EQUAL TO THE WIDTH OF THE RADIANT SURFACE (UP TO A MAXIMUM OF 1 METER)</td></tr>
<tr><th colspan="2">SUCCUMBING</th></tr>
<tr><td></td><td>THE BUILDING PART UNDERGOES INTOLERABLE LARGE DEFORMATIONS OR DEFORMS AT TOO HIGH A SPEED UNDER THE INFLUENCE OF THE LOAD (INCLUDING OWN WEIGHT)</td></tr>
</table>

### SOUND ABSORPTION COEFFICIENTS OF STRUCTURES AND FINISHING MATERIALS (ISSO-24)

| **Material object** | **Frequency [Hz]** | | | | | |
|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1.000 | 2.000 | 4.000 |
| Concrete, masonry plastered | 0,01 | 0,01 | 0,01 | 0,02 | 0,02 | 0,03 |
| Masonry, ungestucted | 0,02 | 0,02 | 0,03 | 0,04 | 0,05 | 0,07 |
| Hard floor finishes (e.g. linoleum, laminate, parquet) on heavy floor | 0,02 | 0,03 | 0,04 | 0,05 | 0,05 | 0,06 |
| Soft floor finish on heavy floor; thickness ≤ 5 mm (e.g. carpet) | 0,02 | 0,03 | 0,06 | 0,15 | 0,30 | 0,40 |
| Soft floor finish on heavy floor; thickness ≥ 10 mm (e.g. high pile carpet) | 0,04 | 0,08 | 0,15 | 0,30 | 0,45 | 0,55 |
| Wooden floor, parquet on control work/slats | 0,12 | 0,10 | 0,06 | 0,05 | 0,05 | 0,06 |
| Windows, glass façade | 0,12 | 0,08 | 0,05 | 0,04 | 0,03 | 0,02 |
| Doors (wood) | 0,14 | 0,10 | 0,08 | 0,08 | 0,08 | 0,08 |
| Vitrage; 0-200 mm away from hard surface | 0,05 | 0,04 | 0,03 | 0,02 | 0,02 | 0,02 |
| Curtain, woven material approximately 0.4 kg/m²; folded/crammed together | 0,10 | 0,40 | 0,70 | 0,90 | 0,95 | 1,00 |
| Air vent, 50% open | 0,30 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 |
| Large openings (smallest size > 1 m | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 | 1,00 |
| Single chair, wood | 0,02 | 0,02 | 0,03 | 0,04 | 0,04 | 0,04 |
| Single chair, padded (= a upholstered chair/padded with soft material) | 0,10 | 0,20 | 0,25 | 0,35 | 0,35 | 0,35 |
| Single person in a group, sitting or standing, 1 person per 6 m² | 0,08 | 0,25 | 0,50 | 0,60 | 0,70 | 0,80 |
| People sitting in a row at 0.9 - 1.2 m distance from each other (public) | 0,20 | 0,40 | 0,50 | 0,60 | 0,70 | 0,70 |
| Children in a classroom with acoustic hard furniture, 1 child per m² | 0,10 | 0,20 | 0,25 | 0,35 | 0,40 | 0,40 |
| Suspended ceiling, mineral wool base, thick 20 mm, directly against substrate | 0,10 | 0,30 | 0,80 | 0,95 | 0,95 | 0,85 |
| Suspended ceiling, mineral wool base, thick 20 mm, cavity 200 mm | 0,20 | 0,60 | 0,95 | 0,95 | 0,95 | 1,00 |
| Suspended ceiling, mineral fibre base, thick 19 mm, 5.5 kg/m², cavity 200 mm | 0,35 | 0,45 | 0,55 | 0,75 | 0,90 | 1,00 |
| Wood wool cement plate, thick 25 mm, directly against substrate | 0,10 | 0,15 | 0,25 | 0,65 | 0,75 | 0,70 |
| Wood wool cement plate, thick 25 mm, cavity 300 mm | 0,55 | 0,55 | 0,35 | 0,65 | 0,70 | 0,80 |
| Perforated plaster ceiling 3.14%, thick 9.5 mm, with mineral wool 40 mm | 0,33 | 0,87 | 0,56 | 0,29 | 0,18 | 0,21 |
| Perforated plaster ceiling 15.5%, thick 9.5 mm, with mineral wool 40 mm | 0,27 | 0,69 | 0,99 | 0,74 | 0,59 | 0,52 |
| Perforated plaster ceiling 20.2%, thick 9.5 mm, with mineral wool 40 mm | 0,33 | 0,79 | 1,00 | 0,83 | 0,65 | 0,54 |
| Baffle, 1200 x 600 x 50 mm, 2 per m² | 0,52 | 0,80 | 1,46 | 1,73 | 1,73 | 1,67 |
| Baffle, 1200 x 600 x 80 mm, 2 per m² | 0,59 | 1,08 | 1,74 | 1,76 | 1,63 | 1,63 |

*Table 4.1 shows that a suspended mineral wool ceiling has a higher sound absorption value than a suspended ceiling based on mineral fibers in the frequency range important for speech between approximately 500 and 2000 Hz (ISSO, 24).*

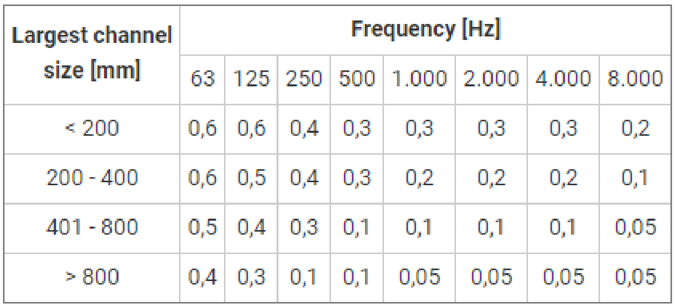
For high sound absorption with a perforated plaster ceiling, in addition to the addition of mineral wool (directly on top of it), the perforation degree should be at least 15%, preferably 20%.

For the low frequency bands (125 and 250 Hz) up to and including 500 Hz, if a sound-absorbing material is not applied directly to the substrate but to a certain cavity (suspension height), such as a suspended ceiling, results in higher sound absorption values compared to the situation where this material is applied directly to the substrate.

Baffles, may have sound absorption values higher than 1 (= sound absorption exceeding 100%) due to the fact that the sound can be absorbed on two sides of the baffle (or all around in the case of a round baffle) rather than predominantly at the bottom at a suspended ceiling.

### *SOUND ATTENUATION VALUES FOR STRAIGHT CHANNEL VENTILATION DUCT SYSTEMS*

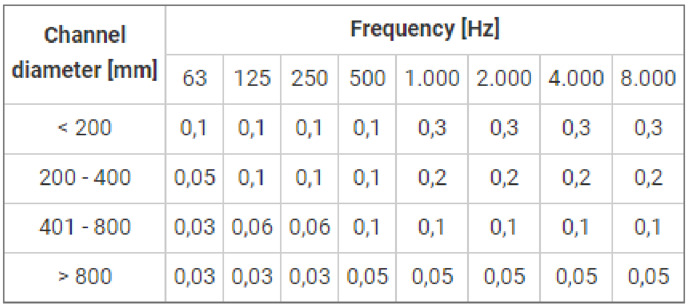
**Table 7.19 Sound attenuation values straight channel pieces, rectangular, in dB/linear meter [dB/m']**



| Largest channel size [mm] | Frequency [Hz] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 63 | 125 | 250 | 500 | 1.000 | 2.000 | 4.000 | 8.000 |
| < 200 | 0,6 | 0,6 | 0,4 | 0,3 | 0,3 | 0,3 | 0,3 | 0,2 |
| 200 - 400 | 0,6 | 0,5 | 0,4 | 0,3 | 0,2 | 0,2 | 0,2 | 0,1 |
| 401 - 800 | 0,5 | 0,4 | 0,3 | 0,1 | 0,1 | 0,1 | 0,1 | 0,05 |
| > 800 | 0,4 | 0,3 | 0,1 | 0,1 | 0,05 | 0,05 | 0,05 | 0,05 |

For straight channel pieces with cylindrical cross-section (round channels), the damping values per linear meter, as shown in Table 7.20, shall apply.

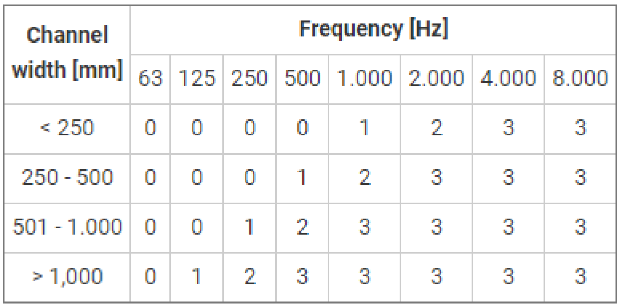
**Table 7.20 Sound attenuation values circular (round) channel pieces, in dB/linear meter [dB/m']**



| Channel diameter [mm] | Frequency [Hz] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 63 | 125 | 250 | 500 | 1.000 | 2.000 | 4.000 | 8.000 |
| < 200 | 0,1 | 0,1 | 0,1 | 0,1 | 0,3 | 0,3 | 0,3 | 0,3 |
| 200 - 400 | 0,05 | 0,1 | 0,1 | 0,1 | 0,2 | 0,2 | 0,2 | 0,2 |
| 401 - 800 | 0,03 | 0,06 | 0,06 | 0,1 | 0,1 | 0,1 | 0,1 | 0,1 |
| > 800 | 0,03 | 0,03 | 0,03 | 0,05 | 0,05 | 0,05 | 0,05 | 0,05 |

### *SOUND ATTENUATION VALUES FOR BENDS IN VENTILATION DUCT SYSTEMS*

**Table 7.21 Sound attenuation values [dB] metal bends, circular or rectangular with guide elements (guide blades)**



| Channel width [mm] | Frequency [Hz] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 63 | 125 | 250 | 500 | 1.000 | 2.000 | 4.000 | 8.000 |
| < 250 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 3 |
| 250 - 500 | 0 | 0 | 0 | 1 | 2 | 3 | 3 | 3 |
| 501 - 1.000 | 0 | 0 | 1 | 2 | 3 | 3 | 3 | 3 |
| > 1,000 | 0 | 1 | 2 | 3 | 3 | 3 | 3 | 3 |

It can be said that the sound attenuation values in Table 7.21 should be handled with some caution given the (almost too) nice course of the frequency dependence with the channel width. The channel height does not seem to play a role in this. It is important to note that the aforementioned sound attenuations for bends apply not only to the bend segment, but to the bend segment in combination with a connecting length straight channel on either side of the bend segment. The length of the connecting channel piece must correspond at least to 2B (2 x largest channel size or diameter bend segment), see figure. It is therefore absolutely not permitted to use the table values for the sound attenuation of four contiguous bend segments.

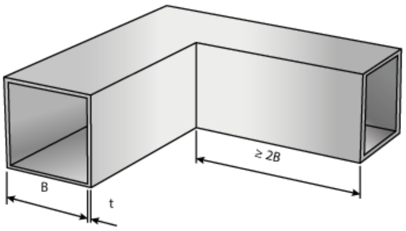


*Figure: Acoustic bend with sound attenuation values: bend segment plus 2B straight channel piece before and after bend segment (ISSO, 24)*

## EXISTING INTEGRATED FLOOR-SYSTEMS

### *Slimline floor systems*

Slimline is a fully prefabricated integrated floor-system that can accommodate services within a total thickness of 263mm between the ceiling and the subfloor. The structural layer comprises of a IPE steel section with one flange integrated into the reinforced concrete floor slab of thickness 70mm. To cater to thermal insulation, the concrete slab can accommodate cooling pipes for core activation. The slab offers dimensional stability, fire protection and sound insulation. The IPE has openings in the web of the section to accommodate other services for ventilation. The subfloor is laid over the IPE sections. The subfloor detail has two variations, raised access floor and screed poured on metal sheeting. The raised access floor offers better flexibility as it is demountable and have access tiles for maintenance. While the second variant, has fixed access opening for maintenance. The total thickness of a slimline floor system is 418mm and spans between 4.5 -16.2 meters. It comes in standard widths of 2400/2700/3000 mm, from the website of Slimline Buildings BV (n.d).

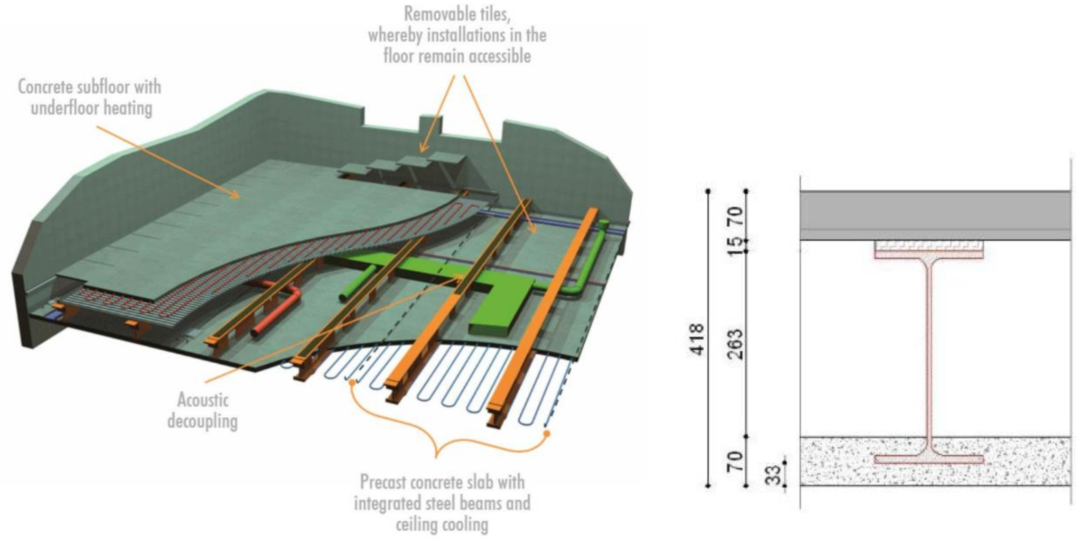


*Figure 14: (left) Slimeline floor configuration (right) Cross-section*

### *Ides floor systems*

Ides expands as integrated deck extra space, it comprises of integrated steel I-profiled, cold formed U-profiles and rock wool. The width of the floor is a multiple of the U-profile width ranging between 333-500 mm and it can 7.2 meters. The total thickness of the floor system is 300mm.

The accommodation of services is limited to the space available between the U-profiles, as seen in the figure. The top slab is supported on the U-profiles and is comprised of either a steel-deck with concrete or a wooden floor panel (van Herwijnen & Jorissen, 2006).

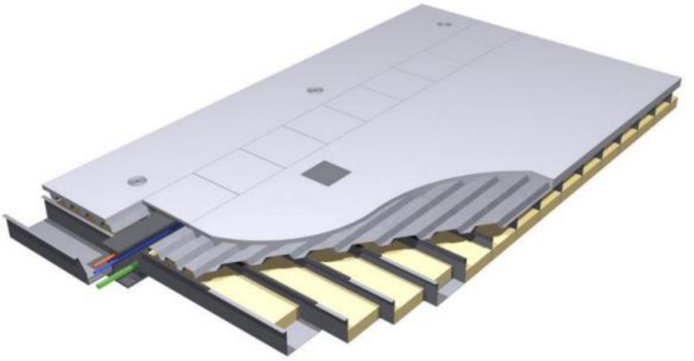


Figure 15: Ides floor-system

*Flex-floor systems*

Flex-floor is an integrated floor system that is composed of timber elements. The load-bearing floor consists of ribs made of KERTO-S and floor plates made of KERTO-Q that are glued together to create a rigid floor element (rib cassette). KERTO is Laminated Veneer Lumber (glue laminated wood veneers) wood. A high-quality product marketed by FinnForest Holland. The floor is supported on a rebate in the building walls and leave the facade free. Large free spans of up to 8 meters can be achieved. It is a prefabricated module of width 2400 mm and length between 7000-8000 mm. The thickness of the rib is 360mm and the floor plate is 25 mm, totally 385 mm thick. The Flex floor is a lightweight system that can be integrated with a floating screed and a free-hanging ceiling. The Flex floor is produced sustainably (wood, industrially made) and offers provision for services between the rib elements as illustrated in *Figure 16*.

*Figure 16: Flex-floor system configuration*

# APPENDIX 6

## INVITATION FOR INTERVIEW

### RESEARCH TITLE:

Decision making framework for a circular integrated floor-system design in Office buildings (Netherlands)

### RESEARCH PREMISE:

The aim of the research is to support the decision making process towards a circular integrated floor-system design in the context of office building (The Netherlands). In a building's structure, floors comprise of more than half of the mass, thereby highly contributing to the environmental impact of the building. An integrated floor system consists of 4 building layers according to Stewart Brand (i.e. structure, services, space plan and stuff). The decisions towards an integrated system is influenced by multiple stakeholders and multiple design requirements. Therefore, to incorporate transparency in the decision making process the goal of this thesis is to develop a framework and a decision dashboard that supports integrated floor system design by generating solutions for case scenarios and assesses the circularity performance to assist the stakeholders in making a suitable decision.

### GOAL OF THE INTERVIEW:

To gain insight into decision-making towards the design of an integrated floor-system. This includes

1. understanding the interaction between different stakeholders involved in the process, i.e. Structural engineer, MEP consultant, Architect and Client, who largely influence the design of the floor-system.
2. understanding integration of the different design aspects that takes priority for each stakeholder
3. understanding the state of incorporating circular design strategies in the design process and who drives/initiates it
4. finding out if efforts are taken to evaluate the degree of circularity or environmental impact of the different design solutions in order to make a decision
5. Lastly, knowing the wishes or expectations of the stakeholders for a decision support system that assists the decision making process for circular integrated floor-system

TIME LIMIT: **25 minutes** (Excluding introduction time)

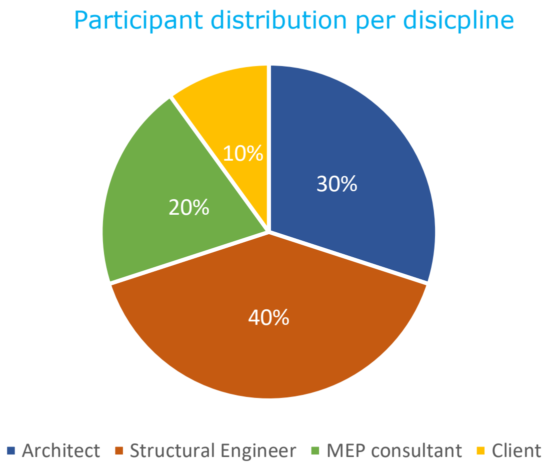
FORMAT: 1 to 1 online interview; Answers will not be sound/video recorded for the reason of privacy/anonymity, however, they will be recorded in writing/memo format during the interview by the interviewer. Majority of questions are closed therefore making the process of recording easier. However, for the open questions, the interviewee will be asked to express his/her answers in maximum of 5 points/sentences. It is valuable to interview 1 to 1 instead of sending out a questionnaire to formalize a connection with interviewee and benefit from qualitative response/feedback.

*Answers analyzed*

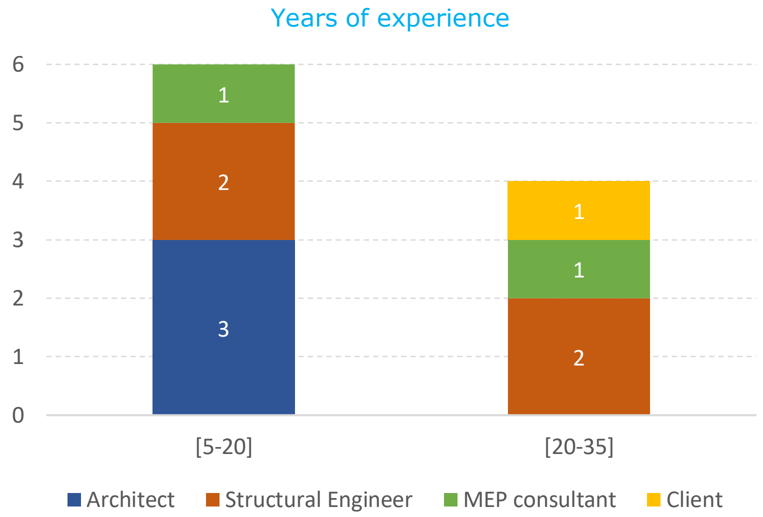
In the following sections the answers received for all questions per topic are summarized in charts or tables.

## 1. General Questions:

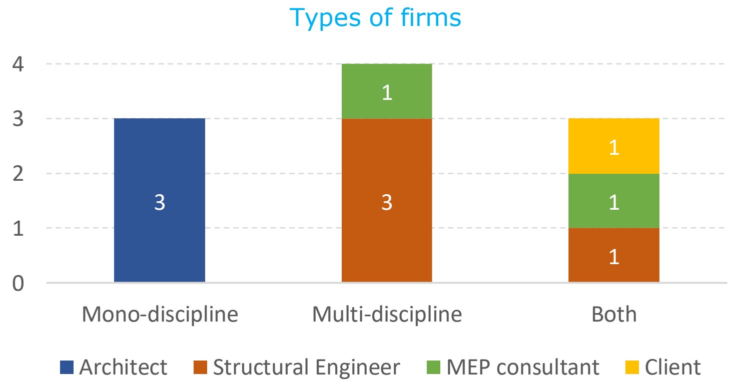
1.1. What discipline do you represent?



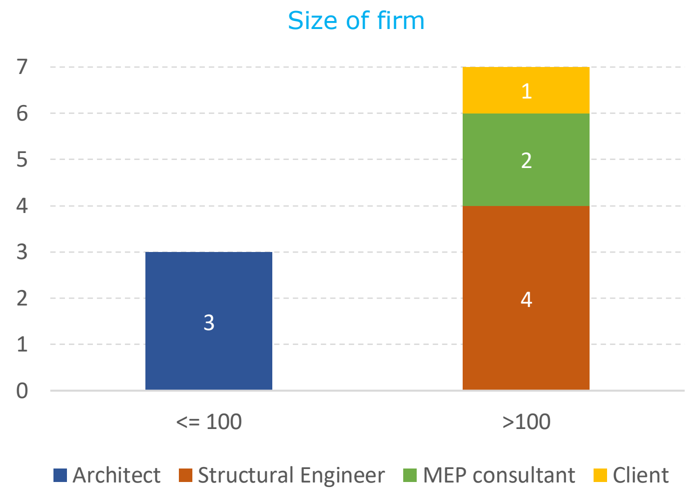
1.2. How many years of experience do you have in practice?



1.3. What type of firms have you worked in?



1.4. What is the size (number of employees) of the current firm you are working in?



## 2. Interaction between different design disciplines, negotiations and decision influencers:

2.1. When during the design process of an office building project are you approached?

| Project partners | Overall answer |
|---|---|
| Architect | Sketch design phase and sometimes at preliminary design. |
| Structural Engineer | Mostly preliminary design phase |
| MEP | Preliminary design |
| Client (when do you approach different design disciplines) | Contacts design disciplines after drafting the program of demands and alignment of budget |

2.2. How does the collaboration between you and other disciplines work while designing an integrated floor-system?

| Project partners | Overall answer |
|---|---|
| Architect | - There are two ways of starting a collaboration with other disciplines<br>1. Clients hire consultants<br>2. Architects themselves hire the consultants<br>- The kind of consultants chosen are based on the building type/use, building scale, technical requirements, and the business case.<br>- Some architects already think of the structure, material, span of the system and create floor matrix themselves in early design stage. To choose based on building type, function, loads, flexibility, sound insulation and fire safety. |
| Structural Engineer | - The collaboration starts with setting and exchanging information on the starting points such as architectural vision and clients requirements. This is communicated in the form of architectural floor plans, programmatic relations, placement of vertical transportation.<br>- This is discussed in design teams during workshop sessions to ideate different options/solutions. MEP and structural engineers start working on the design in parallel at the same time in a project. Discussion between the two is struck especially when placement of installations conflict structural components. |

| | |
|---|---|
| | - For floors especially, factors such as floor height, floor span are crucial to determine floor thickness that informs the clear height. The integration, placement and sizing of service installations effects the clear height of the space.<br>- Other factors such as manufacturing, budget, sustainability (dependent on client ambition and technical possibilities) and acoustics play an important role for floor systems. |
| MEP consultant | - Ideate in a workshop session sitting around a table to discuss possible ambitions and goals (draw building concept together) which informs the different solutions/alternatives.<br>- Based on the client's requirements and the architectural layout structural engineer selects a floor-system depending on the span.<br>- MEP and Building Physics consultants, help in integrating the ducts/piping and contact noise caused due to people traffic. |
| Client | Meeting with design team – to express the integrated design what each one says is considered equally important. |

2.3. List maximum 5 challenges that are usually faced in designing an integrated floor-system.

| Project partners | Overall answer |
|---|---|
| Architect | - Flexibility<br>- cost/budget<br>- Acoustics (400kg/sqm)<br>- Constructability<br>- floor finish<br>- Connection with facade<br>- sustainability<br>- Fire safety<br>- construction height<br>- maximum span<br>- repairability/maintenance (reachability of the MEP installations) |
| Structural Engineer | - overall floor height (reducing the storey height)<br>- clear floor height<br>- MEP layout and sizes, whether integrated into the structure or not<br>- Floor span<br>- Materialization<br>- Constructability<br>- Building grid<br>- Budget<br>- Thickness of the system |
| MEP | - If MEP must be integrated or not within the structure?<br>- What is the economic affects and can it be justified?<br>- technical integration challenges - to make it feasible we need to make smart use of the systems, noise, ventilation, air conditioning system, fire and cost<br>- Amount of space to fit all different components within the floor- the overall thickness of the floor package |
| Client (not applicable for question) | - |

2.4. In maximum five points, explain how you negotiate and arrive at a decision towards a particular floor-system with the design team?

| Project partners | Overall answer |
|---|---|
| Architect | - Money is an important driver for |

| | |
|---|---|
| | Structure<br>Constructability<br>Materialization;<br>However it is not ideal to only look at reducing the cost.<br>- deciding on the material based on look and feel, it is never one but a hybrid.<br>- finding solutions especially based on materials that satisfy the Fire safety requirements<br>- the building grid is decided based on the building type, spacing of the columns and then the span; in discussion with S.E, give three options of floor types.<br>- The MEP consultant is then approached to find out the source of the ventilation air, water, climate ceiling.<br>- The space layout dictates where the power and data points are brought to the desks or work tables (either tubes in the first layer and then partition wall) this further depends on the construction method. (building sequence and impacts top layer of the floor) |
| Structural Engineer | - Collaboration is different for every project; depending on starting points and project requirements<br>- Integrated design – is about making the best product. The key lies in sitting together and sketching the first ideas (brain storming).<br>- Every option has its pro and con (multi criteria analysis), so they need to showcased and discussed to arrive at a conclusion; which is an integral decision<br>- negotiation is based on -Installation-concept/position of MEP; Concrete core activation necessary; Flexibility for free spaces/grid/span; Expression of the building for Materialization; Possible structural floor systems;<br>- Main challenge us the position of the MEP installations if integrated through the beam or below. |
| MEP | - Collaboration is different for every project<br>- First Clients perspective is to be understood, requirements such as flexibility or open floor plan.<br>- MEP consultant for infrastructure (finds out mass for contact noise and space for MEP; determine the HVAC system and acoustics requirements and its integration in the floor-system); Structure for structural system (thickness of the floor); Building physics for fire and noise; architect for cost and appearance; All issues must be considered including sustainability from material preference and use perspective.<br>- Decisions are taken based on experience, intuition and prior knowledge |

| | |
|---|---|
| | - The art lies in the balance between the requirements by every discipline and how all of them are integrated<br>- Broad range of Building services concepts selected based on comfort or appearance which determines the placement of the installation either in the floor or ceiling or above the floor. |
| Client | First step is taken by the architect, we get the proposal, then start asking questions, why this choice or option. In the past more often it was about cost, but now is it sustainable? Is it possible to get more? We are in the position to challenge the design team to push for more between budget and sustainability. (Then it is about which building product or element takes priority) |

2.5. What form of data is exchanged between you and other disciplines?

| Project partners | Overall answer |
|---|---|
| Architect | PD: Sketches or drawings - sharing requirements for fire safety (compartmentalization), fire rating (60,90,120 mins), thermal and sound insulations (contact noise); a lot of thinking in options based on regulations and client's requirements<br>DD: make models together (define zones) BIM |
| Structural Engineer | - In preliminary design phase sketches on architectural plan or written reports with analysis of different alternatives are exchanged and this helps the decision making<br>Data/decisions: Ideas about materializations, desire for flexibility, requirements for fire safety and noise reduction, installation concepts.<br>- DD: Revit based workflows come into play and is based on BIM collaboration between disciplines.<br>Data/decisions: in this stage the main decisions about the floor system are already made. This phase is just finetuning. |
| MEP | - Sketch design/preliminary design: Share Physics, logic and experience, knowledge overlayed with innovation. Main ducts dimensions (to determine holes in the beams), Building physics requirements (for thermal mass for sound insulation)- Size and weight of the components, Mass of the structure components.<br>- Definitive design and technical design: we think about installation of MEP equipments. Post processing or checking the intuition rather than feeding intuition. |
| Client | Client get the data from the design team and then investigate |

2.6. How do you exchange the data?

| Project partners | Overall answer |
|---|---|
| Architect | - PD : In design team meetings (work together in one space, fastest way), share notes of the meeting and drawings through mail or online clouds (eg.dropbox)<br>- DD: BIM model |
| Structural Engineer | PD: workshops and meetings, pdf of sketches/comments/remarks on the architectural plan are shared via wetransfer link through email and platforms such as sharepoint or doc stream.<br>DD: BIM model collaboration |
| MEP | PD: Discussing and sketching on floor plans in pdfs. probably sketch some details (exchanged via mail, however workshops are largely |

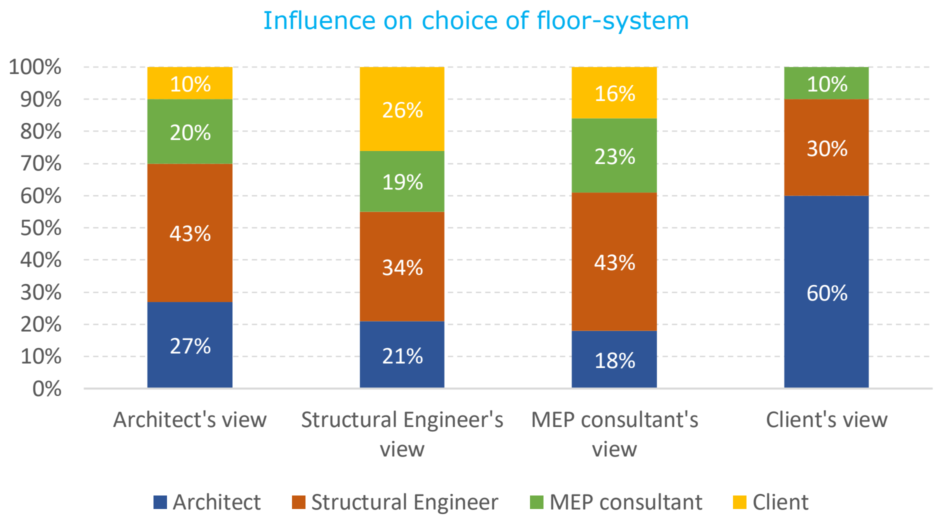
| | |
|---|---|
| | saved for clash control which takes place in definitive stages when working in BIM platforms)<br>DD: Collaboration using BIM, and study clashes between duct routing and beam placement and address them |
| Client | Email, conversation in calls and meetings and clouds (sharepoint- especially for complicated projects) |

2.7. What in your opinion is the most effective way of collaborative decision-making?

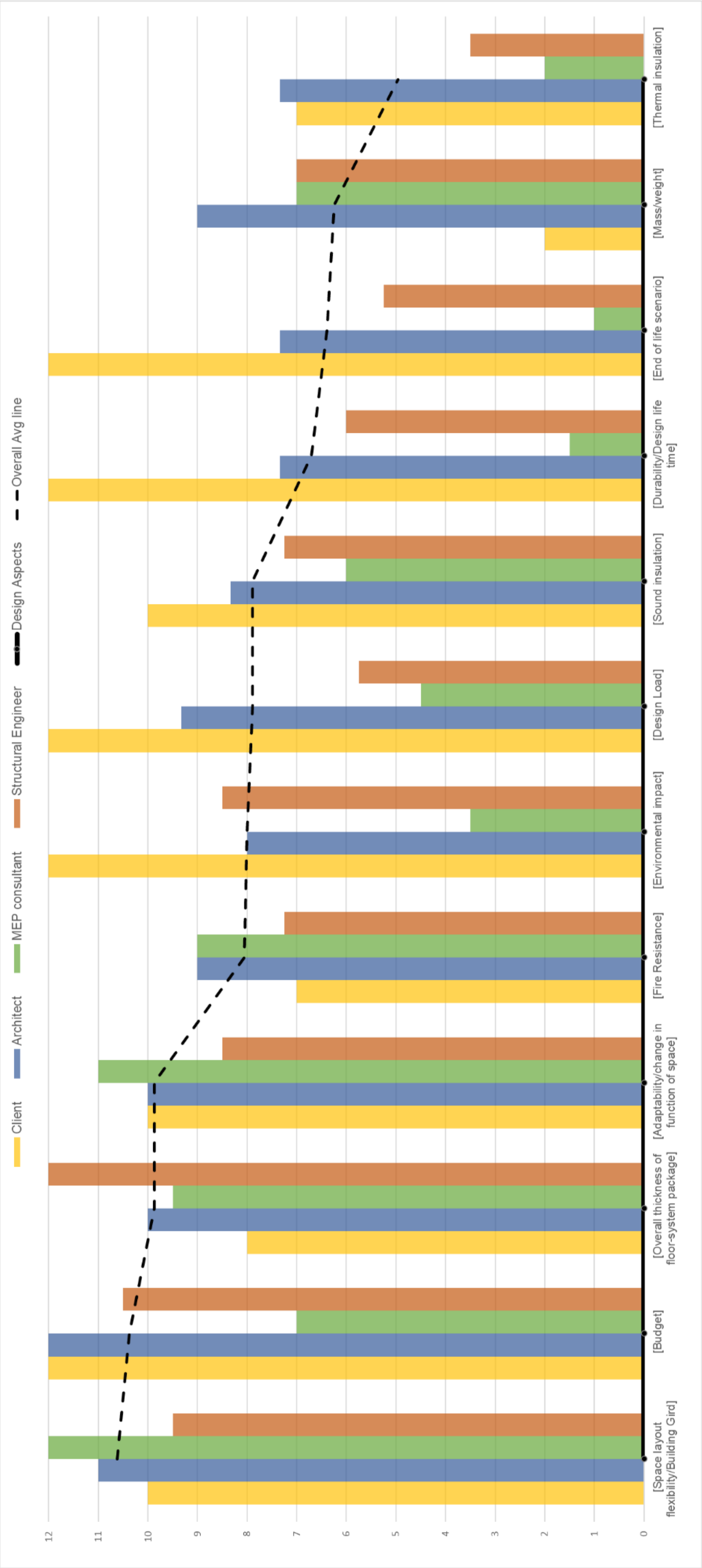
| Project partners | Overall answer |
|---|---|
| Architect | - Work together and talking together in one space, fastest way<br>- It is really important to be analytical and clear about requirements and options and how can one be sure that we have considered every different possibility. As an Architect i see during the process the requirements change- if in due course we could change the system |
| Structural Engineer | - Workshops and sitting together by far the best way to get results.<br>- By comparing 2 or 3 alternates and discuss pros and cons in the design team<br>- Most effective way is when each discipline start off with a preliminary architectural plan options, and other disciplines have some informed options per case and come together in a workshop session to come up with solutions/options to detail further.<br>- Starting points are essential, i.e. the design of the architect/material availability/smaller floor plans these are leading. Most process - architectural vision is leading- then structural and MEP consultation follow and collaborate. |
| MEP | - It is important that all disciplines are involved in choosing the floor type.<br>- So the most effective way is to first gather from all stakeholder what are the floor's functional requirements, and how it can be achieved together which fits the case best. |
| Client | - In the design team- primitive way – every two weeks (2hrs meeting- discuss design and do homework)<br>- Work sessions (1 day 1 room, near the employer, and go work there ask questions, feeling of the building- team building within the design team)<br>It is hard and challenging to convince the design team to schedule a whole day event. |

## 3. Integration of different components into one integrated floor-system design:

3.1. Which party influences the choice of the floor-system used in the project? From a total of 100% divide and assign a percentage of influence between the different parties



3.2. Arrange the following design aspects in descending (high-low) order of priority while choosing an integrated floor-system design for an office building

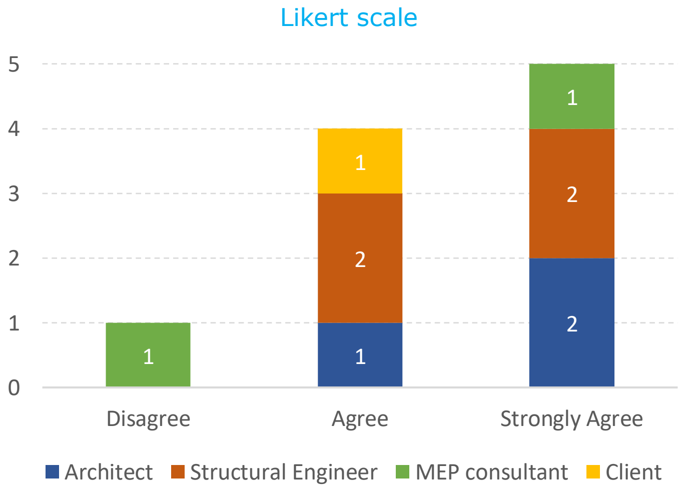

Client
Architect
MEP consultant
Structural Engineer
Design Aspects
Overall Avg line
0
1
2
3
4
5
6
7
8
9
10
11
12
[Space layout flexibility/Building Gird]
[Budget]
[Overall thickness of floor-system package]
[Adaptability/change in function of space]
[Fire Resistance]
[Environmental impact]
[Design Load]
[Sound insulation]
[Durability/Design life time]
[End of life scenario]
[Mass/weight]
[Thermal insulation]

3.3. What influences the positioning/layering/composition of the different system level (structure, services, space plan and stuff) components in an integrated floor-system?

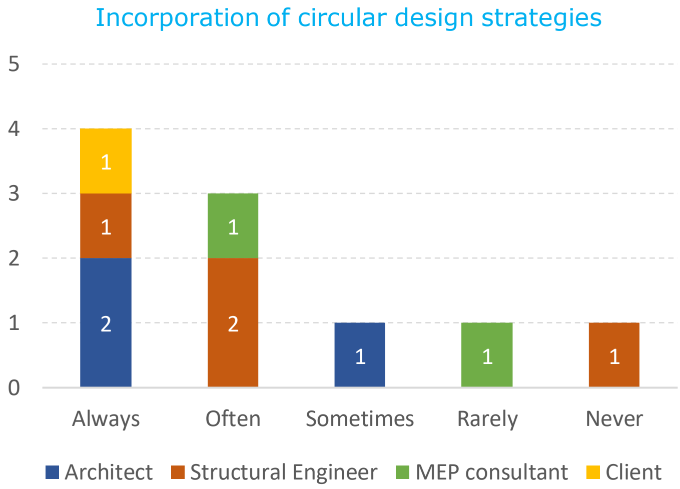
| Project partners | Overall answer |
|---|---|
| Architect | - Flexibility<br>- Building type (function)<br>- Circularity<br>- Budget<br>- Accessibility for MEP installations |
| Structural Engineer | - Installation placement and integration into structure<br>- Flexibility for placing installations into a computer floor<br>- Sound insulation<br>- Ventilation and heating/cooling system<br>- Installation concept<br>- Other functional requirements for the space<br>- Accessibility of MEP<br>- Floor plan and the building grid (vertical supports)<br>- Section of the floor-system; exposed or flat<br>- Thickness of the structure<br>- Fixtures (stuff) plays least important role |
| MEP | - Structural requirements<br>- Sound/acoustics requirement<br>- Building grid<br>- floor heights<br>- Placement of installations is dependent on flexibility and the architectural vision/client requirements |
| Client | - Loads<br>- Acoustics<br>- MEP installation type<br>- Function/Type of building |

## 4. Incorporating circular design strategies in floor-system design for adaptable office buildings

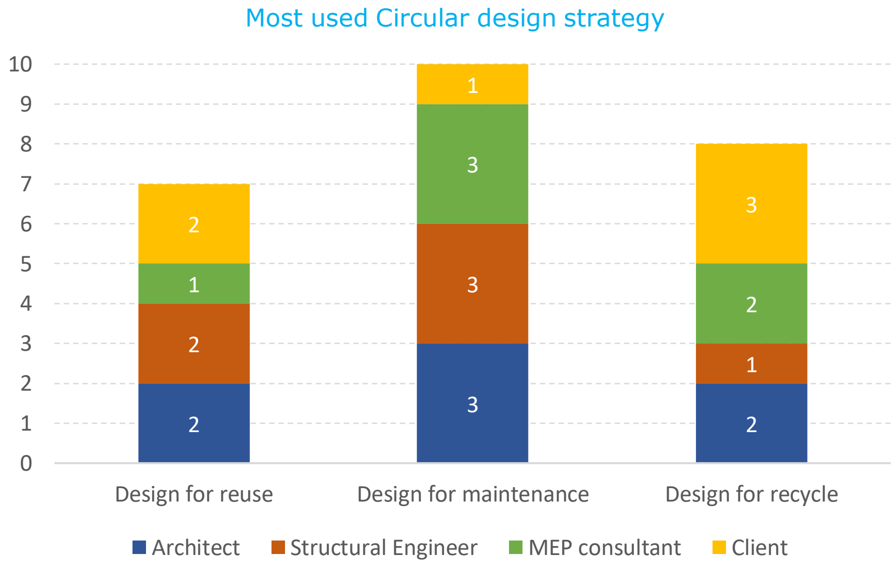
4.1. ‘In order to achieve zero construction/demolition waste and reduce the environmental impact of functionally adaptable/reusable office buildings we must adopt circular design strategies early in the design process’



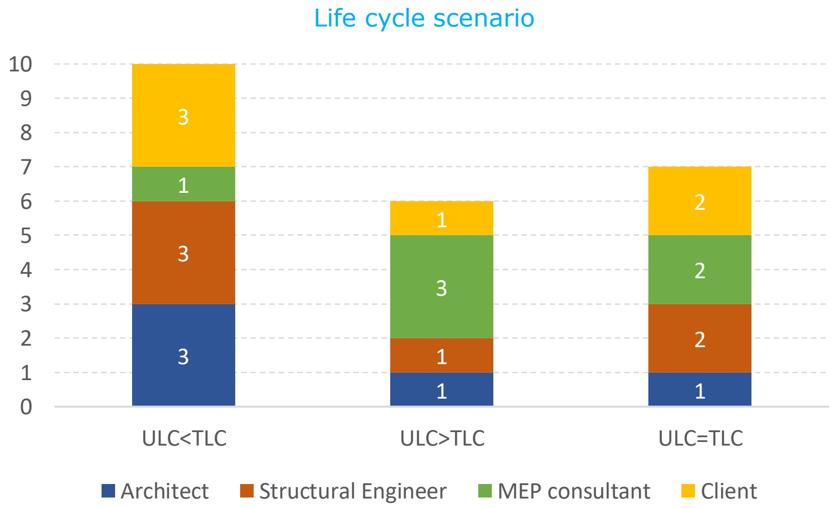
4.2. How often do you incorporate circular design strategies (such as design for disassembly, design for reuse/maintenance/recycle) while designing adaptable floor-systems for office buildings?



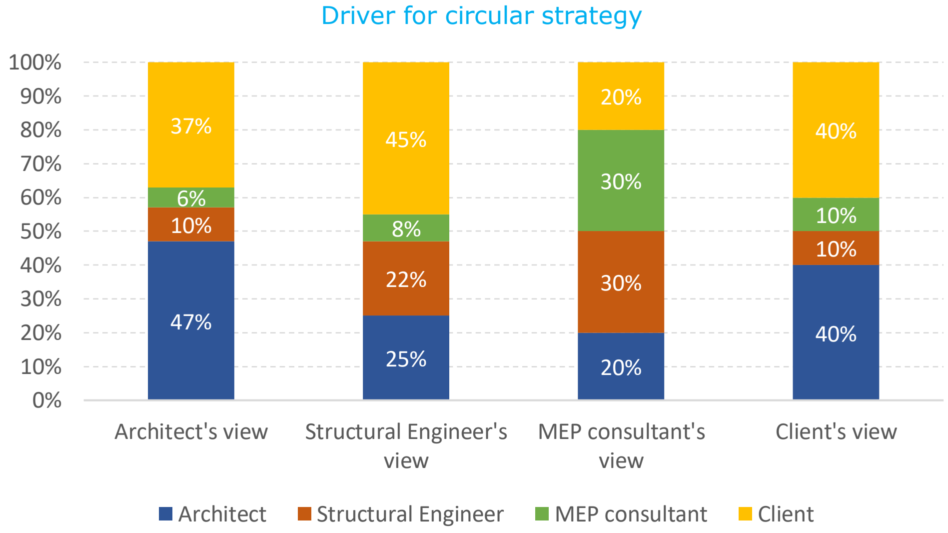
4.3. Score the circular design strategies that are often considered in the composition of a system design? Most used- 3 and least used-1; equal weightage can be assigned



4.4. Which life cycle scenario is often considered in practice for adaptable office building design? Most used- 3 and least used-1; equal weightage can be assigned

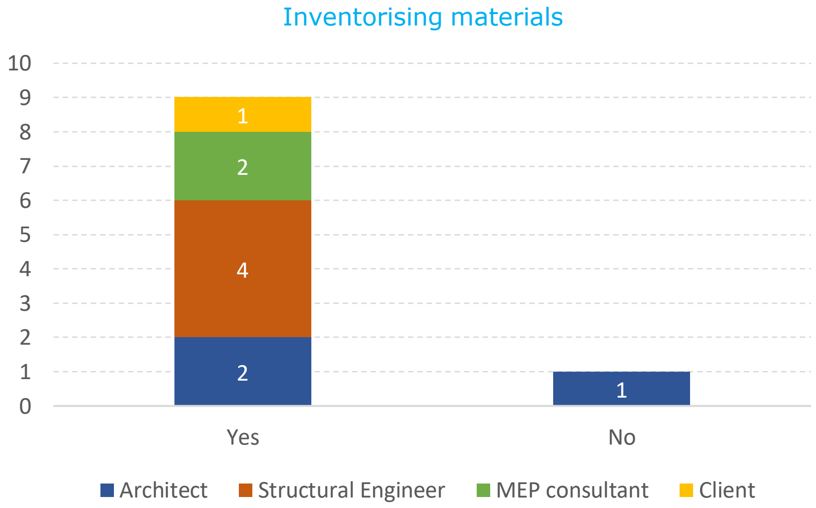


4.5. Who within the project partners drives/initiates incorporation of circular design strategies? From a total of 100% divide and assign a percentage of influence between the parties.



## 5. Evaluating the degree of circularity or environmental impact

5.1. Do you inventorize the materials used in the design?



5.1.1. If yes, How?

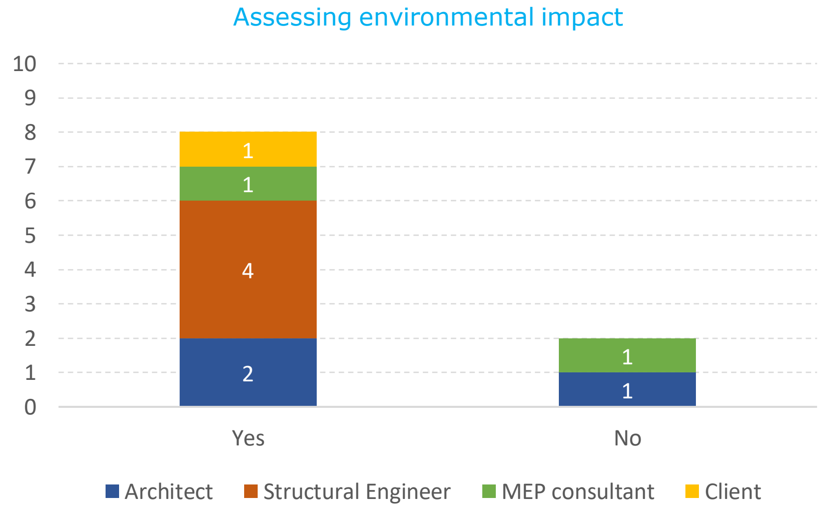
| Project partners | Answers |
|---|---|
| Architect | If the buildings are to stand as long as possible then you don’t need to make material passport.<br>BIM model updated then you always have the latest material quantities |
| | For cost calculation and since two years have to calculate the MPG. Depending on the level of detail, such as smaller contributor eg, door knobs. |
| Structural Engineer | depends to what extent per project. by checking the requirements set by the client and standards and by the standards and in what way full fill the requirements. If client sets high standards from sustainability point of view sets the boundary conditions. MIM tool - honestly never used it, but it is a way to check the CO2 emmisions of the buildings to assess the environmental impact, then every stage of the deisgn we check to make it match the requirements. Challenge is to apply them at the definitive design. |

| | |
|---|---|
| | Preliminary design - by hand - use database of the MIM tool<br>Definitive design - Revit schedules or MIM tool |
| | By MIM checking the MPG and carbon footprint and weight |
| | Inventorize within the Revit model, list of all the material with the dimensions and use them for cost calculations and environmental design. Thinking about alternatives, concrete or steel or wood, in preliminary stage (or before) matrices and schemes are used to balance the advantages and disadvantages |
| MEP | Madaster, Material passport, buildings as material banks they are Revit based. |
| | mostly document the mass of the materials used in the floor-system |
| Client | For building permit and cost estimation, and figure for environmental cost as mpg. Information sourced from cost engineer (drawings and BIM models) |

### 5.1.2. If no, Why?

| Project partners | Answers |
|---|---|
| Architect | Because, it is not in the assignment --> It is commercial answer but it is true. |

### 5.2. Do you assess the environmental impact of the materials used in the design?



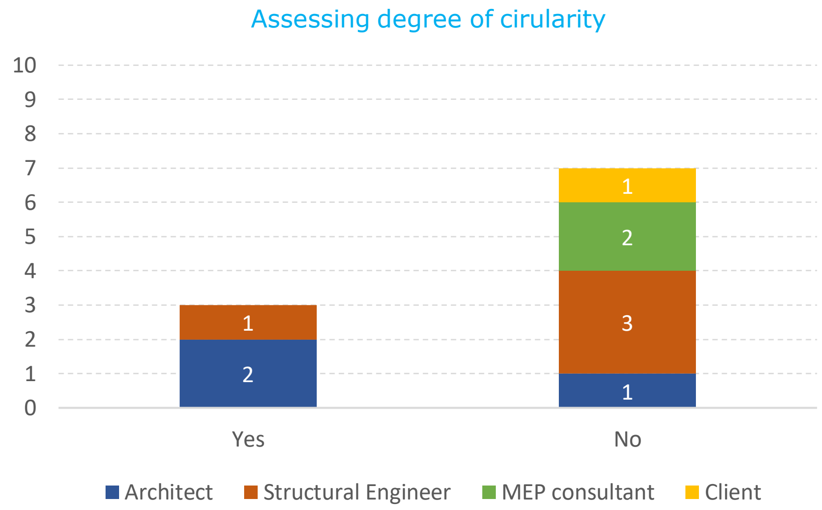
### 5.2.1. If yes, How?

| Project partners | Answers |
|---|---|
| Architect | MPG, for some building is not demanded by law. But it is interesting, as MPG is a coefficient. It will become a design tool instead of the outcome. |
| | Discuss in the design team - to choose for better materials. |
| Structural Engineer | MIM tool |
| | Preliminary design - by hand - MPG calc for example.<br>Definitive design - MIM tool |
| | using MIM |
| | environmental impact tool (MIM) |
| MEP | through MPG, MIM tool integrated in the revit |
| Client | By asking the architect to provide information and then calculate the MPG. It's hard to get access to the database, and the information is not detailed upon. We are working on trying to improve it ourselves, calculating the carbon footprint and MPG. |

### 5.2.2. If no, Why?

| Project partners | Answers |
|---|---|
| Architect | We do feel it is important, but it is more intuitively (unconsciously) and incorporate it in the design. Numbers are always the easiest way to do it but it is probably not the best. |
| MEP | It depends on the sustainability and structural engineer. |

## 5.3. Do you assess the degree of circularity of the materials used in the design?



### 5.3.1. If yes, How?

| Project partners | Answers |
|---|---|
| Architect | We think in of reducing the amount of material used in the building. Make components lightweight (the problem ins then about sound insulation). |
| | Through intuition and existing know-how (common knowledge) not scientific values. |
| Structural Engineer | Yes, for concrete we give the amount of recycled aggregate. |
| | In a primitive way, we think about the material we use, in case of concrete- reuse, steel- recycle, if concrete precast modular- then you can reuse it. These criteria are considered in the assessment matrices and schemes |

### 5.3.2. If no, Why?

| Project partners | Answers |
|---|---|
| Architect | Use sizes that are available (use design aspects) |
| Structural Engineer | because circularity was never a high requirement, especially, in particular is reuse is the means of circularity, we take that into account but not in the system but the design of the structural design level not material level. recycling material is never in play in my project so far. |
| | In general don't do it, but we are trying to collect data on how the materials can be easily recyclable or better details to disassembly. It is not a black and white yes or no. But it is not definitively a yes yet. But the notion towards design and details are implemented but not as a tool such as MIM |
| MEP | the MEP field is not very well-versed with the concept of the circularity; but it is slowing evolving. |
| | Because it not the most important criteria, it is a moving target, do you try to understand the concepts of the environmental impact however, it is not the only single issue |

| | |
|---|---|
| Client | Yes it would be ideal, we want to say something about it, in a team we try to highlight what leads the design to be circular. But in practice not done as it is difficult. |

5.4. What design criteria takes priority while choosing a floor-system design, when the goal is to reduce the environmental impact?

| Project partners | Overall answer |
|---|---|
| Architect | - Materialization<br>- Demountable connections<br>- Insulation & Energy consumption<br>- carbon footprint of the material<br>- transportation of the material<br>- Mass of the material |
| Structural Engineer | - Flexibility (design life time)<br>- Reuse potential<br>- Carbon impact<br>- Span of the floor<br>- Materialization<br>- Floor system |
| MEP | - Budget vs environmental costs vs societal cost comparison<br>- Effectiveness should be preferred over efficiency of the design<br>- Locally available material selection<br>- Disassembly |
| Client | - Carbon footprint<br>- Materialization<br>- endless reuse |

# APPENDIX 8

## *END OF LIFE SCENARIO OF BUILDING MATERIAL FROM NATIONAL MILIEU DATABASE (2020)*

| | | | | Verdeling over fracties % | | | | |
|---|---|---|---|---|---|---|---|---|
| ID | Stroom | Specificatie | % verlies | Laten zitten | Stort | AVI | Recycling | Hergebruik |
| 1 | afwerkingen | verkleefd aan hout, kunststof, metaal | | 0 | 0 | 100 | 0 | 0 |
| 2 | afwerkingen | verkleefd aan puin | | 0 | 100 | 0 | 0 | 0 |
| 3 | aluminium, uit B&U | o.a. profielen, platen, leidingen | | 0 | 3 | 3 | 94 | 0 |
| 4 | aluminium, uit GWW | o.a lichtmasten en randafwerkingen | | 0 | 0 | 3 | 97 | 0 |
| 5 | asfalt | | | 0 | 1 | 0 | 99 | 0 |
| 6 | asfaltgranulaatcement (agrac) | | | 0 | 1 | 0 | 99 | 0 |
| 7 | beton | o.a. elementen, metselwerk, gewapend beton | | 0 | 1 | 0 | 99 | 0 |
| 8 | beton, cellenbeton | o.a. elementen, blokken | | 0 | 1 | 0 | 99 | 0 |
| 9 | bitumen | o.a. dakbedekkingen | | 0 | 5 | 90 | 5 | 0 |
| 10 | coating op staal uit GWW | verwijdering door middel van gritstralen | | 0 | 90 | 10 | 0 | 0 |
| 11 | elastomeren (o.a. epdm) | o.a. dakbedekkingen, folies | | 0 | 10 | 85 | 5 | 0 |
| 12 | eps | funderingen | | 40 | 0 | 50 | 10 | 0 |
| 13 | eps, overig | o.a. isolatie | | 0 | 5 | 90 | 5 | 0 |
| 14 | fijnkeramisch | o.a. sanitair | | 0 | 15 | 0 | 80 | 5 |
| 15 | geen afval | leeg scenario | | 0 | 0 | 0 | 0 | 0 |
| 16 | gips | o.a. blokken, platen | | 0 | 95 | 0 | 5 | 0 |
| 17 | glas | o.a. vlakglas | | 0 | 30 | 0 | 70 | 0 |
| 18 | glasschuim | isolatie | | 0 | 85 | 5 | 10 | 0 |
| 19 | glaswol | isolatie | | 0 | 85 | 5 | 10 | 0 |
| 20 | grind | ballast, verharding | | 0 | 1 | 0 | 0 | 99 |
| 21 | grofkeramisch | o.a. metselwerk, pannen | | 0 | 1 | 0 | 99 | 0 |
| 22 | hout, 'schoon' | o.a. balken, planken | | 0 | 5 | 80 | 10 | 5 |
| 24 | hout, 'schoon' | via restmateriaal | | 0 | 10 | 85 | 5 | 0 |
| 25 | hout, verontreinigd | o.a. geschilderd, verduurzaamd | | 0 | 5 | 95 | 0 | 0 |
| 27 | hout, verontreinigd | via restmateriaal | | 0 | 10 | 90 | 0 | 0 |
| 28 | kalkzandsteen | o.a. elementen, metselwerk | | 0 | 1 | 0 | 99 | 0 |
| 29 | koper | o.a. platen, leidingen | | 0 | 5 | 0 | 95 | 0 |
| 30 | koper, gemengd | elektriciteitsleidingen | | 0 | 10 | 5 | 85 | 0 |
| 31 | kunststoffen | via restmateriaal | | 0 | 20 | 80 | 0 | 0 |
| 32 | kunststoffen, overig | o.a. profielen, platen, leidingen | | 0 | 0 | 90 | 10 | 0 |
| 33 | kunststoffen, vezelversterkt | o.a. profielen, platen, leidingen | | 0 | 0 | 100 | 0 | 0 |
| 34 | lood | o.a. slabben | | 0 | 5 | 0 | 95 | 0 |
| 35 | metalen, gemengd | via restmateriaal | | 0 | 5 | 5 | 90 | 0 |
| 36 | metalen, overig | o.a. bevestiging, hulpstukken | | 0 | 5 | 5 | 90 | 0 |
| 37 | organisch | via restmateriaal | | 0 | 15 | 85 | 0 | 0 |
| 38 | organisch, overig | o.a. isolatie | | 0 | 5 | 95 | 0 | 0 |
| 39 | plaatmateriaal, 'schoon' | grote delen, o.a. bekleding | | 0 | 5 | 85 | 10 | 0 |
| 40 | plaatmateriaal, verontreinigd | grote delen, o.a. bekleding | | 0 | 5 | 95 | 0 | 0 |
| 41 | polyolefinen (o.a. pe, pp) | o.a. leidingen, folies | | 0 | 10 | 85 | 5 | 0 |
| 42 | puin, gemengd | via restmateriaal | | 0 | 90 | 10 | 0 | 0 |
| 43 | pvc, folies | o.a. dakbedekkingen, waterkering | | 0 | 10 | 85 | 5 | 0 |
| 44 | pvc, kozijnprofielen | | | 0 | 10 | 10 | 80 | 0 |

# APPENDIX 9

## Database developed for DSS prototype

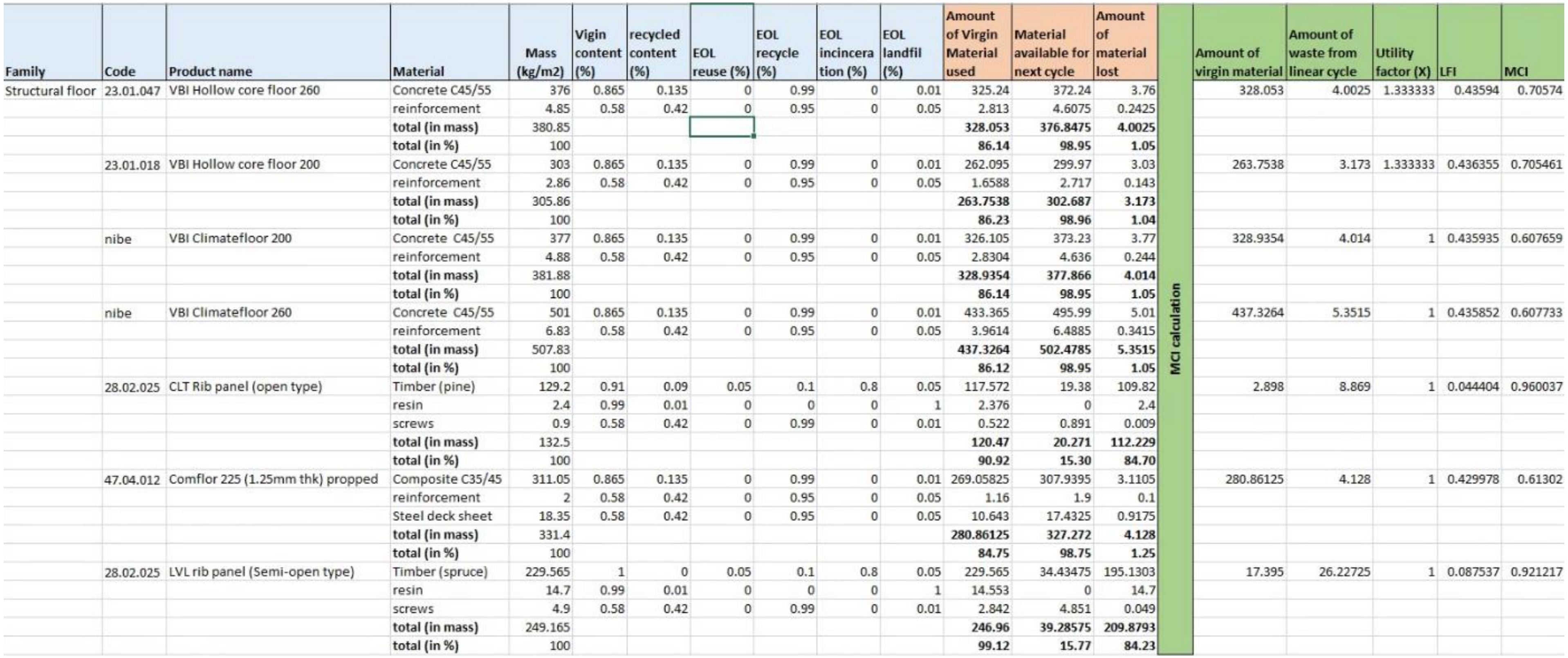
*Table showing the structural layer, structural floor-systems and associated technical specifications*

| Family | MPG calc. Ref. Code | Product name | Material | Slab Thickness (mm) | Width (m) | Length (m) | Mass (kg/m2) | Total applied Load (kN/m2) | Span range (m) | Fire resistance (mins) |
|---|---|---|---|---|---|---|---|---|---|---|
| Structural floor | 23.01.047 | VBI Hollow core floor 260 | Concrete C44/55 | 260 | 1.2 | 7.2 | 383 | 7.5 | 9.5 | 120 |
| | 23.01.018 | VBI Hollow core floor 200 | Concrete C44/55 | 200 | 1.2 | 7.2 | 308 | 7 | 7.2 | 90 |
| | nibe | VBI Climatefloor 200 | Concrete C45/55 | 200 | 1.2 | 7.2 | 384 | 4 | 7.2 | 90 |
| | nibe | VBI Climatefloor 260 | Concrete C45/55 | 260 | 1.2 | 7.2 | 510 | 5 | 9.5 | 120 |
| | 28.02.025 | CLT Rib panel (open type) (320) | Timber | 320 | 2.5 | 7.2 | 150 | 5 | 7.2 | 60 |
| | 47.04.012 | Comflor 225 (295) | Composite C35/45 and steel sheet 1.25mm thk | 295 | 0.6 | 7.2 | 331.4 | 5 | 8 | 60 |
| | 47.04.013 | Comflor 225 (305) | Composite C35/45 and steel sheet 1.25mm thk | 305 | 0.6 | 7.2 | 361 | 5 | 7.9 | 90 |
| | 47.04.014 | Comflor 225 (315) | Composite C35/45 and steel sheet 1.25mm thk | 315 | 0.6 | 7.2 | 385 | 5 | 7.73 | 120 |
| | 28.02.025 | LVL rib panel (Semi-open type) (480) | Timber | 480 | 2.5 | 7.2 | 245 | 6 | 7.2 | 60 |
| | 28.02.025 | LVL rib panel (Semi-open type) (330) | Timber | 330 | 2.5 | 7.2 | 168.3 | 3 | 7.2 | 60 |

*Table showing the structural layer, structural floor-systems and associated circularity indicators and integration strategy related data*

| Family | MPG calc. Ref. Code | Product name | Active heating/pipe integration | Technical life span (yrs) (industry avg) | MPG per unit m2 | Amount of Virgin Material used | Material available for next cycle | Amount of material lost | Pipes Integration type | Dependency on screed | Functional Separation | Functional Dependence | Accessibility | Connection type | Renewable source of material? | MCI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Structural floor | 23.01.047 | VBI Hollow core floor 260 | 0 | 100 | 3.9 | 86.14 | 98.95 | 1.05 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.71 |
| | 23.01.018 | VBI Hollow core floor 200 | 0 | 100 | 3 | 86.23 | 98.96 | 1.04 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.71 |
| | nibe | VBI Climatefloor 200 | 1 | 75 | 7.32 | 86.14 | 98.95 | 1.05 | Gutter | 1 | 0.1 | 0.4 | 0.0 | 0.0 | 0 | 0.61 |
| | nibe | VBI Climatefloor 260 | 1 | 75 | 8.44 | 86.12 | 98.95 | 1.05 | Gutter | 1 | 0.1 | 0.4 | 0.0 | 0.0 | 0 | 0.61 |
| | 28.02.025 | CLT Rib panel (open type) (320) | 0 | 75 | 4.24 | 90.92 | 15.30 | 84.70 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | 0.96 |
| | 47.04.012 | Comflor 225 (295) | 1 | 75 | 9.5 | 84.75 | 98.75 | 1.25 | Capacity | 0 | 0.1 | 0.8 | 0.1 | 0.1 | 0 | 0.61 |
| | 47.04.013 | Comflor 225 (305) | 1 | 75 | 9.8 | 84.75 | 98.75 | 1.25 | Capacity | 0 | 0.1 | 0.8 | 0.1 | 0.1 | 0 | 0.61 |
| | 47.04.014 | Comflor 225 (315) | 1 | 75 | 10.35 | 84.75 | 98.75 | 1.25 | Capacity | 0 | 0.1 | 0.8 | 0.1 | 0.1 | 0 | 0.61 |
| | 28.02.025 | LVL rib panel (Semi-open type) (480) | 0 | 75 | 6.36 | 99.12 | 15.77 | 84.23 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | 0.92 |
| | 28.02.025 | LVL rib panel (Semi-open type) (330) | 0 | 75 | 4.3725 | 99.12 | 15.77 | 84.23 | x | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 1 | 0.92 |

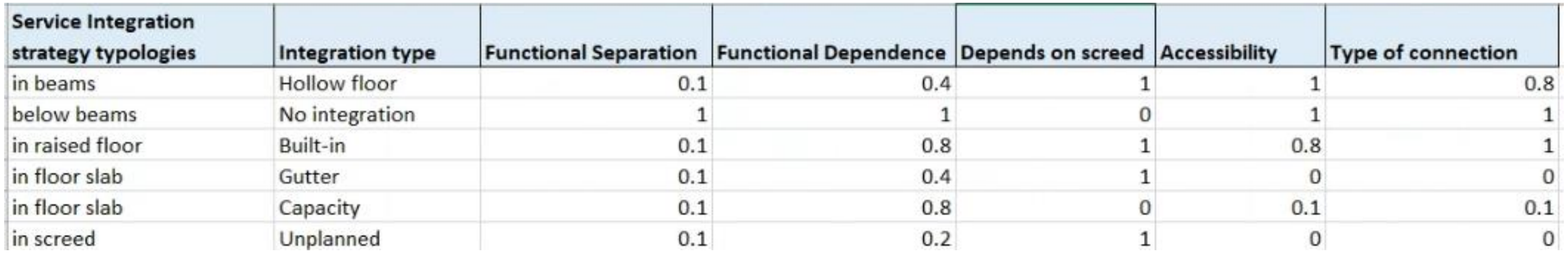
*Table showing the calculation made to determine the material balance and Material Circularity indicators*



| Family | Code | Product name | Material | Mass (kg/m2) | Vigin content (%) | recycled content (%) | EOL reuse (%) | EOL recycle (%) | EOL incinera tion (%) | EOL landfil (%) | Amount of Virgin Material used | Material available for next cycle | Amount of material lost |  | Amount of virgin material | Amount of waste from linear cycle | Utility factor (X) | LFI | MCI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Structural floor | 23.01.047 | VBI Hollow core floor 260 | Concrete C45/55 | 376 | 0.865 | 0.135 | 0 | 0.99 | 0 | 0.01 | 325.24 | 372.24 | 3.76 | **MCI calculation** | 328.053 | 4.0025 | 1.333333 | 0.43594 | 0.70574 |
|  |  |  | reinforcement | 4.85 | 0.58 | 0.42 | 0 | 0.95 | 0 | 0.05 | 2.813 | 4.6075 | 0.2425 |  |  |  |  |  |  |
|  |  |  | **total (in mass)** | 380.85 |  |  |  |  |  |  | **328.053** | **376.8475** | **4.0025** |  |  |  |  |  |  |
|  |  |  | **total (in %)** | 100 |  |  |  |  |  |  | **86.14** | **98.95** | **1.05** |  |  |  |  |  |  |
|  | 23.01.018 | VBI Hollow core floor 200 | Concrete C45/55 | 303 | 0.865 | 0.135 | 0 | 0.99 | 0 | 0.01 | 262.095 | 299.97 | 3.03 |  | 263.7538 | 3.173 | 1.333333 | 0.436355 | 0.705461 |
|  |  |  | reinforcement | 2.86 | 0.58 | 0.42 | 0 | 0.95 | 0 | 0.05 | 1.6588 | 2.717 | 0.143 |  |  |  |  |  |  |
|  |  |  | **total (in mass)** | 305.86 |  |  |  |  |  |  | **263.7538** | **302.687** | **3.173** |  |  |  |  |  |  |
|  |  |  | **total (in %)** | 100 |  |  |  |  |  |  | **86.23** | **98.96** | **1.04** |  |  |  |  |  |  |
|  | nibe | VBI Climatefloor 200 | Concrete C45/55 | 377 | 0.865 | 0.135 | 0 | 0.99 | 0 | 0.01 | 326.105 | 373.23 | 3.77 |  | 328.9354 | 4.014 | 1 | 0.435935 | 0.607659 |
|  |  |  | reinforcement | 4.88 | 0.58 | 0.42 | 0 | 0.95 | 0 | 0.05 | 2.8304 | 4.636 | 0.244 |  |  |  |  |  |  |
|  |  |  | **total (in mass)** | 381.88 |  |  |  |  |  |  | **328.9354** | **377.866** | **4.014** |  |  |  |  |  |  |
|  |  |  | **total (in %)** | 100 |  |  |  |  |  |  | **86.14** | **98.95** | **1.05** |  |  |  |  |  |  |
|  | nibe | VBI Climatefloor 260 | Concrete C45/55 | 501 | 0.865 | 0.135 | 0 | 0.99 | 0 | 0.01 | 433.365 | 495.99 | 5.01 |  | 437.3264 | 5.3515 | 1 | 0.435852 | 0.607733 |
|  |  |  | reinforcement | 6.83 | 0.58 | 0.42 | 0 | 0.95 | 0 | 0.05 | 3.9614 | 6.4885 | 0.3415 |  |  |  |  |  |  |
|  |  |  | **total (in mass)** | 507.83 |  |  |  |  |  |  | **437.3264** | **502.4785** | **5.3515** |  |  |  |  |  |  |
|  |  |  | **total (in %)** | 100 |  |  |  |  |  |  | **86.12** | **98.95** | **1.05** |  |  |  |  |  |  |
|  | 28.02.025 | CLT Rib panel (open type) | Timber (pine) | 129.2 | 0.91 | 0.09 | 0.05 | 0.1 | 0.8 | 0.05 | 117.572 | 19.38 | 109.82 |  | 2.898 | 8.869 | 1 | 0.044404 | 0.960037 |
|  |  |  | resin | 2.4 | 0.99 | 0.01 | 0 | 0 | 0 | 1 | 2.376 | 0 | 2.4 |  |  |  |  |  |  |
|  |  |  | screws | 0.9 | 0.58 | 0.42 | 0 | 0.99 | 0 | 0.01 | 0.522 | 0.891 | 0.009 |  |  |  |  |  |  |
|  |  |  | **total (in mass)** | 132.5 |  |  |  |  |  |  | **120.47** | **20.271** | **112.229** |  |  |  |  |  |  |
|  |  |  | **total (in %)** | 100 |  |  |  |  |  |  | **90.92** | **15.30** | **84.70** |  |  |  |  |  |  |
|  | 47.04.012 | Comflor 225 (1.25mm thk) propped | Composite C35/45 | 311.05 | 0.865 | 0.135 | 0 | 0.99 | 0 | 0.01 | 269.05825 | 307.9395 | 3.1105 |  | 280.86125 | 4.128 | 1 | 0.429978 | 0.61302 |
|  |  |  | reinforcement | 2 | 0.58 | 0.42 | 0 | 0.95 | 0 | 0.05 | 1.16 | 1.9 | 0.1 |  |  |  |  |  |  |
|  |  |  | Steel deck sheet | 18.35 | 0.58 | 0.42 | 0 | 0.95 | 0 | 0.05 | 10.643 | 17.4325 | 0.9175 |  |  |  |  |  |  |
|  |  |  | **total (in mass)** | 331.4 |  |  |  |  |  |  | **280.86125** | **327.272** | **4.128** |  |  |  |  |  |  |
|  |  |  | **total (in %)** | 100 |  |  |  |  |  |  | **84.75** | **98.75** | **1.25** |  |  |  |  |  |  |
|  | 28.02.025 | LVL rib panel (Semi-open type) | Timber (spruce) | 229.565 | 1 | 0 | 0.05 | 0.1 | 0.8 | 0.05 | 229.565 | 34.43475 | 195.1303 |  | 17.395 | 26.22725 | 1 | 0.087537 | 0.921217 |
|  |  |  | resin | 14.7 | 0.99 | 0.01 | 0 | 0 | 0 | 1 | 14.553 | 0 | 14.7 |  |  |  |  |  |  |
|  |  |  | screws | 4.9 | 0.58 | 0.42 | 0 | 0.99 | 0 | 0.01 | 2.842 | 4.851 | 0.049 |  |  |  |  |  |  |
|  |  |  | **total (in mass)** | 249.165 |  |  |  |  |  |  | **246.96** | **39.28575** | **209.8793** |  |  |  |  |  |  |
|  |  |  | **total (in %)** | 100 |  |  |  |  |  |  | **99.12** | **15.77** | **84.23** |  |  |  |  |  |  |

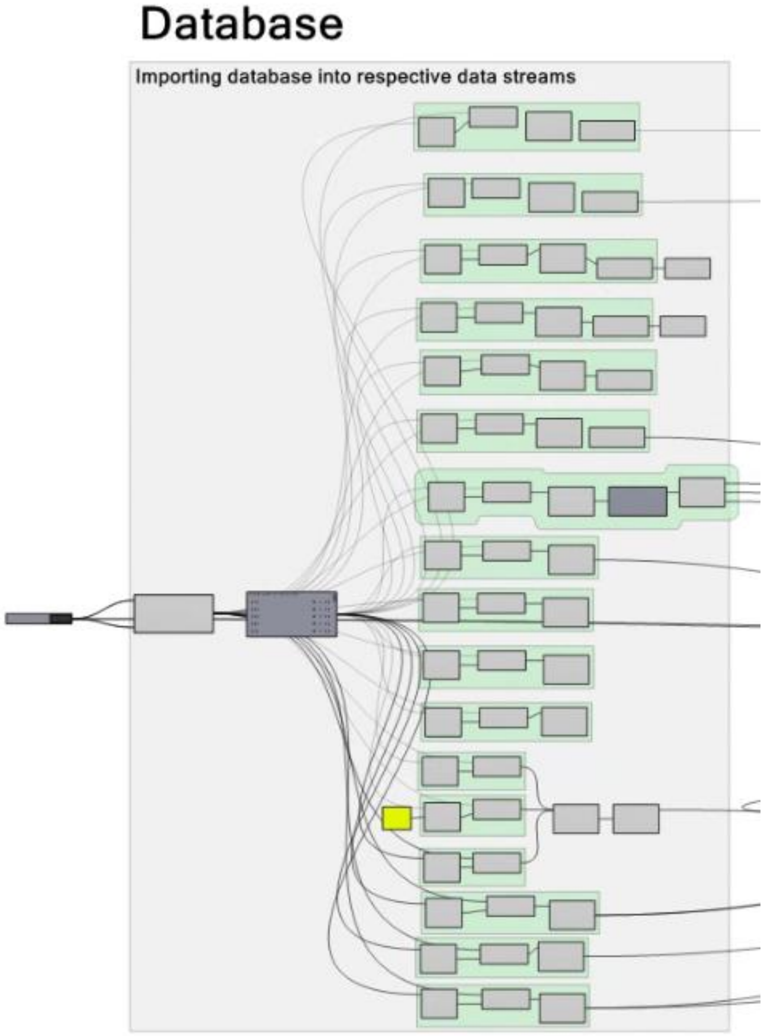
*Tables showing the prescored values for the respective service integration strategies based on E.Dumisevic (2006), DfD factors in Appendix 1*

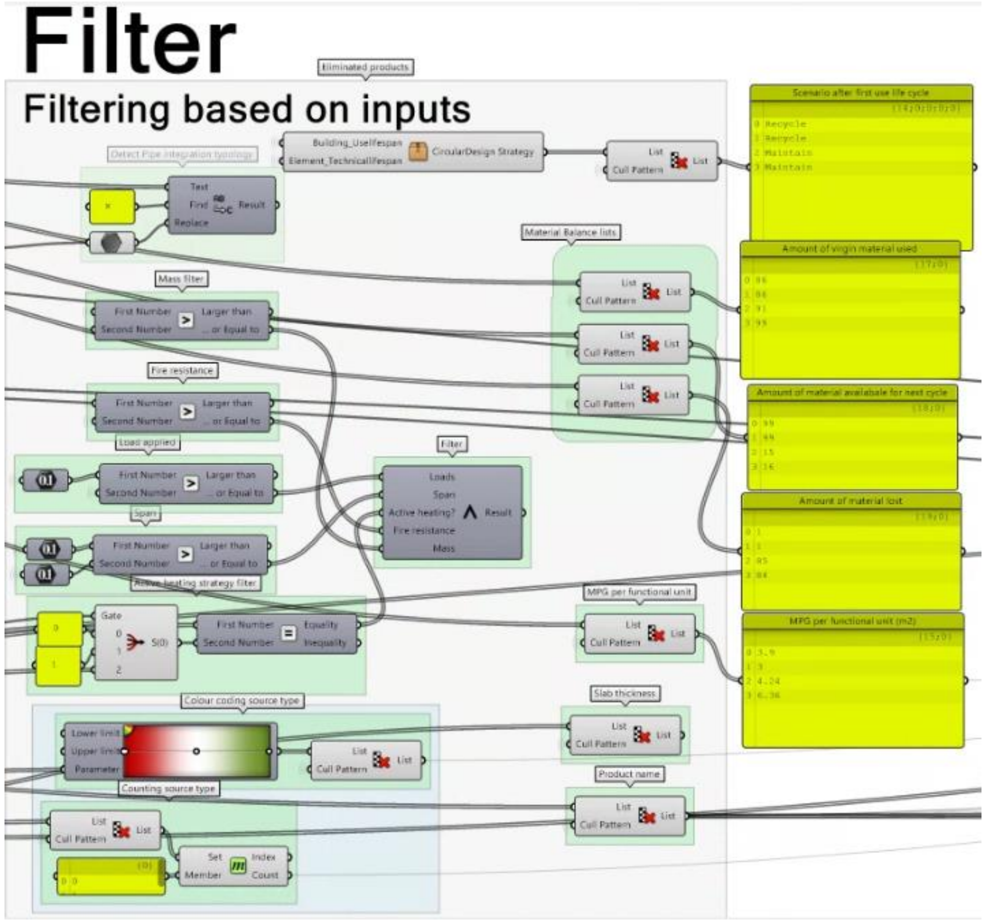
| Service integration in Space layer Type | Accessibility | Type of connection |
|---|---|---|
| Bonded screed | 0.1 | 0.1 |
| Unbonded screed | 0.4 | 0.4 |
| Floating screed | 0.4 | 0.5 |
| Raised floor | 0.8 | 1 |
| floor boards | 0.6 | 0.6 |
| Covered Ceiling | 0.8 | 0.8 |
| no integration | 1 | 1 |

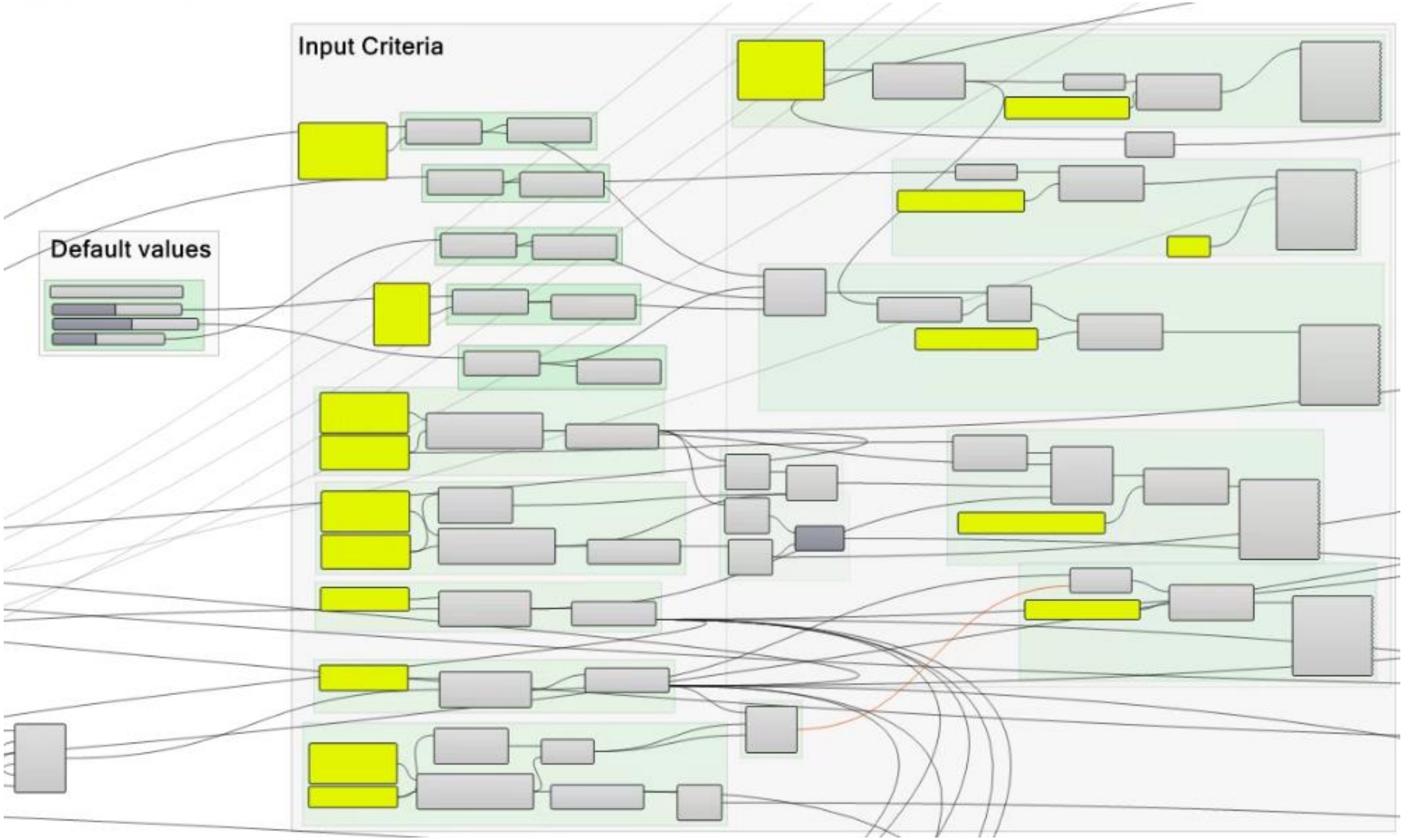


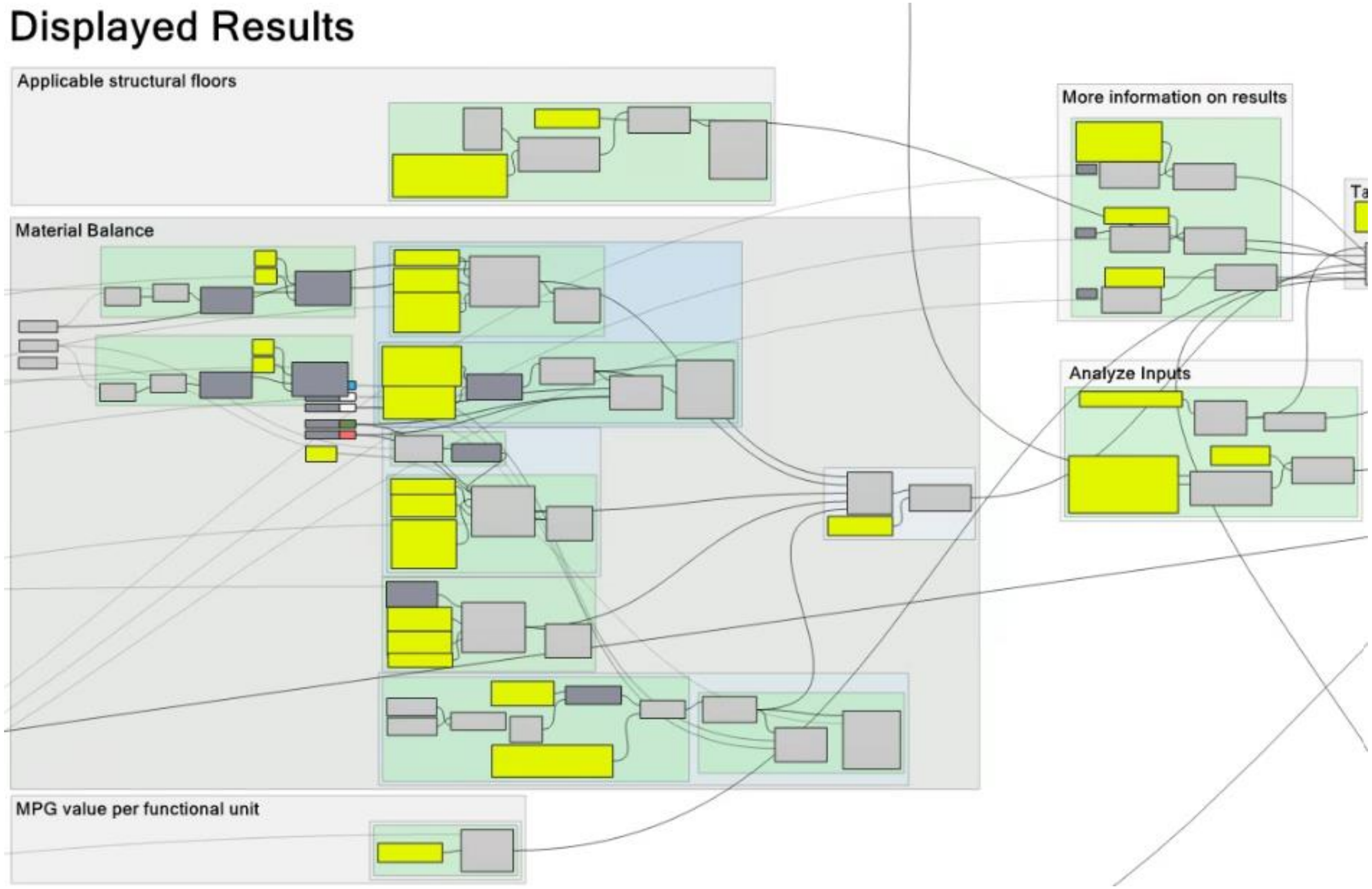
| Service Integration strategy typologies | Integration type | Functional Separation | Functional Dependence | Depends on screed | Accessibility | Type of connection |
|---|---|---|---|---|---|---|
| in beams | Hollow floor | 0.1 | 0.4 | 1 | 1 | 0.8 |
| below beams | No integration | 1 | 1 | 0 | 1 | 1 |
| in raised floor | Built-in | 0.1 | 0.8 | 1 | 0.8 | 1 |
| in floor slab | Gutter | 0.1 | 0.4 | 1 | 0 | 0 |
| in floor slab | Capacity | 0.1 | 0.8 | 0 | 0.1 | 0.1 |
| in screed | Unplanned | 0.1 | 0.2 | 1 | 0 | 0 |

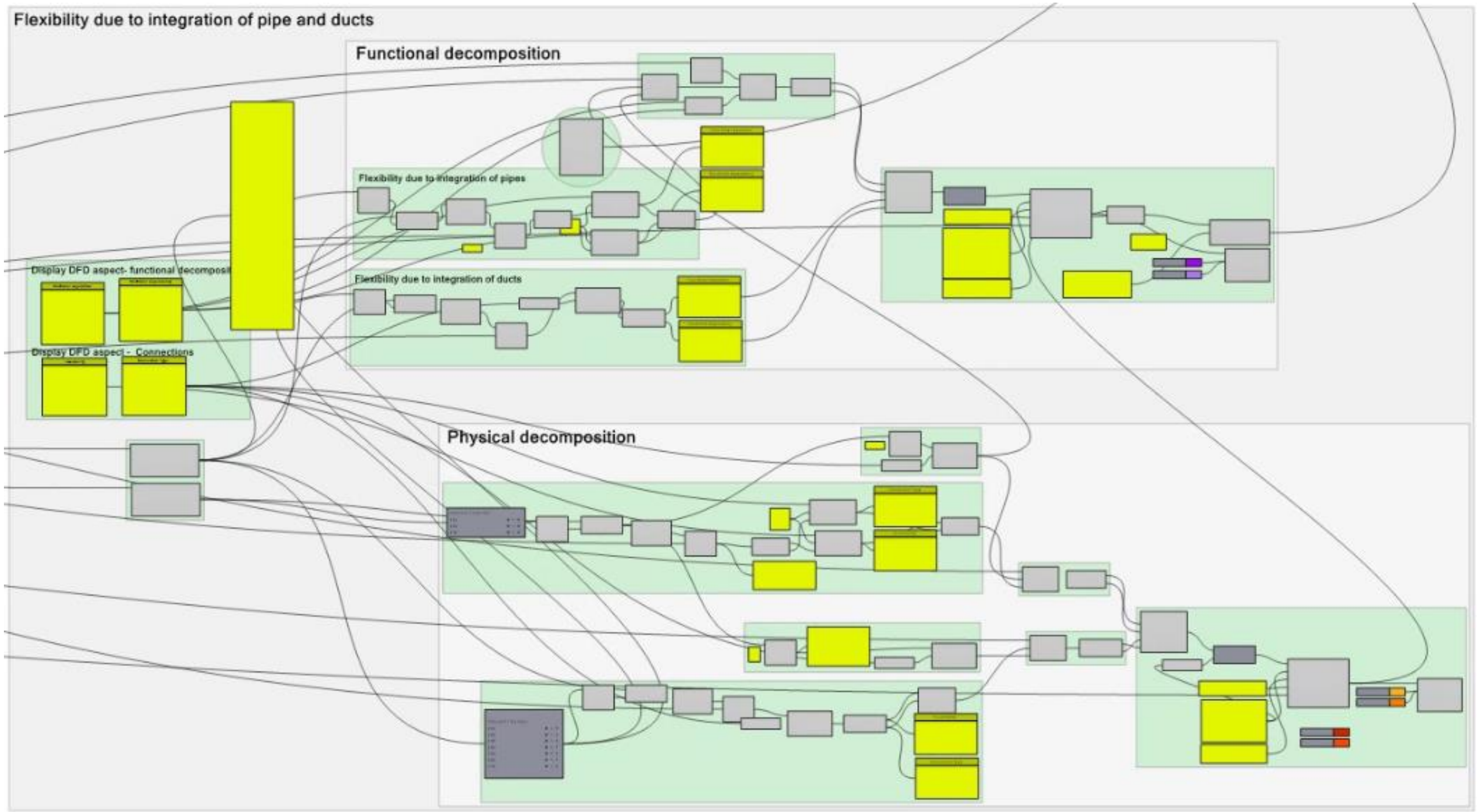
## Grasshopper Scripts blocks developed for DSS prototype



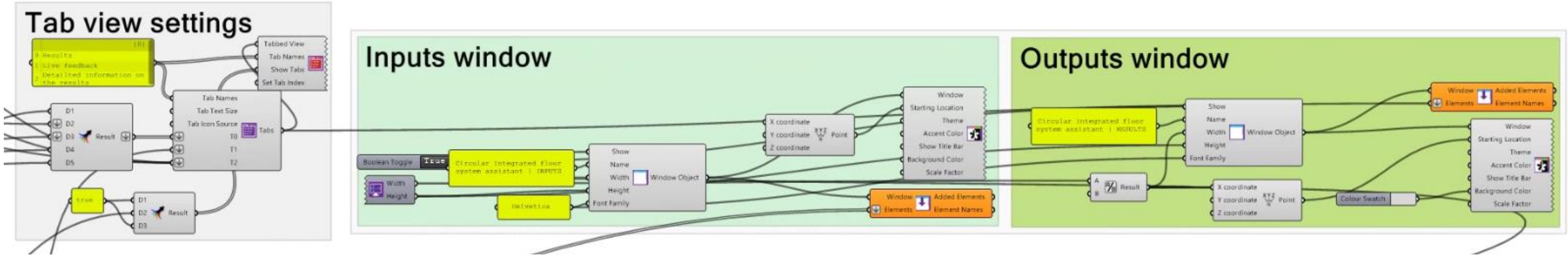



Input Criteria
Default values


Displayed Results
Applicable structural floors
Material Balance
MPG value per functional unit
More information on results
Analyze Inputs
Ta

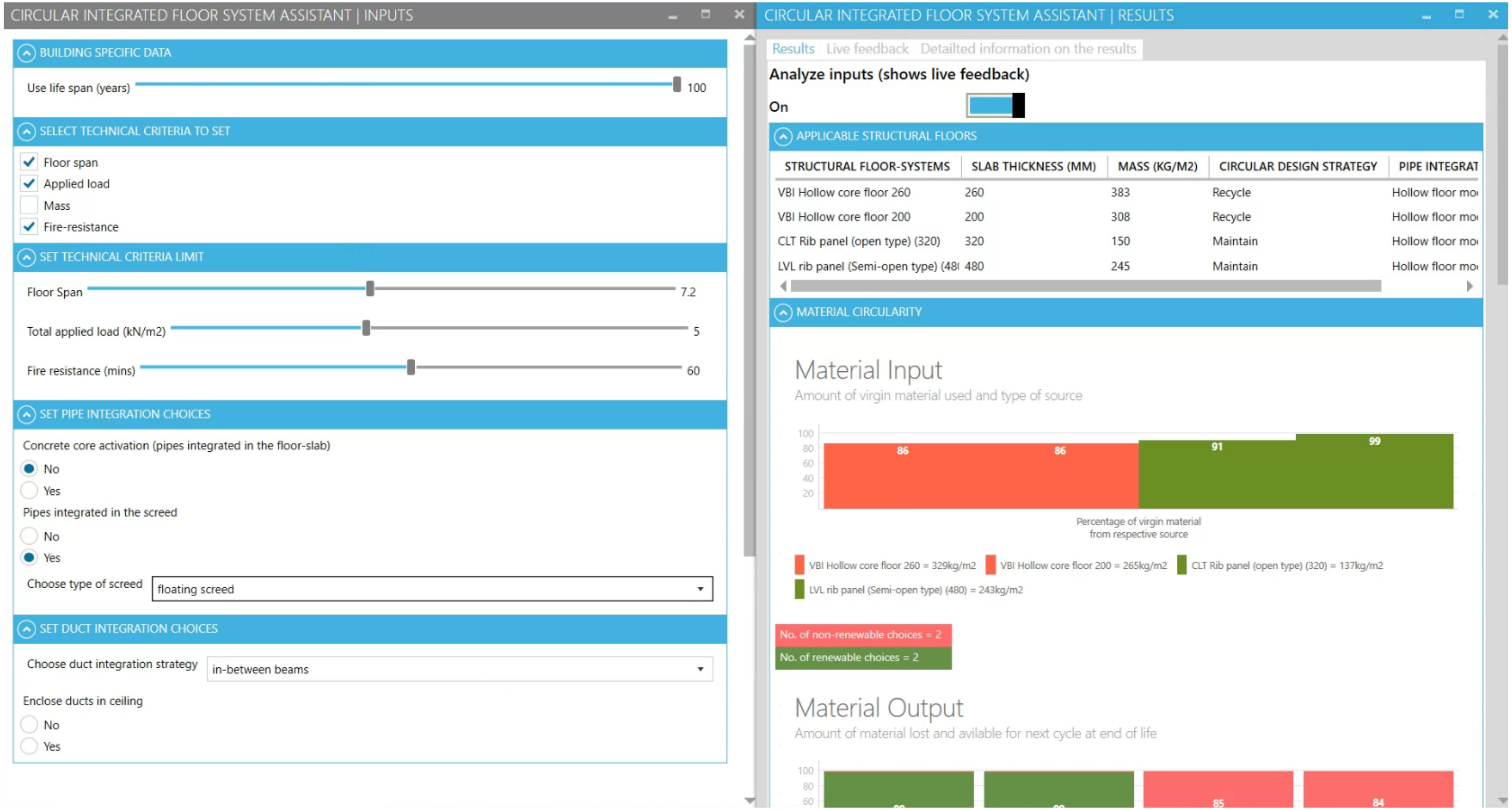

Flexibility due to integration of pipe and ducts
Functional decomposition
Flexibility due to integration of pipes
Flexibility due to integration of ducts
Display DFD aspect- functional decomposit
Display DFD aspect - Connections
Physical decomposition

# Dashboard User Interface



## Dashboard based User Interface

### The main inputs and output windows



CIRCULAR INTEGRATED FLOOR SYSTEM ASSISTANT | INPUTS

BUILDING SPECIFIC DATA

Use life span (years) 100

SELECT TECHNICAL CRITERIA TO SET

☑ Floor span
☑ Applied load
☐ Mass
☑ Fire-resistance

SET TECHNICAL CRITERIA LIMIT

Floor Span 7.2
Total applied load (kN/m2) 5
Fire resistance (mins) 60

SET PIPE INTEGRATION CHOICES

Concrete core activation (pipes integrated in the floor-slab)
● No
○ Yes

Pipes integrated in the screed
○ No
● Yes

Choose type of screed: floating screed

SET DUCT INTEGRATION CHOICES

Choose duct integration strategy: in-between beams

Enclose ducts in ceiling
○ No
○ Yes

CIRCULAR INTEGRATED FLOOR SYSTEM ASSISTANT | RESULTS

Results Live feedback Detailted information on the results

**Analyze inputs (shows live feedback)**

On

APPLICABLE STRUCTURAL FLOORS

| STRUCTURAL FLOOR-SYSTEMS | SLAB THICKNESS (MM) | MASS (KG/M2) | CIRCULAR DESIGN STRATEGY | PIPE INTEGRAT |
|---|---|---|---|---|
| VBI Hollow core floor 260 | 260 | 383 | Recycle | Hollow floor mo |
| VBI Hollow core floor 200 | 200 | 308 | Recycle | Hollow floor mo |
| CLT Rib panel (open type) (320) | 320 | 150 | Maintain | Hollow floor mo |
| LVL rib panel (Semi-open type) (48 | 480 | 245 | Maintain | Hollow floor mo |

MATERIAL CIRCULARITY

Material Input

Amount of virgin material used and type of source

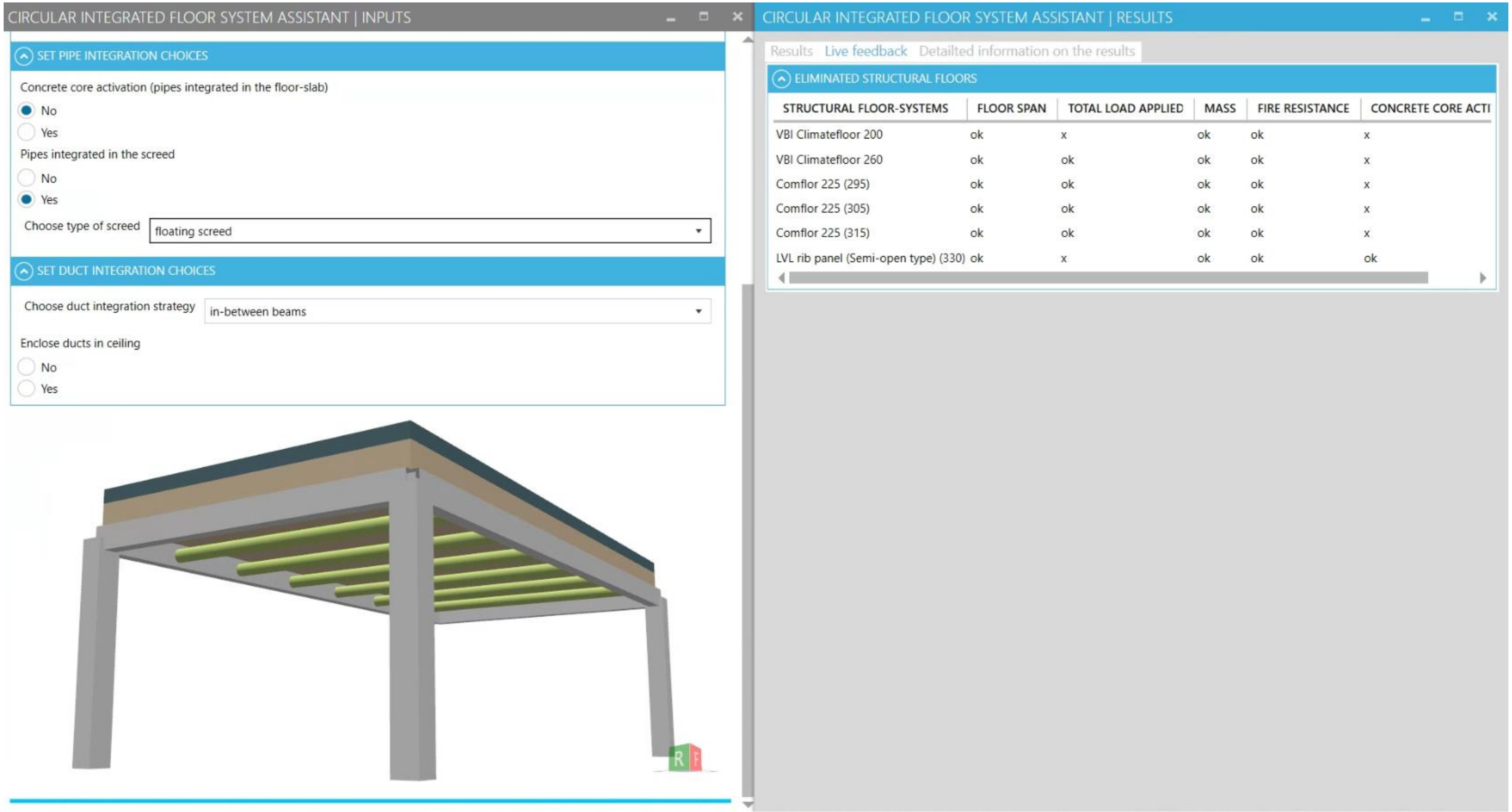
No. of non-renewable choices = 2

No. of renewable choices = 2

Material Output

Amount of material lost and avilable for next cycle at end of life

The eliminated floor-system options shown in the live feedback tab



CIRCULAR INTEGRATED FLOOR SYSTEM ASSISTANT | INPUTS

SET PIPE INTEGRATION CHOICES

Concrete core activation (pipes integrated in the floor-slab)

● No
○ Yes

Pipes integrated in the screed

○ No
● Yes

Choose type of screed: floating screed

SET DUCT INTEGRATION CHOICES

Choose duct integration strategy: in-between beams

Enclose ducts in ceiling

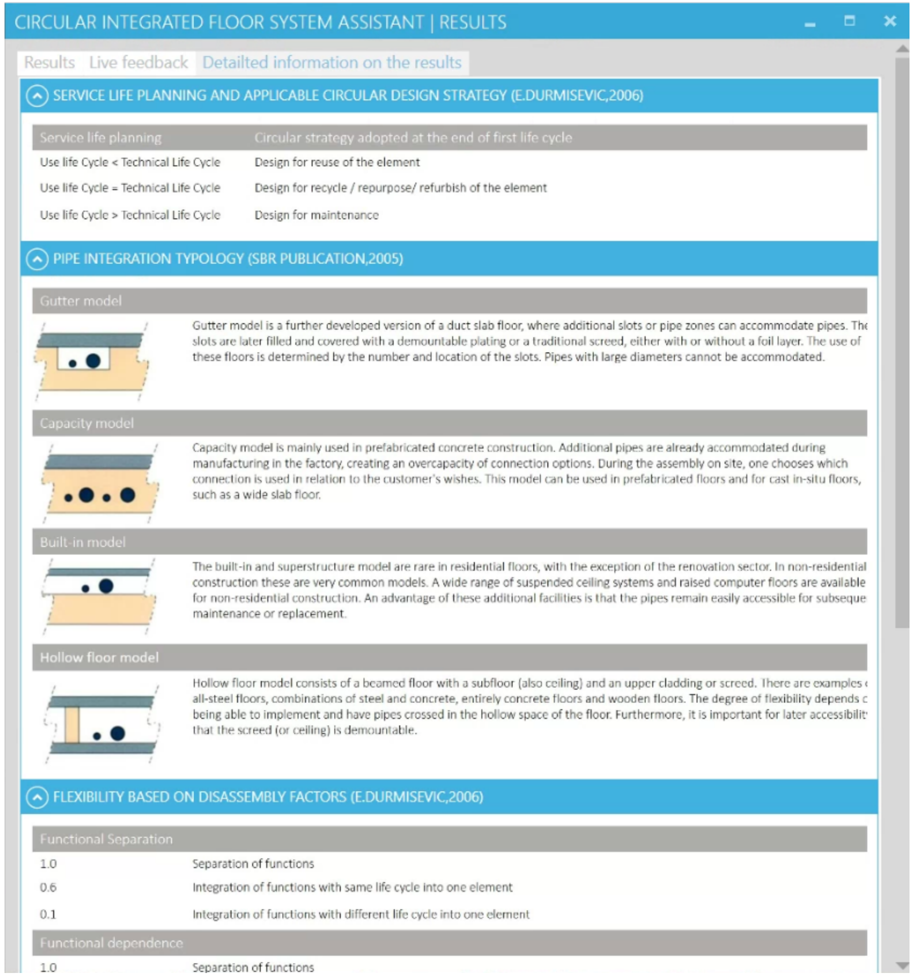
○ No
○ Yes

CIRCULAR INTEGRATED FLOOR SYSTEM ASSISTANT | RESULTS

ELIMINATED STRUCTURAL FLOORS

| STRUCTURAL FLOOR-SYSTEMS | FLOOR SPAN | TOTAL LOAD APPLIED | MASS | FIRE RESISTANCE | CONCRETE CORE ACTI |
|---|---|---|---|---|---|
| VBI Climatefloor 200 | ok | x | ok | ok | x |
| VBI Climatefloor 260 | ok | ok | ok | ok | x |
| Comflor 225 (295) | ok | ok | ok | ok | x |
| Comflor 225 (305) | ok | ok | ok | ok | x |
| Comflor 225 (315) | ok | ok | ok | ok | x |
| LVL rib panel (Semi-open type) (330) | ok | x | ok | ok | ok |

The extended details for each result category explained (results key)



SERVICE LIFE PLANNING AND APPLICABLE CIRCULAR DESIGN STRATEGY (E.DURMISEVIC,2006)

| Service life planning | Circular strategy adopted at the end of first life cycle |
|---|---|
| Use life Cycle < Technical Life Cycle | Design for reuse of the element |
| Use life Cycle = Technical Life Cycle | Design for recycle / repurpose/ refurbish of the element |
| Use life Cycle > Technical Life Cycle | Design for maintenance |

PIPE INTEGRATION TYPOLOGY (SBR PUBLICATION,2005)

Gutter model

Gutter model is a further developed version of a duct slab floor, where additional slots or pipe zones can accommodate pipes. The slots are later filled and covered with a demountable plating or a traditional screed, either with or without a foil layer. The use of these floors is determined by the number and location of the slots. Pipes with large diameters cannot be accommodated.

Capacity model

Capacity model is mainly used in prefabricated concrete construction. Additional pipes are already accommodated during manufacturing in the factory, creating an overcapacity of connection options. During the assembly on site, one chooses which connection is used in relation to the customer's wishes. This model can be used in prefabricated floors and for cast in-situ floors, such as a wide slab floor.

Built-in model

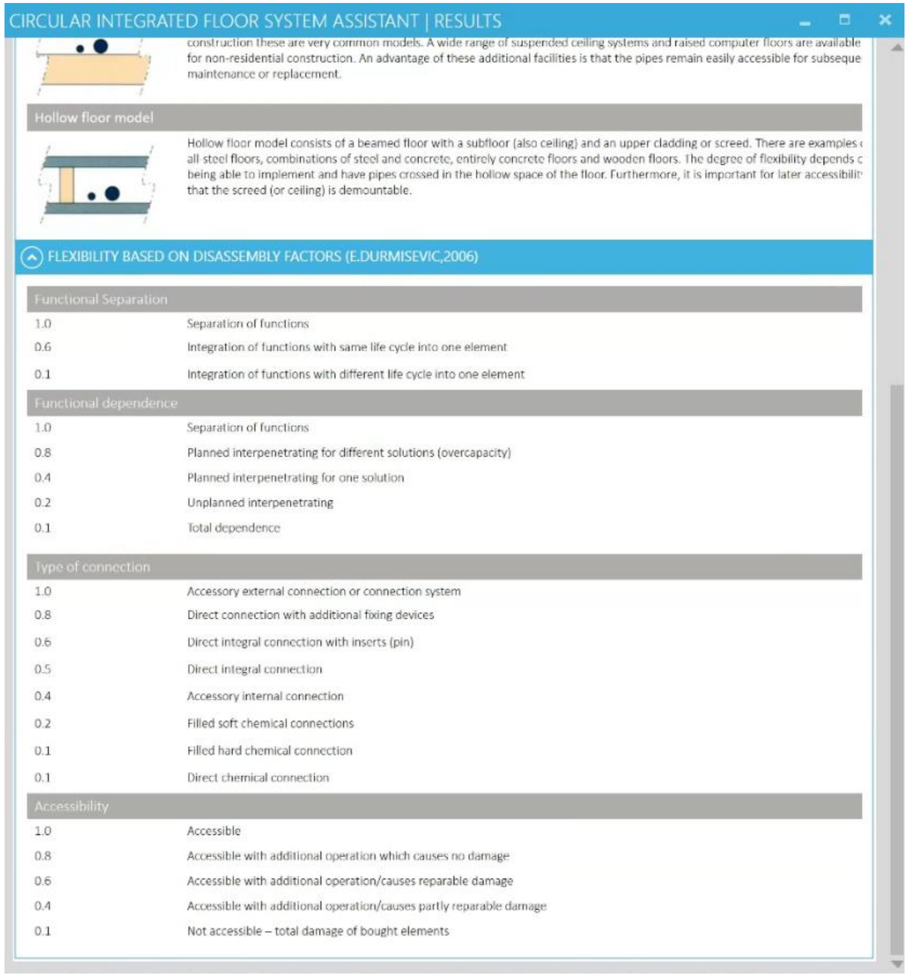
The built-in and superstructure model are rare in residential floors, with the exception of the renovation sector. In non-residential construction these are very common models. A wide range of suspended ceiling systems and raised computer floors are available for non-residential construction. An advantage of these additional facilities is that the pipes remain easily accessible for subseque maintenance or replacement.

Hollow floor model

Hollow floor model consists of a beamed floor with a subfloor (also ceiling) and an upper cladding or screed. There are examples all-steel floors, combinations of steel and concrete, entirely concrete floors and wooden floors. The degree of flexibility depends being able to implement and have pipes crossed in the hollow space of the floor. Furthermore, it is important for later accessibilit that the screed (or ceiling) is demountable.

FLEXIBILITY BASED ON DISASSEMBLY FACTORS (E.DURMISEVIC,2006)

| Functional Separation | |
|---|---|
| 1.0 | Separation of functions |
| 0.6 | Integration of functions with same life cycle into one element |
| 0.1 | Integration of functions with different life cycle into one element |
| Functional dependence | |
| 1.0 | Separation of functions |



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| Functional Separation | |
|---|---|
| 1.0 | Separation of functions |
| 0.6 | Integration of functions with same life cycle into one element |
| 0.1 | Integration of functions with different life cycle into one element |
| Functional dependence | |
| 1.0 | Separation of functions |
| 0.8 | Planned interpenetrating for different solutions (overcapacity) |
| 0.4 | Planned interpenetrating for one solution |
| 0.2 | Unplanned interpenetrating |
| 0.1 | Total dependence |
| Type of connection | |
| 1.0 | Accessory external connection or connection system |
| 0.8 | Direct connection with additional fixing devices |
| 0.6 | Direct integral connection with inserts (pin) |
| 0.5 | Direct integral connection |
| 0.4 | Accessory internal connection |
| 0.2 | Filled soft chemical connections |
| 0.1 | Filled hard chemical connection |
| 0.1 | Direct chemical connection |
| Accessibility | |
| 1.0 | Accessible |
| 0.8 | Accessible with additional operation which causes no damage |
| 0.6 | Accessible with additional operation/causes reparable damage |
| 0.4 | Accessible with additional operation/causes partly reparable damage |
| 0.1 | Not accessible – total damage of bought elements |