RECLAIM

REUSE

Reclaim and reuse potential of load-bearing components of SE school buildings

By Noortje Bouwens

RECLAIM AND REUSE POTENTIAL OF LOAD-BEARING COMPONENTS OF SE SCHOOL BUILDINGS

Research into the criteria to define the reclaim and reuse potential of load-bearing components of SE school buildings in the Netherlands at an early stage

By
Noortje Bouwens

Student number	4349237	
Date	07-01-2022	
Thesis committee	Dr. H.M. Jonkers	Chair, TU Delft
	Ir. A.C.B. Schuurman	1st Supervisor, TU Delft
	Prof. dr. M. Overend	2nd Supervisor, TU Delft
	MSc R. Hartwell	PhD supervisor, University of Cambridge
	MSc J. Scherer	Company Supervisor, HEVO

SUMMARY

Global awareness has arisen for sustainable development to reduce the burden of human activities on the earth's ecosystems. The three performance angles, economy, environment, and society, together ensure sustainable development. By combining these angles, humanity can strive for the sustainability performance aspects of people, planet, profit. The current building sector significantly influences the sustainability performance aspects of people, planet, and profit. Therefore, the government and the building sector have realised the governmental-wide program 'The Netherlands circular in 2050'. The purpose of this program is the transition towards a 100% circular economy with high-quality reuse. However, the sector has insufficient knowledge and understanding about the possibilities and opportunities to transition towards a circular economy.

The circular economy encourages slowing down or closing the linear building cycle to reduce the depletion of natural resources and waste generation (Ellen MacArthur Foundation, 2013). However, the current linear economy demolishes outdated existing buildings and replaces these buildings with new buildings. This research provides knowledge on a new design strategy of giving existing load-bearing components a proper end-of-service life application by reusing them. This research focuses on outdated school buildings in the Netherlands and sees these existing school buildings as urban mines to extract load-bearing components for new school buildings. In this way, the linear building cycle of load-bearing components closes, and the switch to a circular building economy is possible.

This research proposes a quantitative assessment of the potential reclaim and reuse of existing load-bearing components. The assessment of the reclaim and reuse potential can serve as a supportive tool that helps school organisations and the project teams with the initial decision to apply the reuse of load-bearing components in the construction process of a new SE school building. This decision making takes place at an early stage at the end of the first economic life of the school building, referred to in this research as the initial next-life phase.

Determining the degree of reclamation and reusability starts with assessing individual components on several indicators. This research analyses which indicators influence the technical feasibility of reclaiming and reusing load-bearing components from the indoor environment. A literature study, interviews, and surveys with practitioners compile the indicators and sub-indicators that influence reclamation and reusability. Table 1 gives an overview of the selected indicators and sub-indicators of interest for the initial next-life phase. Each indicator and sub-indictor influences the reclaim and reuse of load-bearing components. Moreover, the reuse of existing components takes place in new SE school buildings, and therefore, the component must meet the current technical requirements.

Table 1: The selected indicators and sub-indicators of interest for the initial next-life phase

	Indicator	Sub-indicator
Reusability indicator 1: Breadth of application	2-Dimensional component type (Floors and roofs)	Standardisation
		The supporting method
		Spanning in 1 direction
		Bearing capacity,
		Integration of installations
		The realisation of diaphragm action
		Presence of a or structural layer
	1-Dimensional component type	Standardisation

	(Columns and beams)	Bearing capacity
		Beam height (for beams)
		Sensitivity for lateral-torsional buckling (for beams)
		Sensitivity for buckling (for columns)
	Component length	Multiple of 0.60 m
		Length
Reusability indicator 2: Demountability	Demountability	Type of connection
		Accessibility of the connection
		Crossing components
		Edge confinement
		Number of connections
Reusability indicator 3: Physical quality	Physical quality	Deterioration and damage
		Residual lifespan
		Structural properties translated to the current code

Subsequently, this research collects the required information for each reusability indicator, the theoretical knowledge. Afterwards, the three reusability indicators and associated sub-indicators are translated into an assessment method. The assessment method can quantitatively measure the reclaim and reuse potential technically. This research makes the reusability indicators measurable by giving each indicator and sub-indicator a score for reclaim and reuse. Each reusability indicator has a score ranging from 0 = 'not reusable' to 1.0 = 'highly reusable'. The reusability indicators are independent and weigh equal.

As a product, this research translated the theoretical knowledge and assessment method into a practically usable, rapid supportive assessment tool. In order to develop the assessment tool, this research converts the influence of each reusability indicator and sub-indicator into questions. These questions create a step-by-step process, and the step-by-step process of each influence is the foundation for the rapid supportive assessment tool. Each question and answer influence the reusability score for each reusability indicator. Moreover, each question and answer also influence the associated comments and recommendations for further investigation. Furthermore, the reusability potential highly depends on the available information on the SE school building. Existing information can be, for example, construction drawings or documents, but also previous inspection reports.

The set-up of the assessment tool to define the reusability potential is made using Figma, a program for creating animated prototypes. Animated prototyping makes it possible to test the concept of assessing the reusability of load-bearing components in practice with school organisations and school building project teams. The user can use the tool at the school or any other location since it is web-based. So, the user does not need any specific software but must be proficient in Dutch.

The content of the rapid supportive assessment tool has been validated and verified by conducting interviews and surveys with practitioners. Validation and verification are of interest since the reclaim and reuse of load-bearing components from existing buildings are still in their infancy, and in-depth literature is lacking. Due to insufficient certainty from the literature, this research investigated the unknowns through literature interpretation, followed by validation and verification through interviews and surveys. As a result, there was a difference in interpretation of the reusability potential of existing load-bearing components. The difference in interpretation does not pose for implementing the rapid supportive assessment tool. The application of the tool still provides insight into the possibilities of reclaiming and reusing load-bearing components.

This research recommends further research into the difference of interpretation of the reusability score. Suppose further research is done into the different interpretations. In that case, it is interesting also to include the perspective of demolition contractors and material experts, besides the perspectives of structural engineers and contractors. Additionally, this research recommends further research into the economic and sustainable perspective on reclaim and reuse. For further research, it is interesting to compare the process of a new load-bearing component with an existing component to make the sustainable ambitions and the costs more visual. Another step that can be taken for further research is further developing the current rapid support assessment tool. Weighting factors can be included to add the size of the influence of each indicator. In addition, in-depth research can be done into the new connection method and the exact influence of a non-structural or structural layer on the reclaim and reuse potential. However, different types of buildings can also be added to the rapid supportive assessment tool.

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ABBREVIATIONS

Term	Meaning
KNMI	Koninklijke Nederlands Meteorologisch Instituut
SE	Secondary Education
PO	Primair Onderwijs
VO	Voortgezet Onderwijs
Arbowet	'Arbeidsomstandighedenbesluit'
1D	One Dimensional
2D	Two Dimensional
SDGs	Sustainable Development Goals
ASR	Alkali-Silica Reaction
ISA	Internal sulphate attack
ESA	External sulphate attack

GLOSSARY

Term	Definition	Pages
Linear building economy	The linear building economy uses raw materials to create constructions such as buildings, which turn into waste at the end of their service life. It works according to the principle: produce, construct, use and end-of-service (Klein, 2021).	1, 5, 3, 4, 13, 47, 45
Circular building economy	The linear building life cycle slows down, closes and narrows in the circular building economy. Completing the building cycle reduces the input of raw materials and waste production. Nevertheless, emission and water and energy leakage also decrease (Ellen MacArthur Foundation, 2013).	1
Load-bearing component	A building component that contributes to transferring the vertical or horizontal loads, or both, to the foundation. The load-bearing structure as a whole guarantees the stability and strength of the building.	First mentioned at 5
Construction material	The material used for load-bearing constructions can both be natural or artificial.	1, 6, 8, 13, 26, 26, 30, 37, 47
Next-life phase	The next-life phase is part of the reuse phase. Building components are demounted and harvested from existing buildings. The aim is to preserve materials and reduce waste generation.	8, 13, 25, 26, 30, 31, 37, 41, 47
Reclaim potential	The probability measure expresses the possibility of disconnecting and reclaiming a load-bearing component from an existing school building.	First mentioned at 5
Reuse potential	The probability measure expresses the possibility of reusing a reclaimed load-bearing component for the same function in a new school building design.	First mentioned at 5
The rapid supportive assessment tool	A method to quantitatively assess the reclaim and reuse potential of load-bearing components of existing school buildings at the end of the first economic lifespan.	8, 10, 41, 44, 47, 45, 51

RESEARCH FRAMEWORK

1. INTRODUCTION

1.1. Research context

Human activities change the earth's ecosystem (Sachs, 2012). Extreme weather is more common each year, summers are warmer, and according to the Koninklijke Nederlands Meteorologisch Instituut, KNMI, the last three decades are the hottest years in 1400 years (KNMI, 2018). These visible changes in ecosystem functions could eventually lead to dangerous consequences for human well-being and life on earth. Global awareness has arisen for sustainable development to reduce the burden on the earth's ecosystems. The three performance angles of economy, environment, and society together ensure sustainable development. By combining these angles, humanity can strive for economic growth, ecological sustainability, and social inclusion (Sachs, 2012). This approach is commonly known as people – planet – profit.

The current building sector is one of the sectors that greatly influence the sustainability performance aspects of people, planet, profit (Gencel et al., 2012). Figure 1 shows the linear process of the current building economy: produce, construct, use and end-of-service. Linear construction methods contribute to 26% of the depletion of natural resources and 35% of the generation of waste in the Netherlands (Klein, 2021; Zuo et al., 2012). Moreover, the linear construction methods significantly contribute to the emission of greenhouse gas, dust, and noise (Zuo et al., 2012). A fundamental change to the existing building process is necessary to guarantee the future well-being of people on earth and combat climate change.

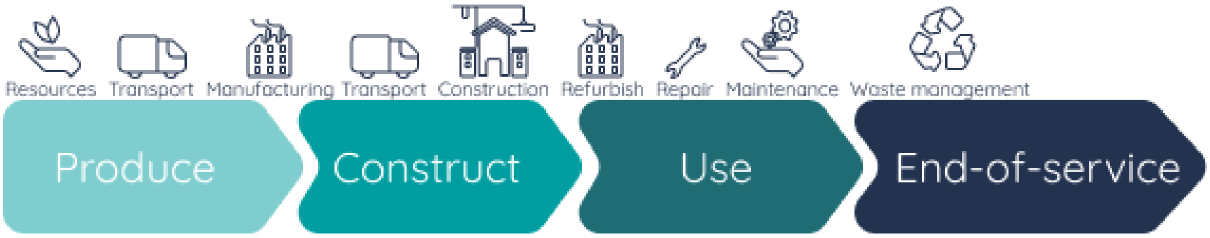


Figure 1: Linear building economy. Adapted from (Klein, 2021)

The building sector must implement sustainable resource flows throughout the entire life cycle of a building. One proposed method to enable the development of sustainable resource flows is to create buildings according to the circular building economy (Rijksoverheid, 2016). Appendix A elaborates on the principle of the circular building economy. The ultimate goal of circular building principles is to achieve a building economy that meets the needs of today's society without harming future generations (Brundtland Committee, 1987; Transitieteam Circulaire Bouweconomie, 2018). The building sector needs to reduce its environmental impact to achieve this goal. The linear building cycle must be slowed down or closed to reduce the depletion of natural resources and the generation of waste (Ellen MacArthur Foundation, 2013). By slowing down and closing the linear building life cycle, the building sector can use raw materials and existing building components more smartly and efficiently (Ellen MacArthur Foundation, 2013). Various methods of closing the building life cycle are possible in different life cycle phases. The various methods are circular building strategies [1].

The composition of a building influences the accomplishment of circular strategies. In addition, the interrelationship of the various building elements has an influence. According to Stewart Brand, a building is composed of several layers. The six different layers are Site, Structure, Skin, Service, Space plan, and Stuff. Each layer of Brand has its development path over time, referred to as the technical lifespan[2] (Brand, 1994). Figure 2 and Table 2 show that some layers of a building have a shorter lifespan than the functional lifespan[3] of the building itself.

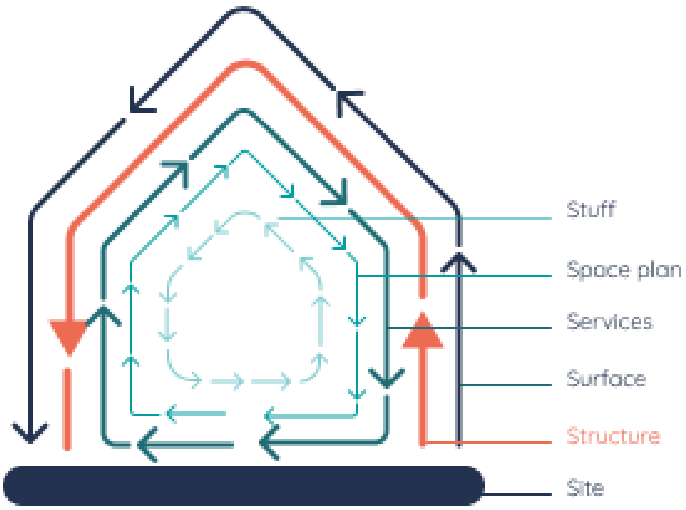


Figure 2: Different building layers. Adapted from (Brand, 1994)

Table 2: Different building layers. Adapted from (Brand, 1994)

Layer	Lifespan	Subject
Site	Infinite	The geographical setting of the location of the building
Structure	30-300 years	Foundation and the load-bearing elements
Skin	>20 years	Façade of the building
Services	7 – 15 years	Installations and systems in the building
Space plan	3 – 30 years	Interior layout building, placing of walls, ceilings, floors, and doors
Stuff	Daily/ monthly	Stuff in the building

In contrast, other layers in buildings have a slower development path than the functional lifespan of a building. The technical lifespan of the load-bearing components is often 30 – 300 years, whereas the functional lifespan of a building is mainly 40 – 60 years (van den Dobbelsteen, 2004). So, there is a gap between the load-bearing construction's functional and technical lifespan (Baelemans, 2020), visualised in Figure 3. The load-bearing construction can thus comprise different functional periods within its technical lifespan. Despite this opportunity, load-bearing components often become waste when the building reaches the end of its functional lifespan (Iacovidou & Purnell, 2016). The design lifespan of the structure of a building is only 50 years, so after 50 years, uncertainty in loading and degradation of the construction material can arise. Eliminating the uncertainties of the technical performance of load-bearing components after 50 years offers opportunities for reuse. Reclaiming

[1] The Appendix A elaborates on the different circular strategies and priorities of the circular strategies.
[2] Technical lifespan, the period a component physically meets the required performance (Hermans, 1999).
[3] Functional lifespan, the period the building meets the function requirements (Vree de, 2021a).

load-bearing components and reusing them at the highest possible level for the same function in another building offers a more sustainable option that fits within the principles of the circular building.

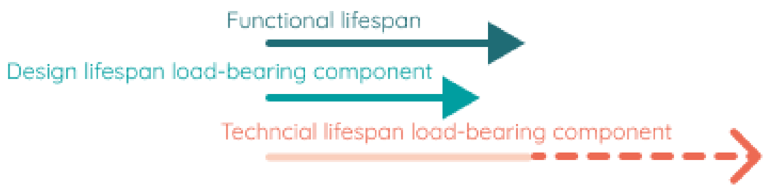


Figure 3: Gap between the functional and technical lifespan of a load-bearing component

Understanding the layer logic of Brand helps to make optimal use of the technical lifespan of each layer. Extending the lifespan of load-bearing components results in making circular design choices. Extending the lifespan is the highest possible circular design choice for existing components, known as reuse. Reuse is applicable on different levels, such as building, component, and material level. Ideally, complete reuse of the load-bearing construction is possible if it is in good functional and technical condition. Renovation of the building and reuse at the component level is chosen when the renovation of the building as a whole is not possible. Extending the lifespan for layers with a slower development path allows the individual components to serve longer lifetimes. Optimal use of components' lifespans leads to less use of raw material and less waste generation, resulting in a less negative impact on the environment.

1.2. Scientific gap

Reclaiming existing load-bearing components to reuse them in the same structural function is promising to achieve environmental value preservation (Iacovidou & Purnell, 2016). High-quality reuse ensures more efficient material and component use and waste reduction (Iacovidou & Purnell, 2016). In addition, reclaiming and reusing existing load-bearing components reduces the release of greenhouse gas emissions associated with the production of new components.

To date, in a linear building economy, structural engineers have not consciously considered high-quality reuse options in the design of load-bearing components. Structural engineers also have not designed the components to be easily dismantled to sort the materials and components during demolition (Rijkswaterstaat, 2015). As a result, it is a significant challenge nowadays to reclaim and reuse the building components from the existing stock of buildings for circular designs (Rijkswaterstaat, 2015). According to (Gorgolewski & Morettin, 2009), "The fastest, easiest and most economical way to get the job done is currently used". This statement shows that there is insufficient understanding of the opportunities of reclaiming and reusing load-bearing components. Inadequate knowledge of the opportunities may arise from insufficient reliable information about the reclaimed components' physical performance and potential reusability (Iacovidou & Purnell, 2016; Volk et al., 2014). In addition, designers and owners choose reclaiming based on personal expertise and experiences (M. Addis, 2016; Phelps & Horman, 2009). Combined with a lack of guidance tools for designers and owners on the specifications of reclaimed components, this creates barriers to using such components (Gorgolewski & Morettin, 2009). Furthermore, new technologies are necessary to ensure that reclaimed components meet the technical, functional, durable, and aesthetic requirements for reuse (Rijkswaterstaat, 2015).

So, there is a lack of a properly functioning system to enable reusing load-bearing components in practice.

1.3. Problem statement

There is currently a gap between a load-bearing component's technical and functional lifespan. The functional lifespan depends on the building type. This research focuses on one specific building type: Secondary Educational (SE) school buildings of MAVO, HAVO, VWO[4]. In the Netherlands, 50.4% of the SE school buildings are older than the functional lifespan of 40 years (Bresser, 2021). On average, a renovation or replacement of a school building takes place after 40 years (PO-raad and VO-Raad, 2016). There are several reasons to replace a SE school building. For example, the indoor climate system is outdated, and the educational housing prevents the possibility of renewal. Another reason can be that the layout of the building cannot adapt to the current educational vision. As visualised in Figure 3, it is not automatically the case that a load-bearing component, or even the entire load-bearing construction, has reached its technical lifespan at the end of its functional lifespan in the SE school building. The load-bearing components can last for more decades even after the functional lifespan of 40 years of the school building.

Reclaiming and reusing the load-bearing components from existing SE school buildings and reusing them into new SE school buildings can reduce the gap between the load-bearing construction's technical and functional lifespan. Thus, reducing waste generation and dependencies on raw material extraction and processing. However, there is insufficient knowledge on the reclaim and reuse potential of individual load-bearing components. The realisation of reclaim and reuse in the technical field is possible with sufficient knowledge about quality, reliability, and usability (van den Berg et al., 2020).

In conclusion, there is a need for a guidance tool for knowledge and awareness about the reclaim and reuse potential of existing load-bearing components from SE school buildings designed according to the linear building economy.

Figure 4: Problem statement

[4] Appendix B discusses the importance of reclaiming and reusing load-bearing components of SE school buildings.

2. RESEARCH PERSPECTIVE

2.1. Objective

The main objective of this research is to focus on *the concluded problem* stated in section 1.3: *"There is a need for a guidance tool for knowledge and awareness about the reclaim and reuse potential of existing load-bearing components from SE school buildings designed according to the linear building economy."*

This research develops a rapid supporting assessment tool to analyse individual load-bearing components and thereby helps to fill the knowledge gap on the reclamation and reusability of existing load-bearing components. These load-bearing components are from SE school buildings designed according to the linear building economy. The rapid assessment tool can technically measure existing load-bearing components' reclaim and reuse potential with acquired knowledge. The tool helps the school organisation and the project teams at the end of the first economic life of the school building with the initial decision to apply the reuse of load-bearing components in the construction process of a new SE school building.

2.2. Research question

The school organisation and the project team can discover the opportunities and bottlenecks of reclaiming existing load-bearing components through a rapid supporting assessment tool. In this way, the user quickly acquires knowledge of existing load-bearing components' reclaim and reuse potential. At the end of the school building's functional lifespan, the school organisation and project team can make a better-informed decision to reclaim and reuse existing load-bearing components rather than demolish them. This research explains the reusability criteria and performance indicators to arrive at the rapid supporting assessment tool. This explanation summarised in one research question reads:

"How to assess the reclaim and reuse potential of load-bearing components of SE school buildings at an early stage to enable the use of these components in new designs of SE school buildings?"

2.2.1. SUB-QUESTIONS

The research has two stages. The first stage analyses the existing knowledge on reusability criteria, which is the theoretical part of the research. The second stage develops a rapid assessment tool. Solving the two research stages leads to solving the main research question.

1. *Based on the reusability criteria and performance indicators, how to assess the reclaim and reuse potential of load-bearing construction components from SE school buildings?*
    1. Based on the existing building stock of SE school buildings from 1901 – 2015, which load-bearing components are reclaimable and reusable?
    2. What are the key factors that affect reclamation and reusability? Based on these, can a list of reusability indicators be defined?
    3. What information is needed to assess the indicators qualitatively and quantitatively?
    4. Which grading can be assigned to the acquired information to assess the reclaim and reuse potential of load-bearing construction components from SE school buildings?

2. *How can the acquired knowledge be converted into a rapid, practically usable supporting assessment tool?*
   1. In which situation is the rapid assessment tool usable?
   2. How can the theoretical knowledge of reusability indicators be translated into a usable, practical tool?
   3. How can the rapid supporting assessment tool be validated?

2.3. Scope

There is no known research into the reclamation and reuse of load-bearing components of school buildings. So, this research focuses only on the technical aspects of reclaiming and reusing. Only the most essential technical aspects for reuse are considered with the scope of this research, as described in Table 3 and visualised in Figure 5.

Table 3: Research boundaries

Subject	Research Boundary
Type of buildings	Appendix B argues why this research focuses on one specific building type: schools, *SE school buildings of MAVO, HAVO, VWO*. In short, more than 50.4% of the SE school buildings in the Netherlands do not meet the current functional requirements. Outdated school buildings can hold valuable resources, such as load-bearing components. These load-bearing components should be returned to the economy rather than be wasted or degraded (Iacovidou & Purnell, 2016).
Structural typology	Appendix C provides an analysis for the desired structural typology, a *Frame-structure*. The history of education shows that changes and developments are constantly taking place in educational concepts, all of which must fit into the educational housing (Carlebur, 2015). A new school building must provide a high adaptive capacity, like the open building structure (Habraken, 1960; Proveniers et al., 1989). Building in frame structures is one of the primary conditions for developing the open building concept (Proveniers et al., 1989).
Load-bearing components	Appendix C analyses the load-bearing components in SE school buildings and provides a rough reclaim and reuse potential for each load-bearing component. *Columns, beams, floors, and roofs* are reusable within the scope of this research • In frame structures, columns, floors/roofs, and often beams form the load-bearing construction. An open building structure uses light partition walls to create spaces that are adaptable in the future. So, walls are not load-bearing in an open building structure, which means load-bearing walls are not reusable within this scope.

Subject	Research Boundary
	• Foundation designs are often made with piles, which have a project-specific design. It is unlikely that a new project will have an identical subsoil and load transfer (Tol & Everts, 2010). Moreover, removing piles from the subsoil often causes damage to the piles and disturbances in the subsoil, making the reuse of the foundation impracticable (B. Addis, 2006; Tol & Everts, 2010).
Construction materials	*Prefab concrete and steel*. Appendix C analyses the construction materials and concludes that steel produced after 1970 and prefab concrete are suitable for reuse (Steel Construction Institute, 2019b). Construction materials that are less suitable for reclaim and reuse are the following: - In-situ concrete is project-specific and difficult to demount. - The construction material for walls in school buildings often is masonry - SE school buildings have a limited amount of timber with good technical quality
Loads and environment	*The same or lower structural application in the indoor environment, no extreme loads* Certain conditions and loads have determined the original design of the existing load-bearing components. Reuse is only possible if both the existing and new situations are not subject to extreme loads, such as dynamic loads, fatigue, fire or earthquakes (Steel Construction Institute, 2019b). The conditions of the existing and new situation remain the same, indoor environment and the same or less demanding structural application as in the existing situation. For example, a floor component from a SE school building is reusable as both a floor and roof component for a new SE school building.

Figure 5: The scope of the research

2.4. Research strategy

The Research questions from section 2.2 form the basis for the research strategy. Figure 6 shows a research strategy that leads to achieving the research aim of section 2.1 Objective.

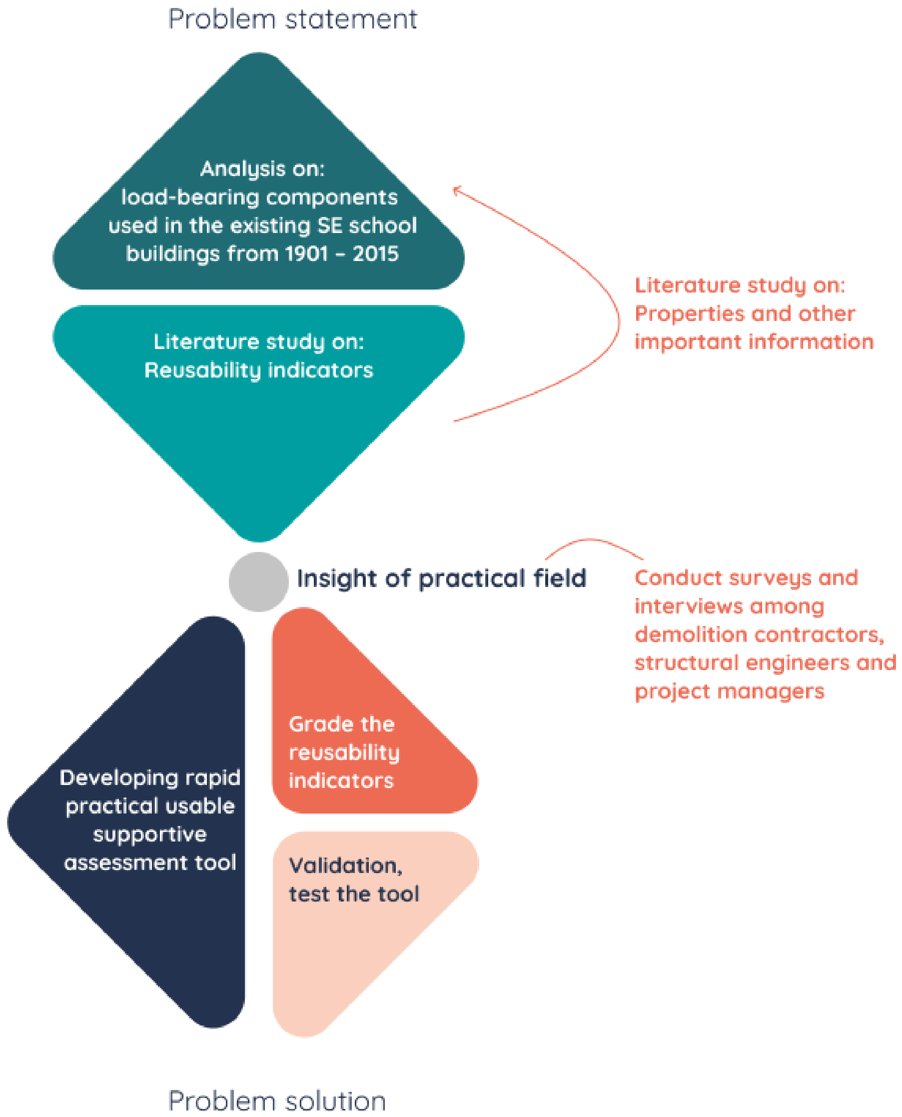


Figure 6: General research strategy

Analysis of load-bearing components

This research starts in a divergent way to provide an overview of the available load-bearing components in existing SE school buildings. Technical drawings and building documents of existing SE school buildings were collated from municipalities and city archives to establish an inventory of load-bearing components, construction materials, lengths of components and type of components. This inventory contributes to the definition of the research scope and answers the first sub-question.

Literature review on reusability indicators

This research conducts a literature study to understand which reusability indicators are essential within the framework of this research. The literature study further analyses the indicators affecting the reclaim and reuse of the load-bearing components from existing SE school buildings. This analysis collects relevant information to quantitatively and qualitatively assess the reclaim and reuse potential of the load-bearing component. The final step of the first research stage is assigning a grading system to the reusability indicators based on literature study and formulas.

Validation reusability indicators

This research conducts a series of surveys and interviews to collect practical insights on reclaiming and reusing load-bearing components from existing SE school buildings. The validated information provides the supporting information for stage 2 of the research. The information from the surveys and interviews validates the founded reusability indicators, necessary information and the grading system scores to validate the content of the rapid supportive assessment tool. The second stage of the research focuses on translating the acquired information on reusability into a practical, usable supportive assessment tool.

The rapid supportive assessment tool

As described, the assessment tool helps school organisations and project teams to make a better-informed choice at an early stage at the end of the first economic lifespan of the SE school building between renovating, refurbishing or building a new SE school building. The focus of the assessment tool is on the potential of reclaiming load-bearing components from existing SE school buildings. Table 4 lists the specifications of the rapid supportive assessment tool. The assessment tool provides the user with different fields of knowledge, referred to as reusability indicators. The knowledge is about the general reusability of the load-bearing components and not the usability for a specific design. Each reusability indicator is a reusability criterion and performance indicator and gets a reusability score. With this reusability score, the tool provides insight into what extent the load-bearing components hold the potential to be directly reused or whether it is better to consider alternative sustainable circular design options such as recycling. The overall aim of the assessment tool is to reduce waste generation and narrow the gap between the functional and technical lifespan of load-bearing components from SE school buildings. Figure 7 shows the outline of the assessment tool.

Chapter 6 explains the development of the rapid supporting assessment tool. The final step is validating the tool in practice.

Table 4: Specification rapid supportive assessment tool

Subject	Specification tool description
Purpose	The assessment provides *an initial, preliminary assessment* of the potential reclaim and reuse of existing load-bearing components. The assessment intends to aid the decision-making process for reclamation. The assessment takes little time, and the tool gives a range of the quality of the load-bearing component. If chosen for reclaim and reuse, further research of the load-bearing components with a formative qualitative assessment will show whether reuse is technically possible.
Building phase	The tool is implementable in the initial *next-life phase*, at the end of the first economic life of an SE school building. The tool is implementable early before reclaiming occurs, in the current situation where all building components are in place.
Users of the tool	Project managers in school building project teams are the users of the assessment tool. *These project managers do not have in-depth structural knowledge* but do know about SE school building projects in general. The tool is user-friendly for people in the building sector with basic structural knowledge.

Subject	Specification tool description
Execution	The tool is *practically usable* since multiple-choice questions form the basis of the tool. A pre-programmed answer pops up by clicking on a multiple-choice answer, making implementation quick and easy.
Software	The assessment tool is *a protective web-based user interface* that makes it possible to assess load-bearing components. The tool's set-up is in Figma, a free online prototyping platform for user interfaces, making further development possible. The user interface makes it possible to guide a user through the reusability indicators.
Results	All reusability indicators are evenly important, and every indicator has *an independent score from 0 (low reuse potential) – 1 (high reuse potential) and comments for points of attention*. Based on the comments and scores of the indicators, the user can choose to reuse load-bearing components and conduct further research into the possibility of reuse.

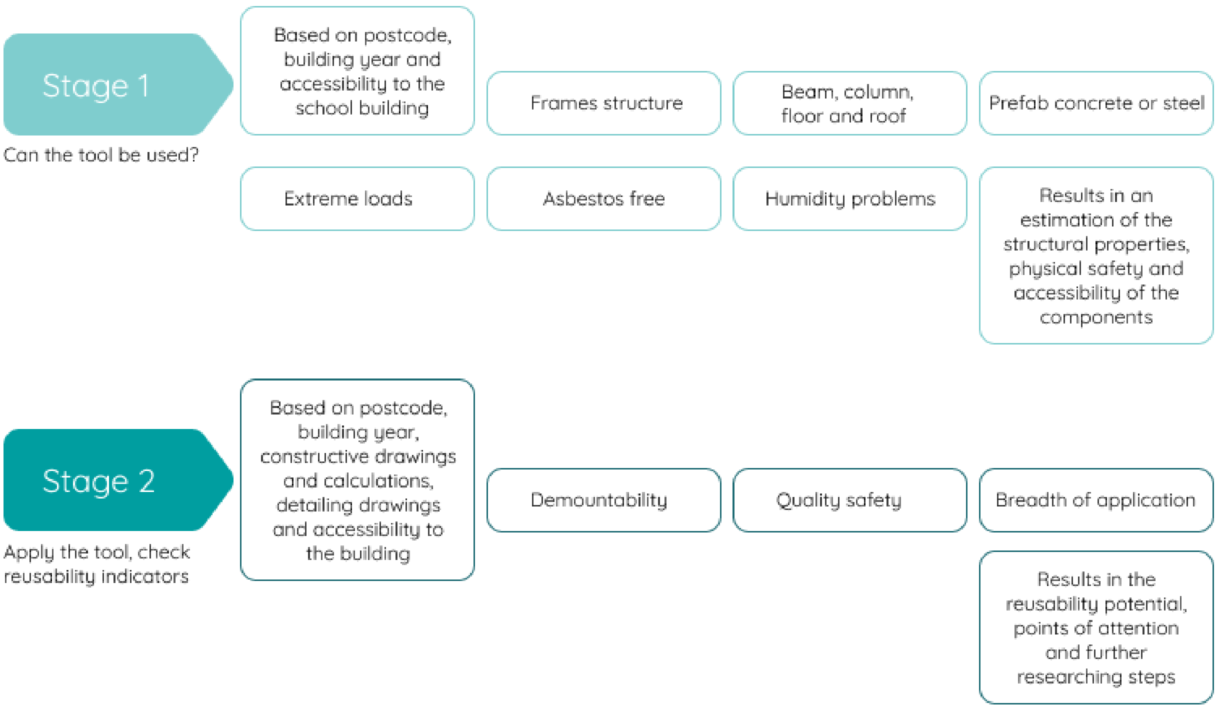


Figure 7: The rapid supportive assessment tool visualised in a flowchart

2.5. Research outline

The research strategy illustrated in Figure 6 and the research questions form the basis for the research outline. The research has a division of three research parts:

- The research framework
- The research method
- The results and final remarks

The part about the research framework introduces the research and forms the foundation of the research with the problem definition, research strategy and research scope. The first sub-question of the first and second research stage of section 2.2.1 partly determines the research's scope. The research framework, therefore, covers answering this first sub-question. The part about the research method deals with the other sub-questions of the first research stage of section 2.2.1. Combining a literature study, three interviews and two surveys give knowledge on the reusability indicators and the grading system to assess these indicators. The part about the results and final remarks contains the translation of the acquired knowledge on reusability indicators into a rapid supportive assessment tool. In addition, the surveys and interviews with practising engineers, contractors and demolition contractors help validate the knowledge about the reusability indicators and the grading system. Figure 8 gives an overview of the research outline.

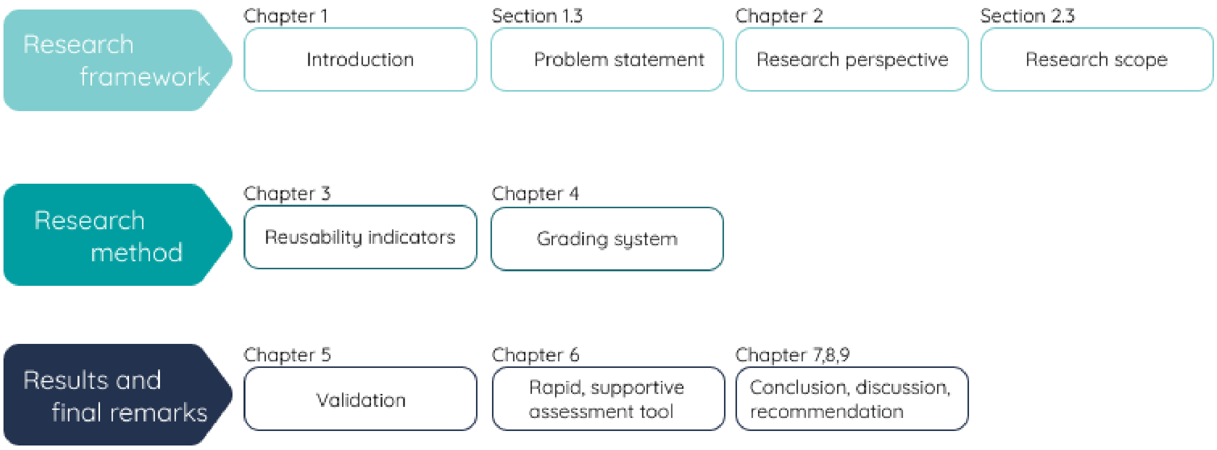


Figure 8: Structure of the research

RESEARCH METHOD

3. REUSABILITY INDICATORS

In a circular economy, the next-life phase replaces the end-of-service life phase of the linear building economy. The next-life phase significantly influences the construction of new SE school buildings and determines where the focus of value lies, value preservation (Khasreen et al., 2009). The next-life phase can be achieved to its full potential by implementing new building strategies. The next-life phase subdivides into two sub-processes: reclaim and reuse; see Table 5. The technical feasibility of reclaiming and reusing and the residual value of components is unknown and thus requires the development of a bespoke set of indicators that measure the reuse potential to this end.

Table 5: Description of the phases reclaim and reuse

Process	Description
Reclaim	Reclaim is the process where disassembling load-bearing components from existing SE school buildings replaces demolition.
Reuse	Reuse is the process where a new school building design uses existing load-bearing components for the same structural function.

This research focuses on existing SE school buildings for which it is not feasible to retain the building partly or as a whole. Various indicators influence the technical feasibility of reclamation and reuse individual load-bearing components from these school buildings. This research determines which indicators are necessary to aid the selection of the next-life phase through a literature review, three interviews with structural engineers, and a survey with structural engineers and contractors compiling the indicators. See Appendix G for the detailed interviews and surveys.

3.1. Relevant reusability indicators

Table 6 shows an overview of the selected indicators of interest for the initial next-life phase. This research subdivides the selected indicators into three primary indicators, shown in Figure 9.

Table 6: Selected indicators of interest for the initial next-life phase

Indicator	Reference
The available information	(Glias, 2013)
Type of load-bearing component	(Glias, 2013; Iacovidou & Purnell, 2016) (Interview 1,2 and 3)
Dimensions	(Iacovidou & Purnell, 2016)
Connections	(R. J. Geldermans, 2016; Glias, 2013; Iacovidou & Purnell, 2016) (Interview 1,2 and 3)
Construction material	(Iacovidou & Purnell, 2016)
Physical quality (Deterioration and damage)	(R. J. Geldermans, 2016; Glias, 2013) (interview 1,2 and 3)
Residual lifespan	(R. J. Geldermans, 2016)
Structural properties and requirements (bearing capacity)	(R. J. Geldermans, 2016; Glias, 2013; Iacovidou & Purnell, 2016) (Interview 1,2 and 3)

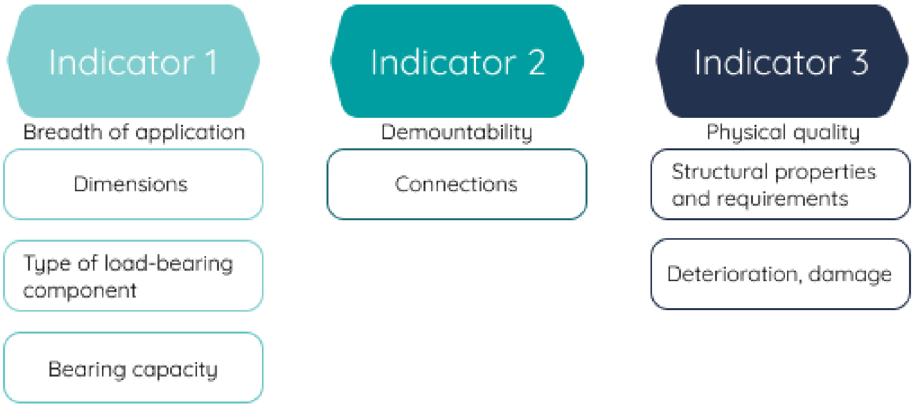


Figure 9: Selection of indicators that influence reclaim and reuse of load-bearing components from SE school buildings

Available information determines whether an existing SE school building is suitable for reclaim and reuse within the scope of this research. Existing information can be, for example, construction drawings or documents, but also previous inspection reports. The flowchart illustrated in Figure 10 helps determine whether the building is suitable for reclaiming and reusing. After following the flowchart of Figure 10, the exploration of the indicators can begin. The subsequent sections describe each primary indicator and the necessary information to make a well-considered choice for the initial next-life phase.

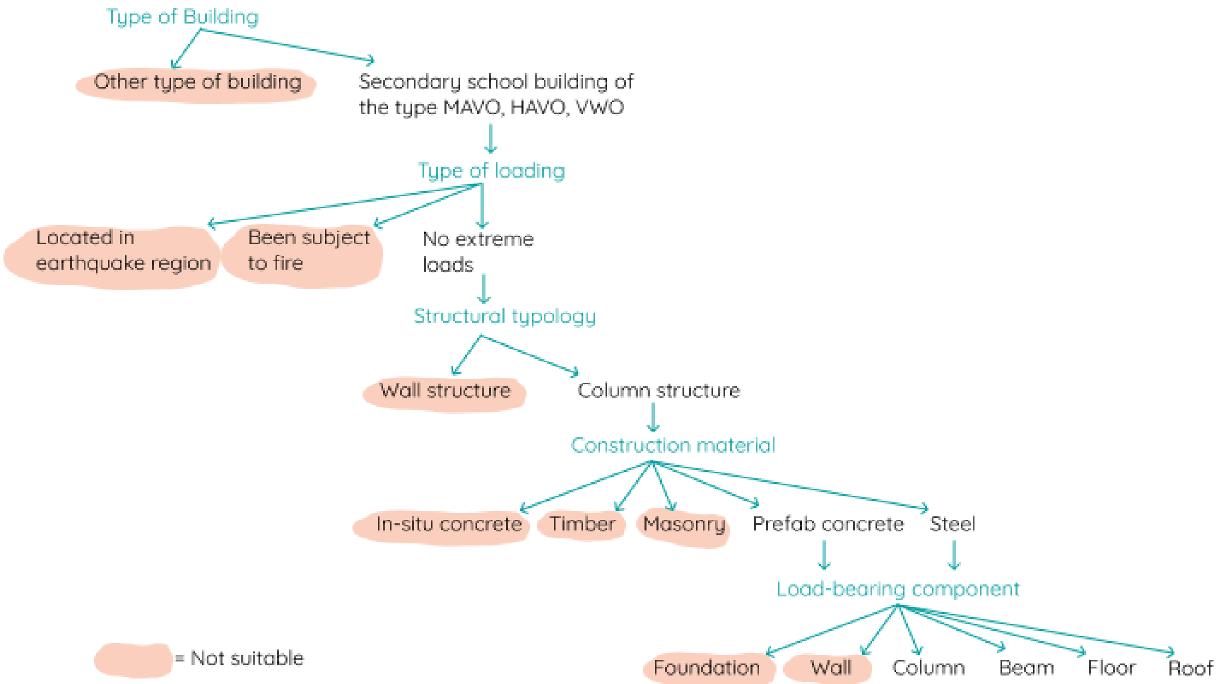


Figure 10: Flowchart for the suitability for reclaim and reuse within the research's scope

3.2. Available information about the original building

The following available information about the original school building influence the reusability indicators:

- The location of the school building, postcode area
- The year of construction

School organisations often have building documents, construction drawings and construction calculations, which provide information about the year of construction, and the properties of the existing load-bearing components in the SE school building. This research simplifies the age of the building to the year of construction, not including the subsequent alterations and renovations. If the building year is missing, the open dataset of Algemene Rekenkamer' Schoolgebouwen PO en VO' can provide the building year (Algemene Rekenkamer, 2016). This dataset also contains the name and location of each SE school building in the Netherlands.

3.3. Reusability indicator 1: Breadth of application

Building a new SE school building goes hand in hand with design requirements, wishes and aspirations. First, the school organisation has financial resources that they could use to construct or renovate the school building (Rijksoverheid, n.d.-b). These financial resources limit a new school building design. In addition, the government sets educational housing requirements that SE school buildings must meet. Moreover, the 'Bouwbesluit' contains general rules for constructing and renovating a SE school building. Lastly, schools must deal with the requirements of the 'Gebruikersbesluit' (Fire Safety) and the building regulations of the municipality. At the same time, a school building is a working environment; Requirements from the 'Arbeidsomstandighedenbesluit' ('Arbowet') apply to workplaces, in particular requirements for the interior design of the school building. It concerns rules for the school grounds, safety, handling of hazardous substances, and the indoor climate (Rijksoverheid, n.d.-b). Unfortunately, the current governmental requirements fall short in the quality criteria for suitable future-oriented educational housing (PO-raad and VO-Raad, 2016). Therefore, Ruimte-OK offers a framework to support the wishes and aspirations for a future-oriented educational housing that meets the objectives of 2050[5] (Ruimte-OK, 2018).

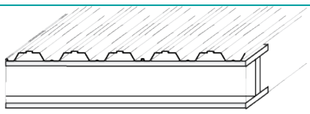
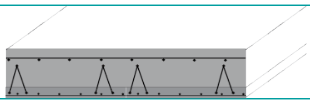
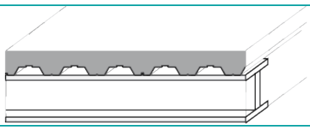
The first reusability indicator: *breadth of the application,* refers to the wishes, aspirations and requirements for a future-oriented SE school building. This indicator focuses on applying existing load-bearing components in new SE school buildings. Appendix D elaborates on the indicator: breadth of application. Each load-bearing component has barriers and opportunities for reuse; this research highlights the most critical aspects concerning the type of component, which varies for 2-dimensional and 1-dimensional components, and the component dimensions, e.g. component length.

3.3.1. 2-DIMENSIONAL COMPONENT TYPE

The type of 2-Dimensional (2D) component, floor and roof components used in an existing SE school building with frame structure can vary. Table 7 illustrates the different variations of 2D components.

[5] The climate objectives of 2050 are in line with realizing a high-quality SE school building with the highest possible degree of sustainability.

Table 7: 2D component types used in existing SE school buildings

2D component type	Picture
Prestressed hollow-core slab	
Steel sheeting	
Reinforced plank floor	
In-situ concrete	-
Prestressed solid slab	
Timber	-
Kwaaitaal	-
TT slab floor	
Deck composite floor	

The reusability of 2D components depends on the following sub-indicators: standardisation, the supporting method, spanning in 1 direction, the bearing capacity, integration of installations, and realisation of diaphragm action. In addition, the presence of a non-structural or structural layer also influences the reusability. Appendix D explains the influence of the sub-indicators on the reclaim and reuse potential for each 2D component type.

Table 8: The influence of sub-indicators on the reclaim and reuse potential of 2D component types

Sub-indicator:		
Standardisation	Description	The load-bearing component must be adaptable in other buildings. When the design of components is project-specific, it is unlikely that a new project will have an identical load transfer. In addition, plenty of information must be available, and many additional actions are necessary to realise reuse. As a result, this research desires load-bearing components with standardised properties to achieve high adaptability. Often these components are factory-made.
	Effects on reusability	A continuous reinforcement configuration along the length of the load-bearing component (Interview 1, 2 and 3) and an unambiguous shape and dimensions ensures a high reuse potential.

<table>
<tr><td rowspan="2">Supporting method</td><td>Description</td><td>The support of a 2D component influence the moment-line of the 2D component field. A continuous 2D component field has a different moment-line than a single 2D component field (Pasterkamp et al., 2014); see Figure 11. In the case of concrete 2D components, the moment-line defines the reinforcement configuration and amount of top and bottom reinforcement and thus the allowable load (Braam & Lagendijk, 2011). Figure 11 a has an upper and lower moment, so the bottom and top reinforcement both take a part of the moment, and Figure 11 b only has a lower moment; the bottom reinforcement takes all the moment.

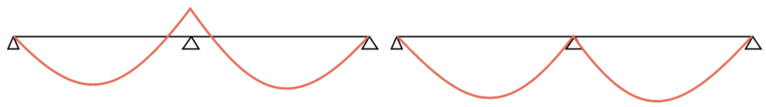
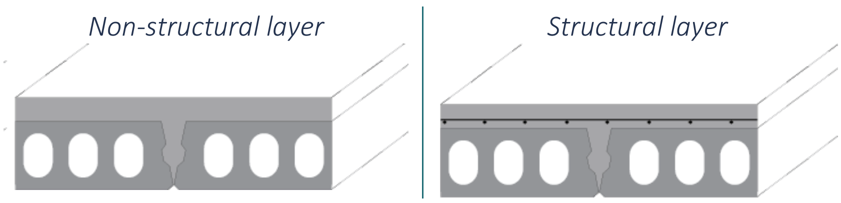



Figure 11: Moment line of, a) continuous 2D component, b) 2D component on two supports

2D components that are often continuous are in-situ floors, reinforced plank and steel composite decks.</td></tr>
<tr><td>Effects on reusability</td><td>A single 2D component field remains the same when disassembling. When disassembling a continuous component, the moment-line will change from Figure 11 a to Figure 11 b. Only the bottom reinforcement can take the occurring moment, reducing the allowable design load. Additional actions are required to create a continuous field again (Interview 1, 2, and 3).</td></tr>
<tr><td rowspan="2">Spanning in 1 direction</td><td>Description</td><td>In the case of concrete 2D components, a 2D component can be load-bearing in one or two directions. A 2D component that transfers the load in two directions has the amount of reinforcement distributed over two perpendicular directions (Pasterkamp, 2016). A 2D component spanning in one direction has the total amount of reinforcement distributed in the single direction and a minimum amount of reinforcement in the perpendicular direction (Braam & Lagendijk, 2011).

The following 2D components often span two directions, in-situ floors and reinforced plank.</td></tr>
<tr><td>Effects on reusability</td><td>A 2D component spanning in one direction remains the same when disassembling. When disassembling a component that transfers the load in 2 directions, the perpendicular reinforcement becomes unnecessary extra self-weight. Only the reinforcement in the spanning direction transfers the load, reducing the allowable design load. The reuse of these 2D components is complex and needs additional action.</td></tr>
<tr><td>Bearing capacity</td><td>Description</td><td>Existing components have already been subjected to loads. Moreover, certain conditions and loads have determined the original design of the existing load-bearing components. The design load of roof components has remained the same since 1972, $P_{rep} = 1.0$ kN/m^2 (TGB, 1972, 1990). However, the design load for floor components in school buildings did change;
• $P_{rep} = 2.0$ kN/m^2 (TGB, 1972),
• $P_{rep} = 2.5$ kN/m^2 (TGB, 1990) and</td></tr>
</table>

		• P_{rep} = 2.0-3.0 kN/m^2 (NEN-EN 1990, 2019). The floor load of TGB 1972, P_{rep}, must be increased by 0.5 kN/m^{2,} and loads of TGB 1990 and NEN-1990, must be increased by 0.5, 0.8 or 1.2 kN/m^2 to consider non-load-bearing interior walls, depending on the weight of the wall (TGB, 1972, 1990). The design information prior to 1972 is unknown. In addition to the design loads, there are also safety factors that vary over the years. Acquired knowledge about construction techniques and the responsiveness of the construction makes it possible to estimate more accurate the responsiveness of components to specific loads (van uffelen, 2012). The safety factors of TGB1990 are lower than TGB1912, and the safety factors of TGB1990 are lower than in the 20th century.
	Effects on reusability	The initial next-life phase assumes that the load-bearing capacity of floor and roof components satisfies P_{rep}'s bearing capacity of Equation 1 (derived from formulas of (NEN-EN 1990, 2019)). In a later next-life phase, destructive tests show the strength of the construction component and the load-bearing capacity of the component. Equation 1: Bearing capacity 2D component $$\frac{\gamma_{load}}{\gamma_{material}} * P_{rep}$$
Integration of installations	Description	According to the structural engineers of the interviews and surveys, integrating the installations into a floor component gives a compact floor height.
	Effects on reusability	A compact floor height reduces the use of material.
Structural layer (providing diaphragm action) and non-structural layer	Description	The analysis of the SE school buildings shows that prestressed hollow-core slabs, pre-stressed solid slabs and TT-slabs have two application possibilities: with a non-structural layer or structural layer, or both. The interviews also confirm these applications (Interview 1, 2, and 3).  The slabs are never completely straight. In addition, the individual 2D components creep and shrink differently, and the individual components may be loaded differently. An extra layer, a non-structural layer, of 5cm sand cement is placed over these types of floor components to prevent cracking in the finishing floor (W. van den Bosch, personal communication, 15 June 2021) (Interview 1). Another option is a structural layer. The choice of a structural layer depends on the fulfilment of three functions: higher cross-section, overall coherence, and diaphragm action. See Table 47 (Pasterkamp, 2016) of Appendix E.

	Effects on reusability	When disassembling a component with a non-structural or structural layer, the layer loses its function (Interview 1,2, and 3). Therefore, based on the current knowledge on reuse of a prestressed hollow-core slab, massive solid slab or TT-slab, reuse is without the structural or non-structural layer (Naber, 2012). Appendix E elaborates on the disassembly process of removing a non-structural or structural layer. Although, the structural engineers from the interviews declare that diaphragm action is desirable in the new situation (Interview 1,2, and 3). New innovative solutions are necessary to achieve diaphragm action without a structural layer.

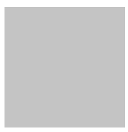
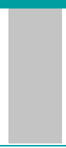
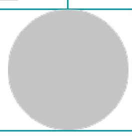
When disassembling the existing SE school building, sawing the 2D components fields makes it possible to take individual load-bearing components out of the building. The original design load was the basis for the amount and configuration of reinforcement, which defined the bearing capacity of the component. The amount and configuration of reinforcement in combination with the new supporting method determines the new bearing capacity of the component and, therefore, the new allowable design load. When the design of components is project-specific, it is unlikely that a new project will have an identical load transfer. In addition, plenty of information must be available, and many additional actions are necessary to realise reuse. As a result, this research desires load-bearing components with standardised properties.

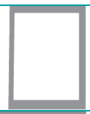
Moreover, sawing the 2D components makes the reinforcement of a continuous 2D component and a 2D component spanning two directions visible and open to the air, which risk harming the component's quality. Additional actions are unavoidable to prevent degradation of the material and ensure quality. With the now available knowledge, reuse of these 2D components needs additional action; reuse is complex and labour- and energy-intensive (Naber, 2012). For this reason, this research considers continuous components and components spanning in two directions with a low reuse potential.

3.3.2. 1-DIMENSIONAL COMPONENT TYPE

Table 9 details the type of 1-Dimensional (1D) components, beam and column, used in an existing SE school building with a frame structure.

Table 9: 1D component types used in existing SE school buildings

Steel profile type	Picture	
Rectangular prefab concrete		
Round prefab concrete		
Integrated concrete-steel	-	
H profile		
IPE profile		

Hollow profile	
Din profile	
UNP profile	

The reusability of beams and columns both depends on the following indicators: the bearing capacity and standardisation. In addition, the reuse of beams also depends on the beam height and lateral-torsional buckling, while the reuse of columns also depends on buckling. Appendix D explains the sub-indicators per 1D component type.

Table 10: The influence of sub-indicators on the reclaim and reuse potential of 1D component types

Sub-indicator:		
Standardisation	Description	Standardised steel profiles have a certified steel quality, shape, and dimensions. The 'Bouwbesluit' includes the steel structural properties.
Bearing capacity	Description	As stated for 2D components, the construction calculations give insides in the bearing capacity of 1D components, which also depends on the safety factors and design loads.
	Effects on reusability	The initial next-life phase assumes that the load-bearing capacity of column and beam components does not give any problems for reuse. In a later next-life phase, destructive tests define the strength and the exact load-bearing capacity of the component.
Beam height	Description	The allowable stresses in the material determine the load-bearing capacity of a beam loaded in bending in the ultimate limited state. The elastic moment of inertia defines the allowable stresses. In addition, the allowable deflection of the beam depends on the moment of inertia.
	Effects on reusability	The elastic moment of inertia formula includes the beam height squared. Therefore, the beam height makes a substantial difference to the allowable stresses. In addition, the height of the beam counts to the third power in the moment resistance formula. It thus has a significant influence on the limited serviceability state of the beam.
(Lateral torsional) buckling	Description	The shape, dimensions, span length, support method, and loading determine the stability of the construction and the sensitivity for instabilities of components such as (lateral-torsional) buckling. The shape of the component and the dimensions determine the moment of inertia, which defines the maximum allowable stresses in the component and, therefore, defines the cross-section's stiffness to resist instability. The moment of inertia can differ in various directions. Lateral torsional buckling can occur due to loading a beam in the 'weak' cross-sectional direction, perpendicular to the longitudinal

		direction of the beam, the bending plane. The beam bends in the perpendicular direction, tilts and rotates. A similar phenomenon can occur with columns loaded in the longitudinal direction, called buckling. The column bends in the longitudinal direction.
	Effects on reusability	Lateral torsional buckling is especially a problem for beams with a relatively low stiffness perpendicular to the loading direction and low torsional stiffness of the cross-section. Steel IPE and UNP profiles are susceptible to lateral-torsional buckling, H-profiles are less sensitive and hollow profiles are not sensitive. Small prefab concrete beams are also sensitive for lateral-torsional buckling. Buckling is a problem for columns with a small cross-section and moment of inertia in a particular direction. Such as a steel H-profile, which has a 'weak' and 'strong' direction. The same can occur for prefab concrete columns that are rectangular.

3.3.3. COMPONENT LENGTH

Column component length

The 'Bouwbesluit' requires a floor level height of 2.60 m (Bouwbesluit Article 4.3.6). According to the wishes for an adaptive future-oriented SE school building, the ideal height of a floor level is 3.20 m (Rijksdienst Ondernemend Nederland, 2021). The floor level is the construction height minus the construction floor, installation height and ceiling thickness. So, since the constructive height is bigger than the floor level height, the ideal construction height is 3.80 – 4.00 m (Interview 2 and 3).

This research subdivides the lengths of the column components into three reuse categories, see Table 11. The categories are multiples of the fixed grid size of 1.80, except for the required 2.60 m.

Table 11: 1D component lengths, columns

Reuse category	Length
Not reusable	<2.60 m
Usable	2.60 – 3.60 m
Good size for an adaptive building	> 3.60 m

2D component length

The length of a 2D component for a future-oriented SE school building with a high adaptable capacity is 7.50 m (Ruimte-OK, 2018). In addition, the 'Bouwbesluit' requires a length of 1.80 m (Bouwbesluit Article 4.3.2). Further, it is desirable to use a fixed grid of 3.60 x 3.60 m or a multiple (Ruimte-OK, 2018). Dimensions in school buildings are multiples of 0.60 m, often starting at 1.20 or 1.80 m (Interview 1). The ideal flexibility length for school buildings and classrooms of Ruimte-OK is not ideal for the existing load-bearing components (Interview 1); 7.50 m is not a multiple of 3.60 m nor 0.60 m. In addition, desired 2D components often have lengths larger than 7.50 m, whereas most existing 2D components have a 3.60 – 7.20 m length (Appendix D).

As explained earlier in this chapter, the design of the new school building must adapt to the existing available load-bearing components, which means that more extensive lengths, such as 7.50 m, are preferable, but shorter lengths are still reusable. This research subdivides the lengths of the 2D components into five reuse categories, see Table 12. The categories are multiples of the fixed grid size of 1.80, up to the maximum transport length of 15.65 m.

Table 12: 2D component lengths

Reuse category	Length
Not reusable	<1.80 m
Almost not reusable	1.80 – 3.60 m
Reusable	3.60 – 5.40 m
Good reusability	5.40 – 7.20 m
Good size for an adaptive building	> 7.20 m

Beam component length

As with a 2D component, the ideal flexibility length for school buildings and classrooms of Ruimte-OK is not ideal for the existing horizontal load-bearing components (Interview 1). However, the desired beams have a length of 7.20 m or even smaller, and most existing beams have a length larger than 7.20 m (Appendix D). The desired shorter spans of beams make reuse of beams more likely. This research subdivides the lengths of the 1D component into the same five reuse categories as 2D components, see Table 12. However, Chapter 4 distinguishes the length of 2D components and beams.

3.4. Reusability indicator 2: Demountability

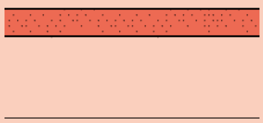
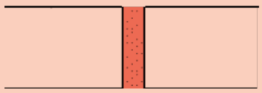
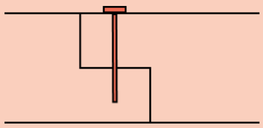
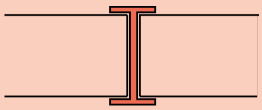
The reclaim chance for load-bearing components depends on the demountability of the component, which depends on the connection between components (van Vliet et al., 2021). The design of existing SE school buildings is according to the principle of the linear economy and does not focus on exchangeability and, therefore, not demountability. Integrating different functions and materials in connections can lead to poor disassembly of the load-bearing components (Durmisevic, 2006). Poor integration of components causes damage when disassembly, which lowers the change for reuse. A combination of previous inspection reports, site visits, and reviewing (detail) drawings define the integration of components and, therefore, the demountability of a component.

The demountability of the component depends on several sub-indicators that affect the disassembly (Durmisevic, 2006). According to the research of Verberne, the technical indicators for demountability are the type of connection, accessibility, the crossing of components, and edge confinement (Verberne, 2016). Alba concept tested Verberne's defined indicators in practice (van Vliet et al., 2021). Kraaijvanger's research adds an extra indicator, namely the aspect 'number of connections' (Kraaijvanger, 2021). The demountability indicators of Verberne, Alba Concept and Kraaijvanger form the basis for this research. Appendix E elaborates the sub-indicators for demountability.

3.4.1. TYPE OF CONNECTION

The research of Durmisevic subdivides the type of connection into "three primary types of connections: direct (integral), indirect (accessory) and filled" (Durmisevic, 2006). This research compares the frequently used connections in SE school buildings with the type of connections from Durmisevic's research. Only the corresponding type of connections are of interest; see Table 13.

Table 13: Hierarchy of disassembly of type of connections. Adapted from (Durmisevic, 2006)

Sketch	Type of connection	Description
	Direct chemical connection	Fixing two components by adhering to each other—for example, reinforced in-situ concrete, a reinforced plank slab or a structural layer. Also welded connection for steel.
	Indirect connection with third chemical material	A third hard chemical material fixes two components. For example, a non-structural layer, mortar filled connections or reinforcement bars in coupling sleeves.
	Direct connection with additional fixing element	A replaceable accessory fixes two components. For example, bolted connections.
	Indirect connection via an independent third element	A third element separates two components, but the assembly depends on each other. All components are potentially reusable due to the dry connection.

3.4.2. ACCESSIBILITY OF THE CONNECTION

An easily accessible connection is a connection that is visible (van Vliet et al., 2021). If the connection is not visible, disassembly is only possible with additional actions. Structural or architectural components may hide the connection, and these components may or may not be removable. It is usually impossible to remove the components without damaging the related components (Durmisevic, 2006). The potential damage must be repaired (van Vliet et al., 2021).

Just as for the type of connection, Durmisevic's research made a subdivision for the accessibility of the connection, consisting of five categories (Durmisevic, 2006). The method demountability of van Vliet tested the five accessibility categories in practice and concluded that four were sufficient (van Vliet et al., 2021). Kraaijvanger's research shows that the categories of Durmisevic are subjective and open to interpretation (Durmisevic, 2006; Kraaijvanger, 2021). This research adds an explanation per category to obtain an unambiguous category division of accessibility of connections; see Table 14 for each category with a technical explanation.

Table 14: The accessibility of connection. Adapted from (Durmisevic, 2006)

Accessibility	Description
Accessible	The connection is independent, visible, and reachable.
Accessible with an additional operation that causes no damage	The connection is not visible and, therefore, not immediately accessible. Constructive or architectural components are independent of the connection and hide the load-bearing component. After removing the constructive or architectural components, the connection is reachable—for example, a ceiling system.
Accessible with an additional operation that causes repairable damage	The connection is not visible and, therefore, not immediately accessible. Constructive or architectural components that are dependent on the connection hide the load-bearing component. The removal of the constructive or architectural components will cause damage to the load-bearing component(s)—for example, an indoor glass partition.
Not accessible, total damage of components	The connection is not visible. Multiple constructive or architectural components that are dependent on the connection hide the associated load-bearing component. The removal of the constructive or architectural components will cause unrepairable damage to the load-bearing component(s)—for example, structural insulated panels.

3.4.3. CROSSING OF COMPONENTS

Crossing components is about the intersection of components from other building layers (van Vliet et al., 2021). The building layers are the building layers of Brand (Brand, 1994). Components can run through each other or can fully integrate (van Vliet et al., 2021). Both components experience hindrance during disassembly due to complexity and additional handlings. The method demountability of van Vliet again tested the aspect crossing components from Durmisevic in practice and concluded that three categories are sufficient (Durmisevic, 2006; van Vliet et al., 2021), visible in Table 15.

Table 15: Division of crossing components. Adapted from (Durmisevic, 2006)

Crossing of components
No crossing
Crossing of components from different building layers
Full integration of components from different building layers

3.4.4. EDGE CONFINEMENT

The edge confinement describes the physical edges of the load-bearing component and the placement in the building (van Vliet et al., 2021). The method demountability of van Vliet again tested the aspect crossing components from Durmisevic in practice and concluded that three categories are sufficient (Durmisevic, 2006; van Vliet et al., 2021). Table 16 provides a technical explanation per category to obtain a category division relevant to school buildings.

Table 16: The edge confinement. Adapted from (van Vliet et al., 2021)

Edge confinement	Description
Component edges are not enclosed	Surrounding components do not enclose component edges, and the edges of components are independent of each other. Disassembly of the component from the building is possible from at least one accessible side.
Component edges overlap	Surrounding components partially enclose component edges, and there is at least one edge with an overlap. Removal of other components first takes place before disassembling the load-bearing component from the SE school building. The load-bearing component depends on other components. For instance, a floor finishing or insulation glued to the roof component.
Component edges are enclosed	Other components completely enclose component edges, and there is inclusion on at least two edges. Removal of other components first takes place before disassembling the load-bearing component from the SE school building. The load-bearing component depends on other components.

3.4.5. NUMBER OF CONNECTIONS

The connection of a load-bearing component can be with one or more components. The number of disassembly operations increases with the number of connections, and each operation increases the risk of irreparable damage. So, each connection may cause additional damage to the load-bearing component, which may hinder potential reuse (Kraaijvanger, 2021). The connection of the component should be with a minimum number of connections to increase the demountability of the component (PIANOo expertise centrum aanbesteden, 2019).

3.5. Reusability indicator 3: Physical quality

The load-bearing components made of steel and prefab concrete are all factory-made. During manufacturing, quality checks determine whether or not the components meet the minimum requirements for the assigned structural function—the minimum quality requirements would be in accordance with the then-applicable standard. The guarantee of the physical quality of an existing load-bearing component is necessary to reuse the components safely in a new school building. Therefore, the minimum requirements of the current building code apply.

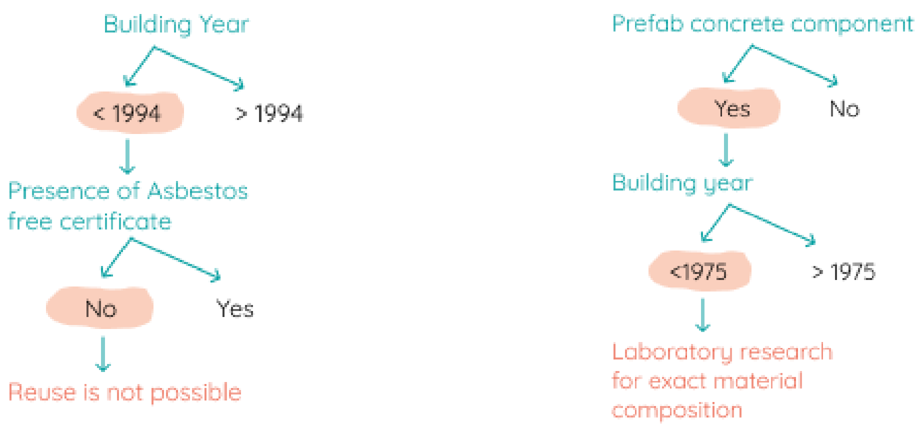
For the initial next-life phase, the focus lies on an initial, preliminary quality assessment. This assessment occurs before reclaiming the components. The initial physical safety depends on sub-indicators: deterioration and damage, residual lifespan, and structural properties translated to the current code (R. J. Geldermans, 2016; Glias, 2013; Iacovidou & Purnell, 2016; Steel Construction Institute, 2019a). This research defines the physical quality of a load-bearing component by the information of the construction and building documents and conservative assumptions. In later next-life phases, visual inspections, careful visual inspections, Non-Destructive Test (NDT) and Destructive Tests (DT) are necessary to guarantee the actual physical quality of the load-bearing components.

3.5.1. TOXIC SUBSTANCES

Requirements for the composition of building materials have become stricter over the years. Therefore, existing load-bearing components can contain substances that are no longer allowed today. This research indicates these undesired substances as toxic substances. Existing load-bearing components which contain toxic substances are not reusable in new SE school buildings; therefore, the composition of construction materials influences the potential reusability of the load-bearing component. (B. Geldermans, 2020; Iacovidou & Purnell, 2016).

Both steel and concrete components can contain the toxic substance asbestos. In addition, concrete can contain chlorides, increasing the risk of corrosion and carbonation (van Berlo, 2019). Both asbestos and chlorides can be detrimental to human health.

Building documents often do not provide information on the exact composition of the construction material. However, previous inspection reports can provide an insight into the presence of toxic substances. Where this information is not available, in a later next-life phase, laboratory research gives the exact composition of the construction material (van Berlo, 2019). For the initial next-life phase, this research determines the presence of toxic substances, asbestos and chlorides, by the building year and the previous inspection reports, based on the flow charts shown in Figure 12.



(a) (b)

Figure 12: Presence of toxic substances. A) presence of asbestos. B) presence of chlorides.

3.5.2. STRUCTURAL PROPERTIES: OVERVIEW

The structural properties of a load-bearing component arise from the material properties of the construction material used. Different standards have been in force throughout the 20th century, each with different requirements. Therefore, the existing load-bearing components are most likely manufactured to an outdated standard.

This research provides information for a range of possible structural properties of steel and prefab load-bearing components by analysing building documents, construction drawings and construction calculations. Building documents, construction drawings and construction calculations provide information about the original structural properties of the load-bearing components and the used standards and requirements throughout the 20th century. However, sometimes little information is available about the load-bearing components of existing SE school buildings, which means that the range of possible structural properties is significant. The more information about the original SE school building, the smaller the range of the possible structural properties.

The initial next-life phase analyses the following structural properties for steel load-bearing components:

- The steel composition
- The steel strength
- The fire resistance

The initial next-life phase analyses the following structural properties for prefab concrete components:

- The concrete composition
- The concrete compressive strength
- The reinforcement steel tensile strength
- The environmental class
- The concrete cover
- The fire resistance

Table 17: An overview of structural properties for steel components

Structural property:		
Steel composition	Description	The chemical elements carbon, manganese, and chopper in the steel composition influence the durability and weldability of the reclaimed structural steel (NEN-EN 10025-2, 2019; Steel Construction Institute, 2019a).
	Assumption	As described in Appendix F.3.3.1 steel composition, this research assumes the maximum allowable percentage of chemical elements for the initial next-life phase (Steel Construction Institute, 2019a).
Steel strength	Description	The composition and physical properties of the steel define the steel strength and steel grade (NEN-EN 1993-1-1+C2+A1, 2016). Commonly used steel grades are S235, S275, S335, and S460. S460 is a high strength steel grade with high yield and tensile strength (Vereniging FME-CWM, 2008).
	Assumption	As described in Appendix F.3.3.2 Steel strength, this research assumes that the steel's material quality and the steel strength in the past is equal to now. In the case of unknown steel strength, the initial next-life phase assumes a conservative lowest steel strength of S235. In later next-life phase, laboratory research provides insight into the exact yield and ultimate strength.
Fire resistance[6]	Description	The reuse of steel load-bearing components takes place without any fire protective layer, and the new design applies a new fire resistance coating to the desired degree (Steel Construction Institute, 2019a).

[6] This research analyses fire resistance in the field of fire safety, see Appendix F.3.1 Fire resistance. Since this research assumes that load-bearing components that have not been exposed to extreme loads are recoverable, this research does not discuss fire degradation and the fire history. However, reuse of the existing components occurs in new school buildings. Therefore, the components must meet the current fire resistance requirements. New school buildings with a height of at least five meters need a fire resistance of 60 minutes.

	Assumption	Often the fire resistance of load-bearing components is not known. Not knowing the fire resistance does not hinder the reuse of steel load-bearing components.

Table 18: An overview of structural properties for prefab concrete components

Structural property:		
Concrete composition	Description	Mixing water with a binding agent, granulate, fillers, and sometimes additives produce concrete construction material. Examples of granulate are sand, gravel and crushed stones. The binding agent for buildings is calcium silicate cement, indicated by NEN-EN 197-1 with CEM. Based on Kamp's research and table 1 of NEN-EN 197-1, this research considers only the most primary types of cement, all containing some Portland clinker (Kamp, 2021; NEN-EN 197-1, 2011). As described in Appendix F.3.2.1 Concrete composition, this research defines CEM I, CEM II/A, CEM II/B, CEM III/A, CEM III/B and CEM III/C as the most primary types of cement.
	Assumption	In the case of unknown cement types, the initial next-life phase assumes a conservative lowest type of cement of CEM II/A, CEM II/B. In a later next-life phase, laboratory research provides insight into the exact type of cement.
Concrete strength	Description	Over the years, there have been several concrete standards. Each standard indicates the concrete quality differently, with different strength classes and structural properties. Starting with the Reinforcement Concrete Regulations (GBV). GBV 1912, 1918, 1930, 1940, 1950 and 1962 have been released. Subsequently, the Concrete Regulations (VB) were issued, VB 1974 and 1984. The Concrete Construction Regulations (VBC) in 1995 and the current standard in 2012, the European standard Eurocode 2 (van uffelen, 2012).
	Assumption	This research compares the differences in concrete compressive strength over the years in Appendix F.3.2.2 Concrete strength to the current concrete strength classes. The current concrete strength classes are C8/10, C12/15, C20/25, C25/30, C30/37, C35/45, C40/50. In the case of an unknown concrete strength class, this research assumes the lowest possible range of concrete strength class used at the time of construction. This assumption is a conservative estimation of the concrete compressive strength class (Bouwdienst Rijkswaterstaat, 2004); see table Appendix F.3.2.2 Concrete strength. In a later next-life phase, laboratory research gives insight into the exact concrete strength class.
Steel reinforcement strength	Description	Each standard from the past indicates the steel grades and properties differently (Bouwdienst Rijkswaterstaat, 2004). In response to the RBBK of Bouwdienst Rijkswaterstaat, this research assumes that the material quality of reinforcing steel in the past was the same as the current one (Bouwdienst Rijkswaterstaat, 2004).
	Assumption	This research compares the steel grades of the old standards with the current standard NEN-EN 1992-1-1 (Hochstenbach & de Vree, 2006; NEN-EN 1992-1-1+C2, 2011; van uffelen, 2012) in Appendix F.3.2.2 Reinforcement steel strength and stiffness. The current steel strengths are FeB220, FeB400, FeB500.

		In the case of not knowing the reinforcement steel grade, this research assumes the lowest possible steel quality at the time of construction to get a first conservative estimation of the reinforcement steel grade (Braam & Lagendijk, 2011). • For buildings before 1960, assume FeB220 • For buildings between 1960-1990, assume FeB400 • For buildings after 1990, assume FeB500 In a later next-life phase, laboratory research gives insight into the exact steel reinforcement strength.
Environmental class	Description	The durability of concrete load-bearing components depends on the expected external influences and whether the component's resistance is sufficient during its lifespan. The durability of reinforced concrete load-bearing components depends on the protection of the reinforcement steel. NEN-EN 206 + NEN 8005 links the expected external influences on the possible defects. The expected external influences distinguish six different environmental influence classes (NEN-EN 206 + NEN 8005, 2017). Appendix F.3.2.4 Environmental class shows the possible environmental classes of SE school buildings within the scope of this research; XC1, XC3 and XS1.
	Assumption	The initial next-life phase assumes the environmental class based on the existing SE school building's postcode zone and indoor humidity.
Concrete cover	Description	The concrete cover protects the reinforcement steel from external influences. The concrete cover is the distance between the concrete surface and reinforcement and depends on the environmental class and fire resistance requirements. Appendix F.3.2.5 Concrete cover shows that the applied concrete covers in the past, according to GBV 1912, 1918, 1940, 1950, 1962, VB 1974 and VBC 1995, are smaller than the currently applied concrete covers.
	Assumption	The initial next-life phase assumes a minimum concrete cover based on the building year, see Table Appendix F.3.2.5 Concrete cover, with a minimum of 10 mm. In the next-life phase, laboratory research gives the exact concrete cover and further actions to meet the current requirements.
Fire resistance[6]	Description	The extent to which the concrete protects the reinforcing steel against heat from fire determines the fire safety of concrete load-bearing components (Zandbergen, 2016). The concrete cover determines the protection of the reinforcement.
	Assumption	The current fire safety requirements for concrete load-bearing components deviate from the outdated standards. Accordingly, not all reclaimed load-bearing components meet the current requirements. If the fire safety of the component is insufficient, actions are necessary to meet the current fire safety requirements. Possible actions include adding extra concrete cover, fire-resistant coating, stucco ceiling, or installing sprinklers (Kamp, 2021).

3.5.3. GENERAL CONDITION

The deterioration of the construction material can be combined with an understanding of the structural properties to define the technical performance. The general condition reflects load-bearing components' technical performance and physical quality (B. Geldermans, 2020). In the Netherlands, NEN-2767 helps determine the general condition of existing load-bearing components (NEN 2767-1+C1, 2019; van Berlo, 2019). NEN-2767 is an objective, uniform condition assessment standard for measuring the physical quality of load-bearing components at the time of a visual inspection (NEN 2767-1+C1, 2019). Note, NEN-2767 does not aim at the condition of a load-bearing component for reclaim and reuse. However, there are aspects in assessing with NEN-2767 that are useful for determining the physical quality of load-bearing components for reclaim and reuse in the initial next-life phase.

Internal or external sources can cause defects, which cause a reduction in the technical condition of a load-bearing component. The objective, uniform condition assessment method maps the technical condition of a load-bearing component by assigning a particular condition score to each possible defect. The condition score ranges from 1 to 6, where this research uses five of the condition scores; see Table 19.

Table 19: Condition scores with description. Adapted from (NEN 2767-1+C1, 2019)

Condition score	Explanation
1	Excellent condition. Minor failures and repairs can immediately restore the defect and bring the load-bearing component back to the necessary intended quality.
2	Good condition. Accidental beginning deterioration. The load-bearing component has visible defects due to dirt. Local defects
3	Acceptable condition. Partially visible deterioration, the performance of the asset is not in danger of failing. Defects such as weathering occur.
4	Poor condition. The building performance is accidentally in danger of failing. Defects can occur that lead to loss of function.
5	Bad condition. Deterioration is irreversible. Significant structural defects occur in the load-bearing component.

This research considers various internal and external deteriorations in the indoor environment of SE school buildings. The Steel Construction Institute and Schoefs et al. form the basis of the internal and external deterioration of the construction material steel (Schoefs et al., 2012; Steel Construction Institute, 2019b; van Berlo, 2019). Appendix F.2.1 Steel deterioration discuss the following deteriorations in the indoor environment:

- Deflection and deformation
- Corrosion

The research of Van Berlo forms the basis of the internal and external deterioration of the construction material concrete. Appendix F.2.2 Concrete deteriorations discuss the following deteriorations in the indoor environment:

- Corrosion
- Cracks

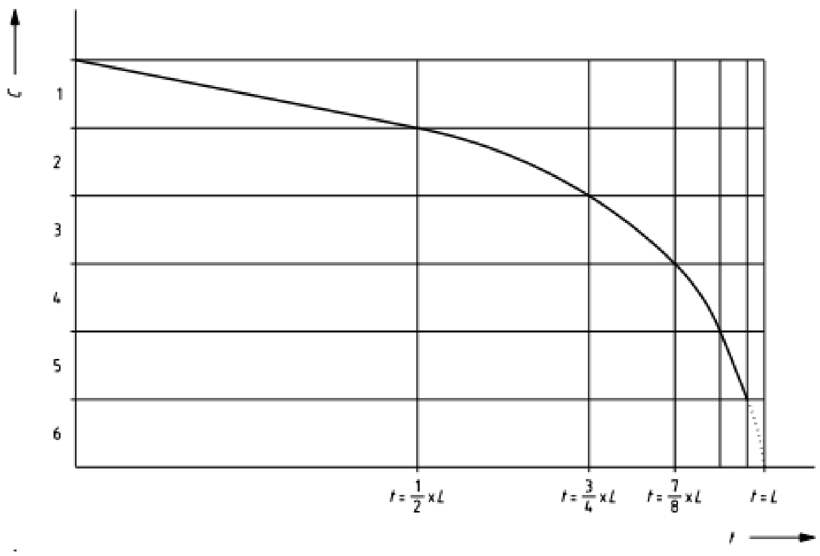
- Alkali-Silica Reaction (ASR)
- Internal Sulphate Attack (ISA)
- Penetration of Sulphates

The initial next-life phase relates the construction material, age and location of the load-bearing component to possible internal or external deteriorations. Based on these possible deteriorations, this research gives a rough estimate of the physical quality of the load-bearing component. The rough estimated physical quality consists of a range of condition scores and a list of defects for further research per possible defects. The highest range is governing. The higher the condition score, the more deteriorated the construction material is and the smaller the reuse chance. In a later next-life phase, a (careful) visual inspection would reveal whether degradations have occurred and the severity and extent of the defects.

3.5.4. RESIDUAL LIFESPAN

The residual lifespan indicates the time a load-bearing component can still perform its function (B. Geldermans, 2020). According to NEN 2767, the residual lifespan of a component depends on the theoretical lifespan (NEN 2767-1+C1, 2019). The calculation of the residual lifespan is the theoretical lifespan minus the lifespan of the building (NEN 2767-1+C1, 2019). For reuse, this way of approaching the residual lifespan can negatively affect. Therefore, the initial next-life phase estimates the residual lifespan differently. The residual lifespan is roughly calculated based on the governing condition range of a load-bearing component (NEN 2767-1+C1, 2019). The highest condition score range gives the lowest residual range, the governing residual range.

Figure 13 shows the course of the theoretical lifespan based on the condition of a load-bearing component. The condition of the component is a score from 1 to 5, so there are five different outcomes for the rough estimate of the residual life (van Berlo, 2019).



C the condition score
t age
L the theoretical lifespan
RL Residual Lifespan

$$RL1 = L - \left(L * \left(\frac{1}{2}^{(C-1)} \right) \right)$$

Figure 13: Theoretical process of the condition as a function of the lifespan

4. GRADING SYSTEM

The three reusability indicators and associated sub-indicators are translated into an assessment method to measure the reclaim and reuse potential technically. This research makes the reusability indicators measurable by giving each indicator and sub-indicator a score for reclaim and reuse (Durmisevic, 2006). The score for reclaim and reuse is the reusability score. Each reusability indicator has a reusability score; the reusability indicators are independent and weigh equal.

This research strives for an objective assessment that comes close to reality. The combination of a literature study, three interviews with structural engineers and a survey with structural engineers, contractors, and demolition contractors, compile the scores of the indicators that influence the reusability of load-bearing components from SE school buildings. The literature study gives the first indication of the reusability scores. Appendix D contains the scores of the breadth of application, Appendix E the score of the demountability and Appendix F the scores of the physical quality. Appendix H elaborates on the scores given by the structural engineers, contractors and demolition contractors. Practitioners scored the reusability indicators of the load-bearing components on a scale from 0 = 'not reusable' to 1.0 = 'highly reusable'. All engineers and contractors are working in the field of school buildings. Comparing the scores from literature with the scores from the surveys assures the reliability of the scores. In this way, the components are objectively measurable.

Appendix H explains per score what kind of research is necessary, more respondents, detailed research, or detailed laboratory research. Table 20, Table 21, Table 22, Table 23, Table 24, Table 25, and Table 26 give the scores conducted by Appendix H. The tables highlight the unreliable scores. According to Appendix H, these scores need further research.

4.1. Type of component scores

Table 20: The scores for the component types

	Type of component	score
2D	Prestressed hollow-core	0.8
	Solid prestressed	0.6
	TT	0.4
	Steel composite	0.2
	Reinforced plank	0.2
	In-situ	0.2
	Steel deck sheeting	1.0
1D: beam	Prefab	0.8
	DIN-profile	0.8
	H profile	0.9
	I-profile	0.8
	Hollow profile	0.8
	UNP-profile	0.7

1D: Column	Prefab	0.8
	DIN-profile	0.8
	H profile	0.9
	Hollow profile	0.8

Table 21: The weighting factors for the presence of a non-structural or structural layer

Weighting factors		
Values	Non-structural layer (Q2)	0.45
	Structural layer (Q2)	0.55

4.2. Component length scores

Table 22: The scores for the column component length

	Component length	score
1D: Column	L < 2.60 m	0.1
	2.60 < L < 3.20 m	0.7
	L > 3.20 m	1.0

The score for the 2D and beam component's length combines the standard dimensions of multiples of 0.60 m and the preference for a long length into one score. The longer the component, the higher the score. In addition, a component's length that is not a multiple of 0.60 needs additional handling before reuse if possible. Therefore, a 2D and beam component's length that is not a multiple of 0.60 scores lower than a length that is a multiple of 0.60. Table 23 shows the scores for components with a length of a multiple of 0.60. Table 24 shows the scores for components with a length that is not a multiple of 0.60.

Table 23: The scores for the component length, multitudes of 0.60

	Component length	score
2D	1.80 m	0.2
	3.60 m	0.6
	5.40 m	0.8
	7.20 m (+n * 0.60 m)	1.0
1D: beam	1.80 m	0.7
	3.60 m	0.8
	5.40 m	0.9
	7.20 m (+n * 0.60 m)	1.0

Table 24: The scores for the component length, no multitudes of 0.60

	Component length	score
2D	L < 1.80 m	0.1
	1.80 < L < 3.60 m	0.3
	3.60 < L < 5.40 m	0.4
	5.40 < L < 7.20 m	0.6
	L > 7.20 m	0.7
1D: beam	L < 1.80 m	0.1
	1.80 < L < 3.60 m	0.5
	3.60 < L < 5.40 m	0.6
	5.40 < L < 7.20 m	0.6
	L > 7.20 m	0.7

4.3. Demountability scores

Table 25: Adjusted demountability scores

	Demountability	score
Type of component	Direct chemical connection	0.1
	Indirect connection with third chemical material	0.2
	Direct connection with additional fixing element	0.8
	Indirect connection via a third dependent element	1.0
Accessibility	Accessible	1.0
	Accessible with an additional operation that causes no damage	0.8
	Accessible with an additional operation that causes damage	0.4
	Not accessible, total damage of components	0.1
Crossing components	No crossing	1.0
	partially overlap each other	0.8
	Components overlap each other over the complete component length	0.5
Edge confinement	Component edges are not enclosed	1.0
	Component edges overlap	0.8
	Component edges are enclosed	0.4
Number of connections	1 or 2 connections	1.0
	Three connections	0.6
	Four connections	0.4
	Five connections	0.1

4.4. Residual lifespan score

Table 26: Scores for the residual lifespan

	years	score
Residual lifespan	≥ 40 years	1.00
	≥ 30 years	0.8
	≥ 15 years	0.60
	≥ 10 years	0.30
	< 10 years	0.10

RESULTS AND FINAL REMARKS

5. VALIDATION

This section discusses the validity of the content for the Rapid Support Assessment Tool. The analysis of construction drawings, construction documents, and literature research form the basis for the content of the assessment tool. This research tests with a scientific method the reliability and correctness of the assumptions made in acquiring knowledge. The first form of validating is conducting three interviews with structural engineers. Subsequently, the second step involved conducting two surveys with 23 practitioners. The practitioners include demolition contractors, contractors, and structural engineers, all involved in school building projects. Appendix G provides information about the interviews and surveys.

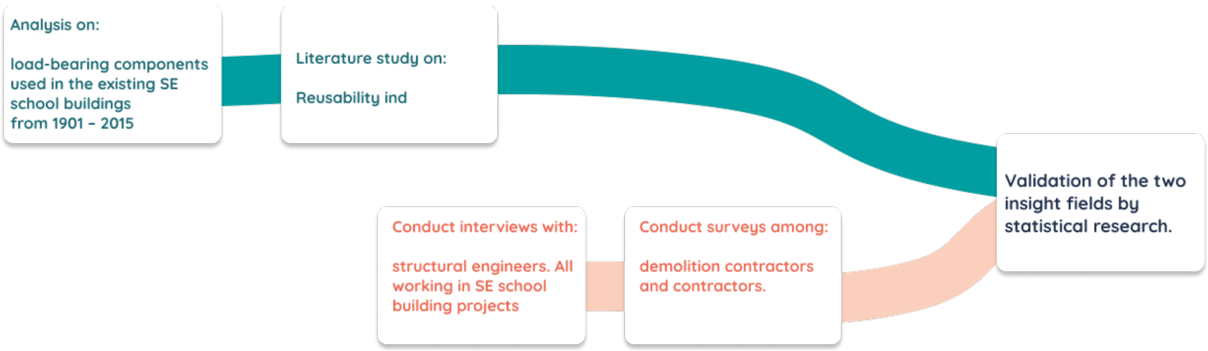


Figure 14: Validation of research content

5.1. Validation of reusability indicators

This research uses three interviews and a survey to validate the chosen reusability indicators. The three interviews conducted among structural engineers are semi-structured interviews using a questionnaire and a subject list to arrive at valid and reliable answers. The information collected reflects structural engineers' facts, thoughts and opinions on the reusability of load-bearing components from SE school buildings. In addition, the information collected also reflects on the reasoning behind thoughts and opinions about the reusability of load-bearing components.

Moreover, the acquired knowledge from the literature and conducted interviews form the basis for the surveys. This research conducted an online survey among seventeen people to collect equivalent information to the interviews from a wider audience—both structural engineers and contractors. Multiple choice questions with multiple answer options and additional free answer options allow the identification of the most critical reusability indicators. A test pilot for the survey was conducted to ensure high clarification of the questions.

5.1.1. INTERVIEWS AND SURVEYS RESULTS

The literature has shown eight indicators influencing the technical feasibility of reclaiming and reusing load-bearing components from SE school buildings. The interviews and the survey results confirm these reusability indicators. Table 27 gives an overview of the relevant reusability indicators and the conformation per interview and survey responses. The eight reusability indicators from the literature provide a reliable and accurate overview of the technical feasibility of reclaim and reuse. Chapter 3 discusses the reusability indicators and analyses the information required for each indicator based on the literature study, interviews and survey to make a well-considered choice for the initial next-life phase.

Table 27: Validation of the reusability indicators

Indicators found in the literature	Interviews	Surveys (17 respondents)
The available information	Available construction calculation	
	Available construction document	
Type of load-bearing components	Type of component	
	Project-specific component or not	7/17
	Spanning in 1 or 2 directions floors	10/17
Dimensions	Dimensions component	
	Component length	14/17
	Height floor, roof, beam	11/17
	Geometric deviations	
Connections	Connection method	2/17
	New connection method	2/17
	Disassembly process	
Construction material	Material	2/17
Physical quality Deterioration, damage	Material quality Deterioration, damage	
Residual lifespan		1/17
Structural properties and requirements Bearing capacity	Structural properties Load-bearing capacity Self-weight Strength classes	 16/17 5/17
	Fire resistance	3/17
	Diaphragm action	6/17
	Sensitivity for (lateral-torsional) buckling	15/17
	Reinforcement configuration (standardisation)	2/17
	Concrete cover	2/17
	Integration of installations in floor	8/17
	Integrated height floor, beams and installation	2/17

5.2. Validation of grading reuse indicators

The combination of literature and formulas compiled by this research have shown an initial score per reusability (sub-)indicator. This research uses two surveys to validate the grading of the reusability indicators. Each survey has a different audience. The first survey was distributed and completed by five demolition contractors. The second survey was distributed and completed by seventeen structural engineers and contractors. The surveys consist of various valuation issues in which the respondents rate the reusability (sub-)indicators with a score from 0 = 'not reusable' to 1.0 = 'highly reusable'. The analysis presented in Appendix G summarises the information collected from the surveys. Appendix H statistically analyses the results of the respondents and compares these results with the literature to gain insight into the reliability and the accuracy of both scores.

Appendix H performs a sensitivity analysis to visualise the spread in the respondents' scores. The spread in the given scores must be as small as possible to assure certainty. The survey from this research involves a small number of respondents, so testing the spread of the results is done with an exact spread of quartiles, which gives a rough indication of the distribution visualised by a boxplot diagram. Subsequently, a T-test gives the confidence interface of the reusability indicator score found in the literature and the given scores by respondents. The likelihood of the literature score being objective must be as small as possible. Therefore, the literature score may not deviate more than ones the standard deviation of the respondent's score's median, which is equal to an exceedance possibility of 32%. If the literature score does not fall within the 68% reliability area of the given respondent's scores, this research tests the score against an exceeding possibility of 5%. Now the scores may deviate twice the standard deviation from the median.

5.2.1. RESULTS OF THE SURVEYS

This research compares only one value, the initial score detailed by the literature and formulas, with a relatively small sample size. As a result, outliers in the data can quickly influence the spread of the respondents' scores and the deviation from the initial score. As stated in Appendix H, the analysis of the surveys has shown that four different types of unreliable scores occur. This section generally explains these unreliable scores, followed by the conclusions of the analysis specifically per sub-indicator, summarised in Table 28.

- The initial score is close to the median of the respondents' score. However, the spread of the respondent's scores is high. The sample size of five and seventeen respondents is minimal, causing outliers to significantly affect the standard deviation of 68% and 95%. Nevertheless, the initial score falls within the respondents' scores' 68% and 95% standard deviation.
- The spread of the respondent's scores is high. However, the initial score falls within the respondents' scores' 68% and 95% standard deviation.
- The initial score deviates from the median of the respondents' score. However, the T-test of the sample size gives no problem between the respondents' scores and the initial score. In addition, However, the initial score falls within the respondents' scores' 68% and 95% standard deviation.
- The initial score deviates from the median of the respondents' score. Also, the T-test of the sample size gives a problem between the respondent's score and the initial score. The initial score is not correct for a standard deviation of 68% and 95% of the respondent's score.

Table 28: Unreliable scores

	Unreliable scores
Type 1	Type of connection: Indirect connection via a third dependent element
	Accessibility: Additional operation, no damage
	Crossing components: No crossing
	2D component length: > 7.20 m
Type 2	2D component length: <1.80 m
	Beam component length: < 1.80 m
	Column component length: < 2.60 m
	1D component: UNP profile
	The weighting of the non-structural layer is 45%
	The weighting of the structural layer is 55%.
Type 3	Type of connection: Indirect connection with a third chemical material
	Crossing components: Partially overlap each other
	Crossing components: Completely overlap each other
	2D component types: TT-floor
	2D component types: Reinforced plank floor
	2D component types: Steel composite floor
	2D component types: In-situ floor
Type 4	Edge confinement: Edges completely enclosed

A larger sample size of 300 respondents provides a more accurate picture of the reality. This research assumes that the scores with a small spread for the used sample size are reliable within the scope of this research. In addition, this research assumes that if the initial score and the respondents' score is the same, the score is reliable and accurate. The tables in chapter 4 highlight the unreliable scores; further research is necessary for these scores. Appendix H explains the further research applicable for each unreliable score, including the suggestion of more respondents, more in-depth research, or laboratory research. In addition, Appendix H gives the chosen scores for the unreliable scores, the initial score or the respondents' score.

The interviews did not find reliable information about the reusability indicator of physical safety. Therefore, further research into the reliability of physical safety scores is essential. However, the method for determining physical safety is reliable because standards include this method, NEN-2767 (NEN 2767-1+C1, 2019; NEN 2767-2, 2008). In addition, at all times, in later next-life phases, there are (careful) visual inspections and constructive tests necessary to determine the physical quality of load-bearing components and enable reuse.

In any case, further research is necessary with a minimum of 300 respondents to be sure that all reusability scores are correct.

6. RAPID SUPPORTING ASSESSMENT TOOL

This chapter translates the validated theoretical knowledge and assessment method of chapters 3, 4 and 5 into a practically usable, rapid supportive assessment tool. The rapid supportive assessment tool is a method to quantitatively assess the reclaim and reuse potential of load-bearing components of existing school buildings. The tool's implementation is at an early stage at the end of the first economic lifespan of the SE school building, referred to as the initial next-life phase in this report. The purpose of the rapid supportive assessment tool is to inform school organisations and school building project teams about the reclaim and reuse potential of existing load-bearing components and adopt the reuse of existing load-bearing components in new SE school buildings as a new design strategy. In this way, school organisations are better informed to choose between renovation, refurbishment and disassembly/new build SE school building.

6.1. Set-up assessment tool

As described in Chapter 3, the reusability indicators depend on several sub-indicators. Therefore, there are many influencing factors for the reuse of existing load-bearing components. This research structures all possible influencing factors in an Ishikawa chart, distinguishing each (sub-)indicator and their influence on the reusability. The Ishikawa chart gives a straightforward graphical representation of all indicators resulting in associated comments and further recommendations (see Figure 15). The Ishikawa chart is the foundation of the rapid supportive assessment tool.

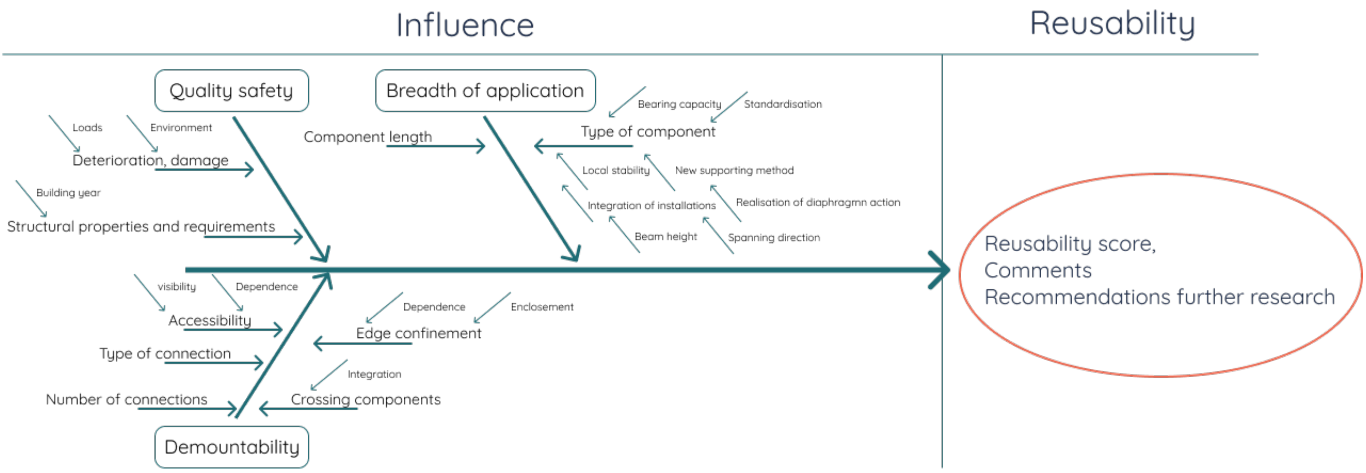


Figure 15: Ishikawa chart of the influence of the indicators on the reusability

The assessment tool provides a step-by-step process of defining the reusability of a load-bearing component from the specific SE school building. This research converts the reusability indicators' influences into questions to create the step-by-step process. Each question is like a node, and the different possible answers are like branches that lead to follow-up questions and answers. All questions and answers eventually lead to a particular reusability score for each reusability indicator. Each reusability score also provides additional comments and future recommendations. In addition, the tool indicates a definition for each reusability score, from 0 = 'not reusable' to 1.0 = 'highly reusable'.

The assessment tool distinguishes two phases, depending on the available information and time. The distinguish in phases is visible in Figure 16. Each phase provides scores and comments, but each phase goes through its step-by-step process. Both step-by-step processes are within the boundaries of this research to guarantee the reliability of the results.

Figure 16: Distinguish two phases in the tool

6.2. Figma

The set-up of the assessment tool is in Figma, a program for creating animated prototypes. Animated prototyping is a form of a Graphic User Interface (GUI). Animated prototyping makes it possible to test the concept of assessing the reusability of load-bearing components in practice with school organisations and school building project teams. The user can use the tool at the school or any other location since it is web-based. The user does not need any specific software but must be proficient in Dutch. Section 2.4 indicates the users of the assessment tool. The user undergoes an interactive experience that starts with choosing between assessment with phase 1 or 2, followed by the tool's manual and the necessary equipment.

The tool's manual explains the purpose, the reusability scores, the interpretation of the scores, how the tool works, the answering options, the clarification option, and the feedback option. The tool has three types of answering options, namely checkboxes, dropdown menus, and buttons, all sampled in the tool's manual. In addition, the clarification button is a question mark button that provides additional information to the user. See Figure 17 for visualising the answering button, clarification button and feedback button. Furthermore, the tool's manual explains that making batches with identical load-bearing components ensures that only one element assessment per batch is necessary. So, creating batches speeds up the process of assessing load-bearing components.

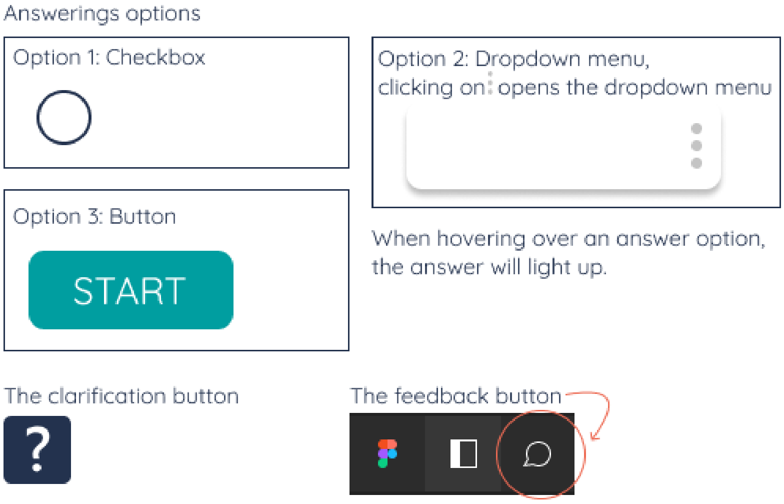


Figure 17: Answering options and the clarification button

Further, suppose the user does not know the answer to the question. In that case, the user can click the answer unknown at any time (if the user does not have enough information or no information to answer the question with certainty). In this case, the reusability score will not be a single number but a range between the lowest and the highest possible scores for the given answers. Figure 18 shows an example of a range of reusability scores.

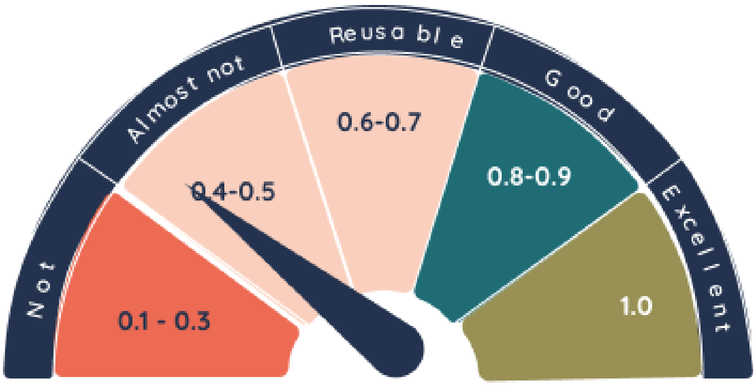


Figure 18: Visual and textual representation of the reusability score

The assessment of individual load-bearing components is easy because the tool shows the user the possible answers and where to find the answer. The tool consists of pre-programmed reusability scores, comments and next steps for each possible answer. Phase 1 needs less information and time; therefore, more is pre-programmed, leading to a more estimated reusability score with more uncertainty. The preliminary conclusions of phase 2 have higher certainties than phase 1 since more specific answers are entered within the tool.

6.3. Hyperlink to the assessment tool

The tool is available online and can be found at this hyperlink:
https://www.figma.com/proto/3ZxqoTQTKj4AsS8rOqbCRG/Rapid-Supportive-Assessment-tool?page-id=0%3A1&node-id=376%3A6741&viewport=298%2C48%2C0.02&scaling=contain&starting-point-node-id=376%3A6741

6.4. Validation of the assessment tool

The development of the rapid supportive assessment tool is a continuous process. The tool presented in this research is a prototype. Figma makes the prototype real-time, making direct feedback and feedback processing possible when testing in practice. The user can post comments in the prototype, which allows the user to provide immediate feedback about defects, lacking information or other matters. See Figure 17 for the visualisation of the feedback button. Since the prototype is real-time, the developer can always process feedback. In this way, the prototype can become as user-friendly as possible.

The first indication of the user-friendliness of the prototype comes from feedback sessions with arbitrarily selected people who are unrelated to the research. The prototype proposed by this research, as it were, is the second version of the prototype. The second version of the prototype has incorporated the following feedback:

- Start the test with a manual
- Explain that the assessment can only assess one constructive element at the time
- Explain where to find the answer in the data
- Explain the derivation of the reusability score, which answers influenced the score
- Explain the interpretation of the score

Chapter 9 Recommendation suggests the future validation of the assessment tool.

7. DISCUSSION

7.1. Research relevance

As mentioned in the Introduction of this research, the current building sector significantly influences the sustainability performance aspects of people, planet, and profit. Therefore, the government and the building sector have realised the governmental-wide program 'The Netherlands circular in 2050'. The purpose of this program is the transition to a 100% circular economy with high-quality reuse. However, the sector has insufficient knowledge and understanding about the possibilities and opportunities to transition towards a circular economy. This research developed a supporting tool to provide knowledge about the possibilities of reclaiming and reusing existing load-bearing components. Designing and building with existing load-bearing components reduce the use of raw materials and the generation of waste.

In addition, 50.4% of the school buildings in the Netherlands are outdated. The current linear building economy demolishes these school buildings and replaces these buildings with new school buildings. However, the circular economy encourages slowing down or closing the linear building cycle to reduce the depletion of natural resources and the generation of waste (Ellen MacArthur Foundation, 2013). This research, therefore, sees the existing school buildings as urban mines to extract load-bearing components for new school buildings. This research provides insight into the indicators that influence the reclamation and reusability of the existing load-bearing components.

A literature study, three interviews with structural engineers and two surveys with structural engineers, demolition contractors and contractors, compile the indicators that influence the reclamation and reusability of load-bearing components. Combining theoretical research and practical experience forms a reusability assessment, which combines existing and new assessment methods to define the reclaim and reuse potential. The perspective and results of the tool are simple and understandable to encourage awareness with the school organisations and the project teams. Awareness among the school organisation is of great importance. Currently, the functionality of the building is the deciding factor for the design of the building, which is striking since the vision of a school changes every 10-15 years. Awareness for the reuse of load-bearing components reduces the school organisation's influence on the building's structural design. It thus increases the chance of usability of existing load-bearing components.

Furthermore, estimating the reclaim and reuse potential at the front of the project increases the choice of a circular building and impacts the rest of the project.

7.2. Research limitations

The first research limitation is the research scope described in section 2.3. In addition, this research also has the following research limitations:

There is a difference in interpretation between the theoretical research, practical experiences, and the researcher's view on reusability indicators.

First, there is a lack of literature on the reclamation and reusability of all load-bearing components. The literature can therefore provide insufficient certainty about the reuse of load-bearing components. For that reason, this research explored the unknowns through its interpretation of the literature, interviews, and surveys.

However, there is little practical experience in reuse, causing the sample size of respondents of the surveys to be relatively small. Small sample sizes cause outliers to affect the results of the respondents significantly. So, this research provides a first verification of the knowledge missing in the literature. However, further research is necessary to conclude that the data given by this research is accurate and reliable. In addition, more practical experience of structural engineers and contractors is necessary. The following sub-indicators needs additional research:

Component type

As follows*: In-situ floor, wide plank slab, steel composite floor, TT-slab and UNP profile.*
This research focuses specifically on school buildings and the reusability of not project-specific load-bearing components which are adaptable/reusable with as few as possible additional actions. Therefore, the researcher gives a low reusability potential to these types of components. However, structural engineers and contractors vary primarily in their opinions about the reusability of these components. Therefore, this research based the reusability score of the component types mentioned above on a formula devised by the researcher.

The influence of a non-structural or structural layer

The literature only briefly mentions that non-structural and structural layers acquire additional actions, but the size of the influence is not known. In addition, the structural engineers and contractors have a large spread in their opinion about the reusability potential of 2D components with these layers. Therefore, this research based the weighting factor of the non-structural and structural layer on a formula created by the researcher.

Demountability

The literature on the demountability of building components is quite extensive. Although, the demountability of building components and load-bearing components is different. The reusability potential from the literature deviates from the opinion of demolition contractors. Therefore, this research based the following reusability scores on the scores given by the demolition contractors:

- Type of connection Indirect connection with third chemical material;
- Crossing components: partially and completely overlapping;
- Edge confinement: completely enclosed.

In addition, the reusability potential acquired from the literature and the opinion of demolition contractors for some demountability indicators are closely related. Although, the spread in the reusability potential given by the demolition contractors is large. Therefore, this research based the following reusability scores on the literature:

- Type of connection: indirect connection via a third dependent element
- Accessibility: additional operations, no damage
- Crossing components: no crossing

The research limitations do not pose for the implementation of the rapid supportive assessment tool. The application of the tool provides insight into the possibilities of reclaiming and reusing load-bearing components. When reuse is chosen, the performance of (careful) visual inspections and constructive tests must verify and certify whether the load-bearing components can be safely reused.

8. CONCLUSION

The research aim, as stated in section 2.1:
"This research develops a rapid supporting assessment tool to analyse individual load-bearing components and thereby helps to fill the knowledge gap on the reclamation and reusability of existing load-bearing components. These load-bearing components are from SE school buildings designed according to the linear building economy. The rapid assessment tool can technically measure existing load-bearing components' reclaim and reuse potential with acquired knowledge. The tool helps the school organization and the project teams at the end of the first economic life of the school building with the initial decision to apply the reuse of load-bearing components in the construction process of a new SE school building."

This research aim summarised in one main research question reads:

"How to assess the reclaim and reuse potential of load-bearing components of SE school buildings at an early stage to enable the use of these components in new designs of SE school buildings?"

Determining the degree of reclamation and reusability starts with assessing individual load-bearing components on several indicators. Subsequently, the result is that the individual indicators have a score and remarks. The rapid supportive assessment tool is not a goal in itself but a tool to provide direction in the decision-making process of the initial next-life phase, at an early stage at the end of the first economic lifespan of the SE school building. The tool is a management tool that allows project managers to measure the potential to reclaim and reuse load-bearing components per SE school building.

To receive the required knowledge on reclamation and reusability for the initial next-life phase and to answer the main research question, this chapter first answers the following sub-questions one by one.

8.1. Sub-questions

Based on the reusability indicators, how to assess the reclaim and reuse potential of load-bearing construction components from SE school buildings?

1. *Which load-bearing components are reclaimable and reusable from the indoor environment of the existing SE school buildings from 1901 – 2015?*

Appendix C analyses the load-bearing components in SE school buildings.

The history of education shows that changes and developments are constantly taking place in educational concepts, all of which must fit into educational housing. Therefore, educational housing must offer a high degree of adaptability to accommodate all kinds of educational concepts. A frame structure offers high adaptability, and a frame structure consists of load-bearing components: columns, floors/roofs, and often beams. Therefore, this research focuses on these load-bearing components. In contrast, walls are not load-bearing in adaptive buildings, which means load-bearing walls cannot be reused and are therefore not reusable for school buildings, according to the scope of this research.

Not only must the new SE school building be adaptable, but also the existing load-bearing components. When the design of components is project-specific, it is unlikely that a new project will have an identical load transfer. In addition, plenty of information must be available, and many additional actions are necessary to realise the reuse of project-specific components. As a result, project-specific load-bearing components are not reusable with the currently available knowledge; therefore, load-bearing components must be applicable in multiple projects. For instance, project-specific load-bearing components are Dutch pile foundations, in-situ concrete, reinforced plank floors, and steel composite floors.

Furthermore, SE school buildings have a limited amount of load-bearing timber components with good technical quality, so reusing these components is not the focus of the new design strategy for the time being. So, the new design strategy focuses on steel and prefab load-bearing components, columns, beams, floors, and roofs, that are implementable in multiple projects.

2. What are the reusability indicators?

The technical feasibility of reclaiming and reusing load-bearing components from SE school buildings' indoor environment depends on various reusability indicators. Summarised from section 3.1, the reusability indicators are the available information, breadth of the application, demountability, and physical safety. Each indicator has its influence on the reclaim and reuse of load-bearing components. Moreover, reuse of the existing components takes place in new school buildings. Therefore, the components must meet the current technical requirements.

3. What information is needed to assess the indicators qualitatively and quantitatively?

Available information determines whether existing load-bearing components are suitable for reclaiming and reusing within this research's scope. Available information depends on building documents, construction drawings, construction calculations, and previous inspection reports. Moreover, a site visit can provide additional information. Summarized from Chapter 3, the required information per reusability indicator is as follows:

- The breadth of the application consists of the component length and the type of 1D and 2D load-bearing components. It focuses on the applicability of existing load-bearing components in new SE school buildings. The reusability of 1D and 2D components both depends on several sub-indicators load-bearing capacity and standardisation. In addition, the reuse of 2D components also depends on the spanning direction, new supporting method, integration of installations and realisation of diaphragm action. Moreover, the presence of a non-structural or structural layer also influences the reusability. For beam components, the beam height and sensitivity to lateral-torsional buckling influence the reusability, while the sensitivity of buckling influences the reuse of columns. Appendix D extensively elaborates on the breadth of the application.
- The demountability of the component, the reclamation, depends on several sub-indicators the type of connection, accessibility of the connection, the crossing of components, edge confinement of the component, and the number of connections. Appendix E extensively elaborates on the demountability of the component.
- The physical safety of a load-bearing component is a combination of sub-indicators, deterioration and damage, residual lifespan, and structural properties translated to the current code. Deterioration and damage depend on the component's general material condition and toxic substances in the construction material. The essential structural properties for the initial next-life phase are the material composition, component strength, fire resistance, and for concrete components also the environmental class and the concrete cover. Appendix F extensively elaborates on the physical quality of the load-bearing component.

4. *Which grading can be assigned to the acquired information to assess the reclaim and reuse potential of load-bearing construction components from SE school buildings?*

Chapter 4 provides the grading of each reusability indicator and sub-indicator.

This research makes the reusability indicators measurable by giving each indicator and sub-indicator a score for reclaim and reuse. This research strives for an objective assessment that comes closest to reality. The combination of a literature study, three interviews with structural engineers and a survey with structural engineers, contractors, and demolition contractors, compile the scores of the indicators that influence the reusability of load-bearing components from SE school buildings. See Appendix H. A reusability score is between 0 = 'not reusable' and 1.0 = 'highly reusable'.

How can the acquired knowledge be converted into a rapid, practically usable supporting assessment tool?

1. *In which situation is the rapid supportive assessment tool usable?*

The rapid supportive assessment tool informs school organisations and project teams about reclamation and reusability of existing load-bearing components in the SE school building to better choose between renovating, refurbishing, or building a new SE school building. The tool's implementation is at an early stage at the end of the first economic lifespan of the SE school building, referred to as the initial next-life phase in this report. The tool is implementable in the current existing situation where all building components are in place.

2. *How can the theoretical knowledge of reusability indicators be translated into a usable, practical tool?*

Section 6.1 structures all indicators and sub-indicators from sub-question 3 of stage 1 in an Ishikawa chart. The Ishikawa chart represents the theoretical knowledge of the reusability indicator. The theoretical knowledge is the influence of each (sub-)indicator on the reusability indicators. This research converts the influences into questions to create a step-by-step process of each influence on the reusability. The step-by-step process of each influence is the foundation for the rapid supportive assessment tool. Each question and answer influence the reusability score for each reusability indicator. Moreover, each question and answer also influence the associated comments and recommendations for further investigation. In addition, the tool defines the scores for each reusability indicator. The reusability score range from 0 = 'not reusable' to 1.0 = 'highly reusable'.

3. *How can the rapid supporting assessment tool be validated?*

Section 5.1 compares the knowledge from the literature with knowledge from interviews and surveys and thereby validates the content of the rapid assessment tool. In addition, Section 5.2 summarises the static validation of the reusability score of Appendix H.

The development of the rapid supportive assessment tool is a continuous process, and the tool presented in this research is a prototype based on the known data. First, the application of the assessment tool itself will take place in practice before validation takes place. Incorporating feedback processing of comments posted by the prototype users increases the accuracy of the results. In this way, increasing the accuracy of the results resolves uncertainties and ambiguities. After one year, face-to-face feedback sessions can take place in the form of interviews with semi-open questions. The starting point of the interviews can be a test case. The face-to-face feedback sessions allow the developer to validate the tool's usability by finding out the different perspectives and interpretations of the different users. The variation in answers will reduce.

8.2. Main question

"How to assess the reclaim and reuse potential of load-bearing components of SE school buildings at an early stage to enable the use of these components in new designs of SE school buildings?"

This research proposes a quantitative assessment of the potential reclaim and reuse of existing load-bearing components. The assessment of the reclaim and reuse potential can serve as a supportive tool that helps school organisations and project teams with the initial decision to apply the reuse of existing load-bearing components in the construction process of a new SE school building. The assessment tool asks the user various questions. Based on the answers and questions, the assessment tool provides theoretical knowledge on the reusability of a load-bearing component. The theoretical knowledge is in the form of several reusability scores, associated comments and recommendations for further investigation. The assessment tool helps school organisations and project teams to make a better-informed choice at an early stage at the end of the first economic lifespan of the SE school building between renovating, refurbishing or building a new SE school building.

9. RECOMMENDATION

As stated in section 7.2 Research limitations, there is a difference in interpreting the reusability potential by different scientific research perspectives. The difference in interpretation is since the reuse of load-bearing components from SE school buildings is still in its infancy. This research shows that further research on several topics could be of great value. This chapter discusses the primary recommendations. This section starts with future validation of the rapid supportive assessment tool, followed by recommendations on expanding and improving the content of the rapid supporting assessment tool.

Development rapid supportive assessment tool

Suppose the prototype is a success after one year. In that case, face-to-face feedback sessions can be held in the form of multiple interviews with semi-open questions. The face-to-face feedback sessions can be conducted with five users of the tool. The face-to-face feedback sessions allow the developer to see the different perspectives and interpretations of the different users. Further, this allows the developer to validate the usability of the assessment tool and resolve uncertainties and ambiguities. The starting point of the interview can be a test case. Prior to the interview, the five users analyse the same test case. The results of comparing the answers of the five respondents are the input for the interviews. Table 29 gives an overview of possible questions for the interview. These face-to-face feedback sessions with the users of the prototype can lead to the development of the rapid assessment tool by a software engineer.

Table 29: Overview of questions for feedback sessions and interviews to validate the assessment tool

Subject	Description
Ambiguities	• If questions are answered with 'unknown', what was the reasoning behind the given answer? • For questions with a wide variation in answers: what was the reasoning behind the given answer? • Were there any ambiguities about the used professional terms? • What questions or possible answers would be made more explicit by adding extra text or images?
Interpretation and perspective	• Are there any indicators in the assessment tool that do not influence the choice for reusing load-bearing construction components? • At what score does the user proceed with the possibility of reusing load-bearing components? • If the user looks at how often he/she used the assessment tool, in how many causes the school organisation was convinced of reusing load-bearing components • What is missing in the assessment tool to convince more school organisations to reuse load-bearing components?

In addition, the software engineer can also extend the tool. The software engineer can implement the assessment of multiple load-bearing components after each other. The prototype of the rapid supportive assessment tool can only assess one load-bearing component at a time. Further, a database can store the input and output of the assessment tool. The database can provide storage for the data on the use of the assessment tool and the application of reclaim and reuse of load-bearing components.

Weighting factors

The rapid supportive assessment tool distinguished four independent reusability indicators. However, it is not the case that every reusability indicator is equally essential in the choice to reclaim and reuse load-bearing components. As mentioned above, it is possible to determine how vital each reusability indicator is for the users in the face-to-face feedback sessions. Further research into the influence of each indicator should provide the opportunity to express a weighting factor for each indicator to create one reusability indicator instead of four independents.

As mentioned in section 7.2, the influence of the non-structural and structural layer is unknown. In addition, further research into the influence of the non-structural and structural layer on the reuse indicator the type of the component (2D component) should provide more certainty about the reclaim and reuse potential. Further research should provide the opportunity to get a more certain weighting factor for the non-structural and structural layer. Multiple lab tests with the detachment of the layers should show the obstacles and how much influence the layers have on the reusability potential.

Validation of the content of the assessment tool

The combination of a literature study, three interviews and two surveys established the four reusability indicators and sub-indicators. Moreover, in the same way, it is also possible to learn more about the perspectives of demolition contractors and material experts on reclaim and reuse. The perspectives of every stakeholder give a more in-depth assessment tool and more complete and accurate reusability indicators. So, this research recommends further research into the perspectives of demolition contractors and material experts on reclaiming and reusing load-bearing components.

Economic perspective

Building new school buildings is often related to a budget. Therefore, school organisations and school building project teams want to know the costs for reusing load-bearing components. The economic perspective on reclaim and reuse is thus of great importance, and adding the economic perspective to the rapid supportive assessment tool provides added value to the assessment tool. This research recommends doing further research into the economic perspective by analysing the costs of each operation required to reclaim and reuse load-bearing components. In addition, it is of interest to compare the costs of a new load-bearing component with an existing component to make the costs of reclaim and reuse more susceptible.

Sustainability perspective

Reclaim and reuse of load-bearing components must offer a solution against raw materials and the generation of waste to achieve sustainable ambitions. However, the reuse of load-bearing components should not come at the expense of other sustainable ambitions, such as reducing CO2 emissions. Therefore, this research recommends further research into the sustainable perspective by analysing the environmental impact of reclaiming and reusing load-bearing components of SE school buildings. CO2 emission can express the environmental impact, and environmental shadow costs can express the CO2 emission. For further research, it is again interesting to compare a new load-bearing component with an existing component to make the sustainable ambitions more visual. If reclaim and reuse have higher environmental shadow costs than a new load-bearing component, other sustainable building strategies are more suitable to implement.

Should the government switch to a payment system for CO2 emission, it would be interesting to conduct further research into the combination of the economic and sustainability perspective and then implement this in the rapid supportive assessment tool.

Different building types

The rapid supportive assessment tool is currently only aimed at SE school buildings of the educational type MAVO, HAVO, VWO. Further research into the implementation of primary school or other educational types can make the assessment tool more versatile. More broadly, the ability to implement different building types in the rapid supportive assessment tool. For this implementation, research into the bearing capacities of the load-bearing components to exchange the various components is necessary. Old standards specify the bearing capacity of load-bearing components for different building types.

Moreover, by implementing different building types, it is essential to analyse the building and construction drawings for different building types. These drawings give insight into the load-bearing components' characteristics used in these different building types. This analysis ensures the possibility to implement these component characteristics in the assessment tool. Furthermore, each building type prefers different component lengths, requiring further research.

Focus on reuse

The focus of the rapid supportive assessment tool is now mainly on the reclaim of the load-bearing components. However, when reclaiming, the old connection options may get lost in some cases. Further research into new connection methods of these existing load-bearing components should give more insight into the reusability of these components. Therefore, this research recommends doing more research into the new connection method.

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APPENDICES

APPENDIX A

THE PRINCIPLES OF CIRCULAR BUILDING ECONOMY

A.1 Definition of circular building economy

We live in a linear building economy that uses raw materials to produce constructions such as buildings, which turn into waste at the end of their service life. It works according to the principle: produce, construct, use and end-of-service. See Figure 19. Life cycle phases of the building cycle in a linear building economy are the foundation for the principle of the circular built environment. The linear building life cycle slows down, closes and narrows in the circular building economy. Raw materials and building components lose their value as little as possible, energy sources are renewable and thinking in systems is vital (Ellen MacArthur Foundation, 2013).

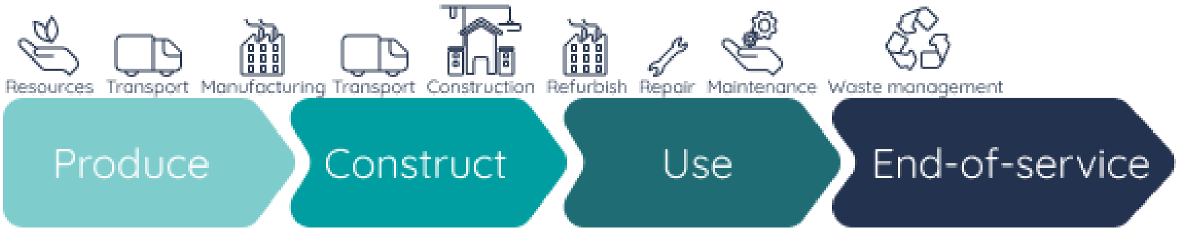


Figure 19: Linear building economy. Adapted from (Klein, 2021)

The circular building economy is an idealised building environment where the material and energy life cycle slows down, closes and narrows. (Ellen MacArthur Foundation, 2013) In a closed building cycle, the four life cycle phases form a closed loop. Completing the building cycle reduces the input of raw materials and waste production. Nevertheless, also, emission and water and energy leakage will be decreased. By closing the building cycle for every life cycle phase, waste can be limited, and there is less economic and ecological value loss (Ellen MacArthur Foundation, 2013). Every life cycle phase minimises value destruction. Value destruction allows the economic and industrial system of the idealised circular building economy to strive for value preservation and high-quality reuse. In this way, it is possible to keep materials and components in use for as long as possible (Antikainen & Valkokari, 2016).

Energy also lasts as long as possible in a circular building economy, like materials and components. The circular building economy uses renewable energy sources and uses high-quality energy (Korhonen et al., 2018). Although an energy cycle is not possible, according to the Ellen MacArthur Foundation, there are other options for energy reduction (Het Groene Brein, 2018).

The circular building economy is about closed material cycles, renewable energy, and innovative business models. The business models will no longer focus on one stakeholder, one company, but on several collaborating stakeholders in different disciplines in the life cycle (Antikainen & Valkokari, 2016). So, companies create partnerships that create value together, and they depend on each other. An action of one stakeholder will have consequences for the whole network of stakeholders (Ellen MacArthur Foundation, 2013).

A.2 The difference between a linear and circular building economy

Closing the building cycle must go behind recycling, where value creation and preservation is changed. It also changes the sustainability of the construction process of buildings and the business models used.

A circular building economy is about the material and components' financial and quality value and generating additional revenue with multiple lifespans over different life cycles. The quality value of a component includes technical, functional, durable, and aesthetic performance. The quality value is measurable, which makes variations visible per life cycle phase of the building or building component or for the entire life cycle.

In contrast to the circular building economy, the profit of a building project in a linear economy is only measurable after the phases *produce* and *construct*. See Figure 19. for the different building phases. The phases *use* and *end-of-service* do not influence the project's profitability, but in these phases, the financial value of the building is the expressed value. In today's linear economic society, the years a component or building is still usable indicates its financial value. A building component that gets older depreciates over the years, reducing the financial value. Assume that the functional lifespan of the component is fifteen years. Then after these fifteen years, the component has a value of zero according to current legislation and regulations for the financial valuation of building components and buildings. However, this component can still work fine in practice or last for another ten years with minor adjustments. The financial values of zero are at odds with the quality value of the component because the real value is not zero. The component is not worthless, and it has a specific residual value. The circular building economy responds to this quality value.

Furthermore, a circular building economy changes the valuation of buildings and building components. Moreover, the associated fiscal rules and laws modify as well. Therefore, the circular building economy necessitates innovative business models. These business models must no longer focus on one stakeholder, one company, but on collaborating stakeholders from different disciplines in the life cycle (Antikainen & Valkokari, 2016). Companies' partnership creates value together, and they depend on each other. An action of one stakeholder has consequences for the whole network of stakeholders (Ellen MacArthur Foundation, 2013). The revenue models in these innovative business models combine hard and soft indicators. A hard indicator is, for example, money, financial value. Examples of soft indicators are social and ecological impact (Jonkers et al., 2018). The aim is to minimise damage to and burden on ecologic and social systems. The negative CO2 footprint will be as small as possible and the positive footprint as large as possible.

A.3 The circulation of materials and building components

As mentioned before, a circular building economy aims to keep materials in use for as long as possible and maintain their value through intelligent technologies and solutions. The circular building economy closes the building cycle to preserve value. The building cycle can be closed on different levels and in several ways. These ways of closing the building cycle are applied to the four-building phases of the linear building economy and will be referred to as the circular built environment approaches. The three basic approaches are:

- More competent material and product use and smarter manufacture
- Extend the lifespan of components and buildings
- Proper end-of-service application of materials and components

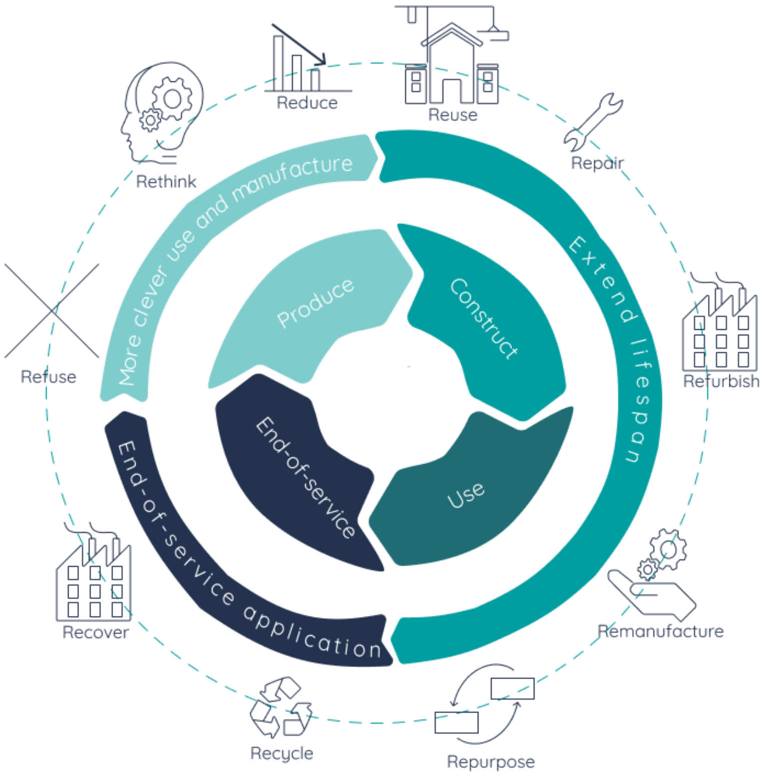


Figure 20: Strategic approaches of the circular built environment. Adapted from (Klein, 2021)

The three basic approaches provide a new way of building and are implementable in every design phase and at different scales. This new way of building is better known as circular building. Therefore, the Circular Built Environment approaches aim at a circular building to enable value preservation (Ellen MacArthur Foundation, 2013). The circular Built Environment approaches are visible in the middle circle of Figure 20. Different R-principles can achieve value preservation, and the different R-principles are subcategories of the various Circular Building Environment approaches. The R-principles are circular strategies that prioritise ways to reduce the use of raw materials and minimise material waste to minimise the adverse impact on the environment (Plan Bureau Voor De Leefomgeving, 2019). The first is to strive for the highest possible quality principle, namely *more clever use and manufacture* of buildings. This Circular Built Environment approach includes the R-principles refuse, rethink and reduce. If this approach is not possible, the circular build Environment approach of *extending the lifespan* of the building or parts of the building is the second option. Reuse, repair, refurbish, remanufacture and repurpose fall within this approach. The last possible step of the Circular Built Environment is a *proper end-of-service* life application for materials and components that would otherwise end up as landfills. The application of the R-principles recycles, and recovery apply. The strategy of the R-principles is like a ladder of priorities, starting with refuse and then clockwise to recover (Plan Bureau Voor De Leefomgeving, 2019). The R-principles are visible in the outer circle of Figure 20, and Table 30 gives the preferred order for closing the building cycles, with a brief explanation for each R-principle.

Table 30: Preferred order for closing cycles according to the R-ladder. Adapted from (Cramer, 2014)

R-Ladder		
Smarter use and manufacture	Refuse	This principle makes a product redundant by giving up its function or delivering it with a radically different product.
	Rethink	Intensify product use
	Reduce	The product is manufactured more efficiently by using fewer raw materials and materials in the product or its use.
Extend lifespan	Reuse	Reuse of discarded, good product in the same function by another user
	Repair	repair and maintenance of broken product for use in its old function
	Refurbish	refurbishing or modernising old product
	Remanufacture	Using parts of discarded products in new products with the same function
	Repurpose	Use discarded products or parts thereof in a new product with a different function.
End-of-life application	Recycle	This principle is about processing materials to the same (high value) or less (high value) quality.
	Recover	Incineration of materials with energy recovery

A.4 The optimal functional and technical performance of a circular building

The starting point of the R-principles focuses on the technical side of the building design, generating a sustainable design with the most negligible negative impact on the environment. This perspective of circular building design is a different take on designing than the linear building economy. A different perspective on designing is essential to create a sustainable built environment by reducing the environment's negative impact.

The transition towards a circular building with the Circular Building Environment approaches have two perspectives:

- On the one hand, an enormous stock of existing buildings will become available in the coming years. These buildings reach the end of their functional lifespan due to being designed according to the linear building economy. See Figure 19. for the linear building economy vision. The building sector can reduce waste and raw materials by applying the R-principles, Reuse, repair, refurbish, remanufacture or repurpose. In this way, the buildings and their building components keep in circulation. If extending the lifespan of components and buildings is not possible, the last approach is to *give the materials and* *components a proper end-of-service application* by applying the R-principles, recycle or recover.

- On the other hand, there is a demand for new buildings. New buildings developed circularly with the R-principles, refuse, rethink or remanufacture. New building technologies and design strategies allow for *more competent material and product use and smarter manufacture*. In the future, these new buildings need to be adaptable in the sense of redesign, upgrade or disassembling without generating waste.

This research will focus on the first perspective, the enormous stock of existing buildings which become available in the coming years. The functional performance of the building determines the functional lifespan of the building, called the serviceability of the building. The serviceability of the building comes to an end when the building can no longer deliver the desired functional performance against acceptable sacrifices. For instance, the climate control systems in the building are outdated, and the height of the new systems is too high to achieve the desired ceiling height. However, not every component in the building has reached the end of its useful life and is no longer of use or value. The performance of these other components determines the remaining usefulness and value.

Moreover, the composition and the interrelationship of the various building components also influence the remaining usefulness and value. The remaining usefulness and value determine circular strategies' accomplishment. According to Stewart Brand, a building is composed of several layers. The six different layers are Site, Structure, Skin, Service, Space plan, and Stuff. Each layer has its development path over time, referred to as the technical lifespan[7] (Brand, 1994). Figure 21 and Table 31 show that some layers of a building have a shorter lifespan than the functional lifespan[8] of the building itself. In contrast, other layers in buildings have a slower development path than the functional lifespan of a building.

Take, for example, the lifespan of structural components. This technical lifespan of load-bearing components is often 30 – 300 years, whereas the functional lifespan of a building is mainly 40 – 60 years (van den Dobbelsteen, 2004). So, there is a gap between the load-bearing construction's functional and technical lifespan (Baelemans, 2020). The load-bearing components can thus comprise different functional periods within their technical lifespan.

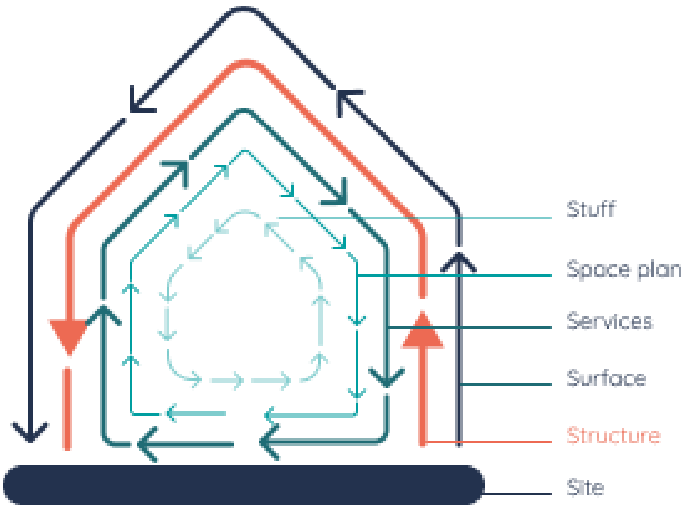


Figure 21: Different building layers. Adapted from (Brand, 1994)

[7] Technical life span, the period a component physically meets the required performance (Hermans, 1999).
[8] Functional lifespan, the period the building meets the functional requirements (Vree de, 2021a).

Table 31: Different building layers. Adapted from (Brand, 1994)

Layer	Lifespan	Subject
Site	Infinite	The geographical setting of the location of the building
Structure	30-300 years	Foundation and the load-bearing elements
Skin	>20 years	Façade of the building
Services	7 – 15 years	Installations and systems in the building
Space plan	3 – 30 years	Interior layout building, placing of walls, ceilings, floors, and doors
Stuff	Daily/ monthly	Stuff in the building

Understanding the layer logic helps make circular design choices for individual load-bearing construction components from the definition phase onwards. The first is to strive for the highest possible R-principle in the Circular Build Environment approach extending the lifespan. This R-principle is reuse, and reuse has different levels, building, component, and material levels. Ideally, the load-bearing construction is good, and full reuse is possible. Renovation of the building takes place. Reuse at the component level occurs if the load-bearing construction no longer meets the functional requirements. If the load-bearing construction no longer meets the safety requirements against acceptable sacrifices, reuse occurs at the material level.

A.5 The circular build economy related to sustainability

However, it is not necessarily the case that the Circular Built Environment approach of a circular building always leads to a lower negative environmental impact. It is a way of achieving sustainability and Sustainable Development Goals (SDGs), but the solution applied can sometimes contradict this goal. Many drastic adjustment measures can be detrimental to the environmental impact. As a result, in some cases, no preference is given to a circular building approach to achieve a lower negative environmental impact. Therefore, a circular building must be a well-considered choice and not at the expense of everything.

APPENDIX B

THE BUILDING TYPE: SCHOOLS, SECONDARY EDUCATIONAL SCHOOLS

The current educational housing development is struggling with outdated school buildings. More than 50% of the Secondary Educational school buildings in the Netherlands do not meet the current functional requirements. The functional lifespan of a school building is 40 years, after which the renovation or replacement of the building takes place (PO-raad and VO-Raad, 2016). The outdated school buildings in the Netherlands date from 1981 or earlier, as visible in Figure 22 (Bresser, 2021). One of the most significant changes of the second half of the 20th century was the introduction of the 'Mammoetwet' in 1968. With the introduction of the 'Mammoetwet', every child, regardless of background, is given the same opportunities for development (van Rixoort, 2021). In combination with the increasing number of births after World War II till 1970, there was a growth in the number of school buildings from 1955 till 1985 (Centraal Bureau Voor de Statistiek, 2021; Jacobs & Heijltjes, 2018).

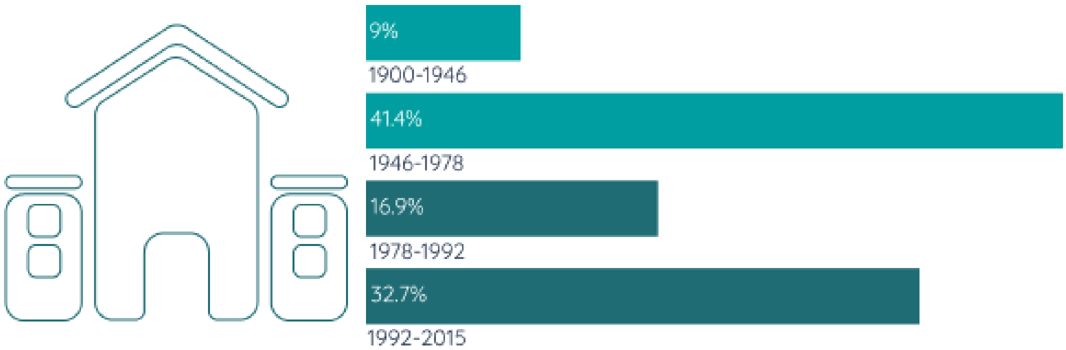


Figure 22: Building years of Secondary Educational School buildings. Adapted from (Bresser, 2021)

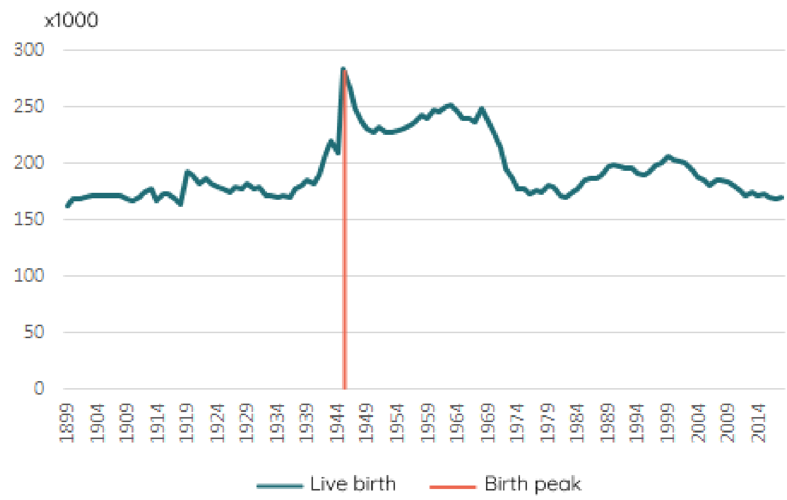


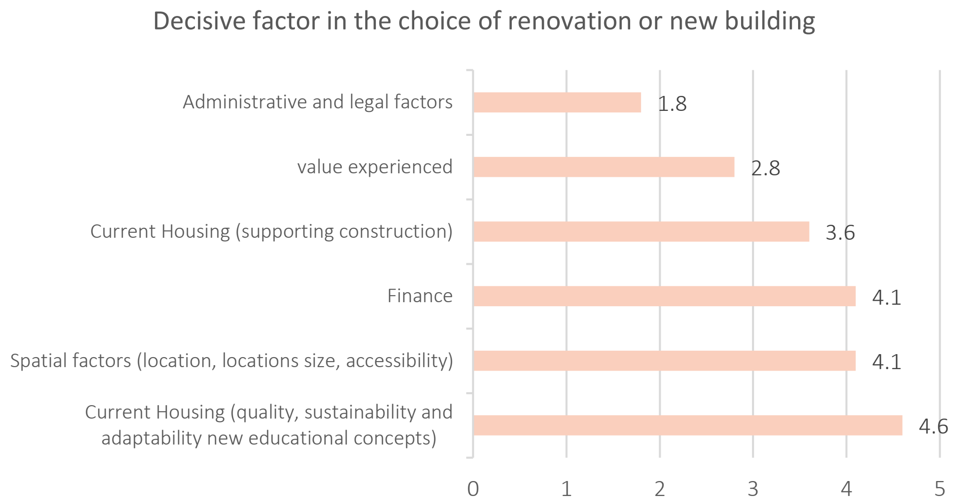
Figure 23: Number of live births from the 20th century until today. Adapted from (Centraal Bureau voor de Statistiek, 2021)

In addition, in the second half of the 20th century, there was a constant change of vision about perspectives on education. After World War ll, new educational typologies arose. Montessori, Dalton, Free, and Jenaplan schools laid the foundation for innovation in educational typologies (Carlebur, 2015; van Rixoort, 2021). These innovations in educational perspectives also had consequences for the construction and furnishing of school buildings. The difference in educational perspectives resulted in different building typologies, which influence structural typologies. Structural typologies, in turn, influence construction techniques (Carlebur, 2015). In other words, the nearly 10,000 school buildings in the Netherlands, all built between 1901 and now, have different types of load-bearing constructions. These different types of load-bearing constructions and ages of buildings cause great divisions in the functional and technical qualities of school buildings (Algemene Rekenkamer, 2016).

The functional life of a school building is 40 years, after which the renovation or replacement of the building takes place. The choice between renovation or replacement of the building depends on the functional and technical quality, which depends on the building typology, structural typology and the construction techniques applied. The extent to which a building no longer meets functional or technical requirements, or both, determines the level at which reuse is possible. Ideally, the load-bearing construction meets the requirements, and complete reuse is possible. This type of reuse already applies in the Netherlands, known as renovation.

Nevertheless, sometimes the load-bearing construction does not meet the functional requirements anymore. For example, in 80% of the Dutch school buildings, the climate system is outdated (Rijksgebouwmeesters, 2009), and in many of these buildings, the building typology limits the possible renewal. Another reason can be that the layout of the school building cannot adapt to the current educational vision. These are reasons to replace the existing school building. In these cases, reuse of the load-bearing construction can take place on a component level.

A survey was conducted within the HEVO organisation to determine whether the individual load-bearing components can be potentially reusable by identifying which aspects are often the deciding factors for replacement. The survey shows in Figure 24 that the load-bearing construction is often not the reason for replacement. *Concluded, existing individual load-bearing components of school buildings are available for possible reuse and therefore provide an opportunity to reduce waste generation and use of natural resources.*



* Sort choices by order of importance. (Answers 21x)

Figure 24: Survey: weighing aspects in feasibility studies between renovation and replacement.

B.1 Dutch educational housing

This research focuses on Dutch school buildings. Information and data about school buildings are public and accessible through municipalities and city archives. In 2016 the Algemene Rekenkamer released an open data set on general information about school buildings in the Netherlands, 'Schoolgebouwen PO en VO' (Algemene Rekenkamer, 2016). The dataset provides names, addresses and building years of school buildings.

In the Netherlands, building documents can be requested by the address and building year from city archives and municipalities. Building documents are submitted with a building or renovation permit application and contain specification drawings, technical drawings, structural calculations, and written documents (Rijksoverheid, n.d.-a). Information about the building or renovation permit application is available for every building in the Netherlands built since 1901. A building and permit application has been mandatory in the Netherlands since the first housing law in 1901 for every renovation or construction (Het Kabinet Pierson, 1902). The purpose of the housing law was to prevent unhealthy, poor buildings, especially for houses (Verham, 2011). This permit application had to comply with the building regulations. Building regulations include the National 'Bouwbesluit' and the building regulation of the relevant municipality (Rijksoverheid, n.d.-a). How much information about the building is available depends on the municipality because municipalities could draw up the regulations for permit applications themselves. Building documents provide factual information about the configuration, format, dimensions, and materials of buildings (Verham, 2011). Also, building documents often contain structural calculations.

Building documentation makes it easier to determine the characteristics of components, such as properties, assembling, and connections to other components. So, building documents give inside into the structural typologies of buildings and the layer logic of the building. Understanding the layer logic is necessary to optimise the lifespan of individual load-bearing components. Therefore, the characteristics of components affect reuse potential. Although much open data is available, there is no existing data set for the Netherlands on structural typologies of school buildings, construction material, dimensions, or the configuration of building components in school buildings. Knowledge about structural typologies is necessary to know what is available to reuse.

B.2 Educational type MAVO, HAVO, VWO

The school buildings in the Netherlands are all designed and built according to the linear building economy. In a linear building economy, virtually all load-bearing components are designed and made to fulfil their purpose in their original building. Although, many load-bearing components are of similar dimensions in terms of length and shape (B. Addis, 2006). Similar dimensions of load-bearing components increase the likelihood of exchanging components between buildings (Hollander, 2021). Extending the lifespan of individual load-bearing components by reusing these components is possible if components are interchangeable.

A compatible and standard school design increases the likelihood that a school building is composed of interchangeable load-bearing components. Employees of HEVO explained that a more traditional form of classroom education leads to more compatible and standard designs for SE school buildings (Y. Ketelaars & J. Vroemen, personal communication, March 9, 2021). Innovative educational concepts use the space of the classroom and building differently from traditional education (Carlebur, 2015). The educational types MAVO, HAVO, and VWO, have a traditional form of classroom education and fewer innovative educational concepts (Y. Ketelaars

& J. Vroemen, personal communication, March 9, 2021). Therefore, this research is limited to Secondary Educational (SE) School Buildings, MAVO, HAVO, VWO.

B.3 Existing SE School buildings in the Netherlands

In secondary education for the types MAVO, HAVO, and VWO, there are 804 school buildings in the Netherlands. The open dataset 'Schoolgebouwen PO en VO' has information of 662 of the 804 SE schools (Algemene Rekenkamer, 2016). This appendix classifies the total stock of existing SE school buildings of MAVO, HAVO, and VWO in the Netherlands into building periods. See Figure 25 and Table 32. The division into building periods indicates the rough quality state of the buildings. The report 'Sectorale routekaart voor verduurzaming van schoolgebouwen' (PO-raad and VO-Raad, 2016) lists four building periods: pre-war, reconstruction, Londo, and building decree period. This research uses the same four building periods.

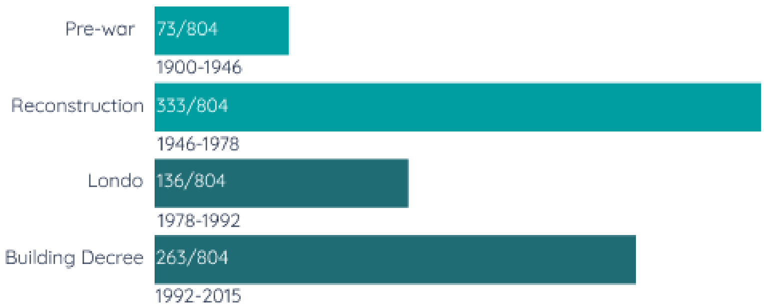


Figure 25: Available SE school buildings in the Netherlands of the type MAVO, HAVO, VWO

Table 32: Classification of SE school buildings

Building period		Characteristics
Pre-war	1900-1946	• Monumental • Often shell renovation[9] •
Reconstruction	1946-1978	• Not very good quality[10] • Model Building Regulation 1965[11]
Londo	1978 – 1992	• Sober and efficient • Durable in maintenance
Building decree	1992-2015	• According to standards with relative good exploitation • Durable in maintenance

[9] (PO-raad and VO-Raad, 2016)
[10] During the reconstruction period, materials were often used that were intended to last 25 years (PO-raad and VO-Raad, 2016).
[11] (Vereninging van Nederlandse Gemeente, 1965)

APPENDIX C

EXISTING LOAD-BEARING COMPONENTS

There is a variation in structural typologies and construction techniques in Dutch SE school buildings. However, there is no documentation of these variants. Structural typologies arise from the shape, dimensions, construction material, and configuration of building components in the building. The program of functional requirements and the architect's vision of the design create the building's spatial structure and shape, and the load-bearing construction is in line with this. The structural engineer designs the load-bearing construction to meet the strength and stiffness requirements on the component and detail level. Detail level refers to the connections between the components. The cross-sectional shape, length and dimensions of the component, the acting loads and the connection method determine the strength and stiffness of the load-bearing component. The shape of the load-bearing construction also depends mainly on the construction material properties.

The construction material and main load-bearing components in existing SE school buildings provide insight into possible reclaim and reuse. In addition, also the building year is essential, the age of the school building.

Appendix B ends by classifying the total stock of existing SE school buildings of MAVO, HAVO, VWO in the Netherlands into building periods. Subsequently, this appendix identifies the main load-bearing components and their construction material of approximately one hundred SE school buildings. The main load-bearing components of interest are foundation, walls, beams, columns, floors, and roofs. Each load-bearing component, construction material, and building period have opportunities and barriers for reuse. This appendix concludes with a selection of potentially reusable load-bearing components and construction materials from existing SE school buildings. This selection of materials and components forms the scope for this research.

C.1 Type of construction materials in main load-bearing components of SE school buildings

This section provides background information on the construction materials, concrete, masonry, steel, and timber, their relevant characteristics and gives insight into the opportunities and barriers for reclaim and reuse in the context of this thesis. Also, this section includes statistics on the different construction materials per structural function and building period.

C.1.1 MASONRY

Masonry construction usually consists of rectangular bricks stacked to form a wall or column. Mortar fills the joints between the bricks. The mortar connects adjacent bricks and functions as filler material that distributes loads evenly over the entire surface of the brick. Since Roman times, masonry has been a common building material in various types of buildings. Masonry construction performs several functions simultaneously: provide structure, division of space, thermal and acoustic insulation, and protection against fire and weather influences (Hendry et al., 2003). Centuries of use of masonry confirm the durability and adaptability to new fashions and needs, as well as the ease of preservation and repair (B. Addis, 2006). The bond between the brick and mortar is solid, at times more robust than the brick itself. The strong bond creates a high probability of cracking in high-strength masonry that runs through the bricks rather than being confined to the mortar. Cracks in the bricks affect the strength of the masonry and its potential for reuse.

Due to many buildings with masonry in the Netherlands, there is a constant supply of used masonry from demolished or dismantled buildings (Haslinghuis, 2005). Masonry is not reused in its entirety but as individual bricks. Therefore, the ability to reuse masonry is highly dependent on the ease of separating and cleaning the individual bricks. The strong bond between bricks and mortar makes it relatively difficult to separate individual bricks. Therefore, Separating and cleaning bricks is highly dependent on the bond and thus on the type of mortar used (B. Addis, 2006). Soft or lime mortars are easy to remove between the individual bricks (Webster, 2005). After 1920, Portland cement or plasters are common mortars. Separating Portland cement between individual bricks is labour-intensive because no cost-effective technology is available to remove the strong bond between the mortar and bricks (Ali et al., 2012; Webster, 2005).

The strength of masonry depends on both the individual bricks and the mortar. Accordingly, the individual bricks must have the same material composition, age, shape, and dimensions. However, by reusing bricks individually, it is aesthetically significant to create unity between the bricks. Using the same colour and dimensions create unity. Variation in dimensions of just a few millimetres in height or length will require a difference in thickness of the mortar joints. (B. Addis, 2006)

C.1.2 TIMBER

Over the centuries, the use of timber has developed as a construction material. Timber components have different structural purposes, such as foundations, beams, columns, floors, and roofs. The connection is primarily metal, including screws, bolts, staples, straps, and nail plates (B. Addis, 2006).

Thousands of tree species provide timber, each with different growth rates, structural properties, and degrees of durability (Structural Timber Association, 2014). In botanical terms, the categorisation of timber is 'softwood' or 'hardwood'. Coniferous trees provide softwood, and deciduous trees provide hardwood. Softwood and hardwood do not necessarily refer to the density or hardness of the wood (Structural Timber Association, 2014). In constructions use softwoods because it is readily available, easy to process, and relatively inexpensive (Ramage et al., 2017). In addition, the high growth rate ensures a continuous supply from regenerated forest areas (Structural Timber Association, 2014).

The durability of timber constructions is strongly dependent on the construction method, the degree of maintenance, and ventilation. Timber is prone to deterioration from wet and dry rot and the infestation of various organisms. Treatments prevent timber structures from rot or organism infestations. Some treatments use hazardous substances, making reusing costly or impossible (B. Addis, 2006). Therefore, the physical and chemical properties of the timber determine the degree of reusability, and an investigation gives the exact properties. The strength class is the most critical consideration when reusing timber because it is affected by natural strength defects, such as knots and grain slope. The assessment of timber considers, among other things, timber type, strength class, age, moisture content, dimensions, surface finish, and treatments, and durability.

Timber has high-value reuse. There are good opportunities to reuse timber due to the wide use and often high quality of the components (B. Addis, 2006; Baiden et al., 2005). The possible high-quality reuse is due to the size of the timber load-bearing components. Sawing, planing, or sanding the component removes discolouration or surface damage and provides a large enough component for reuse (B. Addis, 2006). However, no damage may occur during disassembling the components (Baiden et al., 2005; Webster, 2005). The degree of damage often relates to the connection type between the components. There are three types of connections, connections with additional elements, hard chemical, and dry connections. A hard chemically bonded connection, such as glue, is more difficult to release without damaging the adjacent components than a dry connection. Examples of dry connections are click connections or pin-hole connections. Releasing an adhesive connection requires special equipment and is labour-intensive (Webster, 2005). The most common connection in timber is a connection with additional elements, often with steel elements. These connections are relatively easy to disassemble and reassemble after carefully removing the metal elements (B. Addis, 2006). In addition, dry connections and connections with additional elements are less labour-intensive to disassemble and cause minor damage to the components than hard chemical connections (Baiden et al., 2005; Webster, 2005). The relatively easy disassembly of timber components offers the great advantage of reusing timber constructions.

Knowledge of the type of timber, moisture content, and stiffness allows a more reliable strength estimation (B. Addis, 2006). However, to ensure suitability, the reuse of timber requires much more testing and preparation than new timber, leading to high costs.

C.1.3 STEEL

Steel is an alloy of iron and carbon, and steel contains less than 2% carbon and 1% manganese and small amounts of other chemical elements (World steel association, sd). Steel use is extensive from the end of the 19th century to the present day because the construction material of steel is versatile, durable and has a remarkably high tensile strength, making steel widely applicable (B. Addis, 2006). The load-bearing construction components come in various shapes, such as beams, columns, slabs, and decks (Iacovidou & Purnell, 2016). In addition, the components have a variety of cross-sections, with a distinction in shaping cross-sections, hot rolled sections, welded composed sections, and cold-formed sections. The shape of the steel section determines the structural properties.

At the end of the 19th-century, agencies draw up standards and codes that describe steel's predictable behaviour, specific chemical composition, shape, cross-section, and mechanical properties (Srikanth & Asmatulu, 2013). The age and location determine the structural condition and the reuse potential of steel. The age and location lead to the norms and codes operative at the time of designing the construction. The Steel Construction Institute assumes that the strength of the reused steel is the same as new steel from that age and location (Steel Construction Institute, 2019b). In other words, the standards and codes from that age and location are the basis for determining the strength of reused steel. (B. Addis, 2006).

Construction steel has a long service life, but under the long-term influence of operational factors, it can deteriorate due to fatigue, rust, and corrosion damage (B. Addis, 2006). Nevertheless, plastic deformation due to earthquakes, fire, or scouring can also lead to deterioration (Cooper & Allwood, 2012). Deterioration can lead to a decrease in mechanical properties, embrittlement of steel, and ultimately failure. Operational factors that influence steel quality are pressure, temperature, cyclic loading, radiation, and the environment (Srikanth & Asmatulu, 2013). Still, repairing, strengthening and replacing by cutting or welding is easy (B. Addis, 2006).

The known chemical composition and mechanical properties, the standard cross-sections, and value preservation give a high potential for reuse (Gorgolewski et al., 2006). The most significant drawback to steel construction is the connections. There are two types of steel connections, connections with additional elements, such as bolts and nuts, and hard chemical connections, such as welds (Webster, 2005). In the case of bolted connections, the disassembly process is simple, but remanufacturing of the component is complicated and time-intensive because the reuse of bolt holes is not always possible. With welded connections, the complexity lies in the disassembly of the components, which often causes damage to the components. Dismantling welded joints is labour-intensive and expensive (B. Addis, 2006). Extensive damage to elements means that reuse is no longer possible. Bolt connections do minor damage to steel components during disassembly. In addition, rework of the steel is unnecessary. However, bolt holes are not always reusable (Webster, 2005).

Reinforcement steel in concrete is challenging to reclaim because it is often impossible to separate the steel bars from the concrete. Reuse is only possible by reusing the entire prefab concrete component (Cooper & Allwood, 2012).

C.1.4 REINFORCED CONCRETE

Reinforced concrete consists of concrete and steel. The concrete is a mixture of Portland cement, coarse aggregate, air, and water (Concrete supply co., sd). The tensile strength is considerably less than the compressive strength; reinforcing steel in concrete increases this tensile strength. Concrete is a brittle material, and with high stresses, crack development can lead to failure. The steel restricts the crack width, ensures a more ductile behaviour, and prevents abrupt failure. However, the steel and concrete must work together to ensure this ductile behaviour. The bond strength between the concrete and steel defines the reinforced concrete strength. Good collaboration in this composite material provides a safe distribution of tensile, compression, shear, and bending moment loads (B. Addis, 2006).

Due to its versatility, durability, and low price, concrete is the most widely used construction material in the world today (Srikanth & Asmatulu, 2013). The versatility of reinforced concrete components comes from the separate fabrication of the components in the factory and on-site assembly or entire fabrication on-site. When casting concrete on-site, fabrication on-site creates a monolithic whole of components without air gaps—known as cast-in-situ concrete. Individual factory-made prefab concrete components can be connected on-site through mechanical interlocking or additional steel elements. Cement mortar often fills the air gaps between these precast components, and provides extra stability and protects the steel against corrosion and fire.

Concrete itself is very durable and of good quality when compressed. Take, for example, the arches in churches from the Middle Ages. Unfortunately, reinforced concrete is less durable due to the risk of water and air damage to the reinforcement steel. However, the reinforcing steel damages not quickly if the quality of the concrete is good and the completion of the assembly is so that water and air slowly infiltrate the concrete. In this way, the reinforced concrete can last up to 100 years (B. Addis, 2006). The cracks in the concrete must be limited to a maximum required crack width to keep the steel qualitatively strong and prevent it from damage. Concrete has a very low coefficient of thermal expansion and is subject to shrinkage and creep, causing small cracks is in the concrete (B. Addis, 2006). These small cracks can cause damage to reinforced concrete. The following processes cause damage, microbial or chemical reactions, freeze and thaw, and corrosion of reinforced steel. Thermal expansion of steel can also occur, accelerating the crack width development.

Furthermore, explosion to extreme heat can cause concrete to fail. Although concrete is fire resistant, the pore pressure and sustained thermal temperature can be fatal (Srikanth & Asmatulu, 2013). Damage to the steel reinforcement is ultimately fatal to concrete structures because the steel carries the internal tensile stresses.

The reuse potential of concrete depends on several factors due to the wide variety of cast-in-situ and prefab concrete applications. The composition and strength of the concrete can vary greatly. In addition, substances can contaminate the concrete, which affects the concrete's properties (Iacovidou & Purnell, 2016). In-situ concrete is often project-specific and challenging to analyse if information about the reinforcement is unavailable (Webster, 2005). The monolithic whole of in-situ concrete causes an unclear distinction between components, making it complicated to disassemble the connections without damage. The reuse of prefab parts is much easier due to the standard sizes and standard amount of reinforcement (Iacovidou & Purnell, 2016). The reuse potential of prefab concrete components depends on the condition of the reinforced concrete and the connection method. A typical connection method is built-in steel plates in the concrete and bolted together. Cement mortar seals the connection between prefab components, and disconnecting the components is only possible after removing this mortar (B. Addis, 2006). Other connecting methods, if possible, are much more difficult to disassemble without severe damage. Reclamation of prefabricated columns, beams, and hollow-core slabs can be in such a way that only minor adjustments are necessary (Iacovidou & Purnell, 2016).

C.2 Construction material analysis

This section identifies the main load-bearing components and their construction material of 155 of the 804 Dutch SE school buildings[12] of the educational type MAVO, HAVO, VWO. The basis for this identification is an analysis of architectural and construction drawings, specification drawings and documents from city archives. The location of the analysed school buildings are in several large cities throughout the Netherlands, and see Figure 26 for these locations and names of these cities.[13] Moreover, these school buildings are from different building periods between 1900 and 2010. See Figure 27 for the number of analysed SE school buildings per building period. The analysis of many schools throughout the country gives a reasonable estimation of school buildings' components and construction materials.

[12] The school buildings were chosen from the open data set ‘Schoolgebouwen PO en VO’ (Algemene Rekenkamer, 2016) which provided information about the school’s name, address and building year. This information was needed to request more information about the school buildings from municipalities and city archives.

[13] The choice of cities concerned has to do with the closed city archives during the COVID-19 pandemic. These cities have city archives that have been digitized or are open to student research.

Figure 26: The location of large cities in the Netherlands with analysed SE school buildings.

This analysis aims to see the difference between the past and present construction material and load-bearing components and what becomes available. The analysis defines each load-bearing component's construction material and categorises the components per building period, construction material, and structural purpose. The analysed drawings and documents come from the year of construction. Therefore, this research does not include alterations and renovations.

The conclusion of the obtained data gives the typical construction materials for specific building periods. These typical construction materials are linked to frequently occurring load-bearing components. The data obtained forms the basis for estimating the available load-bearing parts and construction materials for possible reuse.

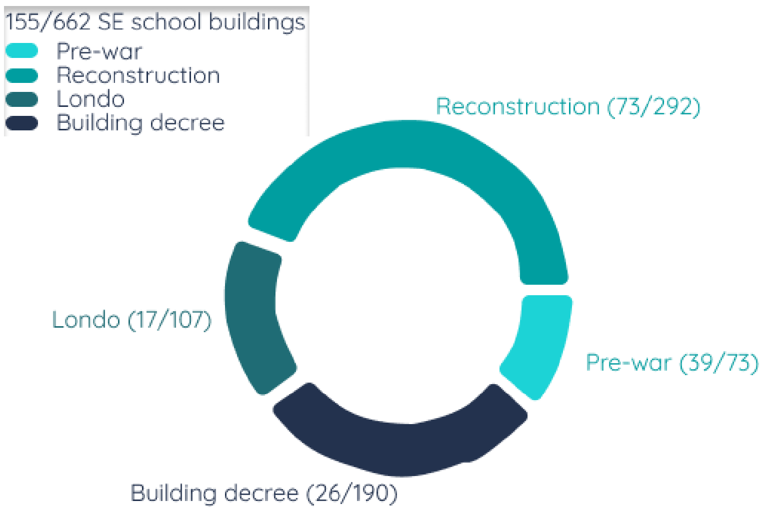


Figure 27: Number of analysed SE school buildings per building period.

C.2.1 CONSTRUCTION MATERIALS FOUNDATION

The analysed school buildings are in large cities of the Netherlands. Many of these large cities in the Netherlands are in the country's West. The West of the country has a clay-based subsoil, due to this subsoil, which has an insufficient bearing capacity, the foundation is often a pile foundation (Tol & Everts, 2010). A pile foundation can consist of concrete, steel, or timber. Occasionally in the south and southeast of the Netherlands, the foundation is not a pile foundation but a shallow foundation. A shallow foundation consists of concrete, brickwork, or steel. In the south and southeast of the Netherlands, the subsoil often consists of sand with a strong bearing capacity (Tol & Everts, 2010).

Steel only applies in a few building periods, although pile and shallow foundations can consist of steel—however, none of the analysed school buildings had a steel foundation. A pile foundation of steel is not the most popular pile foundation method due to the risk of corrosion, lots of vibrations, and high noise levels when driving (Tol & Everts, 2010). Nevertheless, steel pile foundations are still applicable, even though this is not visible in the data. The found steel foundations in the analysed school buildings were all shallow foundations found in the south and south-west of the country, and this corresponds with the literature. Moreover, all found shallow foundations consist of steel or brickwork. However, it is not easy to conclude from this acquired data for the shallow steel and brickwork foundations because most of the analysed school buildings are in the West of the country, and these school buildings are often on pile foundations.

Concluded from the data, using timber pile foundations decreased during the 20th century. Over the years, timber pile foundations have increasingly been replaced by concrete pile foundations because concrete is less affected by changing groundwater levels (Tol & Everts, 2010). Timber pile foundations sometimes have a variant with concrete head extension (Tol & Everts, 2010). However, due to the financial limitations of constructing a school building and the good quality-cost ratio of concrete, it is believed that the most reclaimable pile foundations of school buildings are concrete piles. Figure 28 also show a wide use of concrete in foundations.

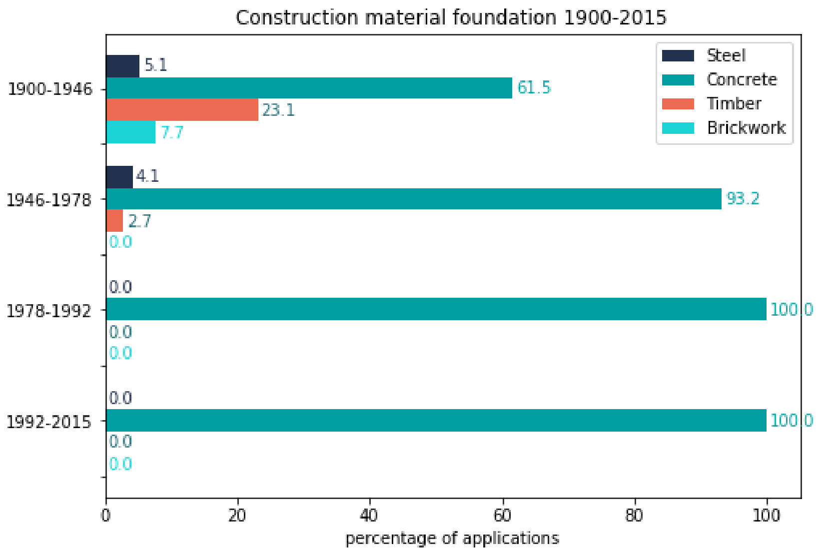


Figure 28: Construction material of the foundation in SE school buildings

C.2.2 CONSTRUCTION MATERIAL WALLS

The traditional building method in the Netherlands is with walls that function as the main vertical supports of the building. Shear forces are the primary loads on walls, but sometimes also tensile loads. According to Proveniers, the traditional building idea did not change until 1930, when experiments started with the open building structures in housing (Proveniers et al., 1989). This change is visible in the analysis, see Figure 29, where the percentage of application of walls in school buildings is visible. Figure 29 shows a decrease in the use of walls from 1946 onwards. Masonry, concrete, or timber are the construction materials for walls (Gerrits, 2008).

The brickwork was a standard construction material for load-bearing walls before the 1960s because masonry walls fulfil multiple functions simultaneously. A masonry wall can serve as sound insulation and load-bearing or separating function (Haslinghuis, 2005). High-strength masonry can crack in tension, and these cracks damage or even break the bricks, reducing the strength. In addition to brickwork, a small number of walls in school buildings are concrete walls, often prefabricated concrete walls. The analysed school buildings do not contain wooden walls, which is probably related to the sound permeability of wood.

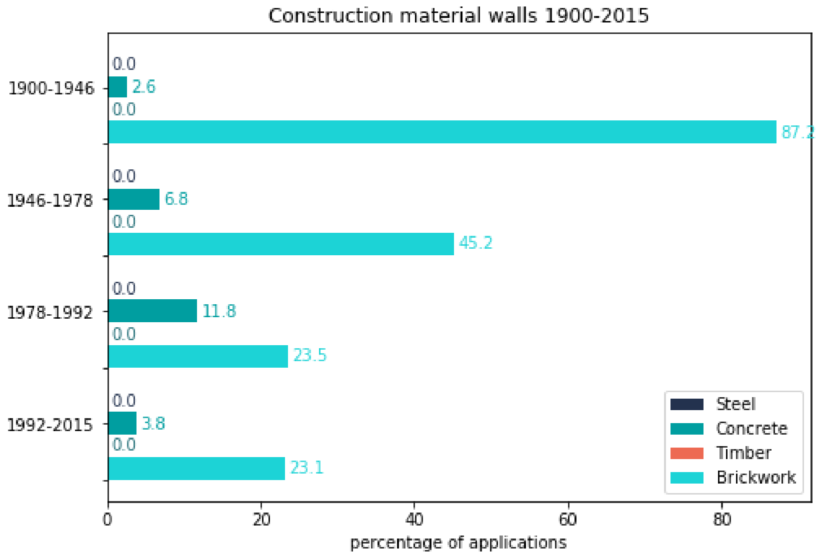


Figure 29: Construction material of walls in SE school buildings

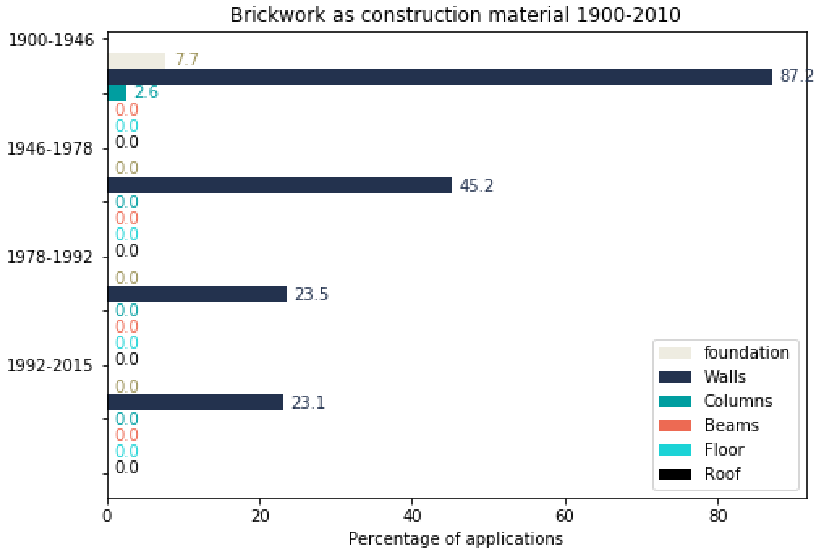


Figure 30: Brickwork as a construction material

C.2.3 CONSTRUCTION MATERIAL COLUMNS

From 1960 onwards, there was an increase in open building structures in buildings (Habraken, 1960). The use of columns is in line with the idea of open building structures, a frame structure. Figure 29 and Figure 31 show a relation between the decline in the use of load-bearing walls and the increase of column use from 1946 onwards. The increase of open building structures and thus columns may be due to emerging innovative educational typologies from the second half of the 20th century (Carlebur, 2015).

Brickwork, concrete, timber, and steel are the construction materials of columns. In the early 20th century, masonry was the construction material for walls and sometimes also for columns. However, the drawbacks of brickwork columns are the relatively large cross-section and the lack of absorbing bending moments (Gerrits, 2008). Due to the large dimensions and the lack of absorption of bending moments of masonry columns, concrete and steel were better materials for columns. The advantage of reinforced concrete columns is that the cross-section is much smaller than masonry columns for the same load-bearing capacity. In addition, reinforced concrete columns can also absorb bending moments (Gerrits, 2008). Steel rectangular columns have the same advantages as concrete columns. However, steel columns are rectangular but more often open profiles, such as I- and H-profiles. Each of these steel profiles has its advantages and disadvantages. In general, both closed and open profiles can absorb bending moments, but open profiles have a strong and a weak bending axis.

Figure 31 and Figure 32 show that the use of steel for columns and beams was low in the first two building periods. The use of steel stagnated in World War II; at that time, steel was only used for weapons (Proveniers et al., 1989). Instead of using steel as a construction material for beams and columns, concrete was an alternative.

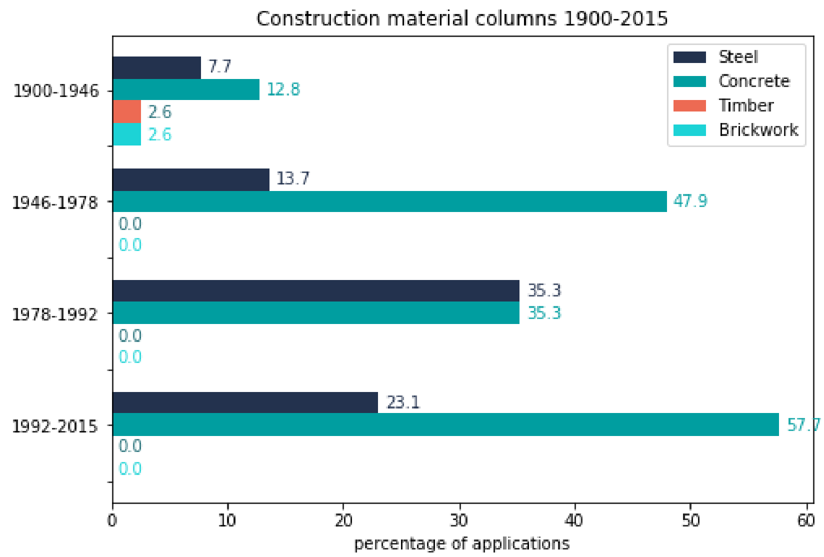


Figure 31: Construction material of columns in SE school buildings

C.2.4 CONSTRUCTION MATERIAL BEAMS

An open building structure can have columns, beams and floors. So, the use of beams relates to the use of columns. Furthermore, beams are sometimes used above masonry walls to ensure a proportional transfer of forces from the floor to the wall (Gerrits, 2008). The analysis of school buildings found beams in 27.6% of the cases with masonry walls. The construction material of beams is concrete, steel, and timber.

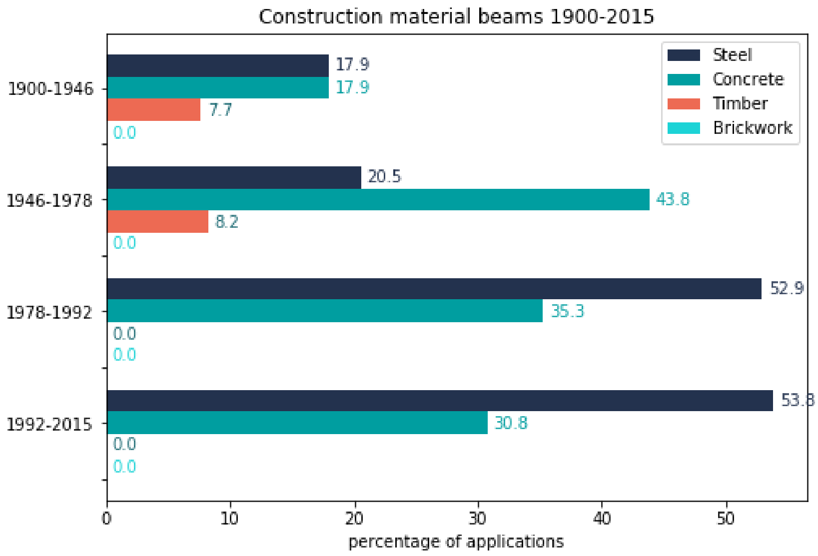


Figure 32: Construction material of beams in SE school buildings

C.2.5 CONSTRUCTION MATERIAL FLOORS

The type of construction material for floors is highly dependent on the building period. At the beginning of the 20th century, timber was the construction material for floor systems, especially the attic. Since 1978-1992, a decline of timber as a construction material for floors is visible in Figure 33 due to the construction safety and quality regulations. The Model Building Regulation of 1965 sets requirements for the load-bearing components concerning fire safety (Vereniging van Nederlandse Gemeente, 1965). Timber floors from before 1965 are of poor construction quality (SEV, 2015).

Steel has been making its appearance as a construction material for floors since 1960 (Ahmed & Tsavdaridis, 2019). A composite floor, called steel deck composite floors, is a steel plate with concrete on top, with the steel acting as reinforcement (Pasterkamp, 2016). These composite floors have made their appearance since 1978 in school buildings, and these floors replace the non-fire-resistant timber floors, see Figure 33. The analysis found concrete floors from the beginning of the 20th century to the present day. Most SE school buildings in the Netherlands use concrete floors, fully concrete floors, but sometimes also combined with timber or steel. Think of hollow-core slab floors, timber floors with concrete covering layer, or a steel deck composite floor. 1% of the 155 analysed floors are concrete-timber floors, and 8% steel-concrete floors.

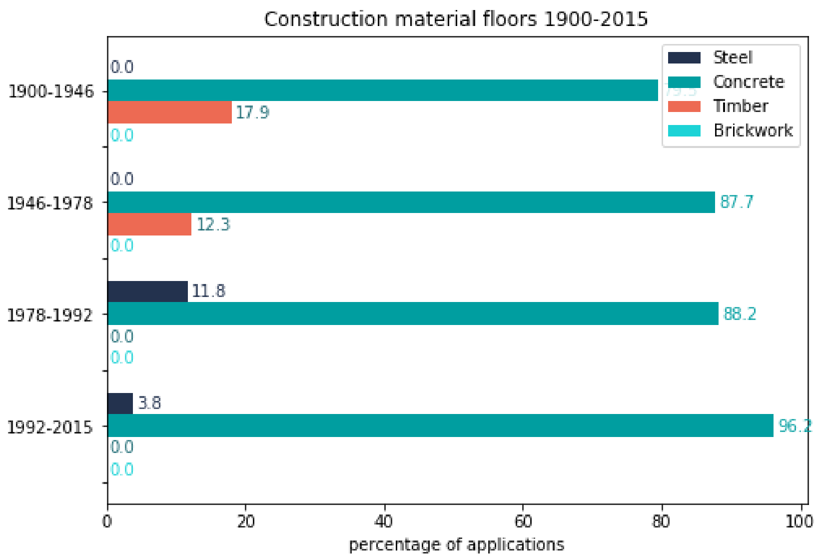


Figure 33: Construction material of floors in SE school buildings

C.2.6 CONSTRUCTION MATERIAL ROOFS

The construction materials of roofs are concrete, steel, and timber. School buildings from before 1940 with load-bearing masonry walls often have a timber roof construction. A timber roof consists of a timber frame construction, often in a point shape, but also flat frames are possible. As for floors, the fire safety requirements have been stricter since 1965. Timber roofs from before 1965 are of poor construction quality (SEV, 2015). As visible in Figure 34, the use of timber has a reduction since 1978-1992.

On the other hand, there is an increase in the number of roofs made of steel and concrete. Steel roods also consist of frameworks for both pointed and flat roofs. Flat steel roofs have steel beams with a timber or concrete floor on top. After World War II, there was an increase in using concrete for roofs. After the reconstruction of cities and villages in the Netherlands, the use of concrete in roof constructions continued. Concrete roofs are mainly flat roofs.

A side note from the perspective of reusability, flat roofs are floors with a lower capacity, a lighter version of floors. So, floor components can apply as roof components. The roof and floor components are exchangeable if considering the capacity of the components. Keep in mind that this means that roofs have less potential for reuse than floor components.

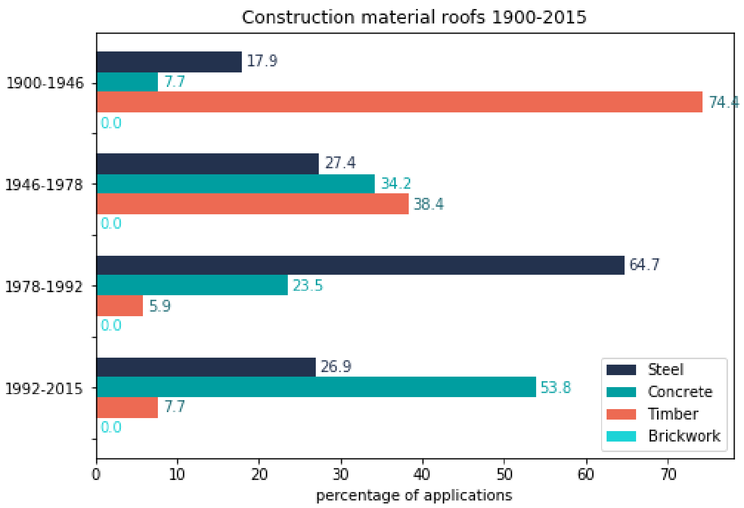


Figure 34: Construction material of roofs in SE school buildings

C.2.7 CONSTRUCTION MATERIALS CONCRETE, STEEL, AND TIMBER

World war | | brought complications for the building sector. After World War ll, the reconstruction of the Netherlands took place because of the bombings, particularly a large part of the city of Rotterdam. There was a high demand for homes and buildings. The idea of the reconstruction was building quickly and cheaply, which required more efficient construction—developing new ways of building, such as prefab concrete to build more efficiently (Bennenk & van der Wurf, 2001). After World war ll, prefab concrete was a standard construction material; the analysis shows this in Figure 35. Especially for the city of Rotterdam. An employee of the Rotterdam City Archives explained that system schools, MUWI-schools, were used in Rotterdam around 1946-1960. MUWI-schools are the same school buildings built simultaneously at several locations. (T. de Bruin, personal communication, May 12, 2021) These MUWI schools were built entirely with prefab concrete load-bearing components.

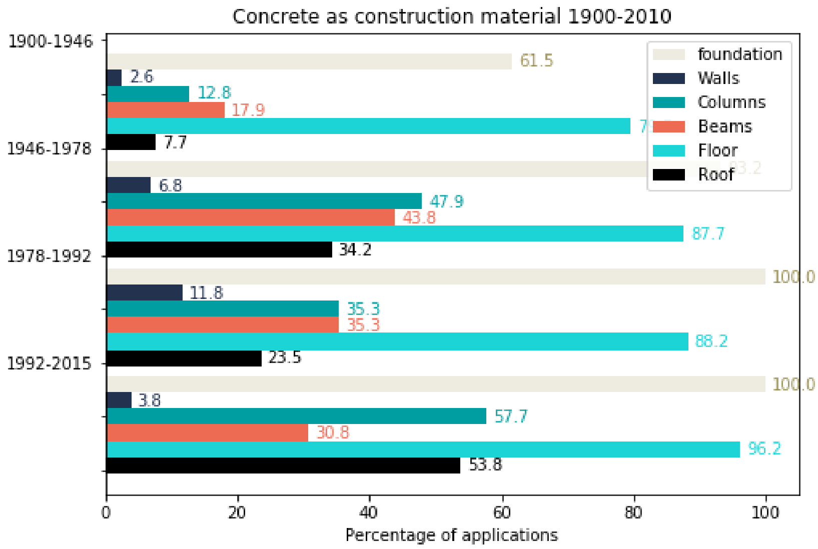


Figure 35: Concrete as construction material

Remarkably, timber has not been used as a construction material in school buildings since 1980, except a few times. However, it is not the case that timber was no longer a construction material

in these years. According to an employee of the Rotterdam City Archives, the maintenance of school buildings was transferred from the state to the school organisations themselves around this time, in the 1980s and 1990s (T. de Bruin, personal communication, May 12, 2021).
The use of concrete over timber may be due to the financial benefits of concrete. Concrete is, besides being cheap to purchase and also cheap to maintain (Srikanth & Asmatulu, 2013). Concrete's excellent quality and inexpensiveness make it a better option than timber for school buildings.

Moreover, concrete meets current sound insulation and fire resistance requirements more quickly than timber. The requirements for the impact sound insulation of floors have been stricter since 1965 (Beentjes et al., 2003). In combination with financial reasons, the sound insulation requirements are probably the reason for the more frequent use of concrete over timber. Although, timber is still sometimes used for roof constructions after 1978.

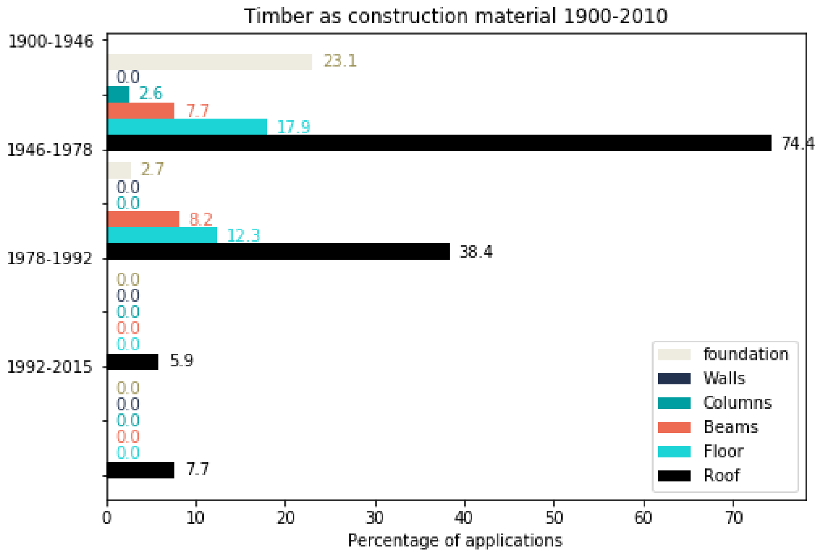


Figure 36: Timber as construction material

By contrast to timber, in the second half of the 20th century, steel was used more and more for columns, beams, and roofs. The first use of steel was at the beginning of the 20th century and was more common. Although, many uncertainties for steel structure cause over-dimension. Innovations and developments lowered the risks and narrowed the safety margins (Proveniers et al., 1989). Narrowing the safety margins did not mean that the requirements for strength, stiffness, stability, corrosion resistance, fire safety, or acoustics changed. Requirements are independent and standalone. Narrowing safety margins reduces the price for steel constructions, making the use of steel more accessible (Proveniers et al., 1989). In combination with the aforementioned open building concept, this leads to more use of steel as a construction material for school buildings, as visible in Figure 37.

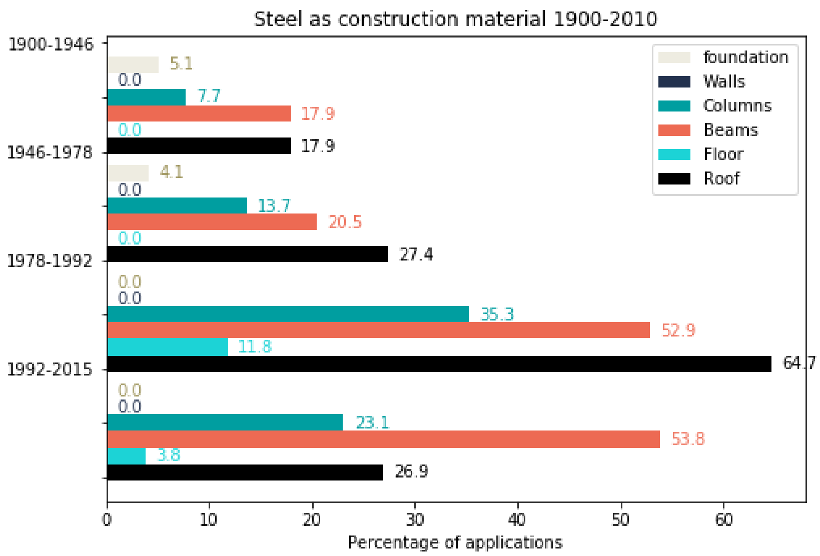


Figure 37: Steel as construction material

C.3 Conclusion load-bearing components and construction materials

The history of education shows that changes and developments are constantly taking place in educational concepts, all of which must fit into the educational housing (Carlebur, 2015). According to employees of HEVO, "New school building must be easily adaptable to accommodate different educational concepts" (Y. Ketelaars & J. Vroemen, personal communication, March 9, 2021). Therefore, the building must provide a high adaptive capacity. An open building structure is a solution for adaptability (Habraken, 1960; Proveniers et al., 1989). Building in frame structures is one of the primary conditions for developing the open building concept (Proveniers et al., 1989). In frame structures, columns, floors, and sometimes beams form the load-bearing construction. Therefore, this research focuses on these load-bearing components. In contrast, walls are not load-bearing in an open building structure, which means load-bearing walls are not reusable. Therefore, reclaiming walls as a load-bearing component is not crucial for this research and is not considered in the further course of this research.

The data analysis shows that load-bearing walls occur in many analysed school buildings. Most walls are masonry walls, and the bricks are reused individually and not the entire masonry wall. Separating and cleaning individual bricks makes the reuse of masonry time-consuming and labour-intensive. In addition, there is a good chance that bricks damage or breaks during separation. Damaged or broken bricks are generally not preferred for reuse from an aesthetic and technical point of view. Therefore, the construction material masonry falls outside the scope of this research.

Although steel foundations such as screw piles have a good chance of reuse, foundations will also fall outside the scope of this research. A small number of available steel foundations and other types of foundations are unsuitable for reclaim and reuse (B. Addis, 2006). The subsurface in the Netherlands varies to a high degree. So, foundation designs are for specific soil composition of the building site (Tol & Everts, 2010). Therefore, it is unlikely that another location in the Netherlands has an identical soil composition. Furthermore, removing foundations is in most cases impossible without damage, and damage to the foundation makes reuse impracticable. In addition, the removal of soil components causes disturbances in the subsoil, leading to adverse effects on the performance of adjacent foundations (Tol & Everts, 2010). Moreover, removing piles from the subsoil is between 2-5 times more expensive than a new pile (B. Addis, 2006). In conclusion, this research is not further investigating the richly present in-situ concrete pile foundations.

Timber roofs are also richly present and are not further investigated in this research. 39% of the roofs are timber roofs, of which 37% date from before 1965. Since these timber roofs come from a relatively poor building period for timber, the technical quality of these load-bearing components cannot be guaranteed. Guaranteeing the technical quality of reclaimed load-bearing components is necessary to enable reuse. Other applications in timber (columns, beams, floors) are so limited that the chance of encountering timber load-bearing components is nill and not relevant for this research.

Of all analysed materials, steel has the best structural properties for reuse. The chemical composition, mechanical properties, standard cross-sections, and value retention offer great possibilities for reuse. In addition, steel is a standard construction material in the second half of the 20^{th} century. Steel has a variety of applications, columns, beams, floors, and roofs. Open building structures often use steel, which also offers room for adaptability in the future. The biggest challenges in reusing steel are the long-term impact of operational factors and the moment rigid connections (welded connections). Furthermore, steel often must be cleaned and processed due to the presence of a fire-resistant coating. As a result of the many advantages of reusing steel as a construction material and the excellent harvesting possibilities, this research further investigates the reuse potential of steel load-bearing components.

Since 1946, concrete has been a standard construction material in SE school buildings. Its prevalence is due to the versatility, durability, and low price of concrete. The durability of concrete depends on the reinforcing steel present in the concrete. Therefore, the success of reuse depends on the condition of the reinforced concrete and the connection method. In-situ poured concrete is unsuitable for reuse due to the connection method and uncertified minimal quality. Many SE school buildings are made of in-situ concrete, making them unsuitable for further investigation of reuse potential. Nevertheless, prefab concrete elements are suitable for reuse. The load-bearing components columns, beams, floors, and roofs in SE school buildings made of prefab concrete, will be of interest in this research.

In conclusion, load-bearing components from SE school buildings are steel, and prefab concrete columns, beams, floors, and roofs are generally suitable for reclaiming and reusing. However, not all prefab concrete and steel parts are easy to reclaim or reuse.

APPENDIX D

BREADTH OF APPLICATION: TYPE OF COMPONENT AND LENGTH OF COMPONENT

The reuse potential of load-bearing components depends on those used in existing SE school buildings. Which components are applied depends on the structural typology used in the existing SE school buildings of the educational type MAVO, HAVO, VWO. In addition, the reclaimed components must be applicable in new SE school buildings. The reuse of existing load-bearing components depends on the contemporary building typologies used to accommodate the current and future educational philosophy of secondary schools of the type MAVO, HAVO, VWO. Moreover, reuse of the existing components takes place in new school buildings; therefore, the components must meet the current technical, functional, and durability requirements. This appendix provides information about the used load-bearing components in existing SE school buildings and the possibility of reusing these components.

This appendix starts with an inventory of existing SE school buildings with frame construction[14]. The inventory shows the individual load-bearing components used for these school buildings. Each load-bearing component has opportunities and barriers for reclaiming and reusing; this research highlights the most critical aspects. In addition, the research indicates the wishes, aspirations and requirements for load-bearing components in new SE school buildings; in terms of dimensions. This appendix concludes with two breadth of application scores. The breadth of application score indicates the potential reuse of the load-bearing component.

D.1 Used structural typologies: frame structure

This appendix continues the analysis of Appendix C, where the interest lies in SE school buildings with frame structures. Appendix C analyses 155 SE school buildings; these buildings can have a frame structure of a wall structure. The analysis shows that 73 out of 155 SE school buildings have a frame structure, light pink in Figure 38. This division in structural typologies is visible in Figure 38. The inner ring of Figure 38 shows the number of SE school buildings with a frame- or wall-structure per different building periods. The outer ring distinguishes SE school buildings per building period. See Appendix B, Table 32 for more information about the building periods.

Of the 73 SE school buildings with frame structure, a portion consists of steel or prefab concrete, while the rest consists of the construction material in-situ concrete. Table 33 shows the different construction materials of the SE school buildings with frame structure per building period. Appendix C mentions that in-situ concrete is outside the scope of this research; interviews[15] with three structural engineers confirm this. All three structural engineers explain that in-situ concrete components have a design specific configuration; therefore, each component has a different capacity. In addition, in-situ concrete creates a monolithic whole, where reclaim is only possible by sawing components. Sawing exposes the reinforcement, which means losing end anchors such as hairpins and head reinforcement. Because of these various complications of reusing in-situ concrete, in-situ concrete is outside the scope of this research. The research continues with the 49 school buildings made of steel and prefab concrete.

[14] The inventory is based on the analysed SE school buildings described in Appendix C
[15] Appendix G includes the elaboration of the three interviews

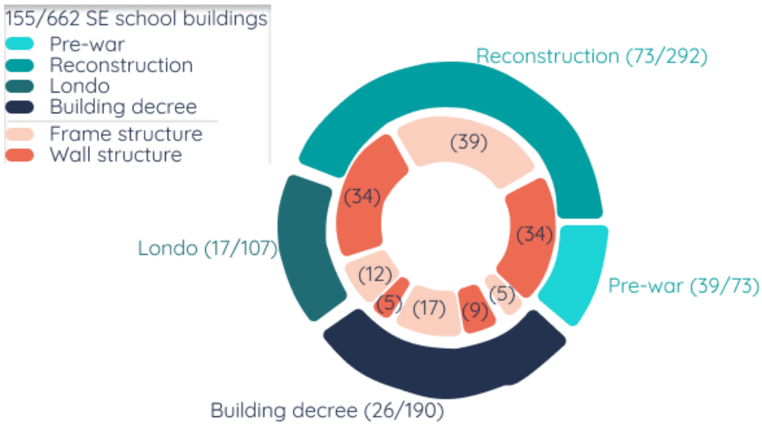


Figure 38: SE school buildings with the structural typology frame structure

Table 33: Construction material of columns

Building period		Steel	Prefab	In-situ
1900-1946	Pre-war	1	0	3
1946-1978	Reconstruction	8	14	18
1978 – 1992	Londo	7	4	1
1992-2015	Building decree	9	6	2
	Total number	25	24	24

Figure 39 shows the 49 suitable SE school buildings per building period to analyse the individual load-bearing components. The interpretation of Figure 39 is as follows, in the Londo building period, 11 of the 17 SE school buildings with frame structures are of interest.

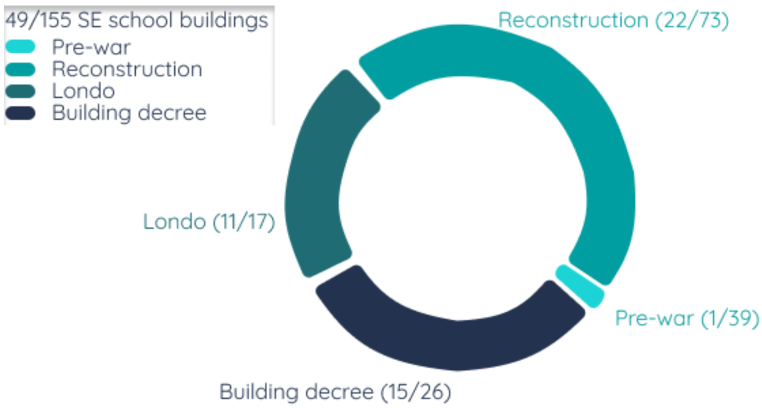


Figure 39: Number of SE school buildings for detailed analysis

D.2 Type of components

The basis for analysing the 49 SE school buildings is building documents and drawings. An inventory shows the different load-bearing components types used in existing SE school buildings. Each load-bearing component has opportunities and barriers for reclaiming and reusing; this section highlights the most critical.

D.2.1 TYPE OF 2D COMPONENTS

2D components in SE school buildings are floor and flat roof components, in total 49 + 49 = 98 2D components, see Figure 40. Appendix C explains that flat roofs are floor components with a lower structural capacity. So, roof and floor components are exchangeable if considering the capacity difference. In terms of breadth of application, floor components have a higher reuse potential than roof components.

The analysis of SE school buildings found nine types of 2D components. Figure 40 shows per 2D component type how often a type occurs in the analysis. The nine types of 2D components are:

- Prestressed slab
- 'Kwaaitaal' floor
- Reinforced plank
- Deck composite slab
- Prestressed hollow-core slab
- TT-slab slab
- Steel roof
- In-situ slab[16]
- Timber slab[16]

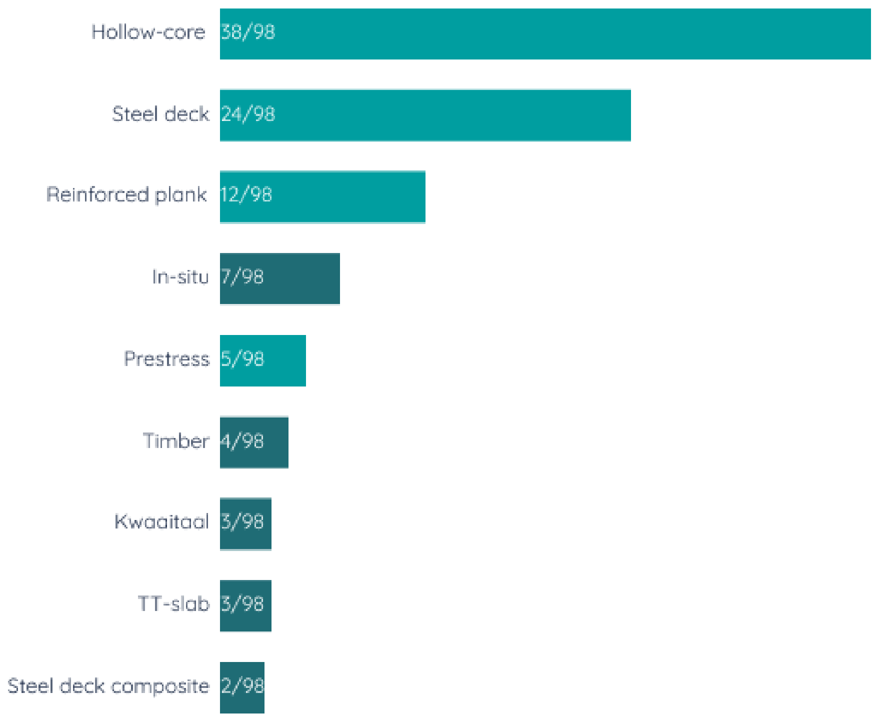


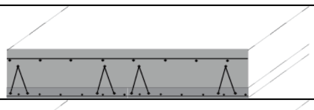
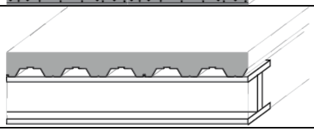
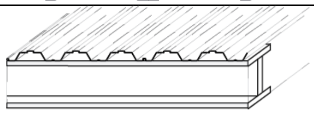
Figure 40: Types of 2D components (floors and roofs) in analysed SE school buildings

The combination of a literature study, three interviews with structural engineers and a survey with structural engineers and contractors compile indicators that influence the reusability of 2D components. The reusability of 2D components depends on the following indicators: the bearing capacity, spanning in 1 direction, standardisation, the new and old supporting method, integration of installations, and realisation of diaphragm action. In addition, the presence of a non-structural or structural layer also influences the reusability.

[16] In-situ concrete and timber are outside the scope of this research.

Appendix H provides the formula for the score. Structural engineers and contractors also score the 2D component's length, with 0 not reusable to 1.0 highly reusable. The combination of the two scores gives an objective the 2D component score. Accordingly, Appendix H adjusts the initial scores if necessary and provides more information about the conducted survey for the scores.

Table 34: 2D component types used in existing SE school buildings

Floor-type	Picture	Score
Kwaaitaal floor		0
Reinforced plank floor		0.2
Deck composite floor		0.4
Prestressed hollow-core slab		1.0
Prestressed solid slab		0.8
TT slab floor		0.6
Steel deck sheeting		1.0

'Kwaaitaal' floor

Kwaaitaal floors were prefab concrete system floors from 1965-1983, mainly used for the ground floor (Geertsma, 2019). Kwaaitaal floors have a concrete mixture with calcium chloride (Renirie, 2016). Calcium chloride is a concrete hardening accelerator and ensures that the concrete mixture can harden faster. In this way, the concrete floor components could be mass-produced. This concrete hardening accelerator causes a chemical reaction with the reinforcing steel after a particular time (Geertsma, 2019; Renirie, 2016). The chemical reaction creates a rusting process in which the rusting causes the reinforcement to expand. This expansion causes cracks in the concrete and affects the outer concrete layer. The outer concrete layer is known as the concrete cover. If the concrete cover cracks, more oxygen reaches the reinforcement, making the concrete rot process even faster (Geertsma, 2019; Renirie, 2016). Due to the high risk of concrete rot, these floor types are unsuitable for reuse.

Reinforced plank

The reinforced plank consists of a prefab concrete 'plank' and a structural layer of in-situ concrete (Pasterkamp, 2016). The rough prefab 'plank' with protruding reinforcement bars lays from beam to beam in a linear building economy. On top of the prefab plank, in-situ concrete is present to create a continuous floor type, a monolithic and robust 2D component (Interview 1,2, and 3). There is good adhesion between the prefab and in-situ concrete.

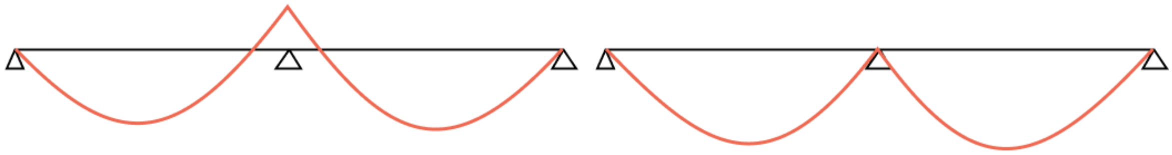


Figure 41: Moment line of, a) continuous floor, b) floor on two supports

The dismantling of a reinforced plank is the same as for an in-situ component. A reinforced plank is a continuous floor field, so there is an upper and lower moment in the floor; see Figure 41. The bottom and top reinforcement both take a part of the moment. The design for the new situation is not a continuous 2D component, and therefore, the bottom reinforcement must take the whole moment (Interview 1,2, and 3). The capacity of the 2D component is lower in the new situation. In addition, a reinforcement plank spans in two directions (Pasterkamp, 2016). The new situation does not use the reinforcement in the perpendicular direction (Interview 3). However, sawing makes the reinforcement visible and open to the air, harming the component's quality.

Another difficulty is the project-specific configuration of the reinforcement in a reinforcement plank (Interview 1,2, and 3). The prefab plank has continuous reinforcement over the entire length, but the reinforcement can vary in the in-situ concrete part (Interview 2 and 3). Each situation must consider the reinforcement configuration and the bearing capacity. With the knowledge that is now available, reuse of a reinforced plank is the same as in-situ concrete, complex and labour- and energy-intensive (Naber, 2012). For this reason, this research considers reinforced planks as not reusable.

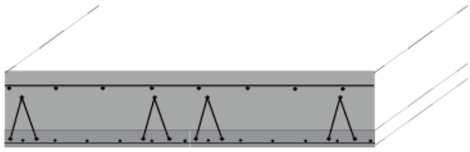


Figure 42: A reinforced plank slab

Steel composite deck

A steel composite deck is a 2D component type composed of a profiled steel plate and in-situ concrete. The steel composite deck has a limited span because the 2D component has no support during the construction phase; the maximum length is 6m (Pasterkamp, 2016). The 'dents' in the steel plate combined with the dowels provide a combined effect between concrete and steel and work together. In addition, the 'dents' allow the 2D component to be load-bearing in only one direction (Pasterkamp, 2016). In the perpendicular direction of the dents, the component's stiffness is very low; this gives difficulties when disassembling. An auxiliary construction is necessary to prevent deflection perpendicular to the span direction (Interview 3).

The interviews show that these 2D components are not often used in SE school buildings, at most in parts (Interview 1,2 and 3). This 2D component has a project-specific configuration – for example, to create curves. Likewise, to reinforced planks and in-situ concrete 2D components, the 2D component is often continuous and can contain additional reinforcement in the in-situ part. So as for the reinforced plank, with the available knowledge, reuse of a reinforcement plank is the same as in-situ concrete 2D components; it is complex and labour- and energy-intensive. This research considers, therefore, a steel composite deck as not reusable.

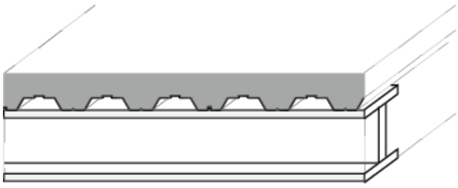


Figure 43: A deck composite slab

Steel sheeting

Reusing steel deck sheeting is relatively easy and requires only minor adjustments. Reclaiming decks from the existing SE school building is almost intact (Bouwen met Staal, n.d.). The components are light-weighted. However, the bearing capacity of steel deck sheeting is relatively low compared to prefab concrete slabs (Pasterkamp et al., 2014).

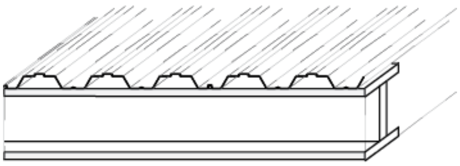


Figure 44: A steel deck sheeting

Prestressed hollow-core slab

A prestressed hollow-core slab is a standardised 2D component (Pasterkamp, 2016). A prestressed hollow-core slab also has the advantage that the components are factory-made. So, the dimensions, the location of the reinforcement and the amount of reinforcement are all known. In addition, a prefab component is light-weighted due to being executed by prestressing the plates. Furthermore, the quality of the component is certified. Lastly, the technical life of a prestressed hollow-core slab is also many times longer than the current lifespan of a school building in which it is used (Naber, 2012).

Figure 45: A prestressed hollow-core slabs

Prestressed solid slab

A prestressed solid slab is a robust, one-directional 2D component type. The reinforcement is provided by prestressing the reinforcement in the longitudinal direction (Pasterkamp, 2016). Prestressing ensures that the cross-sectional height is low. There are two ways of prestressing; see Table 35.

The prestressed solid slab is a prestressed hollow-core slab without hollow cores (Pasterkamp, 2016). The prestressed solid slab is a robust, one-directional 2D component type. The use of prestressed solid slabs has to do with the self-weight and the thickness. Due to the self-weight, a slim variant of 200mm thickness still meets the current sound insulation requirements. This 2D component is suitable for situations where the floor height must remain small (Interview 3).

Figure 46: A prestress solid slab

As for prestressed hollow-core slabs, the prestressing of the reinforcement in the longitudinal direction creates excellent capacity and a low cross-sectional height (Pasterkamp, 2016). There are two ways of prestressing; see Table 35.

Table 35: 2 ways of prestressing

Options	Description
With attachment	The prestress strands attach to the concrete. The component is factory prestressed over 50-130m before pouring concrete. (Pasterkamp, 2016). After concrete hardening, the component gets the correct size by cutting the component. After cutting, the stress in the components should rebuild over the anchorage length. There is some slip between the steel and concrete, which slightly reduces the overall component's capacity.
Without attachment	The prestress does not attach to the concrete along the entire component length but only attach to the end of the 2D component. Also known as VZA ('Voorgespannen Zonder Aanhechting') strands.

There is hardly any literature on the reuse of prestressed components because reuse of prestressed components is complex. Depending on the prestressing, a prestressed component is reusable. Reusing prestressing components without attachment is impossible—the steel reinforcement releases stress when sawing the prestressing fastener at the end of the component and the full prestress capacity is gone. The advantages of the prestressed component disappeared, and the capacity of the floor component became low.

Reuse of prestressed components with attachment is possible but still needs minor adjustments.

TT slab

A TT slab is a prefabricated plate with a thin top plate with thicker prestressed ribs on the sides (Pasterkamp, 2016). In addition, TT slabs can create large spans with relatively low self-weight. Due to the large span and low self-weight, the chance of reuse is high (BouwTotaal, 2020). However, the advantages of a TT slab contradict the requirements for SE school buildings (Interview 1,2 and 3). The 2D component system has too little mass to meet the sound insulation requirements, and extra sound insulation is necessary. In addition, the high ribs cause problems with integrating the crossing installation pipes. As a result, the pipes pass under the high prestressed ribs, resulting in a high storey height. The reuse of a TT slab in a new SE school building is low.

Figure 47: A TT slab

Non-structural layer and structural layer

The analysis of the SE school buildings shows that prestressed hollow-core slabs, prestressed solid slabs and TT-slabs have two application possibilities: with a non-structural layer or with structural layer, or both. The interviews confirm these applications (Interview 1, 2, and 3). The slabs are never completely straight. In addition, the individual 2D components creep and shrink differently, and the individual components may be loaded differently. An extra layer, a non-structural layer, of 5cm sand cement is placed over these types of floor components to prevent cracking in the finishing floor (W. van den Bosch, personal communication, 15 June 2021) (Interview 1). Another option is a structural layer. The choice of a structural layer depends on three functions it can fulfil, higher cross-section, overall coherence and diaphragm action. See Table 49 of Appendix E.

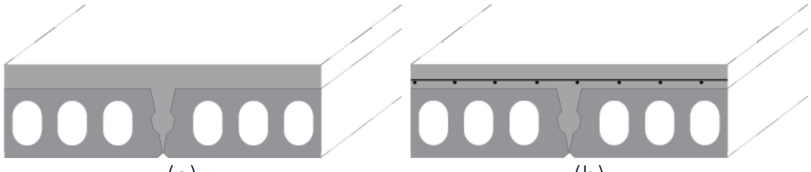


Figure 48: A prestressed hollow-core slab a) with a non-structural layer; b) with a structural layer

When disassembling, a non-structural or structural layer loses its function (Interview 1, 2, and 3). Therefore, reuse of a prestressed hollow-core slab, massive solid slab or TT-slab is without the non-structural or structural layer (Naber, 2012). Appendix E elaborates on the disassembly process of removing a non-structural or structural layer.

The structural engineers from the interviews declare that diaphragm action is desirable in the new situation (Interview 1,2, and 3). New innovative solutions are necessary to achieve diaphragm action without a structural layer.

D.2.2 TYPE OF STEEL PROFILE

The analysis of the SE school buildings found prefabricated concrete beams and columns and several types of steel profiles; see Figure 49. This research assumes that integrated concrete-steel columns are not reusable with current knowledge. Therefore, integrated concrete-steel columns are outside the scope of this research. The several types of steel profiles are:

- D-profile
- H-profile
- I-profile
- Hollow-profile
- UNP-profile

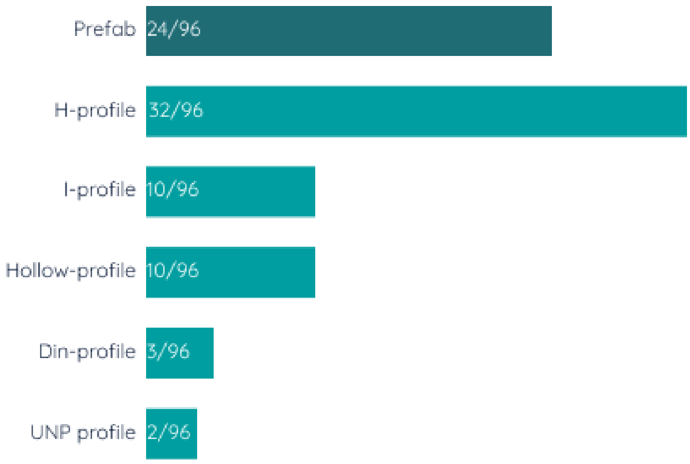


Figure 49: Steel profile types used in analysed SE school buildings

A combination of a literature study, three interviews with structural engineers and a survey with structural engineers and contractors, compile indicators that influence the reusability of beams and columns. The reusability of beams and columns both depends on the following indicators:

the bearing capacity, standardization, and applicability. The reuse of beams also depends on the beam height and lateral-torsional buckling. The reuse of columns also depends on buckling.

Appendix H provides the formula for the score. Structural engineers and contractors also give a score to the type of 1D component with a division in beams and columns, with 0 not reusable to 1.0 highly reusable. All engineers and contractors are working in the field of school buildings. In this way, the components are objectively measurable. The combination of the two scores gives an objective the 1D component score. Accordingly, Appendix H adjusts the initial scores if necessary and provides more information about the conducted survey for the scores.

Table 36: Reclaim and reusability score for type of steel profile

Steel profile type	Picture	Reusability	Comment
Din profile		0.8	Not standardised, old profile. (Deviation in dimensions and structural properties such as steel quality). Need for quality control. Reusable for both columns and beams.
H profile		0.9	Standardised dimensions and structural properties. Good structural properties, not sensitive for (lateral) buckling. Reusable for both columns and beams.
IPE profile		0.8	Standardised dimensions and structural properties. Significant height; sensitive for (lateral) buckling. Reusable for beams.
Hollow profile		0.8	Standardised dimensions and structural properties. Good structural properties, not sensitive for buckling. Reusable for columns.
UNP profile		0.7	Standardised dimensions and structural properties. Not symmetric, sensitive for lateral buckling. Reusable for edge beams.

Din profile

A din profile is a wide-flange German profile with parallel flanges used from 1920 to 1963 for both beams and columns (Bouwen met Staal, 2003). In 1963 the name of these German DIE-, DIN-, DIR- profiles changed to European designation HEA, HEB and HEM profiles (Bouwen met Staal, 2003). The current European dimensions of the profiles deviate from the old German profiles, especially the larger sizes (Deutsche Industrie Normung, 1920; Staal Federatie Nederland, 2021). In addition, the steel quality of DIN-profiles does not correspond with the current building decree steel quality. So, a din profile is not a standardised profile. The analysis of SE school buildings only found twice a din profile in the school building. Reusing this profile is possible if the structural properties are known and compared with the current required properties. Because a din profile has a relatively short body compared to the flanges, this profile is not sensitive to (lateral) buckling.

H-profile

As mentioned in the section of the DIN profile, the H profile is the successor of the DIN profile. The H-profile is a wide-flange profile, where the height is equal to the width of the flanges. An H profile has a relatively low height, is relatively heavy for steel (Vree de, 2021a), and has standardised structural properties and dimensions. As for a din profile, an H profile is not sensitive to (lateral) buckling and is applicable as column and beam.

IPE profile

An IPE profile is a standardised application for a beam component (Vree de, 2021b). The height of an IPE profile, the web, is greater than the relatively short flanges. An IPE profile is generally light-weighted but takes up much height in relation to the structural capacities. Compared to an H-profile, an IPE has a lower moment of inertia, which means less bending and buckling capacity; more sensitivity to lateral buckling than an H-profile (Pasterkamp et al., 2014). The straight flanges and a long body make it easy to fit the IPE profile into the construction. In addition, integrating a secondary beam between the flanges is easy (Vree de, 2021b).

Hollow profile

A hollow profile is a standardised closed type of profile. A hollow profile has no edges where dust or moisture can accumulate, less chance of corrosion (Vree de, 2021c). A hollow profile is an application for a column. A hollow profile has a high buckling capacity and is insensitive to buckling (Pasterkamp et al., 2014). A hollow profile is relatively heavy for a steel profile (Pasterkamp et al., 2014). In addition, concrete can reinforce a hollow profile; a reinforced hollow profile has a different reclaim and reusability potential than a hollow profile and is outside the scope of this research.

UNP profile

The UNP profile is an application for an edge beam or roof beam. A UNP profile is an asymmetric profile with angled flanges with an irregular thickness. Due to the difference in thickness of the flanges, fitting into the construction can sometimes be challenging. Very sensitive for lateral buckling.

D.3 wishes, aspirations, and requirements components [dimensions]

The government sets educational housing requirements that SE school buildings must meet. The ‘Bouwbesluit’ contains general rules for constructing and renovating a SE school building. In addition, schools must deal with the requirements of the ‘Gebruikersbesluit’ (Fire Safety) and the building regulations of the municipality. At the same time, a school building is a working environment; requirements from the ‘Arbeidsomstandighedenbesluit’ (‘Arbowet’) apply to workplaces, in particular requirements for the interior design of the school building. It concerns rules for the school grounds, safety, handling of hazardous substances, and the indoor climate (Rijksoverheid, n.d.-b).

Municipalities and school organisations are responsible for educational housing in secondary education (Rijksoverheid, n.d.-b). The design of a new SE school building is limited to the financial resources that a school organisation can use to construct or renovate the school building. The school organisation is the legal owner of the school building, and the municipality is the economic owner (Carlebur, 2015). Municipalities receive an annual contribution from the Government's Municipal Fund to finance educational housing. In the integrated housing program, the municipality divides the money among the schools in the municipality. A certain financial amount applies to each facility in the school building (Rijksoverheid, n.d.-b). The amount is determined based on standards set by the municipal council. The requirements that the government established for educational housing are the basis for the established standards. The Association of Dutch Municipalities, VNG, has included the requirements set by the government and minimum amounts for municipalities in a model, 'model verordening voorzieningen huisvesting onderwijs' (Vereniging Nederlandse Gemeenten, 2020). Many municipalities use this model as a guideline for the financial contribution of facilities in educational housing. The school organisation acts as a building manager to realise the school building with this financial contribution (Rijksoverheid, n.d.-b).

Apart from the financial limitations and governmental requirements, school organisations are free to furnish and design the building. The current legislation is freely interpretable, resulting in buildings that do not meet the objectives of 2050[17] (PO-raad and VO-Raad, 2016). These kinds of buildings lead to disinvestment for school organisations. The current governmental requirements fall short in the quality criteria for suitable future-oriented educational housing (PO-raad and VO-Raad, 2016). Ruimte-OK has developed a quality framework in collaboration with PO-raad, VO-raad, VNG and educational housing professionals (Ruimte-OK, 2018). The quality framework looks beyond the minimum building decree requirements and broader than the technical requirements concerning the indoor environment and sustainability. The quality framework offers specific, practically applicable quality criteria in the field of experience, use, and technology of an educational building (Ruimte-OK, 2018).

The reusability indicator breadth of application includes the dimensions resulting from the structural design requirements, wishes, and aspirations for a future-oriented SE school building. The dimensions of structural design form the basis for scoring the reuse potential of the lengths of the components.

D.3.1 REQUIREMENTS

The 'Bouwbesluit'

Table 37: Technical building regulations from the safety point of view

Requirement	Description
Width	The classrooms and corridors have a minimum width of 1.80 m. A (Bouwbesluit 2012 Article 4.3.2).
Height	The classrooms and common area have a minimum height of 2.60 m (Bouwbesluit Article 4.3.6).

[17] The climate objectives of 2050 are in line with realizing a high-quality SE school building with the highest possible degree of sustainability.

The building regulations of the municipality

The school building meets the minimum requirements for space and capacity use following "Educational Housing Regulation, Annex 3" (Vereniging Nationale Gemeenten, 2017). Annexe 3 discusses the criteria set for determining capacity and space requirements. The regulations only include minimum standards, and it is up to the school organisation and the municipality to determine the space and layout of the school building. In addition, the requirements from the Building Decree are leading.

The total space requirement of a SE school building is the total of two components: a student-related component and a fixed base. The fixed base for the main SE school building is 980 m^2 of gross floor space. A separate fixed base of 550 m2 of gross floor area applies to a sub-SE school building that, based on a ministerial order, is eligible for additional funding in connection with the need to spread out.

Educational level	Gross floor area per student
Junior classes	6.18
Senior classes	5.85

The 'Arbeidsomstandighedenbesluit' ('Arbowet')

As described in the Arbocatalogus VO, the minimum Arbo requirements relate to a safe and healthy working and learning climate (Arbocatalogus-VO, 2021). These requirements have no direct influence on the design of the load-bearing construction of a SE school building. The quality framework of Ruimte-OK includes the requirements that indirectly influence the load-bearing construction (Ruimte-OK, 2018). Section D.3.2 Wishes and aspirations discusses these requirements.

D.3.2 WISHES AND ASPIRATIONS

The quality framework of Ruimte-OK is a guideline for the wishes and aspirations that arise from the concept of the educational organisation on the school building. It is predominant that an educational building optimally serves the educational function. The educational building suits the educational concept of the school organisation, has a healthy indoor climate and matches the number of students. In addition, the building is in line with the vision of an appropriate, inclusive, approachable, and future-oriented education (PO-raad and VO-Raad, 2016).

Table 38: Definitions key points for SE school building

Term	Description
Appropriate	Appropriate education stands for tailor-made education. For every child, education is in line with his/her abilities and talents. Also, children with a disorder, serious illness, or handicap. These children can receive extra help at a regular school or a school for special education (Encyclo, n.d.)
Inclusive	Inclusive education welcomes all children with differences in background and experience, learning, and load-bearing needs. Every child with or without a disability goes to the same school in the neighbourhood. The inclusive school seeks and matches the needs and possibilities of each child and offers support where necessary (in1school, 2021).

Accessibility	Accessibility in education concerns how a child can complete the program with a diploma. Formal or informal obstacles may hinder the progression (in1school, 2021).

Developments in education continue continuously. Educational concepts come and go (Carlebur, 2015). New educational concepts impose new requirements on the quality of education and educational housing. In addition, the government regularly draw up new laws and regulations are for education. All these developments and changing requirements, wishes, and aspirations have consequences for educational housing (Carlebur, 2015). During the lifespan of a SE school building, the building must move along with developments and requirements. Educational housing must offer the adaptive capacity to move along with the developments and wishes. Adaptive capacity is achievable when choosing several building properties in such a way that the functionality of the building can be kept intact during its technical lifespan in a sustainable and economically profitable way (Garaedts & Remoy, 2013).

Carlebur has developed a helpful method for the most important aspects of adaptive capacity for educational housing (Carlebur, 2015). With this method, key points explain the wishes and aspirations for a future-oriented SE school building and thus adaptive capacity.

Quality framework

The wishes and aspirations for a future-oriented SE school building are quality criteria excluded in current legislation but do affect the quality of the educational housing throughout its lifespan. Ruimte-OK distinguishes three criteria areas of experience, use, and technology. The research only includes the quality criteria concerning the research scope, so construction and space aspects.

The design of the load-bearing construction is adaptable over time with a flexible layout. There is a separation in the Brand layers structure, installation, furniture, and stuff (Brand, 1994)—applying non-load-bearing inner walls. Above, spaces can easily merge or divide, both construction and installation technology. Constructing in this way gives the building a flexible layout; the building is adaptable to the current physical translation of the concept of learning and meeting. Both classroom and environment-oriented education can accommodate itself in the building. In addition, different teaching rooms for different teaching methods and group sizes are possible. The building layout adapts to the educational concept in the building and offers maximum space for the educational experience. Furthermore, the construction design is so that the building can respond to future growth or shrinkage.

With a view to sustainability, efforts must be necessary to reduce the use of raw materials and increase the reuse of materials. Constructing compact with a limited amount of outer walls limits the material to use. In addition, the pipe lengths are as short as possible. Dry, demountable building systems are preferable when striving for an excellent circular value of the building.

Table 39: Quality requirements, indicator experience. Adapted from (Ruimte-OK, 2018)

Quality requirement Indicator experience	Measurements
Interior	- Daylight plays a clear role in traffic- and residential areas: distance between floor and bottom (lowered) ceiling in teaching rooms is 3.20m. "Frisse scholen class A" (Rijksdienst Ondernemend Nederland, 2021)

Routing and walking lines	The building layout is well-arranged.

Table 40: Quality requirements, indicator use. Adapted from (Ruimte-OK, 2018)

Quality requirement **Indicator use**	Measurements
Learning – instruction room	Rooms for educational activities are geared to a minimum of 2.0 m^2 per student and 4.0 m^2 per teacher and can accommodate at least 30 students.

Table 41: Quality requirement, indicator technology. Adapted from (Ruimte-OK, 2018)

Quality requirement **Indicator technology**	Measurements
Flexibility	The building has free spans of $\geq$ 7.50 m due to its free divisibility The building is designed on a fixed grid, preferably on a multiple of 3.6 x 3.6 meters, to respond to future growth or shrinkage.
Multifunctionality	The design floor load is 5 kN /m^2 (Suitable for special events outside school hours)
	Fire safety compartments coincide with user compartments

Adaptive capacity

The wishes and aspirations for a future-oriented SE school building are for a school building that can respond to changes and developments. Carlebur defines this type of school building with class A and B adaptive capacity (Carlebur, 2015). Carlebur divided adaptive capacity into five themes: Construction, Installation, Shell, Space, and Location (Carlebur, 2015). For this research, only the theme construction and space are relevant.

The construction remains unchanged during the functional lifespan of a SE school building. The appropriate type of load-bearing construction is a frame structure; it offers the most freedom of movement for future changes. A well-arranged grid system increases the adaptability of the building, the same grid system throughout the building. The placing of the columns depends on this grid system. The furnishing is not part of the load-bearing construction (Brand, 1994; Habraken, 1960). Consider, for example, easily (re)movable non-load-bearing inner walls (Carlebur, 2015). The structure and internal layers of the building must be separate; the building layers must evolve unhindered (Brand, 1994).

Table 42: Adaptive capacity, indicator construction. Adapted from (Carlebur, 2015)

Adaptive capacity **Indicator Construction**	Measurements
Positioning load-bearing construction	<10% of the rearrangeable of the school building is hindered by load-bearing construction obstacles that are difficult or impossible to remove.
Horizontal extensibility	The horizontal extensibility of the building is limited, only on several sides.
Vertical extensibility	Vertical extensibility of the building. Application of a limited number of fontanel construction/zones in load-bearing

	construction floor components. A fontanel construction is a recess that is covered.
Horizontal repulsion	30-50% of the building is disposable without any hindrance to other building components or units
Building access	The wings with a central combined entrance and core divide the building
Available floor space	5000-10000m^2
Free floor height	>3.00m
Grid system	The exact grid sizes apply in >50% of the building

Table 43: Adaptive capacity, indicator space. Adapted from (Carlebur, 2015)

Adaptive capacity **Indicator Space**	Measurements
Division structure and internal layers	Between 50-90% of the building, there is a distinction between the Brand layer's structure and installations, furniture, and stuff.
(re)movable inner walls	Inner walls are easily removable without major, expensive construction interventions
Multifunctional building	The building is suitable for three different functions
Horizontal routing-corridors	All horizontal access routes link to the central core and the surrounding corridors.

D.4 Length of components

Section D.3 wishes, aspirations, and requirements components [dimensions] formulate the guidelines for the dimensions of future-oriented load-bearing constructions. The basis for the analysis of the 49 SE school buildings is the building documents and drawings. An inventory shows the different load-bearing component lengths used in existing SE school buildings, and in combination with the guidelines for dimensions, the research compiles the reusability scores. According to the structural engineers from the interviews, the longer the load-bearing component, the more applicable the component is in different designs, the higher the reusability. Different structural engineers and contractors have scored the length of the component from 0 not reusable to 1.0 highly reusable. All engineers and contractors are working in the field of school buildings. In this way, the length of the components is objectively measurable.

Note, lengths of the reusable load-bearing components depend on the detachability of the component. The way of disassembling the component from the building defines if the length reduces.

D.4.1 LENGTH OF 2D COMPONENTS

The length of a 2D component for a SE school building with a high adaptable capacity is 7.50 m (Ruimte-OK, 2018). In addition, the 'Bouwbesluit' requires a length of 1.80 m (Bouwbesluit Article 4.3.2). Further, it is desirable to use a fixed grid of 3.60 x 3.60 m or a multiple (Ruimte-OK, 2018). Dimensions in school buildings are multiples of 0.60 m, often starting at 1.20 or 1.80 m (Interview 1). The ideal flexibility length for school buildings and classrooms is not ideal for the constructions (Interview 1); 7.50 m is not a multiple of 3.60 m nor 0.60 m. In addition, preferred 2D components often have lengths larger than 7.50 m, 9.00 m or 12.60 m (Interview 2 and 3). The analysis and interviews with the structural engineers show that most 2D components have a length of 7.20 m (Interview 1 and 3).

This research subdivides the lengths of the 2D components into five reuse categories, see Table 44. The categories are multiples of the fixed grid size of 1.80, up to the maximum transport length of 15.65 m.

Appendix H provides the formula for the score. The score for the 2D component's length combines the multiplication of 0.60 m and the preference for a long length in a score. Structural engineers and contractors also score the 2D component's length. The combination of the two scores gives the reliability of the 2D component score. Accordingly, Appendix H adjusts the initial scores if necessary and provides more information about the conducted survey for the scores.

Table 44: Reclaim and reusability score for 2D component lengths

Reuse category	Length	Score
Not reusable	<1.80 m	0.1
Almost not reusable	1.80 – 3.60 m	0.25
Reusable	3.60 – 5.40 m	0.50
Good reusable	5.40 – 7.20 m	0.75
Good size for an adaptive building	> 7.20 m	1.0

The analysis of the existing SE school buildings does not consider all 2D components. The total number of floors is 44 instead of 49, and the number of roofs is 43 instead of 49; see Figure 50. This difference in numbers has to do with the fact that in-situ and timber 2D components are outside the scope.

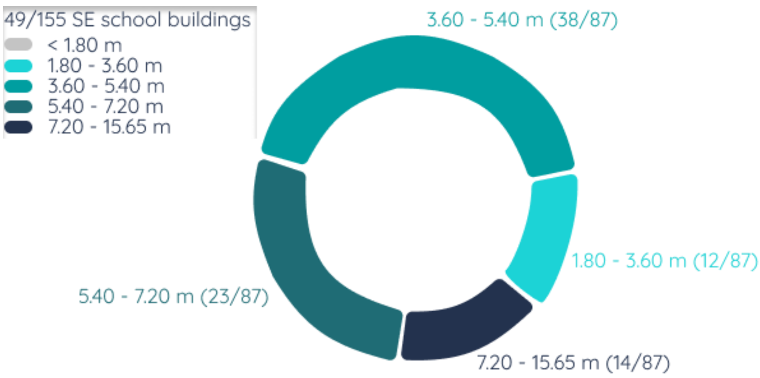


Figure 50: Length of 2D components used in existing SE school buildings

D.4.2 LENGTH OF BEAM COMPONENTS

As with a 2D component, the desired length for a beam component is 7.50 m to make an excellent adaptive SE school building that is future-oriented (Ruimte-OK, 2018). The preferred fixed grid of 3.60 m a multiple thereof also applies for beam components. From a structural point of view, the 2D component makes the long span and the beam the small span, then a light beam can easily suffice, which can easily integrate with the 2D component thickness (Interview 1 and 2). Short spans of beam components make reuse of beams more likely.

This research also subdivides the lengths of the beam components into the same five reuse categories as the 2D components, see Table 45.

Table 45: Reclaim and reusability score for beam component lengths

Reuse category	Length	Score
Not reusable	<1.80 m	0.5
Almost not reusable	1.80 – 3.60 m	0.7
Low reuse potential	3.60 – 5.40 m	0.9
Usable	5.40 – 7.20 m	0.9
Good size for an adaptive building	> 7.20 m	1.0

The analysis of the existing SE school buildings does not consider all beam components. The total number of beams is 46 instead of 49; see Figure 51. This difference in numbers has to do with some SE school buildings having a TT-slab floor, and the TT-slab floor has integrated beams.

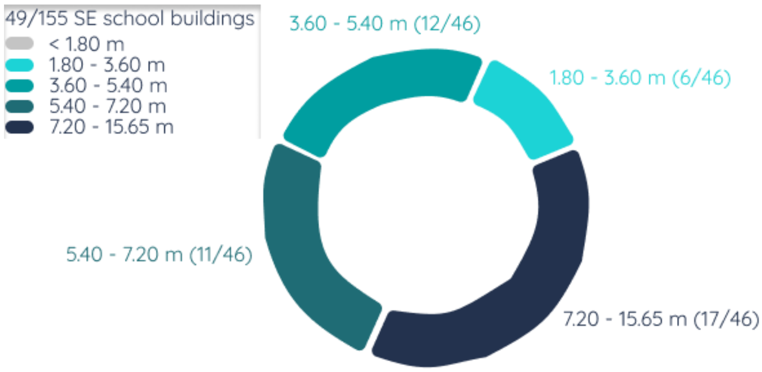


Figure 51: Lengths of used beam components in existing SE school buildings

D.4.3 LENGTH OF COLUMN COMPONENTS

The 'Bouwbesluit' requires a floor level height of 2.60 m (Bouwbesluit Article 4.3.6). According to the wishes for an adaptive future-oriented SE school building, the ideal height of a floor level is 3.20 m (Rijksdienst Ondernemend Nederland, 2021). The floor level is the construction height minus the construction floor, installation height and ceiling height. So, the constructive height is higher than the floor level height; the ideal construction height is 3.80 – 4.00 m (Interview 2 and 3).

Figure 52 shows that the column components have a good chance of reusing in terms of component length. This research subdivides the lengths of the column components into three reuse categories, see Table 46. The categories are multiples of the fixed grid size of 1.80, except for the required 2.60 m.

Table 46: Reclaim and reusability score for column lengths

Reuse category	Length	Score
Not reusable	<2.60 m	0.4
Usable	2.60 – 3.60 m	0.7
Good size for an adaptive building	> 3.60 m	1.0

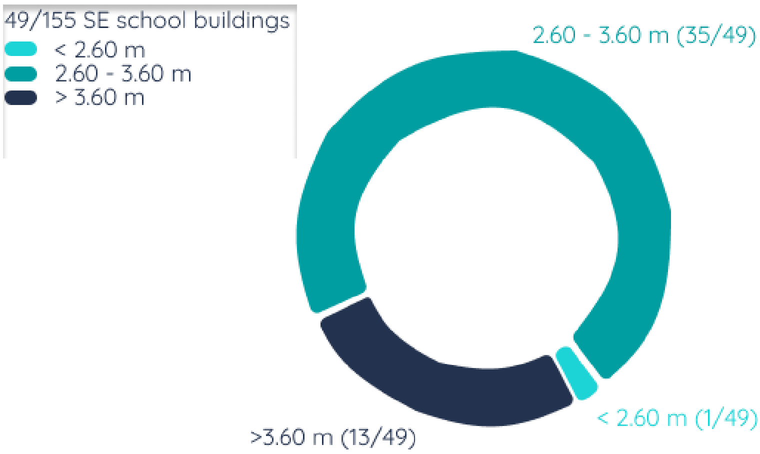


Figure 52: length of used column components in existing SE school buildings

APPENDIX E

DEMOUNTABILITY

The reclaim change for load-bearing components depends on the demountability of the component, which depends on the connection between components (van Vliet et al., 2021). The design of existing SE school buildings is according to the principle of the linear economy and does not focus on exchangeability and, therefore, not on demountability. Integrating different functions and materials in connections can lead to poor disassembly of the load-bearing components (Durmisevic, 2006). Poor integration of components causes damage when disassembly, which lowers the change for reuse. A combination of a site visit and viewing detail drawings defines the integration of components and, therefore, the demountability of a component.

The demountability of the component depends on several indicators that affect the disassembly (Durmisevic, 2006). According to the research of Verberne, the technical indicators for demountability are the type of connection, accessibility, the crossing of components, and edge confinement (Verberne, 2016). Each indicator has a demountability score; in this way, the demountability is measurable (Durmisevic, 2006). Alba concept tested Verberne's defined indicators in practice (van Vliet et al., 2021). Kraaijvanger's research adds an indicator, the number of connections (Kraaijvanger, 2021). The indicators of Verberne, Alba Concept and Kraaijvanger form the basis for this research (Kraaijvanger, 2021; van Vliet et al., 2021; Verberne, 2016). This appendix provides information about each indicator related to existing SE school buildings, and survey results confirm the reliability of the indicators. This appendix concludes with a formula that combines the various indicators into a single demountability score. The demountability score of load-bearing components indicates the possibility of reclaiming and the degree of risk of damage.

E.1 Type of connection

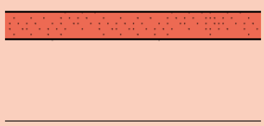
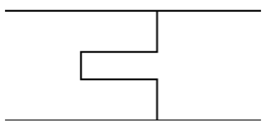
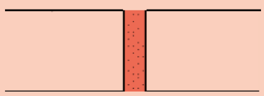
As a start, the research analyses 49 existing SE school buildings with column structures to inventory the frequently used connections. The analysis only considers the connections between components with steel and prefab concrete components. This research compares the frequently used connections with the type of connections from Durmisevic's research. The research of Durmisevic subdivides the type of connection into "three primary types of connections: direct (integral), indirect (accessory) and filled" (Durmisevic, 2006). See Table 47 for the description of the primary type of connection. The type of connection's subdivision has several characteristics: the number of components in the connection, the type of material, and the geometry of the edge of the load-bearing component (Durmisevic, 2006). This research only includes the connection types of Table 48 that correspond to the frequently used connection types found in the analysed SE school buildings. Table 48 highlights these frequently used connection types.

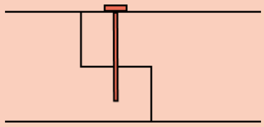
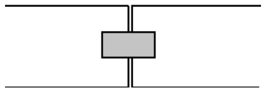
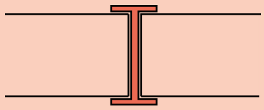
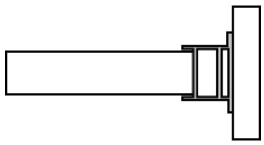
Each frequently used type of connection receives a demountability score based on the scores of Durmisevic (Durmisevic, 2006). The scores range linearly from flexible connections, easy to disassemble, to fixed connections, challenging to remove (Durmisevic, 2006). This research strives for a subjective assessment that comes closest to reality. From the point of view of demolition contractors, the reliability of the scores is tested and adjusted accordingly. See Appendix H for more information about the survey with the demolition contractors and the adjustment of the scores.

Table 47: division of main types of connections. Adapted from (Durmisevic, 2006)

Type of connection	Description
Direct	The geometry of the edges of the load-bearing components fit together to form a connection. The connection option is possible both internal and external: **Overlapping** is an external connection where the component edges partly cover each other. Both are possible for horizontal and vertical components. Disassembly of this connection depends on the construction material and the composition of the components **Interlocking** is an internal connection where the component edges fit precisely into each other.
Indirect	Additional elements in combination with the components form a connection. Again, the connection option is possible both internal and external: The internal connection contains a separate element that connects the load-bearing components—for example, a bolt connection. An external connection is easier to disconnect—for example, cover strips.
Filled	A chemical material connects the components on-site, such as a welded or mortar connection. Disassembly of this connection is very labour-intensive and requires particular deconstruction technologies.

Table 48: Hierarchy of disassembly of type of connections. Adapted from (Durmisevic, 2006)

Type of connection	Description	Sketch	Score
Direct chemical connection	Fixing two components by sticking to each other—for example, reinforced in-situ concrete, a reinforced plank slab or a structural layer. Also welded connection for steel.		0.1
Direct connection between two pre-made components	Two components are dependent in disassembly but also in assembly.		
Indirect connection with third chemical material	A third hard chemical material fixes two components. For example, a non-structural layer, mortar filled connections or reinforcement bars in coupling sleeves.		0.2

Direct connection with additional fixing element	A replaceable accessory fixes two components. For example, bolted connections.		0.8
Indirect connection via a third dependent element	A third element separates two components, but the assembly depends on each other.		
Indirect connection via an independent third element	A third element separates two components, but the assembly depends on each other. All components are potentially reusable.		1.0
Indirect connection with additional fixing element	A third element separate two components. When one component is changed, the other stays untouched. For example, a steel endplate fixes the column web and beam end—better known as dry connections.		

E.1.1 DIRECT CHEMICAL CONNECTION

Welded connection

A welded connection is an irreversible steel connection (Coelho et al., 2020). The materials undergo a phase transition by heating an agent and adjacent load-bearing components. The phase transition creates an entanglement of materials, making it difficult to detach welds without damaging the load-bearing components (Lambert & Gupta, 2004). Often the agent material is the same or stronger than the material of the adjacent components (Abspoel et al., 2013). Therefore, saw cutting detach welded connections (Lambert & Gupta, 2004). Saw cutting destructs partly one or more components next to the weld seam.

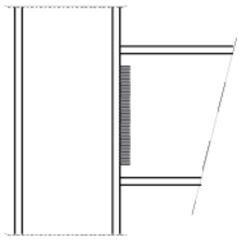
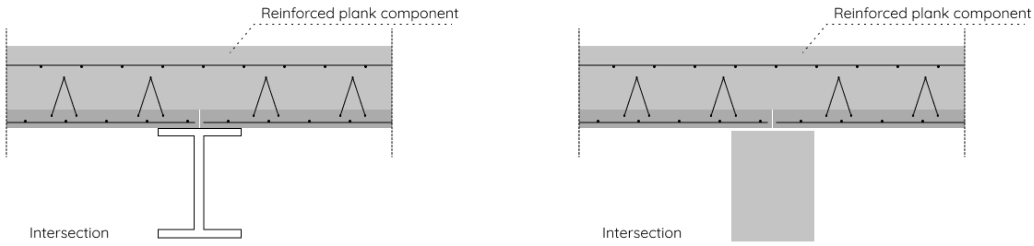


Figure 53: Example of Welded connection

Concrete bonded connection

Cement bonded connections with reinforcement correspond to in-situ concrete structures in terms of demountability. A diamond saw can detach the connection between a steel beam and reinforced plank (Naber, 2012).



(a) (b)

Figure 54: Example of reinforced plank component

Finishing and structural layer

Floor components often have a (structural) top layer in school buildings (W. van den Bosch, personal communication, 15 June 2021). The choice of a structural layer, including reinforcement, depends on three functions it can fulfil higher cross-section, overall coherence (preventing cracking of the finishing layer), and horizontal load-carrying (diaphragm action) (Pasterkamp, 2016). See Table 49 for an extensive description of these functions.

Table 49: 3 Functions of the structural layer. Adapted from (Pasterkamp, 2016)

Function	Benefit
Higher cross-section	Increase of capacity for bending and partly for shear force.
Overall coherence	A structural layer with reinforcement makes it possible to apply unequal loads on floor fields without beams tilting.
Horizontal load-carrying, Diaphragm action	Diaphragm action is often leading to the application of the structural layer. If the transfer of the wind load is via the 2D components to the stability bracing/core, the wind load must be small. The mortar joints between the prestressed hollow-core slabs can only achieve a limited horizontal bearing capacity. A structural layer can realise a more significant horizontal force transfer at high wind loads (often related to the building height). Adding reinforcement to the structural layer further increase the horizontal bearing capacity. Often reinforcement is chosen to be able to absorb the shear force.

The non-structural and structural layers cause difficulties when disassembling floor components because the layers cover the seams between the floor components, making the seams challenging to find (Glias, 2013). The finishing and structural layer lose their function after sawing the floor components and only provides extra self-weight to the reusable floor component (Glias, 2013). For these reasons, the reuse of a floor component takes place without a top layer (Naber, 2012). Moreover, when sawing the floor components, the reinforcement in the structural layer no longer has anchorages.

Tests by VBI in collaboration with Nijhuis in 2005 show that the cement non-structural layer comes off easily. The adhesion between the non-structural layer and the floor component is not good (Buunk & Heebing, 2017). Therefore, a pneumatic hammer can remove the non-structural layer (Glias, 2013; Naber, 2012). A pneumatic hammer is a machine-mounted attachments demolition technique (Kamp, 2021). The pneumatic hammer fragments the non-structural layer, and workers remove these loose fragments from the floor component. Removing the non-structural layer carries the risk of damaging the floor component.

The risk of damaging the floor component is higher with a structural layer. Reinforcement in the top layer makes it more challenging to create loose fragments and separate the top layer from the floor component (Naber, 2012). The removal process is labour and time-intensive (Glias, 2013).

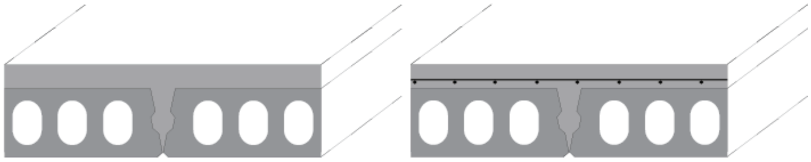


Figure 55: 3 Hollow-core slab a) with a non-structural layer; b) with a structural layer

E.1.2 INDIRECT CONNECTION WITH THIRD CHEMICAL MATERIAL

Mortar filled connections

The seams filled with mortar ensure that the components can carry the shear force together, so high local forces can occur. The filled seams between 2D components prevent interaction between the components. Interaction between the 2D components can occur due to concentrated load or unequal loads.

In addition, the analysis shows that mortar filling to connect the floor components with other load-bearing components is standard in SE school buildings. Sometimes even coupling rods and hairpins in the trench recesses were used (Naber, 2012). Figure 56 shows several options found in the analysis of the SE school buildings. Removing the mortar is necessary to reclaim and reuse the components (Glias, 2013). There are three options for removing mortar, hack, drill or saw. See Table 50. A diamond saw detaches the connections with coupling bars between the floor and beam or column components (Naber, 2012). The saw cut is in the most diminutive dimensions of the component's cross-section (Glias, 2013).

Table 50: Disassembly of connections filled with mortar. Adapted from (Glias, 2013)

Disassembly task	Description
Hack	The mortar can be hacked with a hammer until the reinforcement bar is visible. Subsequently, a thermal demolition technique of electric heating removes the reinforcement bars (Glias, 2013). The advantage of the hammer technique is that no concrete drawings are necessary to know the exact location of the reinforcement. On the other hand, this technique causes much damage to the components (Glias, 2013).
Drill	If concrete drawings are available, the exact location of the reinforcement bar is known. A machine-mounted attachment technique of a pneumatic hammer removes the mortar by drilling (Glias, 2013). In addition, drilling destroys the reinforcement bar, and this technique creates minor damage to the components.
Saw	The technique with the least damage to the components is sawing with a diamond saw (Glias, 2013).

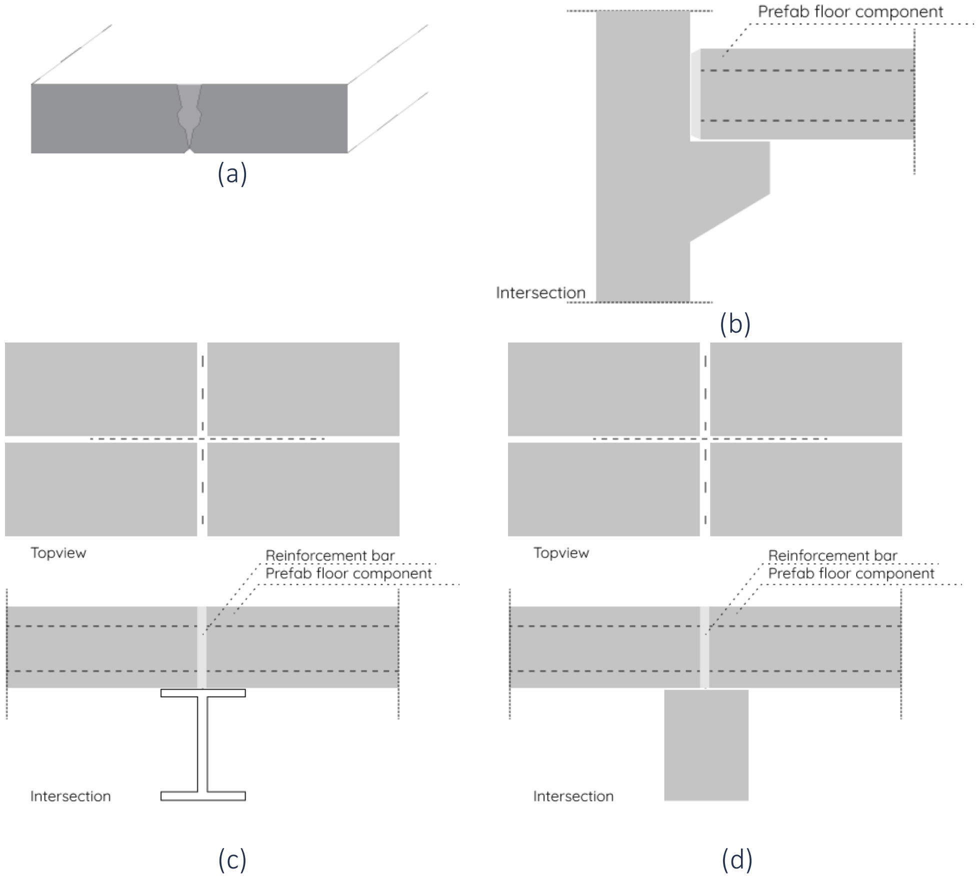


Figure 56: Example connections between beam/column and floor components with mortar filled. a) prefab floor – prefab floor b) prefab column corbel – prefab floor component c) steel beam – prefab floor component. d) prefab beam – prefab floor component.

Reinforcement bars and coupling sleeves

Prefab columns and beams have coupling facilities, such as rebars, rebar anchors, and coupling sleeves (Wurf van den & Bennink, 2001). Coupling sleeves are tubular recesses in the prefab load-bearing components (Lexicon, 2021). The rebars of the lower component stick out, and the subsequent 'stack' component has coupling sleeves that fit over the rebars. Later, mortar or a special plastic fills the coupling sleeves (Wurf van den & Bennenk, 2001). See Figure 57 a and b for the visualisation; the figure shows a connection with a reinforcement bar through two columns and a beam (column – beam-column). This type of connection is a filled connection (Durmisevic, 2006). Destroying the connection is necessary to reclaim and reuse the components (Glias, 2013). Also, for this connection, the three suitable methods of hack, drill or saw are possible explained in Table 50. The coupling facility loses its function after disassembling the components. In the new situation, new coupling facilities are necessary.

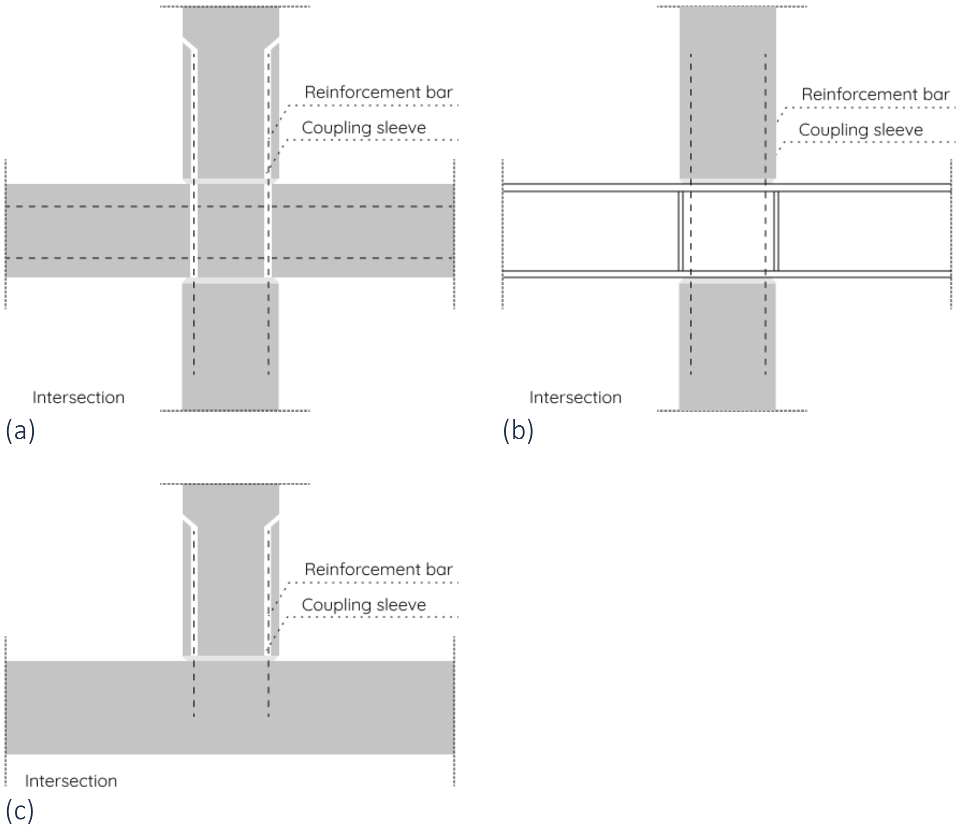


Figure 57: Example connections with coupling sleeves filled with mortar. A) prefab column - steel beam. B) prefab column – beam. C) ground floor – prefab column.

E.1.3 DIRECT CONNECTION WITH ADDITIONAL FIXING ELEMENT

Bolted connection

Bolted connections make disassembly without damage easy due to the reversibility of the connection (Coelho et al., 2020). The bolted connection can transfer the forces shear and tension (Abspoel et al., 2013). Nevertheless, bolted connections are not always favourable from a structural point of view, and the t-shape of the bolt reduces the tensile stress capacity of the component (Abspoel et al., 2013). In addition, bolts can become loose when vibrating. Disassembly follows by removing the bolts (Lambert & Gupta, 2004).

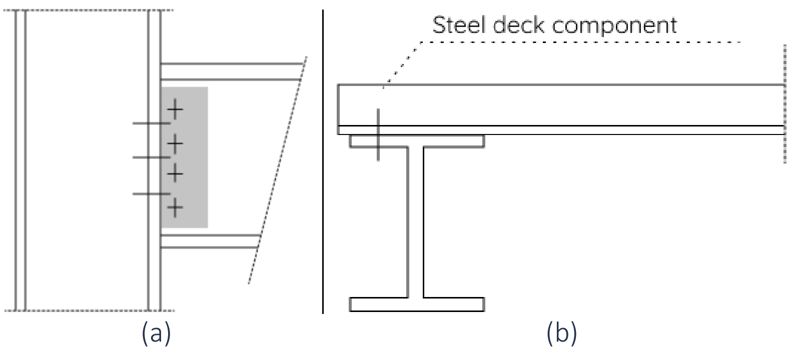


Figure 58: Example of bolted connection: a) Column-beam connection. b) beam-steel deck connection

E.1.4 INDIRECT CONNECTION VIA INDEPENDENT THIRD ELEMENT

Figure 59 shows examples of indirect connection via independent third elements. Also known as dry connections, a dry connection ensures disassembly and reassembly without damage to load-bearing components or additional actions (Durmisevic, 2006). The components can be removed from the building one by one.

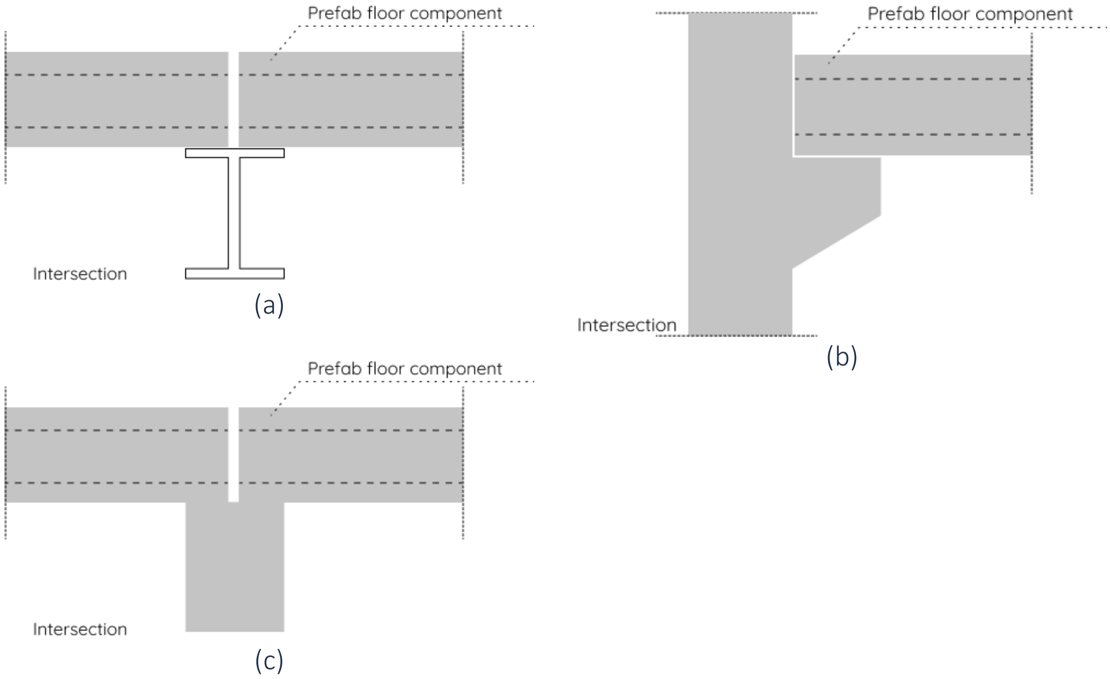


Figure 59: Examples of dry connection: A) steel beam welded– prefab floor connection B) prefab column + corbel – prefab floor. C) prefab column – beam.

E.2 The accessibility of the connection

An easily accessible connection is a connection that is visible (van Vliet et al., 2021). If the connection is not visible, disassembly is only possible with additional actions. Structural or architectural components may hide the connection, and these components may or may not be removable. It is usually impossible to remove the components without damaging the related components (Durmisevic, 2006). The potential damage must be repaired (van Vliet et al., 2021).

The research looks at the composition of a roof to make the accessibility of connection between load-bearing components more susceptible. In general, a roof comprises several layers that affect the demountability of the load-bearing components. In addition to the load-bearing components, a roof has a vapour barrier (closing layer), thermal insulation, and roof covering (Totaal Dak Concept, 2021). The load-bearing components of the roof are reused separately without the other layers. So, before disassembly, the removal of other layers takes place. With roofs built according to the principle of the linear economy, the waterproof protective function of the roof is paramount. Therefore, the connection to the roof is adhesive (Hartwell et al., 2021). For example, glue is present between the roof covering and the insulation or load-bearing components. Therefore, a load-bearing component that comes from a roof is not visible, and architectural components hide the component.

Just as for the type of connection, Durmisevic's research made a subdivision for the accessibility of the connection. According to Durmisevic, the accessibility of a connection has five categories (Durmisevic, 2006). The method demountability (van Vliet et al., 2021) tested the five accessibility categories in practice and concluded that four are sufficient. See Table 51 for each category. Kraaijvanger's research shows that the categories of Durmisevic are subjective and open to interpretation (Durmisevic, 2006; Kraaijvanger, 2021). This study adds an explanation per category to obtain an unambiguous category division of accessibility of connections. See Table 51 for each technical explanation per category.

As for the type of connection, this research tests and adjusts the scores of Durmisevic, see Appendix H.

Table 51: Division of accessibility of connection. Adapted from (Durmisevic, 2006)

Accessibility	Description	Score
Accessible	The connection is independent, visible, and reachable.	1.0
Accessible with an additional operation that causes no damage	The connection is not visible and, therefore, not immediately accessible. The constructive or architectural components independent of the connection hide the load-bearing component. After removing the constructive or architectural components, the connection is reachable—for example, a ceiling system.	0.8
Accessible with an additional operation that causes repairable damage	The connection is not visible and, therefore, not immediately accessible. The constructive or architectural components dependent on the connection hide the load-bearing component. The removal of the constructive or architectural components will cause damage to the load-bearing component(s)—for example, an indoor glass partition.	0.4
Not accessible, total damage of components	The connection is not visible. Multiple constructive or architectural components depend on the connection, or associated load-bearing component hide the load-bearing component, or both. The removal of the constructive or architectural components will cause unrepairable damage to the load-bearing component(s)—for example, structural insulated panels.	0.1

E.3 Crossing components

Crossing components is about the intersection of components from other building layers (van Vliet et al., 2021, and building layers are the building layers of Brand (Brand, 1994). Crossing components means that components run through each other or fully integrate (van Vliet et al., 2021). Both intersecting components experience hindrance during disassembly due to additional handlings. The method demountability again tested the aspect crossing components from Durmisevic in practice and concluded that three categories are sufficient (Durmisevic, 2006; van Vliet et al., 2021). See Table 52 for the subdivision of the categories. Again, this research tests and adjusts the scores of Durmisevic; see Appendix H.

Table 52: Division of crossing components. Adapted from (Durmisevic, 2006)

Crossing of components	Score
No crossing	1.0
Crossing of components from different building layers	0.8
Full integration of components from different building layers	0.5

E.4 Edge confinement

The edge confinement is about the physical edges of the load-bearing component and the placement in the building (van Vliet et al., 2021). The method demountability again tested the aspect crossing components from Durmisevic in practice and concluded that three categories are sufficient (Durmisevic, 2006; van Vliet et al., 2021). See Table 53 of the subdivision of the edge confinement aspect and the technical explanation per category. Again this research tests and adjusts the scores of Durmisevic; see Appendix H.

Table 53: Division of confinement of edges of load-bearing components

Edge confinement	Description	Score
Component edges are not enclosed	Surrounding components do not enclose component edges, and the edges of components are independent of each other. Disassembly of the component from the building is possible from at least one accessible side.	1.0
Component edges overlap	Surrounding components partially enclose component edges, and there is at least one edge with an overlap. Removal of other components first occurs before disassembling the load-bearing component from the SE school building. The load-bearing component depends on other components. For instance, a floor finishing or insulation glued to the roof component.	0.8
Component edges are enclosed	The load-bearing component depends on other components. Other components completely enclose component edges, and there is inclusion on at least two edges. Removal of other components first occurs before disassembling the load-bearing component from the SE school building.	0.4

E.5 Number of connections

The connection of a load-bearing component can be with one or more components. The number of disassembly operations increases with the number of connections, and each operation increases the risk of irreparable damage. So, each connection may cause additional damage to the load-bearing component, which may hinder potential reuse (Kraaijvanger, 2021). The connection of the component should be with a minimum number of connections to increase the demountability of the component (PIANOo expertise centrum aanbesteden, 2019). PIANOo's research subdivided the number of connections into four categories (PIANOo expertise centrum aanbesteden, 2019). See Table 54 for dividing the number of connections. Also, this research tests the scores of PIANOo, see Appendix H. No adjustments were necessary.

Table 54: Division of the number of connections. Adapted from (PIANOo expertise centrum aanbesteden, 2019)

Crossing of components	Score
One or two connections	1.0
Three connections	0.6
Four connections	0.4
Five or more connections	0.2

E.6 Demountability score of a load-bearing component

The demountability score (EI) consists of (EI_c) and (EI_s). The demountability index of the connection (EI_c) is a composite of the type of connection (TC_i), the accessibility of the connection (AC_i) and the number of connections (NC_i). The demountability index of the composition (EI_s) is composed of the crossing components and edge confinement.

Equation 2: Demountability Index of the Connection

$$EI_c = \frac{3}{\frac{1}{TC_i} + \frac{1}{AC_i} + \frac{1}{NC_i}}$$

$EI_c = \text{Demountability } Index\ of\ Connection$
$TC_i = Type\ of\ Connection\ of\ component\ i$
$AC_i = Accessibility\ of\ Connection\ of\ component\ i$
$NC_i = Number\ of\ Connections\ of\ component\ i$

Equation 3: Demountability Index of the Composition

$$EI_s = \frac{2}{\frac{1}{CC_i} + \frac{1}{EC_i}}$$

$EI_s = \text{Demountability } Index\ of\ Composition$
$CC_i = Crossing\ Components\ to\ component\ i$
$EC_i = \ of\ component\ i$

Equation 4: Demountability Index, Demountability Score

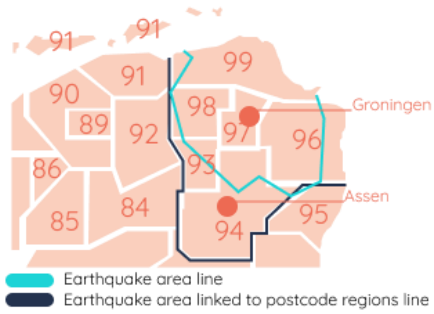
$$EI = EI_c + EI_s = \left(\frac{3}{\frac{1}{TC_i} + \frac{1}{AC_i} + \frac{1}{NC_i}}\right) + \left(\frac{2}{\frac{1}{CC_i} + \frac{1}{EC_i}}\right)$$

APPENDIX F

PHYSICAL QUALITY

The guarantee of the physical quality of an existing load-bearing component is necessary to reuse it in a new school building. The load-bearing components made of steel and prefab concrete are all factory-made. During manufacturing, checks determine that the components met the minimum requirements for the assigned structural function—the minimum requirements were according to the then-applicable standard.

Moreover, certain conditions and loads have determined the original design of the existing load-bearing components. Existing components already are subjected to loads. The Steel Construction Institute state that the reuse of steel load-bearing components is limited to components that were not subjected to extreme loads, such as fire, earthquakes or fatigue (Steel Construction Institute, 2019b). This research sets the identical requirements for concrete load-bearing components for extreme loads. In the Netherlands, earthquakes only occur in certain areas in Groningen. Load-bearing components of SE school buildings from these areas are not reclaimable and reusable because there is no guarantee of the physical quality.



Postcode regions in Groningen with school buildings exposed to earthquakes:
9300-9499
9600-9999

Figure 60: Postcode areas in Groningen subjected to earthquakes

For the initial next-life phase, the focus lies on an initial, preliminary quality assessment. This assessment occurs early before reclaiming occurs, in the current situation where all building components are in place. The initial physical safety depends on the following sub-indicators: Structural properties translated to the current code, deterioration and damage, and residual lifespan (R. J. Geldermans, 2016; Glias, 2013; Iacovidou & Purnell, 2016; Steel Construction Institute, 2019a).

The structural properties of a load-bearing component arise from the material properties of the construction material used. Different standards have been in force throughout the 20th century, each with different requirements for the construction material. Therefore, the existing load-bearing components are most likely manufactured to a withdrawn standard. Building documents, construction drawings and construction calculations provide information about the original physical quality of the load-bearing components and the used standards and requirements. However, sometimes little information is available about the load-bearing components of existing SE school buildings. Due to this fact, this appendix provides information for a range of possible structural properties of the load-bearing components. The range of possible structural properties reduces with increasing available information about the original SE school building.

Moreover, some structural properties determine the possible damage mechanisms. Therefore, construction documents can give information about the possible deterioration and damage mechanisms to the load-bearing component in the indoor environment. However, also a visual inspection can detect possible deterioration. For the initial next-life phase, only the building year and the location of the school building already give enough information about the possible presence of specific damage mechanisms. Nevertheless, in a later next-life phase, a visual inspection provides information about the presence of certain substances in the chemical composition of the construction material, and thus the possible damage mechanisms. After removing the architectural components, the visual inspection occurs when only the load-bearing components remain. So there is a short time frame in which the visual inspection can take place. Above, not all damage mechanisms are visual but can occur. In later next-life phases, Non-Destructive Test (NDT) or Destructive Tests (DT) are necessary to guarantee the actual physical quality of the components. These tests also provide the exact properties of the load-bearing components. This appendix explains the required visual inspections and tests for later next-life phases.

Furthermore, the load-bearing component's general condition and construction year are the basis for the residual lifespan (NEN 2767-1+C1, 2019). As mentioned in Appendix C, this research simplifies the age of the building to the building year, not including the subsequent alterations and renovations of the school. Building documents, construction drawings and construction calculations provide the building year of an SE school building. If the building year is missing the open dataset of Algemene Rekenkamer' Schoolgebouwen PO en VO' can provide the building year (Algemene Rekenkamer, 2016).

F.1 Toxic substances

Requirements for the composition of building materials have become stricter over the years. Therefore, existing load-bearing components can contain substances that are no longer allowed today, and this research indicates these undesired substances as toxic substances. Existing load-bearing components which contain toxic substances are not reusable in new SE school buildings; therefore, the composition of construction materials influences the potential reusability of the load-bearing component. (B. Geldermans, 2020; Iacovidou & Purnell, 2016).

The construction material concrete can contain the toxic substances asbestos and chlorides (van Berlo, 2019, and these toxic substances can increase the risk of human health, corrosion and carbonation.

Building documents often do not provide information on the exact composition of the construction material. However, previous inspection reports can provide insight into the presence of toxic substances. When this information is not available, in a later next-life phase, laboratory research gives the exact composition of the construction material (van Berlo, 2019). For the initial next-life phase, this research estimates the presence of toxic substances by the building year and the previous inspection reports.

F.1.1 ASBESTOS

In the 20th century, asbestos was a common substance in building materials. An employee of the Rotterdam City Archives explains that water drainage systems and cable pipes mainly used asbestos in the past. Construction materials may include embedded drainage systems and cable pipes (T. de Bruin, personal communication, May 12, 2021). After 1983, the law rejects asbestos because of the harmfulness it emits and the health problems it can cause. In 2011, the government called on all school organisations and municipalities to make an asbestos inventory of school buildings older than January 1994 (Rijkswaterstaat, 2011). The asbestos inventory of school buildings gives inside in the presence of asbestos by the availability of an asbestos-free certificate. Reclaiming existing components from a school building built before 1994 is only possible if an asbestos-free certificate is available (Eleveld & Mars, 2006).

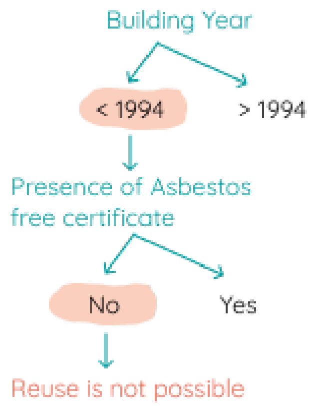


Figure 61: Presence of Asbestos

F.1.2 CHLORIDES

In the past, calcium chloride was an admixture to the prefab concrete mixture as a concrete accelerator to allow the concrete mixture to set faster (Renirie, 2016). Before 1975, 1-2% chloride was allowed in the concrete mixture (Cobouw, 1995). After a particular time, this concrete setting accelerator causes a chemical reaction with the reinforcing steel, rusting; the rusting process causes the reinforcement to expand (Geertsma, 2019; Renirie, 2016). The expansion causes cracks in the concrete which affects the outer concrete layer, the concrete cover. If the concrete cover cracks, more oxygen reaches the reinforcement, making the concrete rot process even faster (Geertsma, 2019; Renirie, 2016). Due to the high risk of concrete rot, load-bearing components with 1-2% chloride are not suitable for reuse. For example, "Kwaaitaal" floors, see Appendix E. If the load-bearing component is not a prefab component built before 1974, the risk of mixed in chlorides is not present.

In a later next-life phase, laboratory research gives the exact material composition that identifies the presence of mixed-in chlorides.

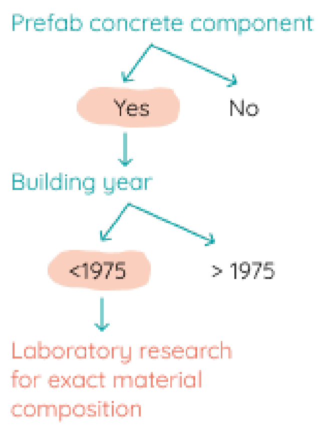


Figure 62: Presence of 1-2% chlorides

F.2 Deterioration and possible damage mechanisms

Deterioration of construction material in combination with structural properties define the technical performance. The general condition reflects load-bearing components' technical performance and physical quality (B. Geldermans, 2020). In the Netherlands, NEN-2767 helps determine the general condition of existing load-bearing components (NEN 2767-1+C1, 2019; van Berlo, 2019). NEN-2767 is an objective, uniform condition assessment standard for measuring the physical quality of load-bearing components at the time of inspection (NEN 2767-1+C1, 2019). The inspection is a visual inspection, so a general non-specific inspection. NEN 2767 makes it possible to assess visual defects by providing a checklist of possible defects. Comparing the visible defect and the defect in the checklist characterise the technical performance of a load-bearing component in an existing building. Note, NEN-2767 does not aim at the condition of a load-bearing component for reclaim and reuse. However, there are aspects in assessing with NEN-2767 that are useful for determining the physical quality of load-bearing components for reclaim and reuse.

The objective, uniform condition assessment method maps the technical condition of a load-bearing component by assigning a particular condition score to each possible defect. The condition score ranges from 1 to 6, as visible in Table 55. Defects are related to the construction material and age of the load-bearing component, which internal or external sources can cause.

Table 55: Condition scores with description. Adapted from (NEN 2767-1+C1, 2019)

Condition score	Explanation
1	Excellent condition. Minor failures and repairs can immediately restore the defect and bring the load-bearing component back to the necessary intended quality.
2	Good condition. Accidental beginning deterioration. The load-bearing component has visible defects due to dirt. Local defects
3	Acceptable condition. Partially visible deterioration, the performance of asset not in danger of failing. Defects such as weathering occur.
4	Poor condition. Defects can occur that lead to loss of function. The building performance is accidentally in danger of failing.
5	Bad condition. Deterioration is irreversible. Significant structural defects in the load-bearing component occur
6	Terrible condition. Technically ready for demolition.

Appendix A.1, A.4 and A.5 of NEN 2767-2 provides insight into the possible defects of load-bearing components in the indoor environment (NEN 2767-2, 2008). Combined with the extent and intensity of the defect, these defects align with the general condition scores of Table 55. The severity of the defect classifies the defect. So, a defect has three aspects: the severity, extent and intensity of the defect (NEN 2767-2, 2008).

Only certified people can perform an official condition assessment of NEN 2767 (NEN 2767-2, 2008). However, this research aims to provide an initial indication of the condition of a load-bearing component by identifying each possible defect without considering the severity and extent of the defect. So, this research gives a rough estimate of the physical quality of the load-bearing component. In a later next-life phase, a visual inspection reveals the severity and extent of the defect. In addition, in a later next-life phase, a detailed examination reveals whether other degradations are not visible and the severity and extent of these defects. The highest condition score is the governing condition score. The higher the condition score, the more deteriorated the construction material is and the smaller the reuse chance.

The research of Van Berlo forms the basis of the internal and external deterioration of the construction material concrete, and the research of the Steel Construction Institute and Schoefs et al. are the basis for the construction material steel (Schoefs et al., 2012; Steel Construction Institute, 2019a; van Berlo, 2019). This research considers various internal and external deteriorations. Take in mind that this research is an initial assessment; in a later next-life phase, a careful visual inspection and laboratory research is necessary.

F.2.1 STEEL DETERIORATION

F.2.1.1 Deflection and deformation

The shape and dimensions of existing steel must be within the tolerances of the standard (Steel Construction Institute, 2019b). Deformations of the existing steel components outside the tolerances can be irreversible deformations. Irreversible deformations are plastic deformations and make steel unreliable and not reusable. Excluding plastic deformations makes it possible to assume that the residual strains and reserves of the ductility of steel are equal to those of 'new' steel (Steel Construction Institute, 2019b).

In a later next-life phase, a visual inspection identifies the possible deflections and deformations of the steel load-bearing components. The visual inspection practitioner measures the deformations of steel components with measuring tape by measuring the upward/downward deflection (Δ) and the span (L); see Figure 63. Comparing the maximal detected deflection/span ratio and the possible occurring deflection/span ratio gives the general condition score. Table 56 contributes to assessing the deflection of steel components.

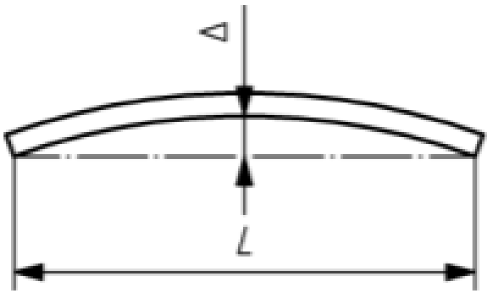


Figure 63: Deflection of steel component, the two measurements

Table 56: Degree of deflection of steel

Deflection/span				
Score 1	Score 2	Score 3	Score 4	Score 5
No deflection	$\frac{\Delta}{L} \leq \frac{1}{750}$			$\frac{\Delta}{L} > \frac{1}{750}$

After demounting the load-bearing component, a careful visual inspection of the component geometry takes place in a later next-life phase. The assessment compares the shape and dimensions of the component with the given geometric tolerances in the standards EN10365, EN 10034, EN 10024, EN 10279, EN10219-2 (Steel Construction Institute, 2019b). If a careful visual inspection detects bow imperfects in steel load-bearing components, lack of straightness, steel components must be straightened before reuse is possible (Steel Construction Institute, 2019b).

F.2.1.2 External deterioration: Corrosion

Corrosion is the natural process by which metals return to their thermodynamically stable compounds, the state in which metals occur in nature (Schoefs et al., 2012). The most common corrosion reaction is the reaction of oxygen and moisture from the atmosphere with metals such as construction steel. Due to exposure to the environment, corrosion deteriorates the construction steel and reinforcing steel (Schoefs et al., 2012; Talsma et al., 2019).

Moreover, environments with a very high sulphur content deteriorate the construction steel (Correia et al., 2018). The steel reacts with the sulphur, causing corrosion, and the steel expands and decreases in strength. In addition, airborne chlorides can also react with construction steel to cause corrosion (Schoefs et al., 2012).

Very high sulphur content does not occur in the Netherlands. Although, chlorides can penetrate from the outside in SE school buildings near the coast (van Berlo, 2019). The exposure environment of these school buildings contains airborne chlorides. Airborne chlorides are present until 25 km land inwards (Talsma et al., 2019). Figure 64 shows the 25km lines from the seawater land inwards with a dark blue line. To quickly see if a SE school building in this area, this research links the postcode areas of the Netherlands to the exposure environment areas. This approach is conservative for some postcode areas, which is not problematic for the initial assessment of the general condition. The construction steel near the coast needs a surface coating to counteract the chloride attack (Correia et al., 2018).

Figure 64: Overview of postcode regions with buildings exposed to seawater

Postcode regions with school buildings exposed to airborne salts:

2000-2799
2900-3299
4300-4699
8600-9299
9600-9999

Follow the flow chart of Figure 65 to find out if corrosion can be a problem and if it is present on the steel component. Take in mind that any load-bearing steel component can contain corrosion. However, the chance of corrosion of a steel load-bearing component outside the 25km from the sea reach is minimal. Therefore, the initial next-life phase assumes that corrosion is only a problem for steel load-bearing components within 25 km of the sea. In a later next-life phase, a visual inspection reveals whether or not there is corrosion.

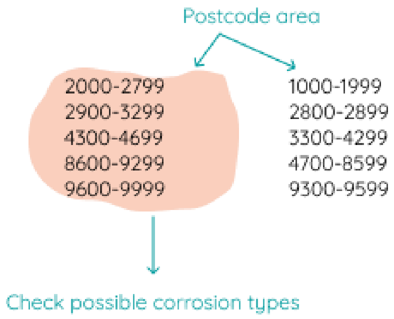


Figure 65: Corrosion possible

In the case of airborne chlorides, defects in the coating system can cause corrosion of the steel load-bearing component (Schoefs et al., 2012). In most situations, the next-life phase removes the existing steel surface coating before reusing load-bearing components (Steel Construction Institute, 2019b). The new design applies a new coating to the desired degree if necessary. Existing coatings may contain hazardous substances that the law now rejects. In addition, the protection level of the coating can decrease over the years to a level below the current requirements. However, it is essential to check if defects in the coating already have caused corrosion and degradation of the steel load-bearing component.

There are several defects of the coating system, which are detectable with a visual inspection. The visual inspection practitioner detects corrosion with a lamp, magnifying glass, binocular, mirror and tape, and the visual inspection does not damage the coating. See Figure 66. The moment a defect is visible, it is already too late, and the coating/preservation is already affected. Comparing the detected type of corrosion and the possible occurring degree of the type of corrosion gives the general condition score (the series of NEN-EN-ISO 4628). The highest condition score is governing.

Figure 66: Measurement equipment for coating defects, corrosion. A) Magnifying glass. B) UV lamp. C) binocular. D) mirror and E) tape

Blistering

Blistering can occur due to substrate corrosion, water entrapment, or solvent entrapment (Schoefs et al., 2012; Stuart, 2013). According to Schoefs, "solvent entrapment may arise from "skin curing" of the top layer of the coating or due to overcoating or immersion of the coating before the evaporation of the solvent (Schoefs et al., 2012).

Rusting

Insufficient coverage of the paint coating causes rusting (Schoefs et al., 2012).

Cracking

Improper application of protective paint coating causes cracking of paint coatings. The applied coating's partial or complete peeling is characteristic of the cracks (Schoefs et al., 2012). See Figure 67 a.

Flaking

Poor adhesion of the protective coating and the steel substrate causes separation of the coating and the steel, which causes flaking. See Figure 67 b. Surface contamination can cause loss of adhesion, for example, rust or dirt. (Schoefs et al., 2012). Moreover, good adhesion is only possible if the steel substrate surface has the proper roughness.

Chalking

Chalking occurs due to the decomposition of the coating binder. A powdery coating appears on the surface of the paint coating. See Figure 67 c. Exposure to the atmosphere, mainly to moisture, causes chalking (Schoefs et al., 2012). Placing and removing the adhesive tape on the dry steel coating can measure the degree of chalking. The length of the tape is at least 40 mm. The first row is for dark coloured coatings and the second row for light coloured coatings (NEN-EN-ISO 4628-6, 2007).

Pitting

The deterioration of the steel surface is limited to a point or a small area, a localised form of corrosion (Schoefs et al., 2012). Localised damage to the coating or poor application of the coating causes pitting. See Figure 67 d.

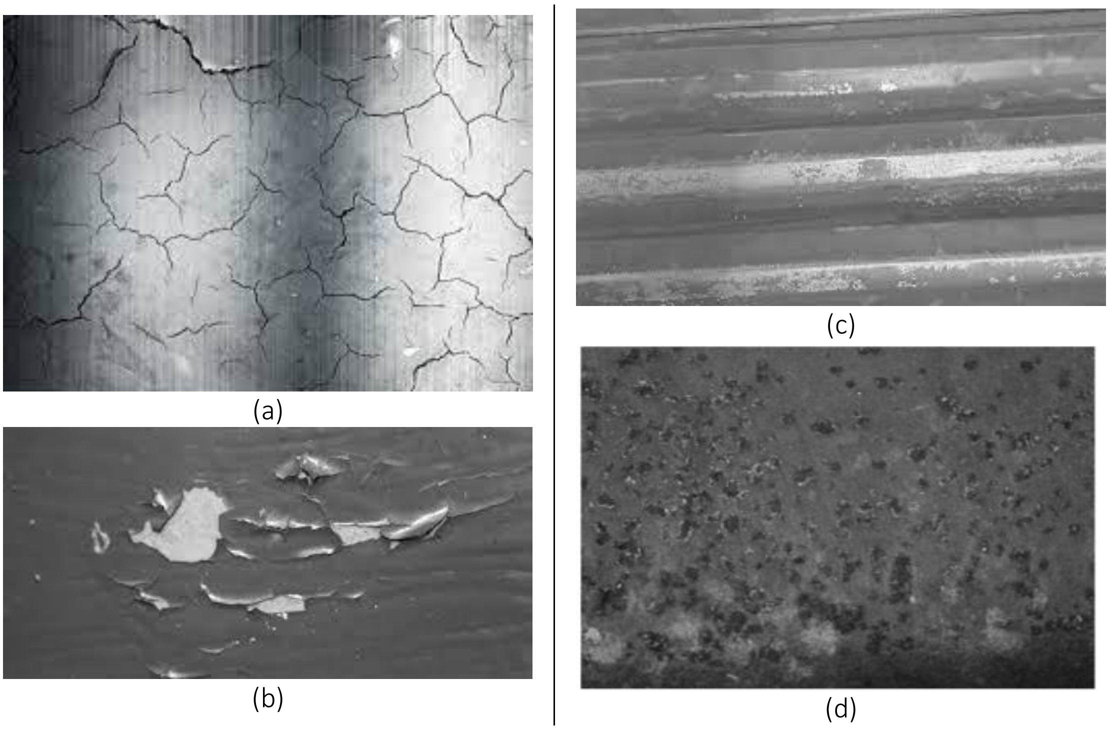


Figure 67: A) Cracking of the steel protection coating. B) Flaking. C) Chalking. D) Pitting.

Delamination due to corrosion around a scribe or other artificial defect

Again a localised form of corrosion. This type of corrosion usually occurs in scribes of shielded load-bearing components. See Figure 68. Think of fixings such as bolts, but the angle between flange and body is also sensitive to this. Changes in the local surface chemistry of the scribe initiate deterioration of the material, which leads to a highly corrosive localised state. The surrounding steel will degrade due to the corrosive localised state of the crevice (Stuart, 2013).

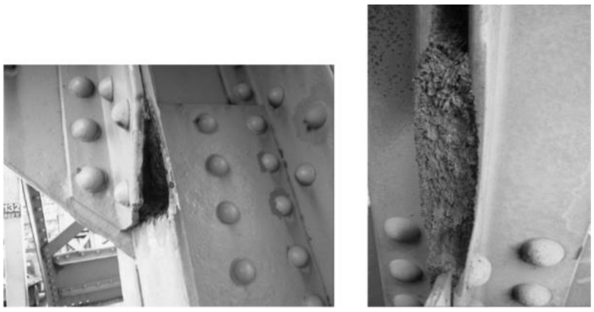
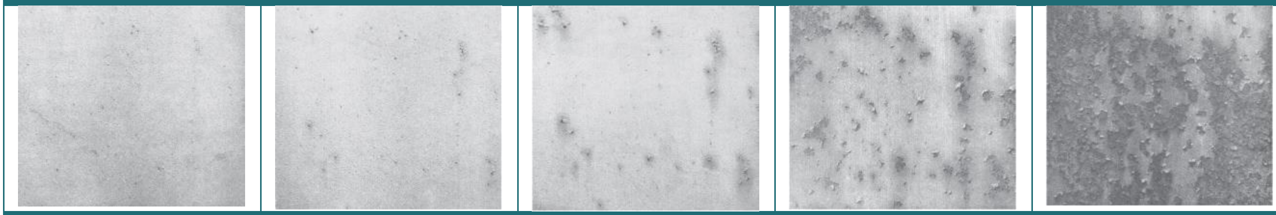
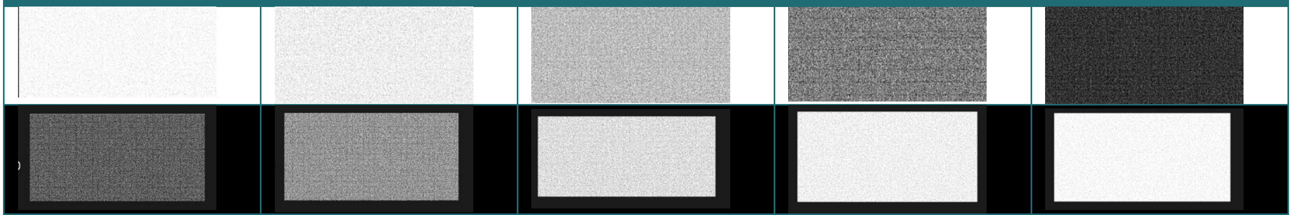
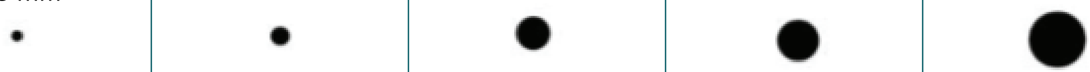
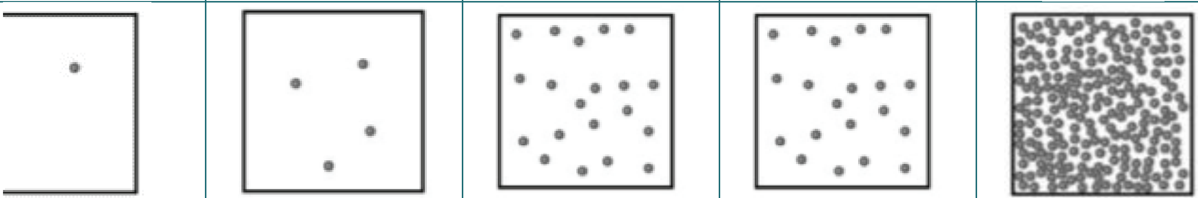
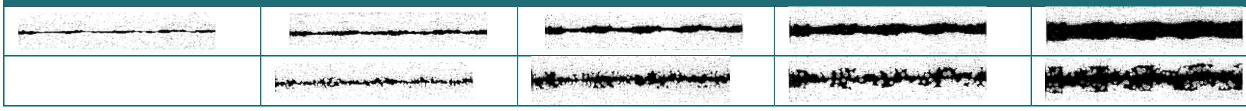


Figure 68: Delamination due to corrosion around the scribe

Table 57: Degree of corrosion per type of corrosion. Adapted from (The series of NEN-EN-ISO 4628, 2016)

Blistering (NEN-EN-ISO 4628-2, 2016)				
Score 1	Score 2	Score 3	Score 4	Score 5
-				

Rusting (NEN-EN-ISO 4628-3, 2016)				
Score 1	Score 2	Score 3	Score 4	Score 5
				
Cracking (NEN-EN-ISO 4628-4, 2016)				
-	$w \leq 0.2$ mm	$0.2 \leq w \leq 0.5$mm	$0.5 \leq w \leq 1$mm	$w > 1$ mm
Flaking (NEN-EN-ISO 4628-5, 2016)				
< 1mm	$\leq$ 3mm	$\leq$ 10 mm	$\leq$ 30 mm	> 30 mm
Chalking (NEN-EN-ISO 4628-6, 2007)				
Score 1	Score 2	Score 3	Score 4	Score 5
				
Pitting (NEN-EN-ISO 11463, 2020)				Scale 1:1
Score 1	Score 2	Score 3	Score 4	Score 5
0.5 mm^2	2.0 mm^2	8.0 mm^2	12.5 mm^2	24.5 mm^2
				
				
Defects around a scribe				Scale 1:1
Score 1	Score 2	Score 3	Score 4	Score 5
				

F.2.1.3 Fretting deterioration

Fretting deterioration occurs at bolted connections of steel load-bearing components, the location of transferring loads. However, vibrations can also cause fretting deterioration to occur. Bolt hole enlargement and other similar surface damage characterise this type of defect (Stuart, 2013).

In a later next-life phase, a careful visual inspection provides insight into the deterioration due to friction of two load-bearing components. First, disassembly is necessary to see the bolt holes, as shown in Figure 69. Fretting deterioration is a local problem and will not affect the remaining load-bearing component after removal. Although, fretting deterioration makes the bolt holes not reusable; so additional handlings are necessary. Shortening of steel load-bearing components makes reuse possible.

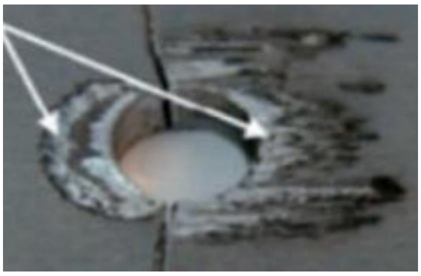


Figure 69: Visible inspection fretting deterioration of bolt holes

F.2.2 CONCRETE DETERIORATIONS

F.2.2.1 Corrosion of reinforced concrete

Airborne chlorides can also react with the reinforcement of concrete load-bearing components. Chlorides can penetrate the reinforced concrete. If the chlorides reach the reinforcement, the steel reinforcement starts to corrode (Kamp, 2021). The same goes for CO_2 from the air that causes carbonation of the concrete. Carbonation makes the pH value of the concrete lower, an acid, which lets the reinforcement corrode. Corroded rebar expands and cause the concrete to crack, spall or delaminate (Talsma et al., 2019). The cracks, spalling or delamination cause more exposure to the atmosphere and, therefore, more corrosion.

As mentioned in F.2.1.2 External deterioration: Corrosion the initial next-life phase assumes that corrosion is only a problem for steel load-bearing components within 25 km of the sea. In a later next-life phase, a visual inspection reveals whether or not there is corrosion of reinforcement. Following the flowchart of Figure 70 gives the possible presence of corrosion. Comparison of the detected possible corrosion to the pictures in the flowchart gives the condition score. Table 58 gives the condition scores for the occurring presence of corrosion.

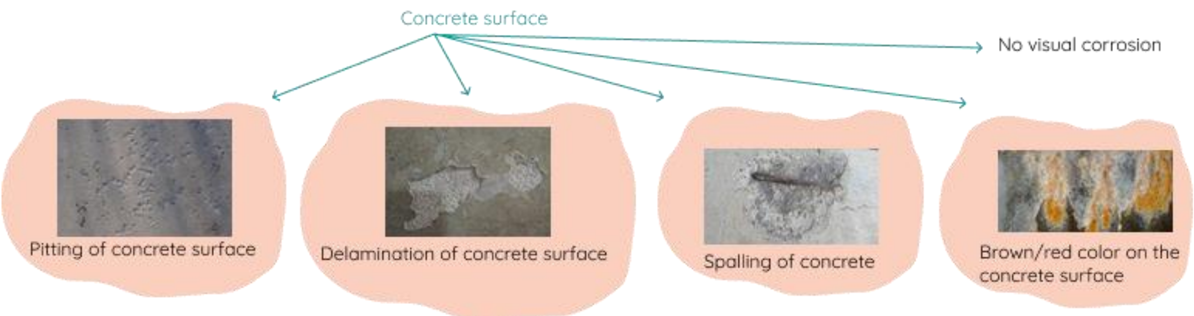


Figure 70: Presence of corrosion on concrete load-bearing component

Table 58: Degree of corrosion

Degree of corrosion				
Score 1	Score 2	Score 3	Score 4	Score 5
No visible corrosion	-	Pitting Or Delamination	-	Spalling Or Brown/red stains

F2.2.2 Concrete cracks

The reinforcement in concrete first must be activated by small cracks in the concrete before it starts working. However, at the same time, the crack width must be limited to a maximum crack width, w_{max}. The limitation of the maximum crack width ensures the qualitatively strong reinforcement steel and prevent it from damage (B. Addis, 2006). Damage to the steel reinforcement is ultimately fatal to concrete structures because the steel carries the internal tensile stresses. Due to small cracks in the concrete, reinforced concrete is prone to many damage processes, such as microbial or chemical reactions, freeze and thaw, and corrosion of reinforced steel. Thermal expansion of steel can also occur, which expands the concrete and accelerates the crack width development.

The interest of this research is in the crack that constructively damages the component. The cause and the crack width determine the severity of the crack formation (Kamp, 2021). In general, small cracks in reinforced concrete are not dangerous for reuse because they can repair themself by silting, continuous hydration and swelling of the concrete (van Berlo, 2019). For a structural crack, $> w_{max}$, the cause of the crack is critical to determine if the load-bearing component is reusable. A reinforced component's maximum crack width depends on the steel stress and reinforcement ratio (NEN-EN 1992-1-1+C2, 2011). The maximum allowable crack width depends on the environmental classes of SE school buildings, see Table 59 and Table 75.

Table 59: Maximum allowable crack width. Adapted from (NEN-EN 1992-1-1+C2, 2011)

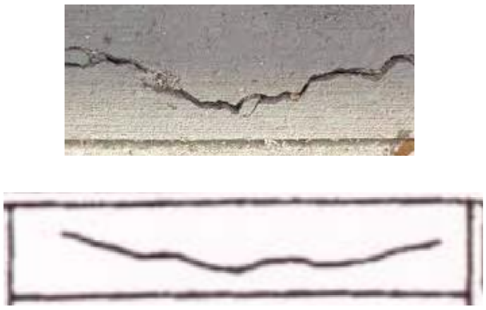
Component	Environmental class	Maximum crack width
Reinforced components	XC1 XC3 XS1	$W_{max} \leq 0.4$ mm $W_{max} \leq 0.3$ mm $W_{max} \leq 0.2$ mm
Prestressed components with prestressing with adhesion (such as prestressed hollow-core slabs and prestressed solid slabs)	XC1 XC3 XS1	$W_{max} \leq 0.2$ mm

In a later next-life phase, the visual inspection measures the crack width with a crack map and cracks magnifier; see Figure 71 (Adema, 2021). Comparing the maximal detected crack width and the possible occurring crack widths gives the general condition score (The International Atomic Energy Agency, 2002). Pay attention to the direction and shape of the crack because cracks can also occur due to deflection, see Figure 72. If longitudinal cracks are visible on concrete load-bearing components, the assessment of the crack must be done with Table 61. Otherwise, the maximum crack width assessment depends on the different allowable maximum crack widths of Table 59. The equivalent condition scores to the maximum crack widths are visible in Table 60.

(a) (b)

Figure 71: Measurement equipment for the crack width. A) crack magnifier and crack map. B) crack map on crack.

Cracks
(a)



Cracks caused by deflection
(b)

Figure 72: Type of cracks. A) normal cracks. B) cracks due to deflections.

Table 60: Degree of cracking. Adapted from (The International Atomic Energy Agency, 2002)

XC1				
Score 1	Score 2	Score 3	Score 4	Score 5
No cracks	$w_{max} \leq 0.4\ mm$	$w_{max} > 0.4\ mm$ and $w_{max} < 1\ mm$	-	$w_{max} > 1\ mm$
XC3				
Score 1	Score 2	Score 3	Score 4	Score 5
No cracks	$w_{max} \leq 0.3\ mm$	$w_{max} > 0.3\ mm$ and $w_{max} < 1\ mm$	-	$w_{max} > 1\ mm$
XS1, prestress				
Score 1	Score 2	Score 3	Score 4	Score 5
No cracks	$w_{max} \leq 0.2\ mm$	$w_{max} > 0.2\ mm$ and $w_{max} < 1\ mm$	-	$w_{max} > 1\ mm$

Table 61: Degree of cracking due to deflection. Adapted from (The International Atomic Energy Agency, 2002)

Deflection / span				
Score 1	Score 2	Score 3	Score 4	Score 5
No deflection	$\frac{\Delta}{L} \leq 1/300$	$\frac{1}{300} \leq \frac{\Delta}{L} \leq \frac{1}{200}$	$\frac{1}{200} \leq \frac{\Delta}{L} \leq \frac{1}{100}$	$\frac{\Delta}{L} > \frac{1}{100}$
Width of crack				
Score 1	Score 2	Score 3	Score 4	Score 5
No cracks	$w_{max} \leq 0.5\ mm$	$w_{max} \leq 1.5\ mm$	$w_{max} \leq 3\ mm$	$w_{max} > 3\ mm$
The total crack length				
Score 1	Score 2	Score 3	Score 4	Score 5
No cracks	$< 6m$	$< 15m$	$< 20m$	$> 20m$

F.2.2.3 Internal deterioration: Alkali-Silica reaction

There are several ways to form an Alkali-Silica Reaction (ASR). Silica from the aggregate reacts with alkalis, sodium-potassium compounds. Alkalis occur in the concrete and seawater environment. The reaction product of an ASR attracts water, the concrete begins to swell, and cracks appear from micro-cracks to visible cracks (Talsma et al., 2019). The cracks are inhomogeneous anisotropic and form a 'map pattern' on the concrete surface. Sometimes, the reaction product, ASR gel, is visible in the cracks. The gel has a white, sometimes glossy yellow colour (Bakker et al., 2002). A visual inspection can detect an Alkali-Silica Reaction.

ASR has been a recognised problem since 1989; since then, concrete mixtures use blast furnace cement (CEM III/B), and there is no chance of ASR (van Berlo, 2019). The risk of a harmful ASR in load-bearing concrete components depends on many factors, such as moist content, alkali content and type of cement used (Talsma et al., 2019). The type of cement that contains alkali is Portland cement.

This research identifies the possible presence of an ASR by the building year and type of cement used. See Figure 73. Often the type of cement is not known; therefore, in a later next-life phase, a visual inspection defines the amount of ASR characteristics present. The possible ASR characters are visible in Figure 74. Per present ASR characteristic, the condition score decreases until all four characteristics are present, visible in Table 62.

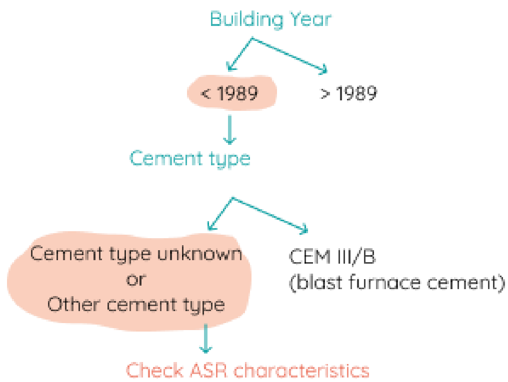
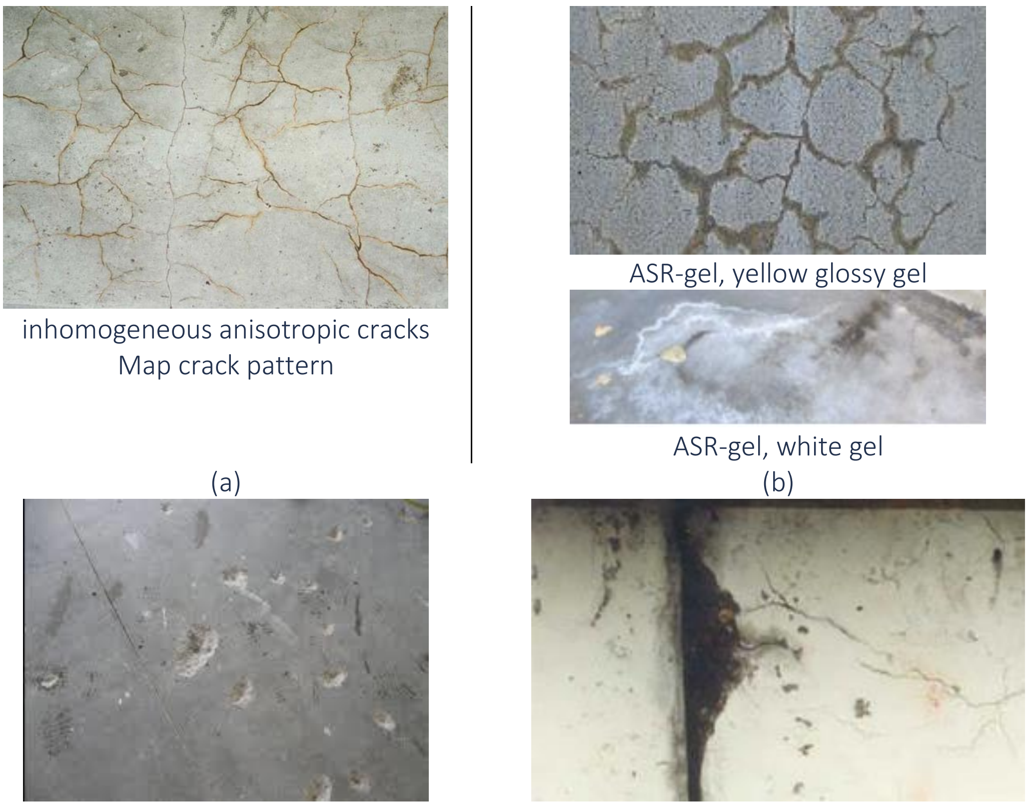


Figure 73: Presence of ASR



Concrete pop-outs (c) | Visible expansion or deformation of the material (d)

Figure 74: The possible ASR characters.

Table 62: Assessment of the presence of ASR. Adapted from (Bakker et al., 2002)

Alkali-Silica reaction				
Score 1	Score 2	Score 3	Score 4	Score 5
> 1989 Or Type of cement used: CEM III/B (blast furnace cement)	1 characteristic	2 characteristics	3 characteristics	4 characteristics

F.2.2.4 Internal deterioration: Internal sulphate attack

Sulphate can occur in concrete due to the aggregate, excessive addition of gypsum in the cement or contamination (Chen et al., 2020). An Internal Sulphate Attack (ISA) can occur if sulphate is present in the concrete mixture (van Berlo, 2019). An ISA results in an expansion reaction that causes cracks in the concrete cover. If the concrete cover cracks, the reinforcement is more exposed to the environment. The cracks are inhomogeneously anisotropic and form a 'tree pattern' on the concrete surface, all kinds of cracks with branches.

The risk of harmful ISA in load-bearing components only occurs if meeting the following three conditions (van Berlo, 2019):

- 'Tree pattern' cracks in the concrete cover,
- Humid environment
- Sulphate-rich aggregate

In the Netherlands, the use of sulphate-rich aggregates is deficient. Concrete mixtures that use CEM I-SR, CEM III/B-SR, CEM III/C-SR, CEM IV/A-SR, and CEM IV/B-SR cement have no change of ISA. In a later next-life phase, during the detailed assessment, laboratory research identifies the concrete composition and the presence of sulphate in the aggregate. In addition, a humid environment only occurs when the concrete load-bearing components are inside a school building with moderate or high air humidity. As described in Table 75, moderate or high air humidity only appears for the exposure class XC3.

This research follows the flow chart of Figure 75 to find out if ISA can be present in the concrete component. Per step in the flow chart, another general condition score applies; see Table 63. In a later next-life phase, a visual inspection identifies if the cracks in the concrete cover have a ‘tree pattern’. Furthermore, in another later next-life phase, laboratory research determines the exact cement type.

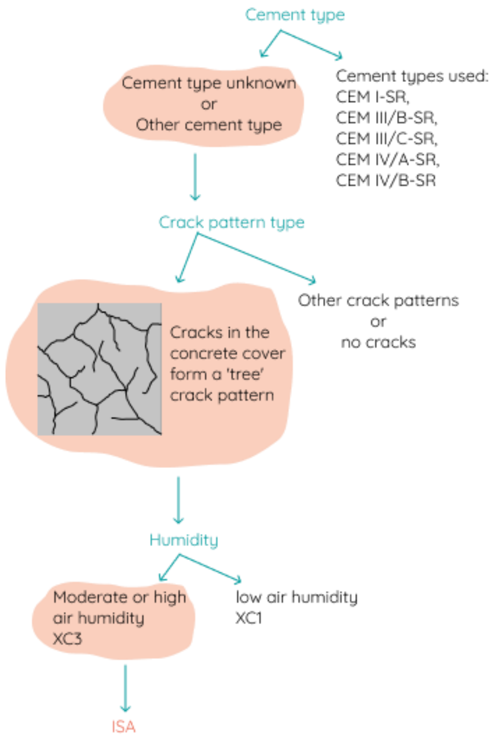


Figure 75: Presence of ISA

Table 63: Internal sulphate attack

Internal sulphate attack				
Score 1	Score 2	Score 3	Score 4	Score 5
Type of cement used: CEM I-SR, CEM III/B-SR, CEM III/C-SR CEM IV/A-SR, CEM IV/B-SR	1 or 2 characteristics			3 characteristics

F.2.2.5 External deterioration: Penetration of sulphates

Sulphate can also penetrate from the outside in SE school buildings near the coast (van Berlo, 2019). The exposure environment of these school buildings is XS1, containing airborne salts. Airborne salts are like airborne chlorides present until 25 km land inwards (Talsma et al., 2019). See Figure 64 for which postcode areas airborne salts can be a problem.

In the case of airborne salts, one of the sulphate attack characteristics is present. This research follows the flow chart of Figure 76 to find out if ESA can be present in the concrete component. Per step in the flow chart, another general condition score applies; see Table 64. Like for ISA, concrete mixtures containing CEM I-SR, CEM III/B-SR, CEM III/C-SR, CEM IV/A-SR, and CEM IV/B-SR cement have no change of ESA. In a later next-life phase, a visual inspection identifies if the cracks in the concrete cover have a 'tree pattern'. Furthermore, laboratory research determines the exact cement type in another later next-life phase.

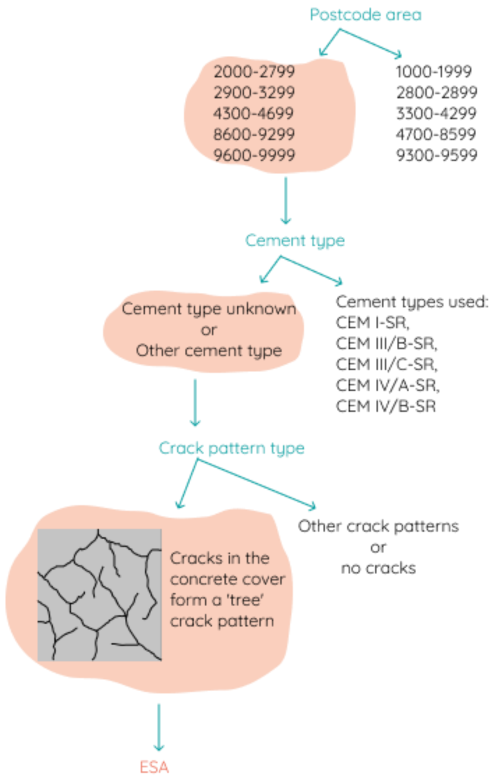


Figure 76: Presence ESA

Table 64: External sulphate attack

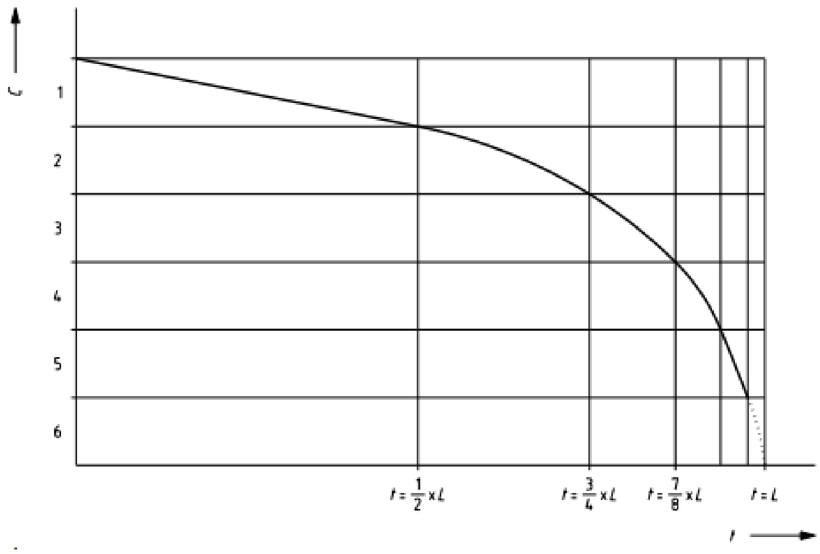
External sulphate attack					
Score 1		Score 2	Score 3	Score 4	Score 5
Cement types used: CEM I-SR, CEM III/B-SR, CEM III/C-SR, CEM IV/A-SR, CEM IV/B-SR	Postcode areas: 0-1999 2800-2899 3300-4299 4700-8599 9300-9599	1 or 2 characteristics	-	-	3 characteristics

F.3 Residual lifespan

The residual lifespan indicates the time a load-bearing component can still perform its function (B. Geldermans, 2020). According to NEN 2767, the residual lifespan of a component depends on the theoretical lifespan (NEN 2767-1+C1, 2019). Brand's layer logic forms the basis for the theoretical lifespan. So, each building component has a different theoretical lifespan, theoretical life cycle. For example, the layer services (installations) has 15 years before replacement is needed. So, there is a link between the theoretical lifespan and the multi-year maintenance of a building. The complete maintenance and replacement cycle of a SE school building is 40 years, based on the layer structure. (E. van Tuil, personal communication, September 14, 2021). The design of the layer structure (construction) fulfils the replacement cycle in 40 years. So, the intended reference service life (RSL), theoretical lifespan, is +/- 40 years of load-bearing components from SE school buildings. The calculation of the residual lifespan is the RSL minus the lifespan of the building (NEN 2767-1+C1, 2019).

For reuse, this way of approaching the residual lifespan can have a negative effect. Therefore, this research roughly estimates the residual lifespan differently; the residual lifespan is calculated based on the governing condition of a load-bearing component (NEN 2767-1+C1, 2019). The highest condition score gives the lowest residual lifespan, which is the governing residual lifespan.

Figure 77 shows the course of the theoretical lifespan based on the condition of a load-bearing component. The condition of the component is a score from 1 to 5, so there are five different outcomes for the rough estimate of the residual life (van Berlo, 2019).



C the condition score
t age
L the theoretical lifespan
RL Residual Lifespan

$$RL1 = L - \left(L * \left(\frac{1}{2}^{(C-1)} \right) \right)$$

Figure 77: Theoretical process of the condition as a function of the lifespan

The theoretical lifespans of Brand's layers are the basis for Table 65. The scores are distributed linearly over the possible residual lifespans. The score for the residual lifespan decreases if the residual lifespan is lower than the reference service life of 40 years (van Berlo, 2019). The potential reuse of a load-bearing component with a residual lifespan of 10 years or lower is very unlikely because the quality is probably insufficient, and recovering the investment costs is not possible in this short amount of time.

Table 65: Grading of the residual lifespan

Residual lifespan	Score
≥ 40 years	1.00
≥ 30 years	0.8
≥ 15 years	0.60
≥ 10 years	0.30
< 10 years	0.10

F.4 Structural properties translated to the current code

F.3.1 FIRE RESISTANCE

This research analyses fire resistance in the field of fire safety. Since this research assumes that load-bearing components not exposed to extreme loads are recoverable, this research does not discuss fire degradation and the fire history. However, reuse of the existing components occurs in new school buildings; therefore, the components must meet the current fire resistance requirements. This research checks whether reclaimed load-bearing components already meet the fire resistance requirements and what is necessary to meet these requirements.

Fire resistance is the criterion for the ability of the load-bearing construction to prevent collapse, fire spread or other failures when exposing the load-bearing construction to a fire of certain severity (NEN-EN 13501, 2021). There must be sufficient time for people to leave the building. Therefore, time in minutes expresses the fire resistance. The reference periods are: 10, 15, 20, 30, 45, 60, 90, 120, 180, 240, 360 minutes (NEN-EN 13501, 2021).

There are three crucial performance criteria for load-bearing components: resistance load-bearing capacity (R), integrity (E), and thermal insulation (I) (NEN-EN 13501-2, 2021). Time also expresses the performance criteria. The most critical performance criteria apply if all three performance criteria are in effect (Zandbergen, 2016). Which performance criteria apply depends on the performance level, building function, and height (NEN-EN 13501, 2021). The building type is a school building, so a utility building without sleeping accommodation. The building height is situation depending. The building height is the distance from the highest floor measured to the measurement level (Zandbergen, 2016). The standards do not mention the performance level of reuse, but reuse of the load-bearing components take place in new school buildings. Therefore, this research assumes the performance level: a new building.

The performance criteria for a permanent fire load density of 500 MJ/m^2 for new non-residential buildings without sleeping accommodation are visible in Table 66. Constructions of concrete or steel most likely give a fire density value of less than 500 MJ/m2, which does not contribute to the fire. If the permanent fire load density is demonstrably less than or equal to 500MJ/m^2, the reduced fire resistance requirement for new buildings with a building height of at least 5m may apply, 60 minutes (Zandbergen, 2016).

Table 66: Fire resistance requirements for new utility buildings without sleeping accommodations. Adapted from (NEN-EN 13501, 2021)

Building Height	Fire resistance [min]	Reduced fire resistance [min]
$\leq$ 5 m	No requirements	-
> 5 m	90	60

Often the fire resistance of load-bearing components is not known; the building documents of a SE school building does not provide information about the fire safety of the building. Not knowing the fire resistance does not hinder the reuse of steel load-bearing components. A fire-resistant coating is sensitive to moisture, and the distribution can be uneven (Steel Construction Institute, 2019b). Therefore, the reuse of steel load-bearing components takes place without any coating or fire protective layer. The next-life phase removes the existing protective layer after reclaiming, and the new design applies a new fire resistance coating to the desired degree.

Good fire resistance is essential for steel components. Steel exposed to fire can quickly deteriorate and loosen its strength (Schoefs et al., 2012). Fire-resistant coating, fire-resistant plaster or sheet material give the steel load-bearing component fire resistance. The fire-resistant coating is a thin intumescent layer that applies to steel load-bearing components that remain visible (L.T. Phan et al., 2010). The fire-resistant plaster and sheet material have a certain thickness to ensure fire resistance.

On the other hand, concrete can better protect itself against fire. The extent to which the concrete protects the reinforcing steel against heat from fire determines the fire safety of concrete load-bearing components (Zandbergen, 2016). The concrete cover determines the protection of the reinforcement. The tensile strength of the reinforced concrete must not deteriorate so that no failure of the load-bearing component can occur (Zandbergen, 2016).

Table 67 shows that the current fire safety requirements for concrete load-bearing components deviate from the withdrawn standards. Accordingly, not all reclaimed load-bearing components meet the current requirements. In addition, the fire safety requirements before 1962 are unknown. Therefore, this research assumes that the minimum concrete cover for fire resistance is equal to the minimum concrete cover for the occurring environmental class. See Table 78. In a later next-life phase, laboratory research gives the exact concrete cover. The applied concrete cover can be more than the minimum prescribed concrete cover.

If the fire safety of the component is insufficient, actions are necessary to meet the current fire safety requirements. Possible actions include adding additional concrete cover, fire-resistant coating, stucco ceiling, or installing sprinklers (Kamp, 2021).

Table 67: Minimal concrete cover for fire resistance of 60 min from GVB 1962 till Eurocode 2 [mm]. Adapted from (Koninklijke instituut van ingenieurs, 1963; NEN 6720, 1995; NEN-EN 1992-1-2, 2005)

Old standards, type of component	Minimal concrete cover [mm]
GBV 1962	
Floors, roofs	20
Beams	30
Columns	35
VB 1974	
Floors, roofs	25
Beams	35
Columns	40
VBC 1995	
Floors, roofs	30
Beams	35
Columns	40
NEN-EN 1992-1-2	
Floors, roofs	35
Beams, columns	40

F.3.2 CONSTRUCTION MATERIAL CONCRETE

F.3.2.1 Composition of concrete

Mixing water with a binding agent, granulate, fillers, and sometimes additives produce concrete construction material. Examples of granulate are sand, gravel and crushed stones. The binding agent for buildings is calcium silicate cement; NEN-EN 197-1 indicates calcium silicate cement with CEM. There are five primary types of cement mentioned in Table 68. The cement reacts with the water as a chemical reaction, hydration and solidifies (Kamp, 2021). The reacted cement with water binds the other elements together. Over time, the concrete hardens and forms a hard, stonelike construction material.

Table 68: Primary cement types. Adapted from (Kamp, 2021; NEN-EN 197-1, 2011)

Cement type	Name	Description
CEM I	Portland cement	Suitable for de-moulding and prestressed load-bearing components. Fast hardening. Start and end strength is high. Light grey colour. 95% Portland cement clinker.
CEM II	Portland-composite cement	Combination of CEM I and CEM III. Less resistance to Alkali-Silica-Reaction and sulphates. 40-90% Portland cement clinker.
CEM III	Blast furnace cement	Suitable for components with standard strength requirements. Begin and end strength is normal. Resistance to Alkali-Silica-Reaction or Sulphates from seawater. Dark grey/blue colour. 65% Portland cement clinker.
CEM IV	Pozzolanic cement	
CEM V	Slag and ash cement	

A filler material is sometimes added to the concrete mixture as an additive or replaces the granules. NEN-EN 197-1 refers to these filler materials with the capital letter(s), described in Table 69.

Table 69: Additive ingredients to the cementitious binding agent. Adapted from (NEN-EN 197-1, 2011)

Additive ingredient	Capital letter	Description
Portland cement clinker	K	Semi-finished product in the manufacture of Portland cement. High CO_2 emission. The three categories A, B, and C, subdivide the clinker content.
Granulated blast furnace slag	S	Obtained by the rapid cooling of slag formed during the melting process of iron ore in a blast

		furnace. Ground as a powder or as granulate
Pozzolanic material	P (natural), Q (natural calcined)	The pozzolans in the concrete mixture form calcium silicate and calcium aluminate compounds with water, which gives the concrete more strength.
Fly ash	V (siliceous), W (calcareous)	Electrostatic or mechanical separation of dust particles from the combustion gases from pulverised coal-fired boilers obtain fly-ash. Silicon or calcium-containing can be in fly ash, which gives the concrete more strength.
Burnt shale	T	In addition to pozzolanic properties, finely ground burnt shale exhibits hydraulic properties like Portland cement.
Limestone	L, LL	Increases the stability stage of the concrete
Silica fume	D	Has strong pozzolanic properties

The combination of the primary cement types and the filler materials define 27 types of cement (NEN-EN 197-1, 2011). The primary type of cement, clinker content (K), filler materials, strength class, and strength development distinguish the 27 types of cement (Kamp, 2021). In addition, due to the exposure, the hardening performance of the concrete differ, which is visible in the grey shade and the sulphate resistance. NEN-EN 206-1 gives requirements for the concrete composition (NEN-EN 206 + NEN 8005, 2017). Insufficient cement can lead to internal degradation of the concrete (van Berlo, 2019).

Based on Kamp's research and table 1 of NEN-EN 197-1, this research considers only the most primary types of cement, all containing some Portland clinker (Kamp, 2021; NEN-EN 197-1, 2011). Portland cement clinker in the concrete mix ensures a long service life of a load-bearing construction (Kamp, 2021). Insufficient cement has excessive sulphate, magnesium oxide, or chalk. Table 70 indicates which primary types of cement and clinker contents this research considers. Kamp's research is fundamental for the analysed cement types (Kamp, 2021).

Table 70: Considered cement types for this research. Adapted from (Kamp, 2021; NEN-EN 197-1, 2011)

Cement type	Description
CEM I	>95% Portland cement clinker
CEM II/A	80-94% Portland cement clinker
CEM II/B	65-79% Portland cement clinker
CEM III/A	35-64% Portland cement clinker
CEM III/B	20-34% Portland cement clinker
CEM III/C	5-19% Portland cement clinker

The concrete mixture used depends on the one hand on the desired strength and structural properties and the other hand on the surrounded environment of the concrete load-bearing component. The surrounded environment determines the durability of the concrete load-bearing component.

F.3.2.2 Concrete strength class

The compressive strength of the concrete (f_c) defines the concrete's strength—different strength forms different strength classes (NEN-EN 1992-1-1+C2, 2011). The most common strength classes are visible in Table 71. 'C' stands for concrete. The first number is the characteristic cylinder compressive strength, and the second number is the characteristic cube compressive strength.

Strength classes higher than C50/60 are high strength concrete (HSC) classes with high strengths and density (Braam & Lagendijk, 2011). HSC concrete requires more care during processing and is often more expensive than regular concrete strength classes. The higher strength classes are more from the recent years (Braam & Lagendijk, 2011)e concrete strength class used depends on the design of the building, the method of execution, and the project's costs (Kamp, 2021). This research focuses on existing load-bearing constructions; therefore, only the regular concrete strength classes are relevant. However, prefab load-bearing components often contain higher strength classes because the production conditions are exceeding; manufactured indoors. Nonetheless, the goal is a fast process, fast hardening of the concrete. Higher-strength concrete can harden faster (Braam & Lagendijk, 201).

Table 71: structural properties concrete in N/mm^2. Adapted from (Braam & Lagendijk, 2011; NEN-EN 1992-1-1+C2, 2011)

Strength class	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60
Characteristic cylinder compressive strength f_{ck}	20	25	30	35	40	45	50
Design value compressive strength f_{cd}	13.3	16.7	20.0	23.3	26.7	30.0	33.3
Design value axial tensile strength f_{ctd}	1.03	1.20	1.35	1.50	1.64	1.77	1.90
Average value axial tensile strength f_{ctm}	2.21	2.56	2.90	3.21	3.51	3.80	4.07
Modulus of elasticity E_{cm}	30000	31000	33000	34000	35000	36000	37000

Over the years, there have been several concrete standards. Each standard indicates the concrete quality differently, with different strength classes and structural properties. Starting with the Reinforcement Concrete Regulations (GBV). GBV 1912, 1918, 1930, 1940, 1950 and 1962 have been released. Subsequently, the Concrete Regulations (VB) were issued, VB 1974 and

1984. The Concrete Construction Regulations (VBC) in 1995 and the current standard in 2012, the European standard Eurocode 2 (van uffelen, 2012).

Testing determines the compressive strength of the concrete. The calculation values for the concrete quality differ from standard to standard due to the different tests and safety margins applied (Bouwdienst Rijkswaterstaat, 2004). Before 1974, the tests were carried out on three concrete test cubes with 200 mm ribs after hardening for 28 days. The average value of the three test cubes was the cube compressive strength. Comparing the average cube compressive strength with the allowable compressive stress from the standard gives the difference was the margin of safety applied (van uffelen, 2012). From 1974, six concrete test cubes with 150 mm ribs gave the concrete compressive strength and the standard deviation. Since the Eurocode of 2012, the concrete tests have been carried out with cylindrical test pieces with a height of 300 mm and a diameter of 150 mm, resulting in different compressive strengths. The cylindrical compressive strength of concrete is lower than the cube compressive strength (van uffelen, 2012).

To equalize and compare the difference in concrete compressive strengths over the years, Bouwdienst Rijkswaterstaat converted the concrete compressive strengths of GBV 1950, GBV 1962 and VB1974 to the strengths of VBC 1995 (Bouwdienst Rijkswaterstaat, 2004). This research translates the concrete compressive strength of VBC 1995 to Eurocode 2; it equalises the VBC 1995 concrete strength to the concrete cube compressive strength of the current Eurocode 2. The concrete strength classes of 1950 lead to the characteristic concrete compressive strength for load-bearing components older than 1950.

In addition, before 1974, there was a general safety factor of 1.8 (Koninklijke Instituut van ingenieurs, 1963). As the spread of concrete quality decreased, the general safety factor could decrease to 1.7 in VB 1974 (Nederlandse Normalisatie-instituut, 1977). Bouwdienst Rijkswaterstaat has drawn up an adjusted material factor for the GBV standards to consider the difference in the spread of concrete quality. The applied material factor for GBV 1912 till GBV 1962 is $\gamma_m = 1.2 * 1.8/1.7 = 1.27$ (Bouwdienst Rijkswaterstaat, 2004).

In VBC 1995, 85% of the maximum concrete quality for the short-term load determines the design value for the concrete compressive strength. In addition, concrete deforms up to 15% over time, reducing the long-term design value for the compressive strength by 85% over the short-term design value for the compressive strength of the concrete (NEN 6720, 1995). The design compressive strength is the characteristic compressive strength multiplied by $0.85 * 0.85 = 0.72$. In the Eurocode of 2012, the compressive design strength is the characteristic compressive strength divided by 1.5 $(\frac{1}{1.5} = 0.67)$, reducing the design compressive strength compared to VBC 1995 (NEN-EN 1992-1-1+C2, 2011). Table 72 shows the concrete strength classes from the old norms converted into the current Eurocode 2.

Table 72: Structural properties from GVB 1912 till VB1995 in N/mm². Adapted from (Bouwdienst Rijkswaterstaat, 2004; NEN-EN 1992-1-1+C2, 2011)

Old standards, Strength class	$f_{ck,cube}$ *	$f_{cd,cube}$ **	γ_m ***	Comparison with EC2	
GBV 1912					
- 135 kg cement with 500-600 l gravel and sand	10	5.25	1.27	<C8/10	
- 135 kg cement with 400-500 l gravel and sand	13	6.82	1.27	C8/10	C12/15
- 135 kg cement with 400 l gravel and sand	16.5	8.66	1.27	C8/10	C12/15
GBV 1918					
125 kg cement with 200 l gravel and sand	16.5	8.66	1.27	C8/10	C12/15
GBV 1930					
125 kg cement with 200 l gravel and sand	13	6.82	1.27	C8/10	C12/15
GBV 1940					
- Concrete without building control	10	5.25	1.27	<C8/10	
- Concrete with building control	13	6.82	1.27	C8/10	C12/15
- Concrete with building control	16.5	8.66	1.27	C8/10	C12/15
GBV 1950					
- B150 (Concrete without building control estimated safety)	10	5.25	1.27	<C8/10	
- B200 (Concrete with building control and guaranteed compressive strength)	13	6.82	1.27	C8/10	C12/15
- B250 (Concrete with building control and guaranteed compressive strength)	16.5	8.66	1.27	C8/10	C12/15
GBV 1962					
K160	11	5.77	1.27	**<C8/10**	
K225	16	8.40	1.27	**C12/15**	
K300	22	11.54	1.27	C8/10	C12/15
K400	33	17.31	1.27	**C12/15**	C20/25
K450	37	19.41	1.27	**C20/25**	C25/30
VB 1974 / 1984					
B30	30	16.67	1.2	C20/25	C25/30
B45	45	25	1.2	C30/37	C35/45
B60	60	33.33	1.2	C40/50	C45/55
VBC 1995					
B25	25	13.89	1.2	**C12/15**	**C20/25**
B35	35	19.44	1.2	**C25/30**	**C30/37**
B45	45	25	1.2	C30/37	
B55	55	30.56	1.2	C35/45	
B65	65	36.11	1.2	C40/50	

* Characteristic compressive strength

** Design compressive strength, $f_{cd,cube} = \frac{f_{ck,cube}}{1.5 * \gamma_m}$

*** Material factor

Moreover, the various standards also applied different overall safety factors. Over the years, the safety philosophy has evolved and become more accurate (van uffelen, 2012). In the past, large safety factors guaranteed the safety of concrete structures because little knowledge about concrete technologies was available. The safety margins before VB 1974 depend on the concrete strength classes and steel grades. The research of van Uffelen concluded that the larger safety margins of the past could lead to more robust concrete load-bearing components than with the margins of Eurocode 2 (van uffelen, 2012). Concrete from the past can be more robust, but it has more uncertainties for the concrete and the steel reinforcement because of the fewer requirements. Furthermore, there was no check for the actual concrete and steel quality, and the allowed error margins were many times higher than is currently allowed. The safety margins include these uncertainties.

The design life of new concrete load-bearing components must meet the requirements of the current standard Eurocode 2, NEN-EN 1992-1-1. These requirements also apply to reusable load-bearing components. The quality of old, existing load-bearing components can be good enough for reuse, but in a later next-life phase, laboratory research must give the exact concrete and steel strength and the quality. This research assumes the lowest possible range of concrete quality to get a first conservative indication of the concrete compressive strength class (Bouwdienst Rijkswaterstaat, 2004). In addition, this research assumes the lowest possible steel quality to get a first conservative indication of the steel grade.

If the building or construction documents do not mention the concrete strength class, Table 72 gives the range of the concrete strengths used at the time of construction of the SE school building. Table 74 gives the range of the steel grade used at the time of construction of the SE school building. The quality of the concrete and steel used is equal to the minimum strength used at that time. If the building documents mention the concrete strength class, Table 72 can express the concrete strength class in the current concrete strength class. The same applies to the steel grades. Table 74 can express the steel grade in the current steel grade.

F.3.2.3 Reinforcement steel strength and stiffness

In this research, the construction material concrete contains steel reinforcing bars (rebar) to improve the low tensile strength of the concrete. Different reinforcement tensile strengths give different steel grades, and each steel grade defines the properties of the steel reinforcing bars. (NEN-EN 1992-1-1+C2, 2011). Table 73 shows the properties of the different steel grades. 'Fe' stands for Ferrum, iron, and 'B' stands for concrete. The number is the characteristic tensile strength (Braam & Lagendijk, 2011).

Table 73: structural properties of steel reinforcement in N/mm^2. Adapted from (Braam & Lagendijk, 2011; NEN-EN 1992-1-1+C2, 2011)

Strength class	B500A	B500B	B500C
surface	Smooth, dented, ribbed	Dented, ribbed	ribbed
tensile strength $f_{t;k}$	500	500	500
Design value tensile strength $f_{t;d}$	435	435	435
The strain of reinforcement at maximum load ε_{su}	3	5	7.5

In response to the RBBK of Bouwdienst Rijkswaterstaat, this research assumes that the material quality of reinforcing steel in the past was the same as the current one (Bouwdienst

Rijkswaterstaat, 2004). Each standard from the past indicates the steel grades and properties differently(Bouwdienst Rijkswaterstaat, 2004). Although in the past, the relatively unknown higher steel grades had a greater material spread and therefore, lower allowable stresses were assumed. This research compares the steel grades of the old standards with the current standard NEN-EN 1992-1-1 (Hochstenbach & de Vree, 2006; NEN-EN 1992-1-1+C2, 2011; van uffelen, 2012) in Table 74.

Table 74: Steel structural properties from GVB 1912 till VBC 1995 in N/mm^2. Adapted from (Braam & Lagendijk, 2011; NEN-EN 1992-1-1+C2, 2011)

Old standards, Strength class	f_{tk}*	f_{td}**		ε_{su}*** [$^0/_{00}$]	Comparison with EC2
GBV 1912 (smooth steel)					
	370	322			FeB220 HWL
	440	383			FeB400 HWL, HK
	500	435			FeB500 HWL, HK
GBV 1918 (smooth steel)					
1B	360	313			FeB220 HWL
GBV 1930					
St. 37 (smooth steel)	370	322			FeB220 HWL
L.St. 52 (smooth steel)	520	452			FeB500 HWL, HK
Sv 36 (ribbed steel)	360	313			FeB220 HWL
Sv48 (ribbed steel)	480	417			FeB400 HWL, HK
GBV 1940					
Merchantable quality	-	-			
St. 37 (smooth steel)	370	322			FeB220 HWL
L.St. 52 (smooth steel)	520	452			FeB500 HWL, HK
Sv 36 (ribbed steel)	360	313			FeB220 HWL
Sv48 (ribbed steel)	480	417			FeB500 HWL, HK
GBV 1950					
QR22	220	191		5	FeB220 HWL
QR24	240	209		5	FeB220 HWL
QR30	300	240	260	5	FeB220 HWL
QR 36	360	270	313	4	FeB220 HWL
QR42	420	300	365	4	FeB220 HWL FeB400 HWL, HK
QRn36	360	270	313	2.75	FeB220 HWL
QRn42	420	300	365	2.75	FeB220 HWL FeB400 HWL, HK
QRn 48	480	330	417	2.75	FeB220 HWL FeB400 HWL, HK
QRn 54	540	360	469	2.75	FeB400 HWL, HK FeB500 HWL, HK
GBV 1962					
QR22	220	191		5	FeB220 HWL
QR24	240	209		5	FeB220 HWL
QR32	320	270	278	5	FeB220 HWL
QR40	400	330	348	4	FeB220 HWL

QR48	480	390	417	3.25	FeB400 HWL, HK
QRn32	320	270	278	2.75	FeB220 HWL
QRn40	400	330	348	2.75	FeB220 HWL
QRn 48	480	390	417	2.75	FeB400 HWL, HK
VB 1974 / 1984 / VBC 1995					
FeB220 HWL	220	191		5	
FeB400 HWL, HK	400	348		4	
FeB500 HWL, HK	500	435		3.25	
FeB500 HKN	500	435		2.175	

* Characteristic tensile strength

** Design compressive strength $f_{td} = \frac{f_{tk}}{\gamma_m}$. $\gamma_m = 1.15$ $(reinfrocement\ steel)$

*** strain by the maximum load

F.3.2.4 Environmental class

The durability of concrete load-bearing components depends on the expected external influences and whether the component's resistance is sufficient during its lifespan. The durability of reinforced concrete load-bearing components depends on the risk of water and air damage to the reinforcing steel. So, protecting the reinforcement steel guarantees the durability of the concrete load-bearing components. NEN-EN 1992 sets requirements for the concrete density, concrete cover quality, and thickness of the concrete cover (NEN-EN 1992-1-1+C2, 2011).

NEN-EN 206 + NEN 8005 links the expected external influences to the possible defects. The expected external influences distinguish six different environmental influence classes (NEN-EN 206 + NEN 8005, 2017). 'X' stands for exposure, the environmental class, the second letter indicate the attack mechanism, and the number indicates the degree of the presence of water saturation (Braam & Lagendijk, 2011). Table 75 shows the possible environmental classes of SE school buildings within the scope of this research.

Table 75: Environmental classes for load-bearing components from existing SE school building. Adapted from (NEN-EN 1992-1-1+C2, 2011)

Environmental class	Location and exposure
XC1	• The concrete load-bearing component is inside a school building with low air humidity. • The environment exposes the component to air, and moisture can cause carbonation of the concrete.
XC3	• The concrete load-bearing component is inside a school building with moderate or high air humidity. • The environment exposes the component to air, and moisture can cause carbonation of the concrete.
XS1	• The concrete load-bearing component is inside a school building that is near the coast. • The environment exposes the component to airborne salt, chlorides originating from seawater.

F.3.2.5 Concrete cover

The concrete cover protects the reinforcement steel from external influences. The concrete cover is the distance between the concrete surface and reinforcement. The greater the distance, the better concrete protects the reinforcement from external toxic substances and high temperatures (Kamp, 2021). The environmental conditions, the environmental class determines the distance of the concrete cover. In addition, the concrete cover also protects the reinforcement against fire and ensures a safe transfer of bonding forces (NEN-EN 1992-1-1+C2, 2011).

The environmental class and strength class determine the minimum concrete cover regarding durability ($c_{min,dur}$) (Kamp, 2021; NEN-EN 1992-1-1+C2, 2011). A construction class S4 is assumed. A distinction is made between floor and roof components and beam and column components because floor and roof components require less concrete cover than beam and column components. See Table 76 and Table 77. The higher the environmental class, the greater the minimum thickness of the concrete cover. For prestressed load-bearing components, the requirements for the minimum concrete cover for these components are stricter because it is of great importance that the reinforcement steel is not affected.

Table 76: Minimum concrete cover per concrete strength class and environmental class for construction class S4. Beam and column load-bearing components. Adapted from (NEN-EN 1992-1-1+C2, 2011)

Environmental requirements for minimum concrete cover $c_{min,dur}$ [mm]						
	For normal reinforced steel			For prestressed reinforced steel		
Construction class	XC1	XC3	XS1	XC1	XC3	XS1
C20/25	15	30	40	25	35	45
C25/30	15	30	40	25	35	45
C30/37	15	30	40	25	35	45
C35/45	15	25	40	25	30	45
C40/50	15	25	35	25	30	40
C45/55	15	25	35	25	30	40
C50/60	15	25	35	25	30	40

Table 77: Minimum concrete cover per concrete strength class and environmental class for construction class S4. Floor and roof load-bearing components. Adapted from (NEN-EN 1992-1-1+C2, 2011)

Environmental requirements for minimum concrete cover $c_{min,dur}$ [mm]						
	For normal reinforced steel			For prestressed reinforced steel		
Construction class	XC1	XC3	XS1	XC1	XC3	XS1
C20/25	15	25	35	25	30	40
C25/30	15	25	35	25	30	40
C30/37	15	25	35	25	30	40
C35/45	15	20	35	25	25	40
C40/50	15	20	30	25	25	35
C45/55	15	20	30	25	25	35
C50/60	15	20	30	25	25	35

The minimum concrete cover for bonding ($c_{min,b}$) ensures the transfer of bonding forces from the steel to the concrete (NEN-EN 1992-1-1+C2, 2011). The minimum concrete cover regarding bonding is at least the same as the reinforcement bar diameter ø, with bundled bars equal to the equivalent reinforcement bar $ø_n$ (Braam & Lagendijk, 2011). See Equation 5. The minimum concrete cover regarding the bonding of steel and concrete is outside the scope of this research (Kamp, 2021).

Equation 5: minimum concrete cover regarding the bonding. Adapted from (NEN-EN 1992-1-1+C2, 2011)

$$c_{min,b} = \min\,(ø, ø_n)$$

The minimum concrete cover is the strictest minimum cover requirement regarding durability and bonding. The minimum concrete cover is at least 10 mm. The minimum cover is the maximum of the three minimum coverages, Equation 6. Table 77 shows that the minimum concrete cover regarding durability is always larger than 10 mm. In combination with the minimum concrete cover regarding bonding, which falls outside the scope, $c_{min,dur}$ forms the basis for the minimum cover. Table 78 shows the applied concrete covers according to the GBV 1912, 1918, 1940, 1950, 1962, VB1974 and VBC 1995. Comparing the concrete covers from the past with the required concrete covers makes an initial estimation of whether the concrete cover is thick enough to protect the steel. Table 78 show that the concrete covers are generally too small compared to the modern environmental classes. In a later next-life phase, laboratory research gives the exact concrete cover. The initial next-life phase assumes a concrete cover of 10mm if the building documents do not provide information about the concrete cover.

Equation 6: Minimum concrete cover. Adapted from (NEN-EN 1992-1-1+C2, 2011)

$$c_{min} = \max\big(c_{min,dur}; c_{min,b}; 10\ mm\big) = c_{min,dur}$$

Table 78: Minimal concrete cover from GVB 1912 till VBC 1995 in N/mm2. Adapted from (Bouwdienst Rijkswaterstaat, 2004)

Old standards Strength class	Minimal concrete cover [mm]
GBV 1912	
Floors, roofs	10
Beams	25
Columns	15
GBV 1918 / 1930 / 1940	
Floors, roofs	10
Beams	25
Columns	35
GBV 1950	
Floors, roofs (≤ 120 mm)	10
Floors, roofs (>120 mm)	15
Beams	20
Columns	30
GBV 1962	
Floors, roofs	10
Beams	20
Columns	25
VB 1974 / 1984	
Floors, roofs	10
Beams	20
Columns	25

Prestressed +10 mm	
VBC 1995	
Floors, roofs	15
Floors, roofs (Sea environment)	30
Beams	25
Beams (Sea environment)	35
Columns	30
Columns (Sea environment)	40

The total concrete cover is the nominal concrete cover (c_{nom}). The nominal concrete cover include the error safety margins, the execution tolerance (Δc_{dev}). The execution tolerance for the Netherlands is 5mm (NEN-EN 1992-1-1+C2, 2011).

Equation 7: Nominal concrete cover. Adapted from (NEN-EN 1992-1-1+C2, 2011)

$$c_{nom} = c_{min,dur} + \Delta c_{dev}$$

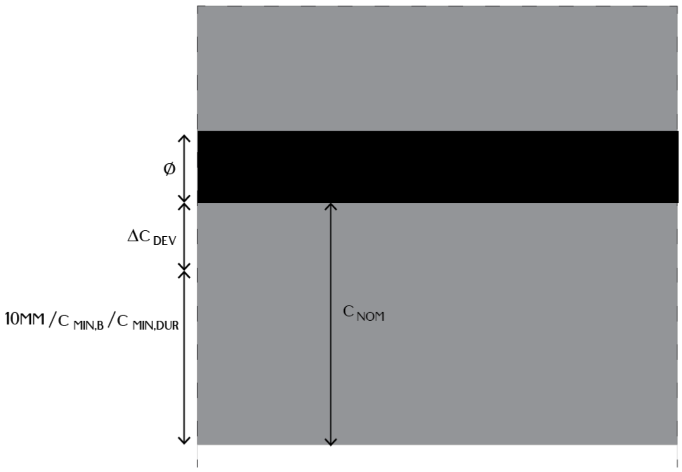


Figure 78: Concrete cover, c_{nom}, c_{dev}, $c_{min,dur}$, $c_{min,b}$, ø. Adapted from (Braam & Lagendijk, 2011)

F.3.3 CONSTRUCTION MATERIAL STEEL

F.3.3.1 Composition of steel

Structural steel is an alloy consisting of iron and carbon and a percentage of chemical elements, such as Silicon, Manganese, Phosphorus, Sulphur, Nitrogen, and Copper (NEN-EN 10025-2, 2019). The chemical composition of structural steel strongly correlates with the structural properties. There are maximum limits on the percentage of the different chemical elements present. In addition, the chemical composition indicates the durability and weldability of the reclaimed structural steel (Steel Construction Institute, 2019b).

Carbon, Manganese, and chopper influence the steel's weldability, all expressed in carbon (NEN-EN 10025-2, 2019). Therefore, the steel's Carbon Equivalent Value (CEV) can measure the weldability and durability of the steel. This research assumes the maximum allowable percentage of chemical elements for the initial next-life phase (Steel Construction Institute, 2019b). Table 79 presents the initial indication of the CEV for reclaimed steel, the maximum CEV.

Table 79: max CEV according to material standard NEN-EN 10025-2 table 5. Adapted from (NEN-EN 10025-2, 2019)

Steel grade	Max CEV [%]
S235	0.37
S275	0.42
S355	0.47
S460	0.49

F.3.3.2 Steel strength

The composition and physical properties of the steel define the steel strength and steel grade (NEN-EN 1993-1-1+C2+A1, 2016). See Table 80 for the most common steel grades. 'S' stands for structural steel, and the number indicates the elastic deformation, the yield stress $f_{y,nom}$. Commonly used steel grades are S235, S275, and S335. S460 is a high strength steel grade with high yield and tensile strength (Vereniging FME-CWM, 2008). The used steel grade depends on the design of the load-bearing construction, the method of execution, and the project's costs. The steel strength values of Table 80 are suitable for steel thickness between 3 mm and 60 mm (Steel Construction Institute, 2019b). This research assumes that the steel's material quality and the steel strength in the past is equal to now.

Table 80: Structural properties steel in N/mm². Adapted from (Simoes da Silva et al., 2017; Steel Construction Institute, 2019b)

Steel grade	S235	S275	S355	S460
Minimum Yield strength $f_{y,min}$	267	313	391	490
Mean yield strength $f_{y,mean}$	293	343	426	529
Minimum ultimate strength $f_{u,min}$	397	452	505	560
Mean ultimate strength $f_{u,mean}$	432	492	540	595
$\frac{f_{y,mean}}{f_{u,mean}}$	1.47	1.43	1.26	1.12

The full designation of steel grade also includes a steel subgrade. The steel subgrade is the impact toughness of the steel, and the amount of energy determines the impact toughness required to break the steel at a specific temperature. The specific temperature for this research is the indoor temperature; the room temperature is 20 ^{o}C. In addition, fatigue is not a problem with the reclaimed load-bearing components. Based on the SCI report on structural steel reuse, this research assumes the minimum impact energy required of 27 J, which is equal to the steel subgrade of JR

Over the years in the twentieth century, various Technical Foundations Building construction (TGB) appeared. The standards indicate the steel grade differently, different steel grades with different structural properties. The relevant standards are TGB 1949 and 1955 (N 1055), 1973 (NEN 3851) and 1990 (NEN 6770). Since 1991 there has been a general European standard for construction steel, EN 10025, for the designation and material properties (de Boer, 1995). The revised version of this standard is in effect today. Comparing the steel grades of the old standards with Eurocode 3 (NEN-EN 1993-1-1+C2+A1, 2016) gives Table 81.

The steel production standards of the Eurocode does not include the steel quality before 1970 because guaranteeing the quality is not possible (Steel Construction Institute, 2019b). Steel reuse, therefore, is limited to the steel produced after 1970. This research assumes that steel used after 1970 meets the material properties of modern design standards (Steel Construction Institute, 2019b). The analysed SE school buildings show that 3/15 of school buildings with steel frame structures are from before 1970. Due to the small number of SE school buildings from before 1970 with a steel frame structure, these SE school buildings are outside the scope of this research.

Table 81: Structural properties from TGB 1972 till Eurocode 3 in N/mm². Adapted from (Nederlands Normalisatie-instituut, 1977; NEN 6770, 1990)

Old standards, Steel grades	yield strength	ultimate strength	Comparison EC3
TGB 1972 (NEN 3851)			
St 37 (Fe 360)	215-235	340-470	S235
St 44 (Fe430)	255-275	410-540	S275
St 50	275-295	470-610	S275
St 52 (Fe510)	335-355	490-630	S355
St 60	315-335	570-710	S355
St 70	345-365	670-830	S355
TGB 1990 (NEN 6770)			
S235	215-235	340-470	
S275	255-275	410-540	
S355	335-355	490-630	

* For thicknesses between 3-60 mm.

Moreover, the various standards also applied different overall safety factors. Over the years, the safety philosophy has evolved and become more accurate. In the past, significant safety factors guaranteed the safety of steel structures because little knowledge about steel was available. Uncertainties in the material properties are considered by dividing the strength by a material factor. The material factor is 1.0 in each steel standard. TGB 1990 makes a distinction between the material factor for the yield strength ($\gamma_m = 1.0$) and the tensile strength ($\gamma_m = 1.25$) (NEN 6770, 1990). The load factor is different for the different standards. In TGB 1955 and 1972 the load factor for steel structures is 1.5 (Nederlands Normalisatie-instituut, 1977). In TGB 1990, the load factor has a permanent load, factor 1.2, and variable load, factor 1.5 (ABT, 2020). In a later next-life phase, laboratory research gives the exact yield point and ultimate strength with a non-destructive hardness test. Therefore, from the standards, the steel grade can be derived.

APPENDIX G

INTERVIEWS, SURVEYS

This research conducted three interviews with structural engineers and two surveys with six demolition contractors and seventeen structural engineers and contractors. All engineers and contractors are working in the field of school buildings. This appendix elaborates the interviews and the survey for the structural engineers and contractors in Dutch. The survey for the demolition contractors is in English. In addition, this appendix includes the two surveys and the survey results. The survey for the demolition contractors gives information about the grading of the demountability indicator. The structural engineers and contractors survey gives information about the sub-indicators for the breadth of application and the grading of the component length indicator and component type indicator.

G.1 Interview 1 Structural engineer

G.1.1 2D COMPONENTS

G.1.1.1 In-het-werk-gestorte vloer

Om in-het-werk-gestort beton uit een gebouw te halen moet je gaan zagen om delen eruit te halen, om vervolgens te gaan vervoeren. Vervoeren zit vast aan maximale afmetingen. Dan krijg je bijvoorbeeld platen die 7.2 m lang zijn en 1.2 m breed. Je kan zagen wat je wilt, als het beton maar tilbaar is (het gewicht van de vloer) en transporteerbaar is.

In-het-werk-gestorte vloeren worden over het algemeen altijd doorgaand ontworpen, over dragende muren of balken heen. Het moment loopt dus van onder wapening naar boven wapening.

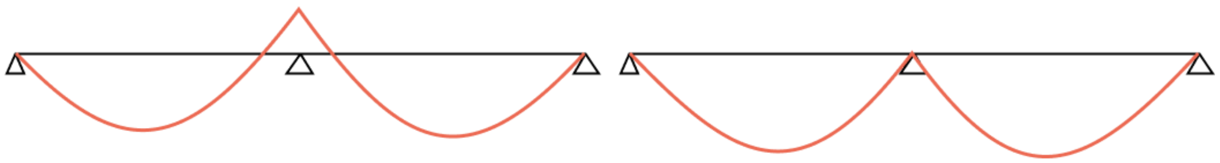


Figure 79: Moment line of, a) continuous 2D component, b) 2D component on two supports

Als je in de nieuwe situatie dan dezelfde stramienmaat gebruikt van 7.20m dan ga je de plaat dus opleggen op 2 steunpunten en niet meer als doorgaande ligger. Dit betekent dat het moment aan de onderzijde veel groter wordt, hiervoor is er dus voor dezelfde vloerbelasting meer onder wapening nodig. Terwijl het moment eerst door zowel de onder wapening als boven wapening werd opgenomen. De capaciteit van de plaat is dus lager als in de eerste situatie.

Daarnaast worden in-het-werk-gestorte vloeren in schoolgebouwen vaak gebruikt bij een kolommen structuur van 7.5m in het vierkant, dus dan krijg je wapeningstroken over de kolommen en dan gaat de vloer 2 richtingen op dragen. De vraag is dan welk stukje moet je dan gaan uitknippen en wat kan je dan nog met dat stukje?

De kwaliteit van een in-het-werk-gestorte vloer kan je prima inschatten als tekeningen en berekeningen bekend zijn. Als je daarnaast ook nog de wapening op tekeningen hebt staan is er helemaal geen twijfel over mogelijk. Een eerste indicatie van een in-het-werk-gestorte vloer zal opgevat kunnen worden uit de constructieberekeningen van het gebouw. Stel de vloer is berekend op 4.0 kN/m^2 dan vergelijk je dat met de nieuwe belasting, als die ver daaronder ligt zal die waarschijnlijk voldoen. Mits de vloer op 2 steunpunten was ontworpen in het huidige gebouw. Daarnaast bevestigen boorproeven of het beton daadwerkelijk zal voldoen. *Voor de respondent ligt de grootste zorg van hergebruik bij hoe de vloer ontworpen is, waar was het voor bedoeld en hoe is de wapening die erin zit. En dat bepaalt voor hem wat je ermee kan.*

G.1.1.2 Breedplaatvloer

De meeste breedplaatvloeren zijn tweezijdig gerekend. In de breedplaatschil zit dan je hoofdwapening. Deze leggen ze neer van balk naar balk. Daarna wordt het boven wapeningsnet gewapend en maken ze er een doorgaande vloer van, die als één geheel werkt. Als laatste wordt dan de druklaag gestort. Een breedplaatvloer kan dus gezien worden als een in-het-werk gestorte vloer. Als je die vloer dan weer gaat zagen dan heb je ook weer het probleem dat je een vloer veld doorzaagt wat eigenlijk doorgaand berekend is. Dit is dus hetzelfde probleem als bij een in-het-werk-gestorte vloer, maar ook voor een bollen plaatvloer. Al deze vloeren zijn vaak doorgaand berekend en niet voor steunend op 2 steunpunten.

De respondent ziet niet in hoe je een In-het-werk gestorte vloer of breedplaatvloeren kan hergebruiken. Het is ontworpen voor specifieke configuraties en die kom je gewoon niet meer tegen. De enige manier hoe de respondent het voor zich ziet om deze vloersystemen her te gebruiken is om ze weer doorgaand toe te passen. Dit kan door de bovenkant van de druklaag ter plaatse van de kolommen ruw te hakken en daar een nieuwe druklaag over te storten met nieuwe boven wapening. Je maakt als het waren een nieuwe arm. Het gewicht van de plaat is meer geworden maar het weerstandmoment is de hoogte in het kwadraat waardoor die sneller zal toenemen dan het toegenomen gewicht. Hierdoor kan je met minder wapening toch een grotere belasting opnemen. Echter vindt de respondent dat dit zo incidenteel is en erg ver afzit van hergebruik.

G.1.1.3 Prefab elements

Een prefab element zelf zal geen asbest bevatten volgens de respondent.

Prefab elementen zijn bijna allemaal tweezijdig opgelegd uitgerekend dus als je die loshaalt kan je die heel makkelijk ergens opnieuw inzetten voor eenzelfde capaciteit. Het losmaken en verwijderen van kanaalplaatvloeren uit een schoolgebouwen moet voorzichtig gebeuren doordat er geen boven wapening in een kanaalplaatvloer zit. Aan de uiteindes wordt de vloer opgetild. Als de vloer toch een klap krijgt of verkeerd wordt opgetild dan kan er een boven moment ontstaan in de vloer, dit zal een scheur van boven naar beneden veroorzaken. Vervolgens wordt de vloer weer door zichzelf dichtgetrokken en de scheur is niet meer zichtbaar. De respondent zou dus het sloop proces willen monitoren, zodat je ziet wat er gebeurt, want als die scheur toevallig net op 1 m van het einde van de vloer zit, kan je dan nog aan dwarskracht overbrengen

G.1.1.4 Kanaalplaatvloeren

7.20m is in het verleden een hele traditionele maat geweest voor kanaalplaatvloeren. Kanaalplaatvloeren zonder afwerklaag of druklaag komt zover de respondent weet niet voor in schoolgebouwen. Er zit bijna altijd een afwerkvloer over een kanaalplaatvloer, doordat de platen nooit helemaal recht liggen en daar rechtstreeks een vloerbedekking of zijl oplegt gaat dat allemaal kapot. De vloeren gaan verschillend kruipen en krijgen verschillende belastingen. Daarom wordt er 5cm zandcementvloer overheen gelegd en die is daarna helemaal glad en dan kan je er wat opleggen. De aanhechting tussen vloer en afwerklaag is niet heel goed waardoor deze afwerklaag makkelijk is weg te hakken en dan zou je die platen wel kunnen hergebruiken.

Het cement tussen de kanaalplaten moet er ook uitgehakt worden of de platen moeten op zijn minst op dit punt doorgezaagd worden. Dit cement wordt aangebracht om belasting wisselingen tegen te gaan. Afbrokkelen ter plaatse van de naad en daarna zagen en waarna afbrokkelen van het cement tussen de platen is de beste manier op zo min mogelijk schade.

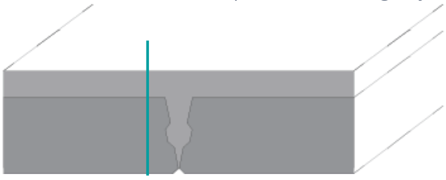
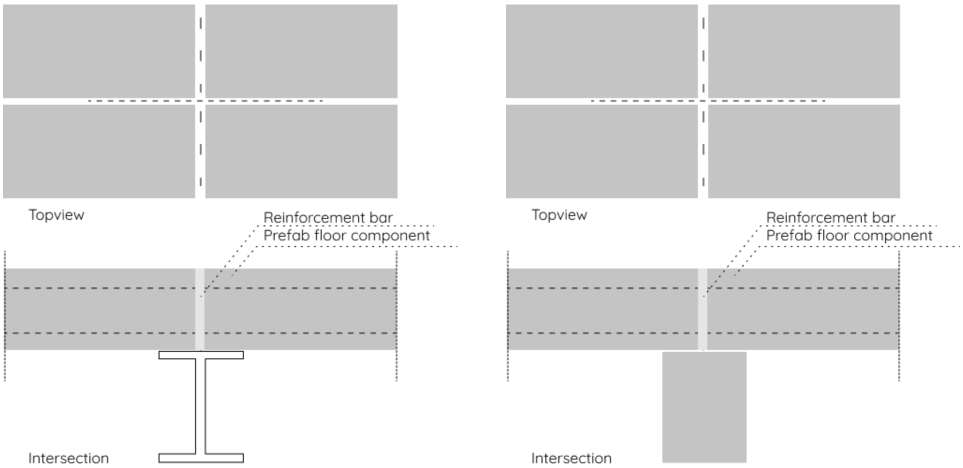


Figure 80: Sawing spot for prefab 2D components

De kanaalplaatvloer kan ook meteen doorgezaagd worden en de ballast van de afwerklaag of druklaag wordt meegenomen in het nieuwe ontwerp. Als een kanaalplaatvloer hergebruikt wordt in een schoolgebouw zal er altijd weer een nieuwe afwerklaag toegevoegd moeten worden op de kanaalplaten.

Vaak wil men toch schijfwerking creëren tussen de vloeren. Daarvoor is of een druklaag gebruikt of twee kanalen van de vloer zijn open gehakt om ter plaatse van het knooppunt wapeningstaven in te leggen en deze staaf in te storten. De complexe verbindingen maakt het nog complex voor hergebruik.



(a) (b)

Figure 81: A) steel beam – prefab floor component. B) prefab beam – prefab floor component.

Een kanaalplaatvloer met druklaag heeft wapening over het steunpunt heen lopen. Door het loszagen van de plaat kan de plaat met niet-functionerende druklaag opnieuw gebruikt worden.

- Wat gedaan kan worden is een strook van 1 m breed aan beide kanten eraf zagen. Dat kan je dan natuurlijk fabrieksmatig doen. Als je het helemaal los gaat hakken dan zie je daar een wapeningsnet vrij komen. En dan ga je dat later ga je daar een nieuw stukje druklaag aanbrengen, dat zou kunnen. Is wel bewerkelijk, Maar het kan wel.
- Een andere optie is, een nieuwe druklaag over de oude druklaag aanbrengen. Dan heb je een plaat met een druklaag die eigenlijk niks doet, die ligt daar gewoon en dan ga je daarna een nieuwe druklaag overheen aanbrengen. Dus opruwen en opnieuw opstorten, dit wordt gedaan over het gehele oppervlak. Economisch onvoordelig en je haalt capaciteit weg, want als je nieuwe laag eroverheen legt komt er zo weer 5, 6 cm overheen wat weer 120 kg extra draagvermogen afneemt. Scholen worden bijna altijd

ontworpen op 400 kg ontworpen, een extra 120kg brengt de het vermogen als snel in de gevarenzone. Daarnaast is de norm voor scholen al omhoog aan het gaan.

- Optie 3, de plaat terug naar de fabriek brengen. Bij het laatste stukje wordt het beton weggehaald, zodat er een laslengte gemaakt kan worden en het wapeningsnet doorgetrokken kan worden. Dus we gaan een stukje inkorten. Hij is ontworpen voor 7m en als we naar 6m gaan kan er toch ineens meer belasting gehaald worden doordat de lengte van de plaat in het kwadraat gaat. Hiermee kunnen de nieuwbouw eisen gehaald worden en kan het gebouw weer 50 jaar vooruit. De vraag is alleen is dit lonend? Ideaal gezien wil je het element in een keer van de ene plek naar de andere plek brengen.

Ideaal gezien wil je gewoon dat een element geclassificeerd wordt op belastingcapaciteit, lengte van de kanaalplaatvloer, of de kop is vrij gehakt of niet, afwerklaag wel of niet, druklaag wel of niet, beschadigingen. Dus bijvoorbeeld voor een belastingcapaciteit, de vloer kan 4 kN/m^2.

G.1.1.5 TT vloeren

Een TT-vloer is voor scholen niet zo handig. Het is een vloer met dikke ribben en de vloer zelf is maar heel dun, 80mm. Er is bij deze vloer te weinig massa om geluidisolatie te bieden. Extra geluidisolatie is nodig. Daarnaast geeft de doorsnede van de TT-vloer problemen met de installatie buizen, waardoor de buizen onder de hoge ribben door moeten, geeft een hoge plafond hoogte wat onnodig is.

G.1.1.6 Voorgespannen massieve vloer

Respondent ziet geen voordelen in van een massieve voorgespannen vloer ten opzichte van een kanaalplaatvloer. Waarschijnlijk kom je dit zo weinig tegen dat het niet relevant is voor hergebruik.

G.1.1.7 Staalcomposiet vloeren

Deze typen vloeren vallen binnen de breedplaatvloeren en in-het-werk gestorte vloeren. Heeft een erg kleine overspanning. Over de stalenplaat gaat er een laag met in-het-werk gestorte vloer met boven wapening. Het zijn dus doorgaande vloeren, waardoor de capaciteit weer een probleem geeft. Het zijn wel vloersystemen die in één richting dragend zijn. Daarnaast worden deze vloeren niet heel vaak toegepast in schoolgebouwen, hooguit in delen van het schoolgebouw. Het is meer project specifiek toegepast om plaatselijk specifieke vormen toe te passen.

G.1.2 STRUCTURAL PROPERTIES

G.1.2.1 Constructieve eigenschappen

5 belangrijke eigenschappen die de respondent wil weten voor het toepassen van hergebruikte elementen:
- Wapening en wapeningsconfiguratie (hoe ligt de wapening erin en voor welk moment en dwarskracht is het ontworpen)
- Betonklasse (betonsterkte)
- Onbeschadigd of niet, sloopproces monitoren
- Scheurvorming
- Geen elementen hergebruiken die onderhevig zijn geweest aan brand
- Betondekking

De respondent is van mening dat de betondekking hoogstwaarschijnlijk altijd op het minimum gezeten heeft. Met de minste wapeningsdekking kan je de grootste arm creëren waardoor je met de minste wapening de grootste kracht kan opnemen. Door de jaren heen is de minimale betondekking groter geworden. Extra dekking tegen het beton aan zetten, heeft geen nut want dat hecht niet aan. Dus dan zou je eerst moeten opruwen en dan een extra laag er tegenaanzetten die wel aanhecht. De respondent denkt dat voor de brandveiligheid deze extra laag niet werkt omdat deze er gelijk afspat bij hoge temperaturen. Voor brandveiligheid moet er een andere oplossing komen, dus een extra brandwerende laag creëren zoals gips.

Is een vloer een onderdeel van een hoofddraagconstructie. Als er een plaat bezwijkt wat is er dan aan de hand? De hoofddraagconstructie blijft staan en het heeft geen voortschrijdende instorting tot gevolg. Alleen als het een brandcompartiment is moet de vloer 60 minuten brandwerend zijn. Voor een dak kunnen deze vloeren met te weinig dekking altijd worden toegepast doordat een dak geen brandwerendheidseisen heeft. Ook qua capaciteit kan het toepassen van een vloer als een dak altijd. Dit zou dus op een veilige simpele manier moeten kunnen. Alleen wordt de vloer niet volledig benut op deze manier, echter zou de niet functioneren druklaag de capaciteit van de vloer iets doen verlagen.

G.1.2.2 Brandwerendheid stalen profielen

Vaak krijgen stalen profielen die in het zicht liggen een brandwerende laag, deze laag is vaak een verfcoating van een aantal mm dikte, de dikte van de coating staat voor de beschermingsduur van het staal. Tijdens brand, dus vanaf een bepaalde temperatuur, zal de coating zich uitzetten als een schuimlaag die het hele staal zal bedenken en beschermen tegen de beschadiging en bezwijking. Bij het demonteren van de stalen balken of kolommen, zal er een stalen strop bevestigd worden en deze zal het element omhoogtillen. Dit veroorzaakt schade aan de coating. Voor hergebruik is het dus van belang dat de coating opnieuw wordt aangebracht voor de nieuwe situatie.

Staal in het binnenklimaat hoeft niet verzinkt te worden, zolang er geen condens kan optreden. Dus de enige coating voor staal in het binnenklimaat is een brandwerende coating.

G.1.3 COMPONENTS LENGTHS

G.1.3.1 Horizontal lengths

Als je naar scholen kijkt zit je vaak aan 7.2 of 7.5 m, kleiner zie je steeds minder omdat er meer flexibiliteit gecreëerd wordt in het gebouw. Om hergebruik van kortere elementen toe te passen moet het ontwerp dus aanpassen aan het element en niet het element toepasbaar zijn in het ontwerp. De manier van ontwerpen moet dus gaan veranderen. Dit moet heel erg afgestemd worden op de afmetingen van de lokalen, die vaak rechthoekig zijn. De school levert met kortere elementen wel in op flexibiliteit, maar je wint wel weer op hergebruik en afval creëren. Het ligt er dus aan wat het doel van het project is, willen we ontwerpen met de elementen die we hebben of willen we zo veel mogelijk flexibiliteit creëren, wat komt door grotere overspanningen.

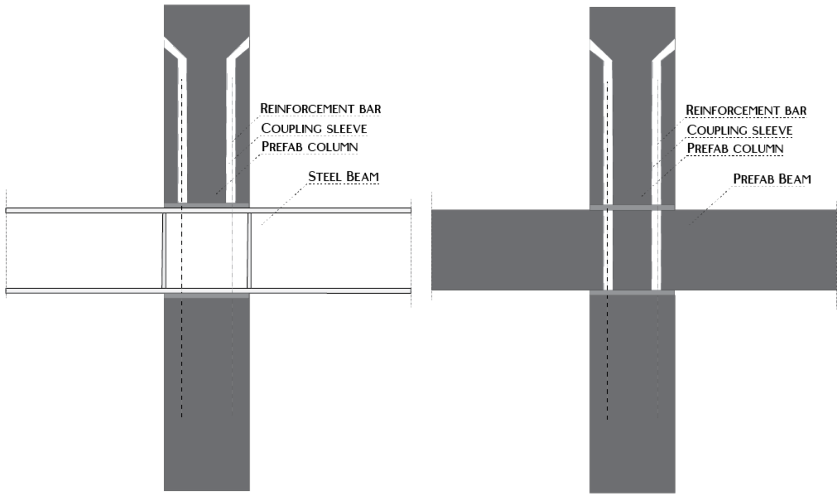
Maatvoering, meervouden van 0.6 dus 1.2 of 1.8. 7.8 voor parkeren is een gangbare maat. Ideale flexibiliteit maat voor de scholen en klaslokalen is niet ideaal voor de constructie. Functioneel is vaak de doorslag. Terwijl de visie van de school na 10-15 jaar veranderd. Maar daar denken schoolbesturen toch niet over na.

Ideaal gezien voor constructeurs wil je korte balken en lange kanaalplaten zodat de hoogte van vloer en ligger gelijk uitkomen en er minder extra elementen nodig zijn voor de verbindingen.

G.1.3.2 Verdiepingshoogte

Verdiepingshoogte in schoolgebouwen zijn vaak 2.8 of 3.0 m. Daarnaast is de verdieping van de begane grond bijna altijd groter, bijvoorbeeld 4.0m (wel regelmatig). Voor de onderwijslokalen geldt 2.8 en de gangzones 2.6, dit heeft te maken met de kanalen van de luchtsystemen. Constructief gezien is de verdiepingshoogte dus nog groter, het systeemplafond wordt dan niet meegerekend.

G.1.4 1D COMPONENTS, PREFAB COLUMNS



Prefab kolommen worden vaak met stekken en aanstorten verwezenlijkt. Bij het demonteren worden de kolommen afgezaagd ter plaatse van de verbinding. De bestaande stekken hebben dus geen functie meer. De bestaande stekken bevinden zich in de 4 hoeken van de kolommen. Er zullen dus nieuwe stekken geplaatst moeten worden, in het midden tussen de 4 hoekpunten in. Wat moeilijker is, hoe krijg je de aanstortvoorziening goed in een schuine hoek. Stekken zijn ongeveer 80-90 cm. Stekken moeten vanaf boven worden aangegoten anders komt er lucht in en komt het beton er niet in.

G.1.5 BEGANE GROND VLOEREN (KANAALPLAATVLOER)

Begane grondvloeren die gemaakt zijn van kanaalplaatvloeren hebben vaak geen druklaag. Wel zit er isolatielaag onder de kanaalplaatvloer. Je hebt minder vaak een schijfwerking nodig in de funderingsvloer, doordat er maar een klein beetje horizontale belasting op deze vloer werkt.

De isolatielaag onder de kanaalplaatvloer krijg je er niet meer vanaf, wel kan deze kanaalplaat hergebruikt worden voor een funderingsvloer. De isolatielaag is wel vaak te dun, maar de juiste isolatielaag voor de geëiste RC-waarde kan eraan geplakt worden.

G.2 Interview 2 Structural engineer

G.2.1 RESEARCH SCOPE

De scope van het afstuderen is gefocust op prefabbeton en stalen kolommen, balken, vloeren en daken. Daarnaast mogen deze elementen niet onderhevig zijn geweest aan extreme belastingen zoals aardbeving, brand en dynamische belastingen. De respondent geeft aan het hier mee eens te zijn, aangezien hij/zij liever niet werkt met elementen die onderhevig zijn geweest aan extreme belastingen voor de zekerheid van de kwaliteit en constructieve eigenschappen van het element.

G.2.2 END RESULT RESEARCH, TOOL

Als je met een projectgroep al rondloopt op een bestaand gebouw, dan heb je met behulp van de tool meteen wat expertise in huis. Hierdoor kunnen mensen meteen bekijken wat wel kan niet kan. Aangezien HEVO geen constructieve kennis heeft is de tool binnen HEVO erg handig om wat makkelijker en sneller de inschatting te kunnen maken of iets herbruikbaar is of niet.

G.2.3 VISION ON REUSE

1. Wat is u kijk op hergebruiken van constructie elementen?

"Ik ben voor het hergebruiken van constructie elementen, wel het liefste in de situatie waar ze oorspronkelijk geplaatst zijn zoals het geval is bij renovaties. Bij renovaties is het altijd de kunst en de uitdaging om de bestaande constructie te hergebruiken en op plekken waar nodig wat te versterken in plaats van een geheel nieuwe constructie gebruiken." – antwoord email
De respondent is voor hergebruik maar de randvoorwaarde moeten wel goed zijn.

2. Als de situatie zich voor doet zou je dan constructieve elementen hergebruiken? En wat zijn de aspecten die je dan graag zou willen weten van het element?

Hoe is het element eraan toe?
Wat kan het element aan?
Wat is de staat nu? Dus bijvoorbeeld bij verweerd staal dat de doorsnede zodanig is aangetast, verroest is, dat de doorsnede eigenlijk niet meer volledig is. Of er zitten er gaten in de doorsnede terwijl je eigenlijk dadelijk toch meer belasting kwijt wilt, kan dat dan nog?
Voor betonnen constructies, betonbeschadiging zoals betonrot of blootliggende wapening, scheurvorming.
Dit zijn eigenlijk de aspecten die de respondent wil weten bij een bestaande constructie die blijft staan, zoals bij renovatie.

Hergebruiken van elementen van locatie A naar locatie B is lastiger. Hergebruik van betonnen onderdelen is lastiger dan stalen onderdelen. Kijk bijvoorbeeld naar een kanaalplaatvloer met afwerklaag of een druklaag, dit maakt al een flink verschil. Kanaalplaatvloeren zijn wat dat betreft relatief fijn om her te gebruiken en al helemaal als ze los eerst ergens zijn toegepast omdat er dan bijna niks mee hoeft te gebeuren. Alleen de voegvulling, maar deze voegvulling is redelijk makkelijk door te zagen of anders deels te verwijderen. Maar dat is niet per se nodig. Wel zou de respondent op het moment van hergebruik van een kanaalplaatvloer willen weten wat de draagkracht in eerste instantie was, omdat hij/zij de aanwezige wapening wil weten. Zodat je weet wat je er daarna weer mee kan.

Eigenlijk wil de respondent net als bij een nieuwe kanaalplaatvloer weten wat die precies nodig heeft. Voor een nieuwe situatie bepaald de respondent aan de hand van een eerste berekening wat hij/zij ongeveer nodig heeft aan wapening, hoogte etc. Vervolgens gaat de informatie in de uitvoeringsfase weer naar de onder leverancier en die levert een idee aan en dan ga je weer checken of alles wel klopt en overeenkomt. Deze check wil de respondent nog steeds kunnen doen met een hergebruikt element.
Zowel het leg plan als de constructieve berekening is gewenst van de elementen. De afmetingen en het type element worden hierdoor bekend. En daarmee de capaciteit, sparingen en welk type voorspanning en de hoeveelheid wapening.
Een andere optie is uitgaan van het minimale, maar dan kom je misschien niet altijd goed uit.

In eerste instantie wil je weten wat de vloer heeft belast en ook als die vanuit een eerdere norm is berekend, wat betekend dat dan voor de draagkracht. Vanuit daar gaat de respondent kijken naar de nieuwe situatie. In een nieuw schoolgebouw wordt een vloercapaciteit ontworpen en doorgerekend op 4 kN/m^2. In het geval van hergebruik moet er dus gecontroleerd worden wat de ontwerp vloercapaciteit was en of die $\leq$ 4.0 kN/m^2. Als de capaciteit lager is zijn er dan andere functies in het schoolgebouw die minder capaciteit nodig hebben die dan deze vloer kunnen gebruiken. De respondent zou als eerste indicatie het bouwjaar en de functie gebruiken om te kijken met welke capaciteit vroeger gerekend is. Daarnaast wil de respondent natuurlijk ook de kwaliteit van het element weten.

G.2.4 2D COMPONENTS

Het typen vloersysteem wordt vaak gekozen aan de hand van de vorm van de school. De voorkeur ligt eigenlijk altijd wel voor kanaalplaatvloeren, alleen worden ook vaak breedplaatvloeren gekozen.
In een voorbeeld wat de respondent liet zien is er bewust gekozen voor breedplaatvloeren omdat de school een vorm heeft waarin kanaalplaatvloeren niet kunnen worden toegepast, door de vervelende hoekjes en afrondingen. Voor een rechttoe rechtaan ontwerp meer is een kanaalplaatvloer voordeliger.

Breedplaatvloeren zijn vaak in 2 richtingen dragend. Breedplaatvloeren zijn volgens de respondent snel project specifiek in verhouding tot kanaalplaten. Daarnaast kunnen breedplaatvloeren op verschillende plekken bijlegwapening hebben, hierdoor is een breedplaat element niet zo continu als een prefab element. Kanaalplaten kan je in dat opzicht sneller hergebruiken door de standaardisatie van de elementen en één richting dragend zijn. Voor een breedplaatvloer moet je dus meer weten wat er in het materiaal zit, bij een kanaalplaatvloer is dit allemaal al bekend. Kanaalplaten hebben daarnaast als voordeel dat ze in de fabriek gemaakt zijn, waardoor de doorsnede, de locatie van de wapening en de hoeveelheid allemaal al bekend is. Bovendien is de kwaliteit met een certificaat bevestigd.

Als de respondent kanaalplaten wil hergebruiken wil hij/zij dat het liefste in de standaardafmeting, de oorspronkelijke afmeting en zonder toplaag. Alleen in sommige gevallen worden er afwerklagen of druklagen toegepast. Met de afwerklaag is het los hergebruiken van een kanaalplaatvloer realiseerbaar maar met een druklaag is dit een stuk moeilijker en kosten intensief. Daarnaast wil de respondent het liefste schijfwerking in het schoolgebouw, wat gerealiseerd wordt door de druklaag. Maar zij/hij denkt dat dit ook mogelijk is met andere oplossingen, wat mogelijk is als de bouw verder innoveert en doorontwikkeld. Maar voor nu zou de respondent het betonoppervlak opruwen en een nieuwe druklaag aanbrengen. Dan heeft hij/zij toch iets meer voorkeur voor een druklaag ten opzichte van een afwerklaag, dit is psychisch omdat mocht er geen goede hechting zijn blijft het geheel door de wapening toch wat beter bij elkaar op die ene plaat waar de hechting dan toch wel weer goed was.

Daarnaast weet je per fabrikant per dikte van kanaalplaat wat de opties zijn qua draagkracht, voorspan strengen en welke voorspanning. Je hebt dus meer input en meer zekerheid over de draagkracht zelf en eigenlijk dus ook de kwaliteit van het element.

Een voorgespannen massieve geprefabriceerde vloer geeft meer massa aan het gebouw, waardoor die door de respondent minder geliefd is dan de kanaalplaatvloer. Als een kanaalplaatvloer zonder druklaag 100% herbruikbaar zou zijn dan zou de massieve variant 85% zijn. Dit doordat de onderconstructie ook weer zwaarder moet zijn. Aan de andere kant als de druklaag achterblijft op de vloer is dit extra gewicht minder in verhouding op de massieve vloer dan op een kanaalplaatvloer. De voorkeur van de respondent gaat uit naar een licht vloersysteem.

De respondent heeft nog geen schoolgebouw gezien met TT-vloeren. In het ontwerp zal minder snel gekozen worden voor een TT-vloer omdat je best wel wat hoogte kwijt bent met de hoge ribben. De constructie hoogte is dus hoog, maar de installatie moeten ook oversteken en deze installatie hoogte moet dus onder de constructie hoogte door. De verdiepingshoogte wordt dus erg groot.

Terugkomend op een breedplaatvloer. Een breedplaatvloer lijkt erg op een in-het-werk gestorte vloer. Beiden worden toegepast in ontwerp specifieke situaties. Als je kijkt naar hoe een breedplaatvloer geleverd wordt, ruwe bovenkant met uitstekende tralies zodat het gestorte cement goed hecht aan het geprefabriceerde gedeelte. Echter is door dit geprefabriceerde onder gedeelte is een breedplaatvloer meer gestandaardiseerd. De wapening is vaak bij deze vloertypes doorlopend. Je ontwerp in de nieuwe situatie dus op de capaciteit van de onder wapening. Met een druklaag kan er nog iets van hoogte gewonnen worden maar er is een grote kans dat de capaciteit van de oude situatie niet gehaald kan worden. Het enige wat kan is opnieuw een doorlopende vloer creëren door de druklaag dusdanig dik te maken dat het fungeert als boven wapening.

G.2.5 COMPONENT LENGTHS

Balken hebben vaak een lengte tussen de 5 en 8 m, afhankelijk van staal of prefabbeton. Wat je vaak ziet in scholen is dat er best wel grote overspanningen gebruikt worden, door middel van kanaalplaten of breedplaatvloeren. Deze elementen zijn vaak 7.5 m en 9.0 m. Deze waarden zijn opgezocht in de ontworpen scholen door het bedrijf waar de respondent werkt.
De schoolprojecten waar de respondent bij
betrokken is geweest werd er echt gehamerd op een flexibele indeling en dan zelfs ook voor stabiliteitselementen. Ze willen een vrij indeelbare plattegrond hebben. Hierdoor is de schijfwerking van vloeren juist extra belangrijk. Waardoor de respondent vaak een druklaag toepast in vloeren.

Voor kolommen is de constructieve hoogte 3.60 – 3.80 en 4.00. Dit is afhankelijk van wat de uitstraling was en wat het schoolbestuur wil bereiken met het gebouw. Er wordt vaak gerekend met een verdiepingshoogte van 3.3 tot en met 3.70 m.

“In de toekomst zal het ontwerp zich moeten aanpassen aan een beschikbare constructie element of moet moeten elementen zich aanpassen aan het ontwerp?”
Ik denk wel echt dat je naar beide kanten moet gaan als je als doelstelling hebt dat je meer hergebruik wil toe gaan passen. Daar moet de architect ook al rekening mee kunnen houden, dan kan je niet blijven hangen in het oude. Dit gebeurt nu vaak nog te weinig. Kijkend naar de stramien maten moet er echt gehamerd worden op dat de stramienmaten die de architect aanhoudt. De respondent geeft aan dat er meer bekend moet zijn over de beschikbare constructie elementen zodat architecten en constructeurs daar wat mee kunnen gaan doen. Hierin zal nog geïnnoveerd moeten worden, want zover de respondent weet kan een architect nog te weinig ontwerpen met herbruikbare elementen.

G.2.6 STRUCTURAL PROPERTIES

De respondent wil graag een eerste indicatie krijgen van de kwaliteit van het element. Vroeger was er minder kennis over materialen, dit geeft marges in de materiaalveiligheidsfactoren en de daadwerkelijke staalsterkte. Bijvoorbeeld de minimale staal sterkte van S235, het staal kan echter een vloeigrens hebben van 280 waardoor het nu geclassificeerd zou worden als S275. Materialen zouden dus gunstiger kunnen uitkomen. De respondent wil dus de staalkwaliteit weten voordat hij/zij er mee gaat werken, dit kan door middel van het bekijken van oude tekeningen en berekeningen of door trekstaafjes te maken van een van de maatgevende stalen constructie elementen. Daarnaast zou de respondent graag van de maatgevende constructie elementen willen weten of de doorsnede heel hard veranderd is of niet, heeft het staalprofiel wel nog de gewenste afmetingen, de toleranties moeten vallen binnen de gegeven marges. De lijfdikte en flensdikte moeten wel de gewenste waarde hebben. Dit is minder van belang voor praktische profielen. Als deformatie is ontstaan door corrosie, zorg ervoor dat corrosie stopt. Daarna kun je gaan kijken wat er nog over is van het staal, waar kan je mee werken. Uit een visuele inspectie kan al heel veel informatie komen. Vervolgens als dus daar de corrosie blijft waar het zit, dan ga je gewoon in eerste instantie kijken of dit iets wat maatgevend is, en wordt het element al op zijn zwaarste belast, of was het gewoon meer praktisch. Als het meer praktisch is, dan heeft het vaak niet zoveel effect. Anders zou de respondent in kaart brengen wat de dikte van een flens is en wat de tolerantie is [mm].

Voor de brandveiligheid van stalen constructie elementen zal de respondent de constructie inpakken of een coating aanbrengen. Echter dit is situatie specifiek en een keuze van de architect. De respondent zou het liefste de constructie niet inpakken.

Het hergebruiken van boutgaten is voor de respondent afhankelijk van waar de boutgaten zitten, is het bijvoorbeeld op je kopplaat. Of zitten er in de ligger zelf bijvoorbeeld enorme sparingen, dan zou de respondent in eerste instantie kijken of er nog voldoende moment en dwarskrachtcapaciteit over is om de kracht op te nemen, of moet er verstevigd worden door het aanbrengen van schotjes of zelfs de spring dichtmaken. Voor de verbindingen zou de respondent eerst de verbindingen gaan bekijken en anders wordt het met consoles werken in plaats van met een kopplaat werken. Het is dus erg situatie afhankelijk.

Voor een betonnen constructie zou de respondent eerst kijken hoe de constructie in elkaar zit. Vervolgens zou hij/zij van de maatgevende elementen ook wel echt boorproeven laten doen en een visuele inspectie om schade mechanismes zoals betonrot in kaart te brengen. De respondent zou voor de indicatie van hergebruik van tevoren al de betonsamenstelling willen weten op maatgevende plekken in kolom, balk en vloeren uit de hoofddraagconstructie (door boorproeven).

Zoals te zien in de tabel over de betonsterktes van 1912 tot nu, is te zien hoe slecht de betonsterkte eerst was maar je ziet ook dat vanaf 1962 ook een aanzienlijke switch omhoog en meer diversiteit in de sterkteklassen. Je wilt als constructeur weten waar je aan toe bent omdat hier een enorm verschil zit in de sterktes. Voor de sterkte klassen van voor 1962 zou de respondent conservatief rekenen met de laagste sterkte klassen, vanaf 1962 zou de respondent eerst de betonsamenstelling willen weten voordat ze kan gaan rekenen aan de constructie.

De betondekking heeft een flink effect bij brand. De respondent hoeft niet helemaal in het begin te weten wat de betondekking is, behalve als uit de visuele inspectie blijkt dat er een aantastingsmechanisme heerst op het beton, zoals betonrot of blootliggende wapening. Als boorproeven worden uitgevoerd, kan er meteen gekeken worden naar de betondekking zodat die ook bekend is. Uiteindelijk moet de betondekking natuurlijk bekend zijn om te weten of een constructie ingepakt moet worden voor de brandveiligheid of niet. Een andere optie is conservatief omgaan met de betondekking en uitgaan van de minimale betondekking en de aanvullende veiligheid voor brand toepassen door de constructie in te pakken. Deze laatste optie is de respondent geen voorstander van doordat dan je constructie niet meer zichtbaar is en dat vindt hij/zij zonde.

G.3 Interview 3 Structural engineer

G.3.1 RESEARCH SCOPE

60% van de schoolgebouwen in Nederland is verouderd. Het is niet per definitie zo dat de individuele constructie elementen niet meer voldoen aan de technische en functionele eisen. Er wordt gekeken of bestaande constructieve elementen opnieuw ingezet kunnen worden in een nieuw schoolgebouw. (*De scope van het afstuderen is gefocust op prefabbeton en stalen kolommen, balken, vloeren en daken uit middelbare schoolgebouwen (MAVO, HAVO, VWO). Daarnaast mogen deze elementen niet onderhevig zijn geweest aan extreme belastingen zoals aardbeving, brand en dynamische belastingen.*)

Van april tot en met september heb ik literatuuronderzoek gedaan naar hergebruik van constructie onderdelen. In de maanden april, mei en juni ben ik de stadsarchieven ingedoken om kennis op te doen over de constructie elementen die gebruikt zijn in schoolgebouwen in de afgelopen jaren (1900-2015). In de maand oktober worden er interviews gehouden onder constructeurs om de opgedane kennis voor te leggen en hun visie te zien over hergebruik, met voor- en nadelen.

Het uiteindelijke doel van dit afstuderen is om HEVO te helpen bij de keuze voor hergebruik. Waarbij een werknemer van HEVO kan beslissen of een element herbruikbaar is of niet, ondanks het gebrek aan constructieve kennis. Een tool die ik ga ontwikkelen zal dienen als hulpmiddel voor het gemis aan constructieve kennis.

G.3.2 VISION ON REUSE

De respondent doet veel herbestemmingsprojecten. Hierbij is geen cases hetzelfde. Er is een grote diversiteit in gebouwen. In het begin kan de structuur overzichtelijk overkomen maar als je op detail niveau gaat kijken zijn er heel wat uitdagingen.

Hergebruik van constructieve elementen ligt voor de respondent heel erg aan wat voor elementen er hergebruikt worden. Voor stalen balken en kolommen ziet de respondent hergebruik voor zich. De respondent heeft twijfels voor hergebruik van beton.

Welke karakteristieken van een vloer zou je willen weten voor hergebruik mogelijk is?
- wapening
- beton sterkteklasse
- veiligheidsklasse
- veranderlijke en blijvende belastingen

Eigenlijk alle berekeningskarakteristieken.
Ja uiteraard de wapening, wapening, beton, sterkteklasse.
Als er helemaal aan het begin van de hergebruikfase wordt gekeken of het mogelijk is, is voor de respondent de belangrijkste karakteristiek de veranderlijke ontwerpbelasting. Op basis daarvan kan er een conclusie getrokken worden of hergebruik mogelijk is of niet.

G.3.3 REUSE STEEL

Hergebruik van stalen balken en kolommen. Als daar de uiteindes van afgesneden worden kunnen deze heel goed hergebruikt worden, doordat je teruggaat naar het uitgangsprofiel. Daarvan wil de respondent wel weten waarvoor het profiel gebruikt is. Bijvoorbeeld vermoeiing bij een kraanbaanligger. Het uitgangspunt van dit afstuderen is dat de elementen statisch gebruikt zijn. Hierdoor kunnen bestaande stalen balken en kolommen gezien worden als nieuwe elementen.

Voor hergebruik van staal is de staalsoort van belang voor de respondent. De respondent zou dus trekproefjes met het staal willen doen voor dat hij/zij de elementen hergebruikt.

G.3.4 2D COMPONENTS

Grofweg gezien heb je twee hoofdsystemen. Als je een mooi orthogonaal stramien hebt met een beuk en dan lokalen, gang en weer lokalen. Een rechthoekig stramien, dan is kanaalplaat gewoon het systeem. Waarbij ideaal gezien in de korte richting de liggers en in de lange richting de vloeren. Maar voor een wat grilliger ontwerp met vloeiende lijnen, organische vormen of overstekken aan de gang of gevelzijde dan is een in-het-werk-gestorte vloer of een breedplaatvloer logischer om te kiezen. De vloeren kunnen dan flexibeler gekozen worden, zonder gebonden te zitten aan de maatvoering van een plaat. Een kanaalplaat kan bijvoorbeeld alleen afgezaagd worden op 45graden, wat beperkingen geeft in de vormgeving. Daarnaast voor wat grotere belastingen en overspanningen is vaak een massievere vloer nodig, wat in-het-werk-gestorte vloer kan zijn.

G.3.4.1 In-het-werk gestort beton

In-het-werk-gestorte vloeren kunnen klein gezaagd worden voor hergebruik. Het nadeel is echter dat je de eindverankering van je wapening kwijt bent, zoals haarspelden. Je hebt dan alleen langswapening en geen kopwapening, of boven en onder wapening zonder randwapening. De vraag is dan in hoeverre kan je deze betonnen elementen nog goed hergebruiken. Het zijn dan ook elementen die je alleen nog maar statisch bepaald gaat toepassen als een ligger op twee steunpunten.

G.3.4.2 Breedplaatvloer

De respondent ziet hergebruik van breedplaatvloeren voor zich dat de vloer in stukken gezaagd wordt en wordt toegepast ondersteunend aan twee zijde. Je weet namelijk de onder wapening zeker doordat de onderkant van een breedplaatvloer geprefabriceerd is. Over de volle lengte heerst dezelfde wapening. Je kan de breedplaatvloer dan zien als een prefab vloersysteem, waarbij de wapening in de andere richting ‘niet’ wordt gebruikt. De belasting wordt dus niet van de een op de andere plaat overgedragen. Dit komt ook overeen met hoe de gemiddelde breedplaatvloer wordt uitgerekend door een leverancier, lineair. Een richting overspannen als een ligger op twee steunpunten. Echter werkt een breedplaatvloer wel in twee richtingen.

G.3.4.3 Staalplaatbeton vloeren

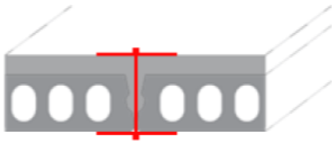
Staalplaat betonvloeren heeft een constante wapening over de volle lengte van het vloerdeel. Als je de vloer tussen de kolommen uitzaagt heb je een vloer die je kan hergebruiken. Waar je volgens de respondent wel op moet letten is dat de vloer uit het vlak een hele beperkte stijfheid heeft. Na het loszagen, tijdens het hijsen kan de plaat opbuigen, loodrecht op de overspanningsrichting. Er zal dus een hulpconstructie nodig zijn om dit vloertypen eruit te kunnen hijsen.

Breedplaatvloeren, staalcomposiet vloeren en in-het-werk gestorte vloeren moeten locatie specifiek bekeken worden. Wat voor vloer is het en wat de wapening in de vloer is, zoals bijlegwapening. Vooral in gebouwen van de jaren 50/60 werd er wapening neergelegd voor wat er nodig was, doordat materieel veel duurder was dan arbeid. Ieder gezaagde in-het-werk-gestorte vloer zal dan een andere capaciteit hebben. Een breedplaatvloer is dus minder locatie specifiek en meer uniform door de geprefabriceerde onder schil.

G.3.4.4 Kanaalplaatvloer

Een kanaalplaat op twee steunpunten is prima weer her te gebruiken in een nieuw ontwerp.

Tegenwoordig voorziet de respondent kanaalplaten standaard van een druklaag, zeker in schoolgebouwen. De platen zitten dus aan elkaar vast. De druklaag verzekerd schijfwerking van de vloeren. Kanaalplaten met druklaag moeten bij hergebruik eerst losgezaagd worden op de naden (om de 1.20m). Maar ook de kanaalplaten met afwerklaag. Volgens de respondent is het belangrijk voor hergebruik dat de voegvulling in de naden tussen de platen weer gevuld kunnen worden met cement/grout. De voegvulling moet hechten aan de platen zodat ze weer samen kunnen werken en schuifkracht kunnen opnemen. Hierdoor wordt wisselen van platen door geconcentreerde belastingen tegengehouden. Met een druklaag kan dit probleem voorkomen worden. Dus een druklaag wordt toegepast voor de schijfwerking en het voorkomen van het doorscheuren van de plaatnaden. In de toekomst zou deze wisselwerking tussen platen ook opgelost kunnen worden door een mechanische koppeling, zie onderstaande afbeelding.



Als er een angst is dat door een dergelijke beweging in het vlak inderdaad scheurvorming in de afwerklaag zouden kunnen ontstaan, dan kan er altijd gekozen worden voor een zwevende dekvloer. Dus over de losse kanaalplaten kan een zwevende dekvloer gelegd worden zodat doorscheuren voorkomen wordt. Volgens de respondent zijn er oplossingen voor de wisselwerking tussen platen en het niet opnieuw kunnen vullen van de voegen tussen de platen.

Volgens de respondent zijn er nieuwe innovatieve oplossingen nodig om de problemen van hergebruik van constructieve elementen mogelijk te maken. Er moet buiten de standaard principes gedacht worden, dat is wel een uitdaging in de bouw.

Echter heeft de respondent ook wel eens een staalconstructie met kanaalplaten zonder druklaag toegepast in een schoolgebouw. De voegen tussen de platen worden dan gevuld met een voegwortel en de platen zijn goed vastgemaakt met stekken en haarspelden aan de staalconstructie. De staalconstructie is op zichzelf stabiel, waar de kanaalplaatvloer gewoon opgelegd kunnen worden. De gevulde voegen tussen de platen nemen de schuifkracht op en het vastmaken van de platen aan de staalconstructie zorgt voor een samenwerkend geheel. De vloerconstructie kan dan ook gezien worden als een schijf zonder een druklaag toe te passen. Deze verbindingen met een kopsleuf en een stek erin is lastig los te maken. En zal open gefreesd moeten worden. Door het zaag en frees werk om de elementen geschikt te maken is de respondent bang dat de kosten voor hergebruik de bocht uit vliegen.

Een druklaag heeft nog een derde voordelen, een hoger eigengewicht voor het behalen van de gewenste verticale geluidsisolatie eisen. Een kanaalplaat van 200mm +70mm druklaag is al onvoldoende in een schoolgebouw. Een kanaalplaat van 260mm +70mm druklaag is minimaal vereist tegenwoordig. Dit principe kan ook gerealiseerd worden door het vastleggen van de afwerklaag. Echter wil je een afwerklaag liever niet vastleggen, ten aanzien van brandwerendheid mag de gebonden dikte van gesteente niet te veel zijn doordat dit bij brand delamineert en scheurt over de dammen.

G.3.4.5 Voorgespannen massieve vloer

De respondent heeft vanwege de geluidsisolatie eisen wel een voorgespannen massieve vloer toegepast. Maar als structurele oplossing biedt een massieve vloer geen oplossing. Het nadeel is namelijk dat het veel eigengewicht meebrengt waardoor je beter naar een gestorte vloer kan gaan kijken. Het gaat om de verhouding van de vloerdikte, overspanning en gewicht. Een massieve vloer is met een dikte van 200mm wel interessant. Een dikker massieve plaat voegt niets toe en werkt tegen je. In de slanke variant van 200mm voegt het gewicht daarentegen wel iets toe. Vaak worden massieve voorgespannen vloeren toegepast omdat je de vloerdikte niet dikker kan maken, maar in de bepaalde dikte moet toch massa gecreëerd worden.

Als de kanaalplaatvloer zonder druklaag of afwerklaag een 100% herbruikbaarheidsscore zal krijgen. Zal een kanaalplaatvloer met afwerklaag 90% score, doordat de afwerklaag gemakkelijk eraf gehaald kan worden. De afwerklaag wordt verwijderd omdat er een nieuwe afwerklaag nodig is en de oude niet kan blijven zitten vanwege het eigengewicht wat dan te groot wordt. De handeling van het verwijderen van de afwerklaag geeft de respondent een reductie van 10% op de herbruikbaarheidsscore. Een kanaalplaatvloer met druklaag krijgt een hergebruikscore van 40-50% voor hergebruik in een schoolgebouw, volgens de respondent. De respondent is overtuigd dat de druklaag verwijderbaar is doordat het een lagere betonsterkte klasse heeft, maar wanneer is het te veel werk/moeite om deze laag te verwijderen

G.3.4.6 TT-vloer

De respondent heeft nog nooit TT-vloeren toegepast in een schoolgebouw. Wel in parkeergarages. Het idee van een TT-vloer is een zo laag mogelijk gewicht met een zo groot mogelijk overspanning behalen. Alleen veroorzaakt dit lage gewicht een hele dunnen vloer, deze dunne vloer voldoet niet aan de verticale geluidseisen van een schoolgebouw. Daarnaast is de doorgaanshoogte erg groot, vrij grote bruto vrije hoogte.

G.3.5 COMPONENT LENGTHS

Heel vaak heeft de architect al een voorzet gedaan voor een stramien voor de plattegronden. Wat je tegenwoordig vaak ziet is in de diepte 9m of 12.60m en in de gevel van 7.20m of 7.50m. De respondent probeert in de gevel naar een zon klein mogelijk stramien te gaan en haaks hierop een lange overspanning. Constructief gezien moet de vloer de overspanning maken en de ligger de kleine, dan kan een relatief lichte, efficiënte ligger volstaan die makkelijk in de vloerdikte geïntegreerd krijgt.

Kijk bijvoorbeeld naar een vierkant stramien. 7.50m voor een kanaalplaat overspannen is niets, maar 7.50m voor een ligger overspannen is heel veel, wat een zware ligger als resultaat heeft. Als je dan naar een geïntegreerde oplossing moet zoeken, krijg je een hele zware ligger die je in een relatief dunne vloer moet verwerken. Dat is per definitie niet efficiënt.

Over het algemeen zijn de constructie elementen van vroeger wel wat kleiner dan de bovengenoemde stramienmaten van tegenwoordig, de stramien maten moeten zich dus aanpassen aan de beschikbare constructieve elementen. Als je gaat hergebruiken, en er is een vloer beschikbaar van lengte x, dan is lengte x het vertrekpunt.
Normaal gesproken heb je in een schoolgebouw een maat A voor de gang en B voor het lokaal. Waarbij je één grote overspanning maakt inclusief gang en een ander overspanning voor het andere lokaal, 12.60m en 9m. Als deze overspanningen veroorzaakt moeten worden met een kleinere maat zal er een koppelbalk toegevoegd moeten worden. Het is niet zo dat je met een vloeroverspanning van 7.20m geen schoolgebouw kan maken, maar het vraagt een andere ligger structuur.

Een gangbare hoogte in schoolgebouwen is minimaal 3.80m, maar 4.00m wordt tegenwoordig ook vaak toegepast. De respondent heeft kortgeleden ook 3.70m toegepast maar daar werd aangegeven dat er problemen waren opgetreden met de installatie systemen. De hoogte van de kolommen hangt af van het type installatie systeem en de vloerdikte.

Scholen willen graag een zo flexibel mogelijk gebouw krijgen zodat het gebouw mee kan bewegen met de veranderende onderwijsvisie. Zo min mogelijk kolommen en zo weinig mogelijk wanden zorgt voor een zo flexibel mogelijk schoolgebouw. Flexibiliteit en hergebruik van constructie elementen staat een beetje haaks op elkaar. De respondent is van mening dat we moeten ontwikkelen naar een bouwwereld waarin wij acteren naar wat er mogelijk is, dan wat wij vinden dat er moet. Er moet een stap teruggedaan worden en er moet worden gekeken naar wat kunnen we met wat we hebben en hoe kunnen we dat zo goed mogelijk inzet? Er moet dus niet gestreefd worden naar nog grotere overspanningen.

G.3.6 MATERIAL QUALITY

De respondent heeft een beter gevoel bij een prefab producten voor herbruikbaarheid dan voor elementen die gemaakt zijn op de bouwplaats. Het uitgangsmateriaal van een kanaalplaat is van een hogere kwaliteit omdat het uit de fabriek komt, doordat het genormeerd en gecertificeerd is en dubbel gecheckt. Het heeft over de volle hoogte een hoge betonsterkte klasse. Terwijl de op stort van een breedplaat toch onzeker blijft doordat er op de bouwplaats nog wat met de vloer is gebeurd. Zeker kijkend naar het verleden met de problematiek van de bolle plaatvloeren en de aanhechting van de druklaag.

De respondent geeft aan dat het vrij uniek is als de betonsterkte klasse bekend is, doordat uit de tekeningen van vroeger niet is af te leiden van wat voor soort beton het is gemaakt. Om de betonsterkte klasse te weten en de vloercapaciteit te kunnen doorrekenen zou de respondent graag boorproeven willen doen. Mocht de betonsterkte klasse wel bekend zijn dan rond de respondent de oude betonsterkte af naar boven om tot een eurocode sterkteklasse te komen. De betonsterkte ontwikkeling staan theoretisch nooit stil en ontwikkeld door in de tijd dat het in een gebouw zit. Het beton is dus iets sterker dan dat je theoretisch zou verwachten, dit is ondervonden wanneer er boorproeven zijn verricht bij herbestemmingsprojecten door de respondent.

In verband met brandveiligheid zou de respondent de betondekking willen weten voordat hij gaat hergebruiken. De betondekking vroeger was kleiner dan de betondekking tegenwoordig, dat is qua brandwerendheid een probleem omdat de vloer volgens de norm aan nieuwbouweisen moet voldoen. Er zal dus een brandwerend plafond moeten worden toegepast, zodat de vloer beschermd wordt voor brand en hoge temperaturen. Een andere optie is opruwen van vloer en beton ertegen aan spuiten vanaf de onderkant. Echter heb je veel terugslag en veel afval waardoor deze optie snel te duur en te moeilijk wordt gevonden. Brandwerend spuiten van een opschuimende coating of een brandwerend plafond zijn betere opties.

In schoolgebouwen is de respondent geen fan van brandwerend spuiten van stalen elementen omdat dat een onderhoudsverplichting op zich afroept. Staal waar je bij kunt is beschadigingsgevoelig. De respondent gebruikt in schoolgebouwen met staal heel vaak staalgevulde kokerprofielen, als dit geen optie is, is de respondent eerder van het omkleden van de profielen met brandwerend materiaal en spuiten is de laatste optie.

G.4 Survey 1 demolition contractors

G.4.1 QUESTIONS

Ease of demountability of structural components

For my graduation research I am looking at the demountability of existing structures. This research focuses on the technical aspects of demounting structural components. I want to assign a demountable score for each structural component.
In this survey, various technical aspects are discussed, to which you assign a demountability rating from 0 (easy to remove) to 10 (very difficult to remove without damage).

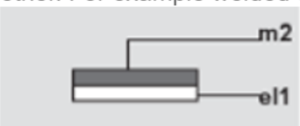
This Survey will have 6 questions and will take 5-10 minutes (can only be made on the computer!)

>>

QUESTION 1 of 6: Type of connection

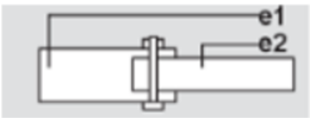
Easy to remove take apart — Difficult to remove

	1	2	3	4	5	6	7	8	9	10	Don't know
Direct chemical connection Two components are fixed by sticking to each other. For example welded connection.	○	○	○	○	○	○	○	○	○	○	○

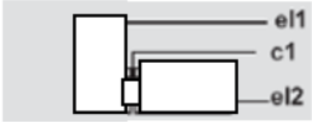


	1	2	3	4	5	6	7	8	9	10	Don't know
Indirect connecion with third chemical material Two components are fixed by a third hard chemical material. For example grout filled connection	○	○	○	○	○	○	○	○	○	○	○

	1	2	3	4	5	6	7	8	9	10	Don't know
Direct connection with additional fixing element Two components are fixed with an accessory that can be replaced. For example bolted connection	○	○	○	○	○	○	○	○	○	○	○



	1	2	3	4	5	6	7	8	9	10	Don't know
Inidrect connection via a dependent third element Three components are non-adhesively connected. The assembly is dependent on each other.	○	○	○	○	○	○	○	○	○	○	○



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QUESTION 2 of 6: Accesibility

Easy to remove / take apart — Difficult to remove

	1	2	3	4	5	6	7	8	9	10	Don't know
Accessible The connection is independent, visible, and reachable.	○	○	○	○	○	○	○	○	○	○	○

	1	2	3	4	5	6	7	8	9	10	Don't know
Accessible with an additional operation that causes no damage The connection is not visible and therefore not immediately accessible. The connection is hidden behind constructive or architectural components that are independent of the connection. After removing the constructive or architectural components the connection is reachable. For example, a ceiling system.	○	○	○	○	○	○	○	○	○	○	○

	1	2	3	4	5	6	7	8	9	10	Don't know
Accessible with an additional operation that causes repairable damage The connection is not visible and therefore not immediately accessible. The connection is hidden behind constructive or architectural components that are dependent on the connection. The removal of the constructive or architectural components will cause damage to the structural component(s). For example, indoor glass partition.	○	○	○	○	○	○	○	○	○	○	○
Not accessible, total damage of components The connection is not visible. The connection is hidden behind multiple constructive or architectural components that are dependent on the connection and/or associated structural component. The removal of the constructive or architectural components will cause unrepairable damage to the structural component(s). For example, structural insulated panels.	○	○	○	○	○	○	○	○	○	○	○

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QUESTION 3 of 6: Crossing components:

Crossing of components means that components run through each other or are even fully integrated.

Easy to remove / take apart — Difficult to remove

	1	2	3	4	5	6	7	8	9	10	Don't know
No crossing 	○	○	○	○	○	○	○	○	○	○	○
Components partially overlap each other For example, 	○	○	○	○	○	○	○	○	○	○	○
Components overlap each other over the full component length For example, 	○	○	○	○	○	○	○	○	○	○	○

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QUESTION 4 of 6: Edge confinement

Easy to remove / take apart — Difficult to remove

	1	2	3	4	5	6	7	8	9	10	Don't know
Component edges are not enclosed Component edges are not enclosed by surrounding components. The edges of components are independend of each other. You can completely disassemble the component from the building from at least one accessible side.	○	○	○	○	○	○	○	○	○	○	○
Component edges overlap The component edges are partially enclosed by surrounding components. There is at least one edge with an overlap. To disassemble the component from the building, other components must first be disassembled. The structural component is depending on other components. For instance, a floor finishing or insulation glued to the roof component.	○	○	○	○	○	○	○	○	○	○	○
Component edges are enclosed Component edges are completely enclosed by other components. There is overlap on at least two edges. To disassemble components from the building, other components must first be disassembled. The structural component is entirely dependent on the removal of overlapping components at edges.	○	○	○	○	○	○	○	○	○	○	○

<< >>

QUESTION 5 of 6: Number of connections

A structural component can be connected to one or more other components. How does the number of connections affect the demountability rating? With 0 (easy to remove) to 10 (very difficult to remove without damage).

Easy to remove / take apart — Difficult to remove

	1	2	3	4	5	6	7	8	9	10	Don't know
1 or 2 connections	○	○	○	○	○	○	○	○	○	○	○
3 connections	○	○	○	○	○	○	○	○	○	○	○
4 connections	○	○	○	○	○	○	○	○	○	○	○
5 connections	○	○	○	○	○	○	○	○	○	○	○

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QUESTION 6a of 6: In your opinion what are the key factors that make it easier to disassemble a structural component?

Please answer the question in as much detail as possible.

QUESTION 6b of 6: In your opinion what are the key factors that make it difficult to disassemble a structural component?

Please answer the question in as much detail as possible.

G.4.2 RESULTS

G.4.2.1 closed question results

		Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Type of connection							
	Direct chemical connection	0.5	0	0	0	0.1	0.2
	Indirect connection with third chemical material	0	0.4	0.2	0.7	0.5	0.2
	Direct connection with additional fixing element	0.6	0.8	1	0.7	0.8	0.3
	Indirect connection via a dependent third element	0.5	0.8	1	0.5	0.7	0.3
Accessibility	Accessible	0.5	0.7	1	0.7	0.8	0.7
	Accessible with an additional operation that causes no damage	0	0.1	0.7	0.5	0.6	0.6
	Accessible with an additional operation that causes damage	0	0.5	0.2	0.5	0.3	0.2
	Not accessible, total damage of components	0	0	0	0.2	0	0
Crossing components	No crossing	0.6	0.6	1	0.2	0.8	0.8
	partially overlap each other	0.5	0.6	0.8	0.4	0.5	0.8
	Components overlap each other over the full component length	0	0.3	0.6	0.3	0.1	0.5
Edge confinement	Component edges are not enclosed	0.5	0.8	1	0.5	0.8	0.6
	component edges overlap	0	0.6	0.8	0.5	0.4	0.7
	component edges are enclosed	0	0.2	0.5	0.2	0.1	0.4
Number of connections	1 or 2 connections	0	0.8	1	0.5	0.8	1
	3 connections	0	0.6	0.8	0.3	0.6	0.7
	4 connections	0	0.4	0.7	0.2	0.3	0.4
	5 connections	0	0.2	0.6	0	0.1	0.1

G.4.2.2 open question results

		Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Question 6A	In your opinion, what are the key factors that make it easier to disassemble a structural component?	Disassemble is not the same as demolition. Demolition is undertaken mainly by mechanical means and is undertaken in a controlled manner, and predominantly allows materials to be processed once at ground level. Disassembling components in situ increases the health and safety risks, i.e. working at height; it also prolongs the work programme and increases costs to clients. A further issue with the reuse of materials is that both architects and clients do not want to use them as they are often seen as outdated and not in keeping with the new structure's design. Furthermore, designers and engineers will not warrant used materials required to take the structural load, so items can only be used as decorative items. Storage and transportation costs also mean that items are often separated and recycled rather than reused.	Simple and standard connections	Easy access and mechanical fixings such as nuts and bolts	Easy of access. The construction method of the component. Removing from the work area once the components are apart.	-	-
Question 6B	In your opinion, what are the key factors that make it difficult to disassemble a structural component?	Please see the response to the previous question. Health and safety concerns, cost, programme, limited scope for reuse, structural integrity, components such as glazing not meeting current building regulations, storage of components, transportation costs, bounded components that cannot be easily separated, components containing hazardous substances.	Bonded connections	Products that are glued	Answer of 6A	-	-

G.5 Survey 2 structural engineers and contractors

G.5.1 QUESTIONS

Herbruikbaarheid van constructie elementen afkomstig uit schoolgebouwen

50% van de middelbare schoolgebouwen in Nederland voldoen niet meer aan de functionele eisen voor een hedendaags schoolgebouw. Echter is het niet per definitie zo dat alle elementen uit de schoolgebouwen verouderd zijn. Bijvoorbeeld de individuele constructie elementen kunnen nog steeds voldoen aan de technische en functionele eisen. Daarom ben ik voor mijn afstuderen aan de TU Delft (Structural Engineering) aan het kijken naar het terugwinnen van bestaande constructie elementen uit middelbare schoolgebouwen. Dit onderzoek richt zich op de technische aspecten bij terugwinnen en hergebruiken van individuelen elementen.

Als eindresultaat van dit afstuderen wordt er een tool ontwikkeld die een eerste indicatie geeft of het terugwinnen en hergebruiken van individuele constructie elementen mogelijk is. Deze tool is bedoeld als hulpmiddel bij de keuze renovatie, sloop, en nieuwbouw van een schoolgebouw. Het is van belang dat deze tool in een relatief korte tijd een herbruikbaarheidsscore van 0 tot 10 kan toekennen aan een constructie element. Waarin 0 niet herbruikbaar en 10 goed herbruikbaar is. Doordat de mogelijkheid tot hergebruik niet door 1 aspect bepaald wordt, zal er een individuele score komen per bekeken aspect.

In deze enquête zal er worden ingegaan op de lengte van een element en typen element (vloer systemen en type staal profiel). Aan u de vraag om aan te geven welke aspecten voor u van belang zijn om een herbruikbaarheidsscore te kunnen toekennen. Vervolgens wordt u gevraagd verschillende elementen en lengtes een herbruikbaarheidsscore van 0 (niet herbruikbaar) tot 10 (goed terug winbaar en herbruikbaar) toe te kennen.

De enquête heeft 10 vragen en zal ongeveer 5-10 minuten duren.

[>>]

Vraag 1/11: Als de situatie zich voordoet zou u dan openstaan voor hergebruik van constructie elementen?

- Nee, ik zie het voordeel hier nog niet van in.
- Ja, ik wil graag bijdrage aan de circulaire economie

[<<] [>>]

Vloersystemen

Vraag 2/11: Welke van de volgende aspecten wegen voor u mee voor het bepalen van een algemene herbruikbaarheidsscore voor een vloersysteem (en dus niet voor een specifiek project)? Selecteer de 5 belangrijkste

Aspecten als kwaliteit en losmaakbaarheid van het element worden apart inzichtelijk gemaakt in de methodiek voor het bepalen van de herbruikbaarheid, die hoeven hier niet meegewogen te worden

- Eigen gewicht
- Dragend in 1 of 2 richtingen
- Gestandaardiseerde dimensies
- Gestandaardiseerde wapeningshoeveelheid
- Belasting capaciteit
- Overspanningslengte
- Horizontale belasting (Normaalkracht) capaciteit
- Schijfwerking
- Integratie van installaties
- Aspect dat niet in de lijst voorkomt
- Aspect dat niet in de lijst voorkomt

[<<] [>>]

Vraag 3/11: Hoe zwaar zou een druklaag op een constructieve vloer mee moeten wegen in de herbruikbaarheidsscore?

Gegeven: een element zonder druklaag heeft een herbruikbaarheidsscore van 10

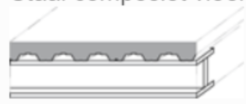
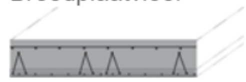
Niet goed herbruikbaar — Goed herbruikbaar

	1	2	3	4	5	6	7	8	9	10	Geen idee
Druklaag	○	○	○	○	○	○	○	○	○	○	○
Gewapende druklaag	○	○	○	○	○	○	○	○	○	○	○

<< >>

Vraag 4/11: Met de gegevens uit vraag 2. beoordeel de volgende vloersystemen:

Niet goed herbuikbaar — Goed herbuikbaar

	1	2	3	4	5	6	7	8	9	10	Geen idee
Kanaalplaatvloer (voorgespannen) 	○	○	○	○	○	○	○	○	○	○	○
Massieve voorgespannen vloer 	○	○	○	○	○	○	○	○	○	○	○
TT-vloer 	○	○	○	○	○	○	○	○	○	○	○
Staal composiet vloer 	○	○	○	○	○	○	○	○	○	○	○
Breedplaatvloer 	○	○	○	○	○	○	○	○	○	○	○
In-het-werk gestort beton	○	○	○	○	○	○	○	○	○	○	○

<< >>

Vraag 5/11: Beoordeel de lengte van een vloerelement op herbruikbaarheid

Niet goed herbuikbaar — Goed herbuikbaar

	1	2	3	4	5	6	7	8	9	10	Geen idee
< 1.80 m	○	○	○	○	○	○	○	○	○	○	○
1.80 m - 3.60 m	○	○	○	○	○	○	○	○	○	○	○
3.60 m - 5.40 m	○	○	○	○	○	○	○	○	○	○	○
5.40 m - 7.20 m	○	○	○	○	○	○	○	○	○	○	○
> 7.20 m	○	○	○	○	○	○	○	○	○	○	○

<< >>

Balken

Vraag 6/11: Welke van de volgende aspecten wegen voor u mee voor het bepalen van een algemene herbruikbaarheidsscore voor een prefab en stalen balk (en dus niet voor een specifiek project)? Selecteer de 5 belangrijkste

Aspecten als kwaliteit en losmaakbaarheid van het element worden apart inzichtelijk gemaakt in de methodiek voor het bepalen van de herbruikbaarheid, die hoeven hier niet meegewogen te worden

- Eigen gewicht
- Gestandaardiseerde dimensies
- Gestandaardiseerde wapeningshoeveelheid (voor betonnen balken)
- Belasting capaciteit
- Kip stabiliteit
- Overspanningslengte
- Hoogte van de balk
- Aspect dat niet in de lijst voorkomt
- Aspect dat niet in de lijst voorkomt

<< >>

Vraag 7/11: Met de gegevens uit vraag 6 beoordeel de volgende stalen balkprofielen:

Niet goed herbruikbaar — Goed herbuikbaar

	1	2	3	4	5	6	7	8	9	10	Geen idee
Din profiel	○	○	○	○	○	○	○	○	○	○	○
H-profiel	○	○	○	○	○	○	○	○	○	○	○
I-profiel	○	○	○	○	○	○	○	○	○	○	○
Koker profiel	○	○	○	○	○	○	○	○	○	○	○
UNP profiel	○	○	○	○	○	○	○	○	○	○	○

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Vraag 8/11: Beoordeel de lengte van een balkelement op herbruikbaarheid

	Niet goed herbuikbaar								Goed herbuikbaar		
	1	2	3	4	5	6	7	8	9	10	Geen idee
< 1.80 m	○	○	○	○	○	○	○	○	○	○	○
1.80 m - 3.60 m	○	○	○	○	○	○	○	○	○	○	○
3.60 m - 5.40 m	○	○	○	○	○	○	○	○	○	○	○
5.40 m - 7.20 m	○	○	○	○	○	○	○	○	○	○	○
> 7.20 m	○	○	○	○	○	○	○	○	○	○	○

<< >>

Kolommen

Vraag 9/11: Welke van de volgende aspecten wegen voor u mee voor het bepalen van een algemene herbruikbaarheidsscore voor een prefab en stalen kolom (en dus niet voor een specifiek project)? Selecteer de 5 belangrijkste

Aspecten als kwaliteit en losmaakbaarheid van het element worden apart inzichtelijk gemaakt in de methodiek voor het bepalen van de herbruikbaarheid, die hoeven hier niet meegewogen te worden

- Eigengewicht
- Gestandaardiseerde dimensies
- Gestandaardiseerde wapeningshoeveelheid (voor betonnen kolommen)
- Belasting capaciteit
- Knik gevoeligheid
- Voor stalen kolommen, gevuld met beton of in een betonkolom opgenomen
- Aspect dat niet in de lijst voorkomt

<< >>

Vraag 10/11: Met de gegevens uit vraag 9 beoordeel de volgende stalen kolomprofielen:

	Niet goed herbuikbaar								Goed herbuikbaar		
	1	2	3	4	5	6	7	8	9	10	Geen idee
Din profiel	○	○	○	○	○	○	○	○	○	○	○
	1	2	3	4	5	6	7	8	9	10	Geen idee
H-profiel	○	○	○	○	○	○	○	○	○	○	○
	1	2	3	4	5	6	7	8	9	10	Geen idee
Koker profiel	○	○	○	○	○	○	○	○	○	○	○

<< >>

Vraag 11/11: Beoordeel de lengte van een kolomelement op herbruikbaarheid

	Niet goed herbuikbaar								Goed herbuikbaar		
	1	2	3	4	5	6	7	8	9	10	Geen idee
< 2.60 m	○	○	○	○	○	○	○	○	○	○	○
2.60 m - 3.20 m	○	○	○	○	○	○	○	○	○	○	○
> 3.20 m	○	○	○	○	○	○	○	○	○	○	○

<< >>

G.5.2 RESULTS

G.5.2.1 Results for floor components

	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6	Response 7	Response 8	Response 9	Response 10	Response 11	Response 12	Response 13	Response 14	Response 15	Response 16	Response 17
Sub-indicators																	
Self-weight		x			x	x		x				x					
Span in 1 or 2 directions	x	x			x	x	x	x		x		x	x		x		
Standardised dimensions	x		x		x			x	x		x						
Standardised amount of reinforcement													x			x	
2D Component's height	x			x		x					x			x			
Bearing capacity	x	x		x	x		x	x	x	x	x	x	x	x	x	x	x
Span length		x	x				x	x	x	x		x			x	x	x
Diaphragm action	x	x	x			x							x			x	
Integration of installations			x	x							x		x	x	x	x	x
Possible adjustment recesses				x													
Adaptability					x									x			
Material						x						x					
Residual lifespan											x						
Weighting																	
Non-structural layer	0.8	0.2	Unknown	0.2	0.4	Unknown	0.2	0.6	0.3	0.6	0.2	0.8	0.5	0.4	0.5	0.5	0.1
Structural layer	0.8	0.2	Unknown	0.4	0.2	Unknown	0.1	0.6	0.5	0.3	0.2	0.9	0.5	0.8	0.2	0.4	0.1
Type of 2D component																	
Prestressed hollow-core slab	0.8	0.6	0.7	0.7	0.7	1	0.8	0.7	0.8	0.8	0.9	0.8	0.5	0.6	0.9	0.9	0.9
Solid prestressed slab	0.8	0.6	0.7	0.7	0.6	0.3	0.5	0.4	0.3	0.4	0.5	0.8	0.3	0.7	0.8	0.9	0.7
TT-floor	0.8	0.8	0.6	0.3	0.5	1	0.8	0.7	0.7	Unknown	0.6	0.7	0.8	0.4	0.6	0.8	0.8
Steel composite floor	0.4	0.6	0.2	0.3	0.2	0.7	0.4	0.3	0.7	0.2	0.8	0.6	0.5	0.4	0.3	0.5	0.2
Reinforced plank slab	0.8	0.2	0.1	0.8	0.1	0.7	0.2	0.7	0.5	0.4	0.3	0.7	0.3	0.8	0.2	0.6	0.2
In-situ concrete floor	0.2	0.2	0.1	0.6	0.1	0.6	0.2	0.5	0.5	0.4	0.3	0.7	0.5	0.8	0.2	0.7	0.2
Component's length																	
<1.80m	0.8	0.2	0.1	Unknown	Unknown	1	0.6	0.9	0.3	0.2	0.8	0.5	1	0.2	0.1	0.2	0.2
1.80 - 3.60m	0.8	0.3	0.3	Unknown	Unknown	1	0.7	0.7	0.6	0.3	0.8	0.6	1	0.3	0.4	0.4	0.4
3.60m - 5.40m	0.7	0.4	0.7	Unknown	Unknown	1	0.8	0.7	0.8	0.4	0.8	0.7	1	0.4	0.9	0.8	0.6
5.40-7.20m	0.7	0.8	1	Unknown	Unknown	1	0.8	0.7	0.8	0.8	0.8	0.8	1	0.5	0.9	1	0.7
> 7.20m	0.6	0.9	Unknown	Unknown	Unknown	1	0.7	0.7	0.6	1	0.8	0.9	1	0.7	0.9	1	0.8

G.5.2.2 Results for beam components

	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6	Response 7	Response 8	Response 9	Response 10	Response 11	Response 12	Response 13	Response 14	Response 15	Response 16	Response 17
Sub-indicators																	
Self-weight		x						x									
Standardised dimensions	x		x		x	x				x	x						
Standardised amount of reinforcement (concrete beams)													x			x	
Bearing capacity	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x
Lateral torsional buckling	x	x				x			x		x		x		x		
Span length	x	x	x		x	x	x	x	x	x		x		x	x	x	x
Beam's height	x	x	x	x			x	x	x	x		x			x	x	
Detailing rules according to Eurocode 2 (concrete), Dimensional deviations				x									x			x	
Integrated height of beam with installations				x										x			
material												x					
Fire resistance														x			
Type of 1D component																	
Din-profile	0.8	0.9	0.2	0.7	0.7	Unknown	0.8	0.7	0.8	Unkown	1	0.9	1	0.8	0.9	0.9	0.9
H-profile	0.8	0.9	1	0.7	0.8	1	0.8	0.7	0.8	0.8	1	0.9	1	0.8	1	1	0.9
I-profile	0.8	0.9	0.8	0.7	0.7	1	0.8	0.7	0.7	0.7	1	0.7	1	0.8	1	1	0.9
Hollow profile	0.8	0.9	0.7	0.4	0.6	1	0.7	0.7	0.8	0.6	1	0.8	1	0.3	1	1	0.7
UNP-profile	0.8	0.9	0.4	0.4	0.4	0.1	0.6	0.4	0.8	0.6	1	0.6	0.7	0.2	1	1	0.9
Component's length																	
<1.80m	0.9	0.8	0.1	Unknown	Unknown	1	0.5	0.7	0.6	0.2	0.8	0.5	1	Unknown	0.6	0.2	0.3
1.80 - 3.60m	0.9	0.8	0.6	Unknown	Unknown	1	0.6	0.7	0.8	0.3	0.8	0.6	1	Unknown	0.8	0.8	0.5
3.60m - 5.40m	0.9	0.8	0.8	Unknown	Unknown	1	0.8	0.7	0.8	0.4	0.8	0.7	1	Unknown	0.9	1	0.7
5.40-7.20m	0.8	0.9	1	Unknown	Unknown	1	0.8	0.7	0.8	0.7	0.8	0.8	1	Unknown	0.9	0.9	0.8
> 7.20m	0.8	1	Unknown	Unknown	Unknown	1	0.7	0.7	0.8	1	0.8	0.9	1	Unknown	0.9	0.9	0.9

G.5.2.3 Results for column components

	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6	Response 7	Response 8	Response 9	Response 10	Response 11	Response 12	Response 13	Response 14	Response 15	Response 16	Response 17
Column components																	
Sub-indicators																	
Self-weight	x					x											
Standardised dimensions	x		x		x		x	x			x						
Standardised amount of reinforcement (concrete columns)													x			x	
Bearing capacity	x	x	x		x	x	x	x	x	x	x	x		x	x	x	x
buckling	x	x	x		x	x		x	x	x	x	x	x	x	x	x	x
For steel-concrete columns	x	x					x	x	x	x		x			x	x	
Fire resistance		x											x	x			
New mountable connections			x													x	
Structural function													x				
Detailing rules according to Eurocode 2 (concrete), Dimensional deviations													x				
Component type																	
Din-profile	0.9	0.9	0.2		0.8	Unknown	0.7	0.7	0.8	Unknown	0.8	0.9	1	0.8	0.8	0.8	0.9
H-profile	0.9	0.9	1		0.9	1	0.8	0.7	0.8	0.8	0.8	0.9	1	0.8	0.9	0.9	0.9
Hollow profile	0.7	0.9	0.7		1	1	0.6	0.7	0.7	0.8	0.8	0.8	1	0.4	0.9	1	0.7
Component's length																	
<2.60m	1	0.2	0.2		0.2	1	0.6	0.4	0.3	0.2	0.8	0.6	1	Unknown	0.4	0.4	0.7
2.60m - 3.20 m	1	0.3	0.7		0.6	1	0.7	0.6	0.8	0.6	0.8	0.7	1	Unknown	0.8	0.8	0.8
> 3.20m	1	0.9	1		1	1	0.7	0.8	0.6	0.9	0.8	0.9	1	Unknown	0.9	1	0.9

APPENDIX H

GRADING SYSTEMS AND SENSITIVITY OF SCORES

The reusability indicators are translated into an assessment method to technically measure the reclaim and reuse potential. This research makes the reusability indicators measurable by giving each indicator and sub-indicator a score for reclaim and reuse (Durmisevic, 2006). The score for reclaim and reuse is the reusability score.

This research strives for an objective assessment that comes closest to reality. The combination of a literature study, three interviews with structural engineers and a survey with structural engineers, contractors, and demolition contractors, compile the scores of the indicators that influence the reusability of load-bearing components from SE school buildings. The literature study gives the first indication of the reusability scores. The appendixes for each reusability indicator elaborate on the first indication of the reusability scores. So, Appendix D contains the scores of the breadth of application, Appendix E the score of the demountability and Appendix F the scores of the physical quality. This appendix elaborates on the scores given by the structural engineers, contractors and demolition contractors. The people from the practical field score the reusability indicators of the load-bearing components with 0 not reusable to 1.0 highly reusable. All engineers and contractors are working in the field of school buildings. Comparing the scores from literature with the scores from the surveys assures the reliability of the scores. In this way, the components are objectively measurable.

A sensitivity analysis is necessary before the scores of the structural engineers and contractors are helpful for this research. This research desires that the spread in the given results is as small as possible to assign the score with certainty. This research's survey involves few participants, so testing the spread of the results is done with an exact spread of quartiles, which gives a rough indication of the spread visualised by a boxplot diagram. The boxplot shows whether the respondents' scores are the same or more spread out over the range from 0 to 1. This research desires that the spread should be around the mean.

Example check for the scores

The scoring of the prestressed hollow core slab is an example of how this research determines the spread of the scores and forms the boxplot. The given scores for the prestressed hollow-core slab are as followed:

0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.8	
0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	1.0

1) The spread width

The highest given score is 1.0, and the lowest given score is 0.5; this gives a spread of $1.0 - 0.5 = 0.5.$

2) The quartiles

The median value of the spread is 0.8 and forms the second quartile.

The method of Tukey divides the given scores into two groups, where the middle score is in both groups. The two groups are as followed:

0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8

0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	1.0

The median value of the spread of set 1 is 0.7 and forms the first quartile. The median value of the spread of set 2 is 0.9 and forms the third quartile.

3) The quartile distances

The distance between the first a third quartile, $IQR = Q3 - Q1 = 0.9 - 0.7 = 0.2$

Given scores that are lower than $Q1 - 1.5 * IQR$ or higher than $1.5 * IQR + Q3$ are outliers. This research removes the outliers from the given scores to get a more realistic overview. The spread of the prestressed hollow-core slab's score does not have outliers. The lowest and highest values are within the margins.

$$Q1 - 1.5 * IQR = 0.7 - 1.5 * 0.2 = 0.7 - 0.3 = 0.4$$
$$Q3 + 1.5 * IQR = 0.9 + 1.5 * 0.2 = 0.9 + 0.3 = 1.2$$

4) The boxplot

The scored aspect gets a boxplot. This boxplot shows the spread of the given scores by the respondents. The lowest value, the first quartile, the second quartile, the third quartile, and the highest value from the boxplot, see Figure 82.

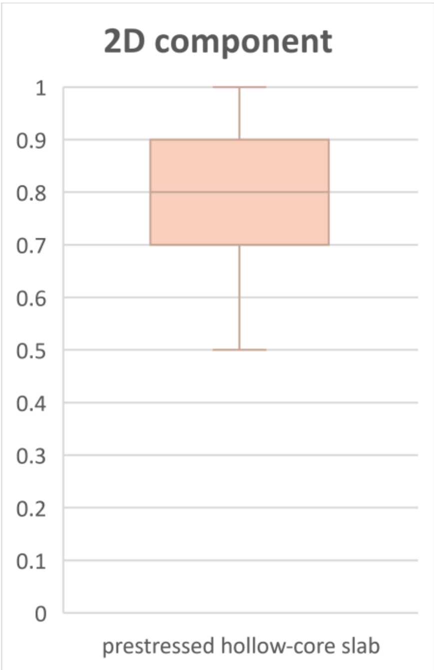

Figure 82: Boxplot for the score of a prestressed hollow core slab

5) Hypothesis score

The literature study conducts the hypothesis score for the prestressed hollow-core slab, following from the thesis of Naber (Naber, 2012):

$$H_0: \mu \approx 1.0$$

6) One sample T-test

The T-test gives the confidence interface of the reusability indicator score found in the literature and surveys. The score from the surveys is the mean of all the respondents. Because the sample size is small, this research assumes that the median provides the most reliable mean. So, this research compares the median of the surveys with the score from the literature.

The number of respondents is the sample size for the T-test, $n = 17$. The median of the sample size is equal to the second quartile, $Q2 = 0.8$.

The standard deviation maps the spread around the mean. The following formula estimates the standard deviation of the sample:

$$s_x = \sqrt{\frac{\sum(x_i - Q2)^2}{n_x}}$$

With s_x = The standard deviation of the scoring range x
x_i = One of the scores in the range
$Q2$ = The mean score of the range, the median
n_x = The number of scores in the range

The standard deviation of the prestressed hollow-core sample is:

$$s_x = \sqrt{\frac{(0.5-0.8)^2+(0.6-0.8)^2*2+(0.7-0.8)^2*4+(0.8-0.8)^2*6+(0.9-0.8)^2*4+(1.0-0.8)^2}{17}} = 0.131$$

The following variable represents the likelihood that the reusability indicator from the literature is not due to chance:

$$t = \frac{Q2-\mu}{s_x/\sqrt{n}}$$

With t = The likelihood of the objectiveness of the score
μ = The score found in the literature
$Q2$ = The mean score of the range, the median
s_x = The standard deviation of the scoring range x
n_x = The number of scores in the range

The likelihood of the objectiveness of the score of the prestressed hollow-core sample is:

$$t = \frac{abs(0.8-1.0)}{0.131/\sqrt{17}} = 6.295$$

The likelihood that the score from the literature is not objective must be as small as possible. Therefore, this research chose a high exceedance possibility of 32%; the scores may deviate ones the standard deviation from the median. The critical score $t_{\alpha,v}$ wherefore the reusability score falls within the 68% reliability area is determined with the table for the critical t-values and the degree of freedom, $n_x - 1$.

The critical t value of the score of the prestressed hollow-core sample is:

$$t_{\alpha=0.32,v=16} = 1.1024$$

If the critical t-value is smaller than the t-value, the reusability score given in the literature is reliable, and this research uses this score.

For the prestressed hollow-core sample:

$$t_{\alpha=0.32,v=16} < t$$

The score given in the literature is reliable.

Although for the prestressed hollow-core slab scores, the reliability of 68% is achievable, this is not the cause for all indicator scores. If an indicator does not fall in the 68% reliability area, this research tests the score against an exceeding possibility of 5%. Now the scores may deviate twice the standard deviation from the median. In addition, further research in that reusability indicator score is necessary.

H.1 Check of the component's type score

H.1.1 CHECK OF THE 2D COMPONENT TYPE

The score of the 2D component type combines the influence of the sub-indicators into a reusability score. This research assumes that each sub-indicator has an equal influence. The sub-indicator structural or non-structural layer significantly influences the reusability of a floor component. Therefore, this sub-indicator influences the score with a weighting factor deducted from the surveys with the structural engineers and contractors.

The 17 respondents disagree about how much influence a structural or non-structural layer has on the reusability of a 2D component. The spread of the scores is:

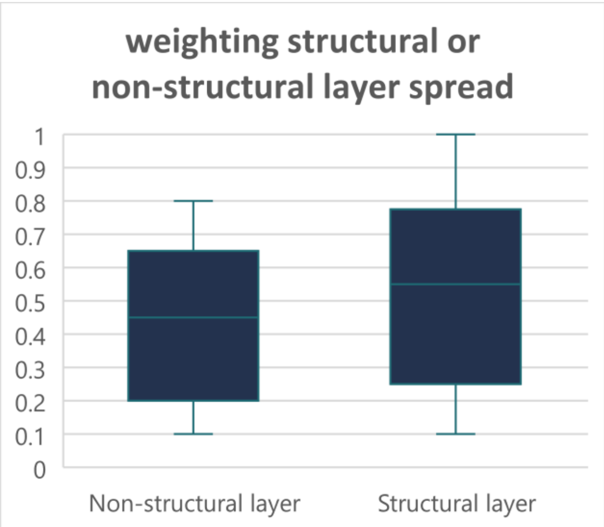

Figure 83: Spread of the scores for the weighting of the non-structural and structural layers given by the respondents

- The quartile distance for the non-structural layer, $Q3 - Q1 = 0.65 - 0.2 = 0.45$
- The quartile distance for the structural layer, $Q3 - Q1 = 0.75 - 0.25 = 0.50$

- The median for the non-structural layer, $Q2 = 0.45$
- The median for the structural layer, $Q2 = 0.55$

Although from the literature study and the interviews, it is sure that these layers lose their function when disassembling, so the layers do influence the reusability potential. In addition, the literature indicates that a non-structural layer has a minor influence on reusability than a structural layer (Naber, 2012). This research assumes that a non-structural layer influences 45% and a structural layer of 55%. Further detailed laboratory research must give insight into the correctness of these assumptions.

Table 82: Weighting factors for the presence of a non-structural or structural layer

Weighting factors		
Values	Non-structural layer (Q2)	0.45
	Structural layer (Q2)	0.55

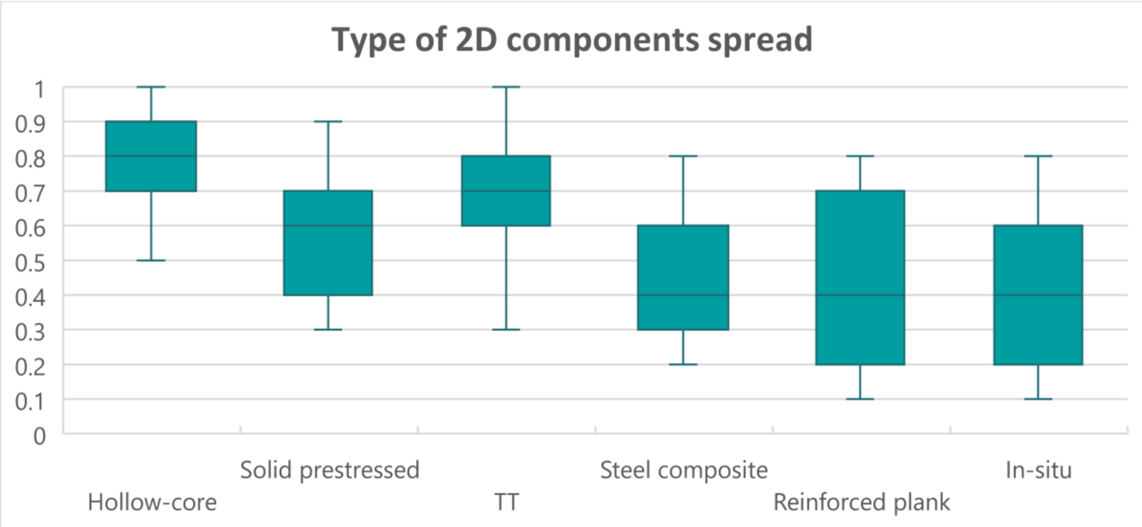

Figure 84: Spread of the scores for 2D component type given by the respondents

Table 83: Testing of the 2D component type score

Values	Hollow-core	Solid prestressed	TT	Steel composite	Reinforced plank	In-situ
Q2	0.8	0.6	0.7	0.4	0.4	0.4
μ	0.8	0.6	0.4	0.2	0.2	0.2
s_x			0.176	0.196	0.265	0.229
n_x	17	17	17	17	17	17
t			6.820	4.205	3.113	3.599
$t_{\alpha=0.32,v}$			0.477	0.477	0.477	0.477
$t_{\alpha,v} < t$	YES	YES	YES	YES	YES	YES

H.1.2 CHECK OF THE BEAM COMPONENT TYPE

The score of the beam component types combines the influence of the sub-indicators into an initial reusability score. This research assumes that each sub-indicator has an equal influence.

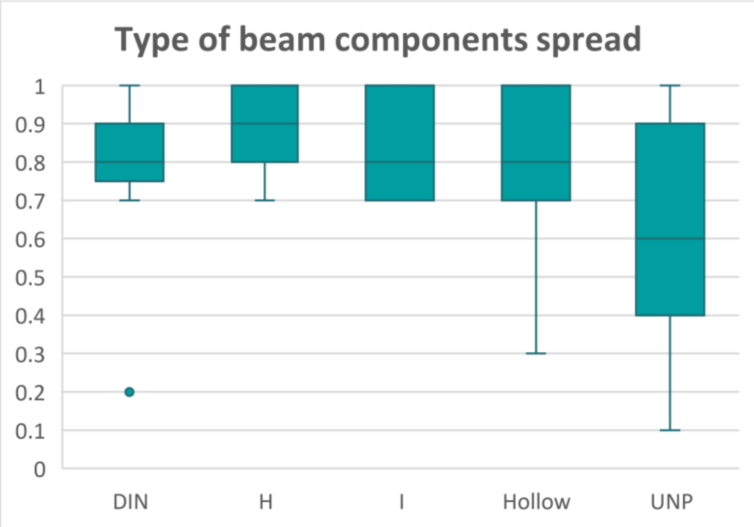

Figure 85: The spread of the given beam component type scores

Table 84: The testing of the beam component type score

Values	DIN	H	I	Hollow	UNP
Q2	0.8	0.9	0.8	0.8	0.6
μ	0.8	0.9	0.8	0.8	0.7
s_x					0.289
n_x	15	17	17	17	17
t					1.447
$t_{\alpha=0.32,v}$					0.477
$t_{\alpha,v} < t$	YES	YES	YES	YES	YES

H.1.3 CHECK OF THE COLUMN COMPONENT TYPE

The score of the column component types combines the influence of the sub-indicators into an initial reusability score. This research assumes that each sub-indicator has an equal influence.

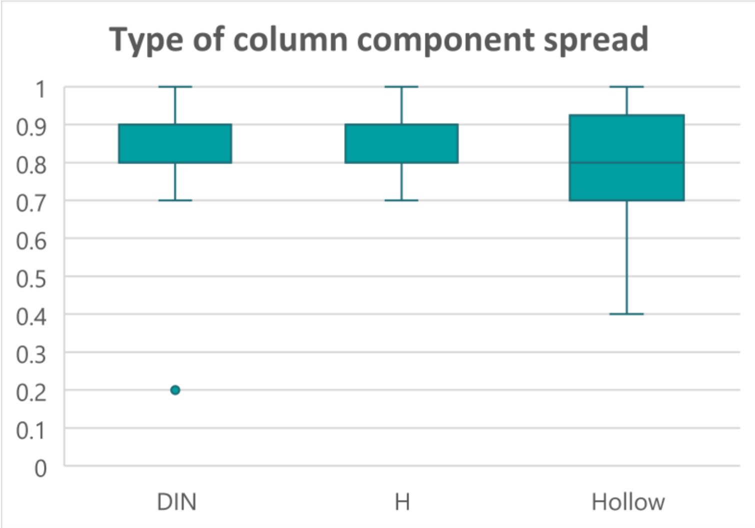

Figure 86: The spread of the given column component type scores

Table 85: The testing of the column component type score

Values	DIN	H	Hollow
Q2	0.8	0.9	0.8
μ	0.8	0.9	0.8
s_x			
n_x	14	16	16
t			
$t_{\alpha=0.32,v}$			
$t_{\alpha,v} < t$	YES	YES	YES

H.1.4 ADJUSTMENT OF THE COMPONENT TYPE SCORE

The scores for the floor types are high. Although the components can be reusable, many additional actions are necessary; this is a problem for in-situ concrete floors, reinforced plank floors, and steel composite floors. These floor types are project-specific; much information must be available before these floors are reusable. Therefore, this research gives low scores to these three-floor systems. These initial scores given by the research deviate from the given scores by the respondents and are therefore unreliable. Although the T-test of the sample size of 17 respondents gives no problem between the respondents' scores and the formula, the scores given by the formula are correct for a standard deviation of 68% and 95%. More respondents, 300, are necessary to conclude that the scores given by the respondents are accurate and reliable. In addition, more detailed research into these types of 2D components is necessary. The scores given by the formula are more accurate for reuse in a SE school building; therefore, this research assumes that the following scores given by the formula are accurate and reliable for now:

- 2D component types: Reinforced plank floor
- 2D component types: Steel composite floor
- 2D component types: In-situ floor

In addition, the given score of the TT floor deviates from the given score of the 17 respondents. TT-floors are good reusable but impractical for school buildings. Therefore, a difference in the scoring of the TT-slab by this research and the score of the 17 respondents appears. The scores given by the formula are more accurate for reuse in a SE school building; therefore, this research assumes that the following score given by the formula is accurate and reliable for now:

- 2D component types: TT-floor

Furthermore, the spread of the given scores for the beam component type: UNP profile and the weighting of the structural and non-structural layer is extreme. Although of the UNP profile, the T-test of the sample size of 17 respondents gives no problem between the scores of the respondents and the formula of the beam component type; the scores given by the formula are correct for a standard deviation of 68% and 95%. In addition, the scores are close. The sample size of 17 respondents is small, which causes outliers to have a significant effect on the standard deviation; therefore, more respondents, 300, are necessary to conclude that the scores for the UNP profile and the finishing and structural layer are accurate and reliable. Moreover, the finishing and structural layer weighting accuracy can increase by performing detailed laboratory research. This research assumes that the following score given by the formula is reliable for now:

- Beam component type: UNP profile

Furthermore, this research assumes that the following weighting factors given by the 17 respondents are reliable for now:

- The weighting of the non-structural layer is 45%
- The weighting of the structural layer is 55%.

Further detailed laboratory research must give insight if the correctness of these assumptions.

	Type of component	score
2D	Prestressed hollow-core	0.8
	Solid prestressed	0.6
	TT	0.4
	Steel composite	0.2
	Reinforced plank	0.2
	In-situ	0.2
	Steel deck sheeting	1.0
1D: beam	Prefab	0.8
	DIN-profile	0.8
	H profile	0.9
	I-profile	0.8
	Hollow profile	0.8
	UNP-profile	0.7
1D: Column	Prefab	0.8
	DIN-profile	0.8
	H profile	0.9
	Hollow profile	0.8

Table 86: Weighting factors for the presence of a non-structural or structural layer

Weighting factors		
Values	Non-structural layer (Q2)	0.45
	Structural layer (Q2)	0.55

H.2 Component's length score

H.2.1 CHECK OF THE 2D COMPONENT LENGTH

The score for the 2D component's length combines the multiplication of 0.60 m and the preference for a long length into a score. The first part of the formula consists of the multiplication of 0.60 m. If the length is a multiple of 0.60 m, the length receives a score of 1.0. However, if the score is not a multiple of 0.60 m, the length receives a score of 0.7.

Equation 8: Length multiplication of 0.60 m

$$\begin{cases} Length\%0.6 = 0\ [1.0] \\ length\%0.6 \neq 0\ \ [0.7] \end{cases}$$

The second part consists of the preference for a long length. The score linear divides over the 2D components categories. The combination of the two scores gives the following scores:

Table 87: The reclaim and reusability score for 2D component lengths

Length	Score multiplication	Score long lengths	Score
<1.80 m	0.7	0.2	0.1
1.80 m	1.0	0.4	0.4
1.80 – 3.60 m	0.7	0.4	0.3
3.60 m	1.0	0.6	0.6
3.60 – 5.40 m	0.7	0.6	0.4
5.40 m	1.0	0.8	0.8
5.40 – 7.20 m	0.7	0.8	0.6
7.20 m (+n*0.60 m)	1.0	1.0	1.0
> 7.20 m	0.7	1.0	0.7

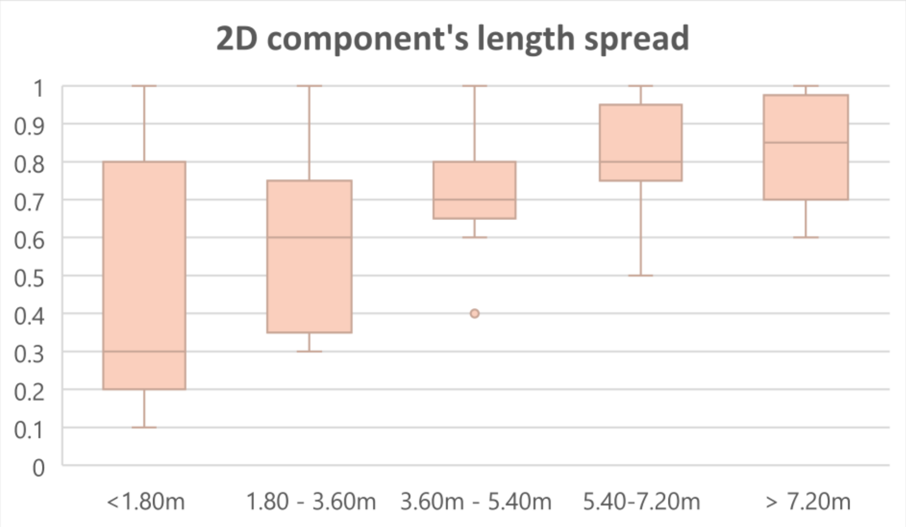

Figure 87: The spread of the given score for the 2D component lengths

Table 88: The testing of the 2D component length score

Values	<1.80 m	1.80-3.60 m	3.60-5.40 m	5.40-7.20 m	>7.20 m
Q2	0.3	0.6	0.7	0.8	0.85
μ	0.2	0.4	0.6	0.8	1.0
s_x	0.343	0.252	0.196		0.149
n_x	15	15	15	15	15
t	1.128	3.073	1.977		-3.767
$t_{\alpha=0.32,v}$	0.478	0.478	0.478		0.478
$t_{\alpha,v} < t$	YES	YES	YES		NO
$t_{\alpha=0.05,v}$					-1.771
$t_{\alpha,v} < t$					NO

H.2.2 CHECK OF THE BEAM COMPONENT LENGTH

The composition of the beam component length score is the same as that of a 2D component. The first part of the formula consists again of Equation 8, and the second part is a score linearly divided over the beam components categories, starting with a score of 0.60. The combination of the two scores gives the following scores:

Table 89: The reclaim and reusability score for beam component lengths

Length	Score multiplication	Score long lengths	Score
<1.80 m	0.7	0.6	0.4
1.80 m	1.0	0.7	0.7
1.80 – 3.60 m	0.7	0.7	0.5
3.60 m	1.0	0.8	0.8
3.60 – 5.40 m	0.7	0.8	0.6
5.40 m	1.0	0.9	0.9
5.40 – 7.20 m	0.7	0.9	0.6
7.20 m (+n*0.60 m)	1.0	1.0	1.0
> 7.20 m	0.7	1.0	0.7

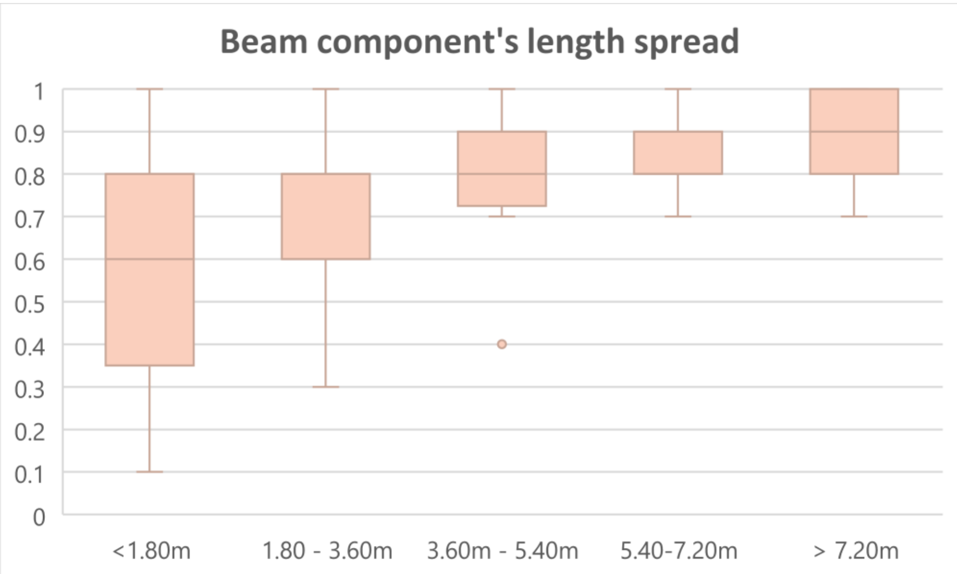

Figure 88: The spread of the given score for the beam component lengths

Table 90: The testing of the beam component length score

Values	<1.80 m	1.80-3.60 m	3.60-5.40 m	5.40-7.20 m	>7.20 m
Q2	0.6	0.8	0.8	0.8	0.9
μ	0.6	0.7	0.8	0.9	1.0
s_x		0.194		0.102	0.109
n_x	14	14	14	14	13
t		1.93		3.672	3.302
$t_{\alpha=0.32,v}$		0.479		0.479	0.479
$t_{\alpha,v} < t$	YES	YES	YES	YES	YES

H.2.3 CHECK OF THE COLUMN COMPONENT LENGTH

The score for the column component's length only focuses on the preference column length, giving the following scores:

Table 91: The reclaim and reusability score for beam component lengths

Length	Score
< 2.60 m	0.1
2.60 – 3.20 m	0.7
> 3.20 m	1.0

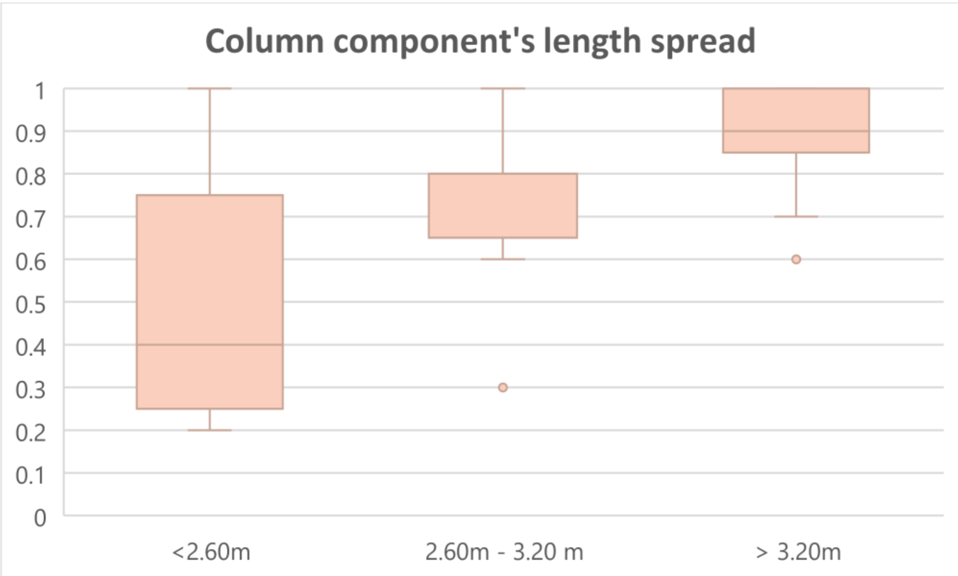

Figure 89: The spread of the given score for the column component lengths

Table 92: The testing of the 2D component type score

Values	<2.60 m	2.60-3.20 m	>3.20 m
Q2	0.4	0.8	1.0
μ	0.1	0.7	1.0
s_x	0.306	0.185	0.122
n_x	15	15	15
t	3.794	2.097	3.167
$t_{\alpha=0.32,v}$	0.478	0.478	0.478
$t_{\alpha,v} < t$	YES	YES	YES

H.2.4 ADJUSTMENT OF THE COMPONENT LENGTH SCORES

The spread of the scores for the lowest component lengths for each load-bearing construction component is extreme. However, the T-tests of the sample size of 17 respondents give no problem between the scores of the respondents and the formula of the component's length. The scores given by the formula are correct for a standard deviation of 68% and 95%. The sample size of 17 respondents is small, which causes outliers to have a significant effect on the standard deviation; therefore, more respondents, 300, are necessary to conclude that the scores for the component's length are accurate and reliable. This research based the initial score of these component's length on the requirements of the 'Bouwbesluit'; therefore, this research assumes that the following scores given by the formula are reliable for now:

- 2D component length: <1.80 m
- Beam component length: < 1.80 m
- Column component length: < 2.60 m

Table 93: The scores for the component length

	Component length	score
2D	< 1.80 m	0.1
	1.80 m	0.2
	1.80 – 3.60 m	0.3
	3.60 m	0.6
	3.60 – 5.40 m	0.4
	5.40 m	0.8
	5.40 – 7.20 m	0.6
	7.20 m (+n * 0.60 m)	1.0
	> 7.20 m	0.7
1D: beam	< 1.80 m	0.1
	1.80 m	0.7
	1.80 – 3.60 m	0.5
	3.60 m	0.8
	3.60 – 5.40 m	0.6
	5.40 m	0.9
	5.40 – 7.20 m	0.6
	7.20 m (+n * 0.60 m)	1.0
	> 7.20 m	0.7
1D: Column	< 2.60 m	0.1
	2.60 – 3.20 m	0.7
	> 3.20 m	1.0

H.3 Demountability score

H.3.1 CHECK OF THE DEMOUNTABILITY SCORES

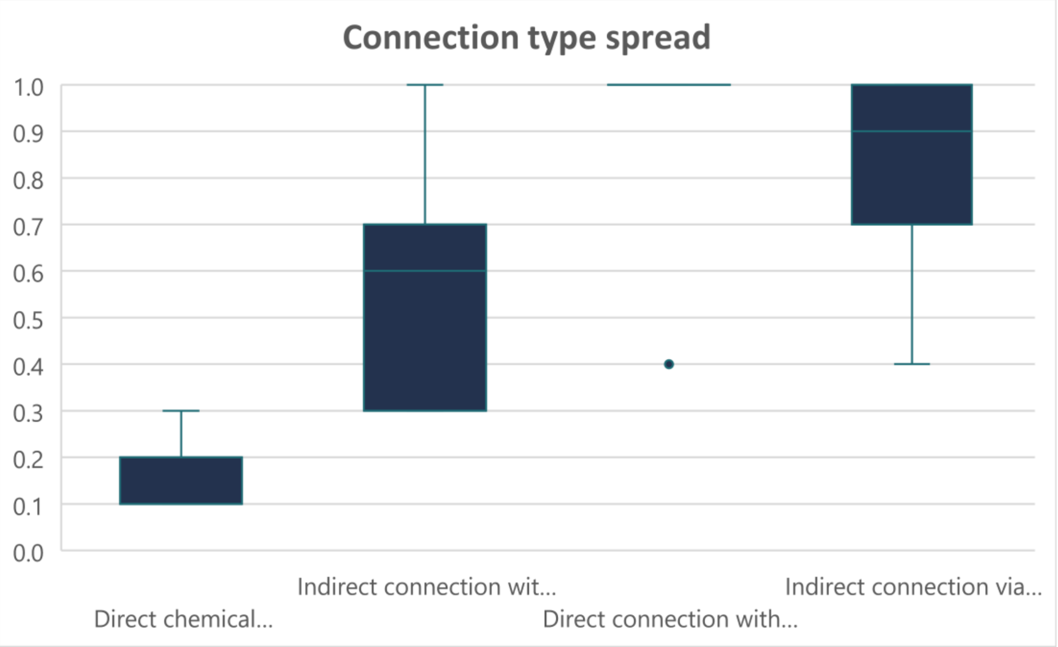

Figure 90: The spread of the type of connection scores given by the respondents

Table 94: Testing the type of connection scores

Values	Direct chemical connection	Indirect connection with a third chemical	Direct connection with additional fixing	Indirect connection via a third dependent element
Q2	0.1	0.6	1.0	0.9
μ	0.1	0.2	0.8	1.0
s_x	0.292	0.295	0.268	0.255
n_x		5	5	5
t		3.035	1.667	-0.877
$t_{\alpha=0.32,v}$		0.505	0.505	0.505
$t_{\alpha,v} < t$	YES	YES	YES	NO
$t_{\alpha=0.05,v}$				-2.132
$t_{\alpha,v} < t$				YES

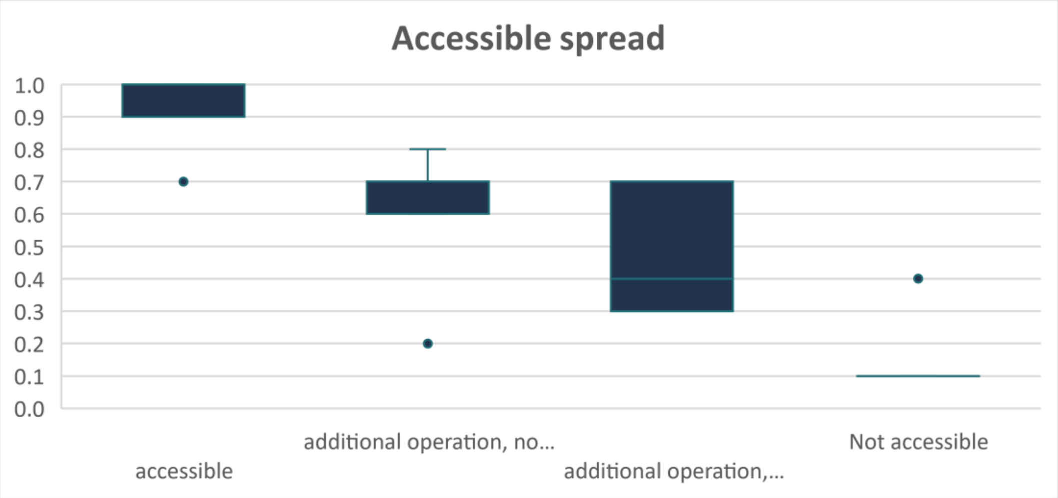

Figure 91: The spread of the accessibility scores given by the respondents

Table 95 Testing the accessibility scores:

Values	Accessible	The additional operation, no damage	The additional operation, damage	Not accessible
Q2	1.0	0.7	0.4	0.1
μ	1.0	0.8	0.4	0.1
s_x		0.235		
n_x		5	5	
t		-0.953		
$t_{\alpha=0.32,v}$		0.505		
$t_{\alpha,v} < t$	YES	NO	YES	YES
$t_{\alpha=0.05,v}$		-2.132		
$t_{\alpha,v} < t$		YES		

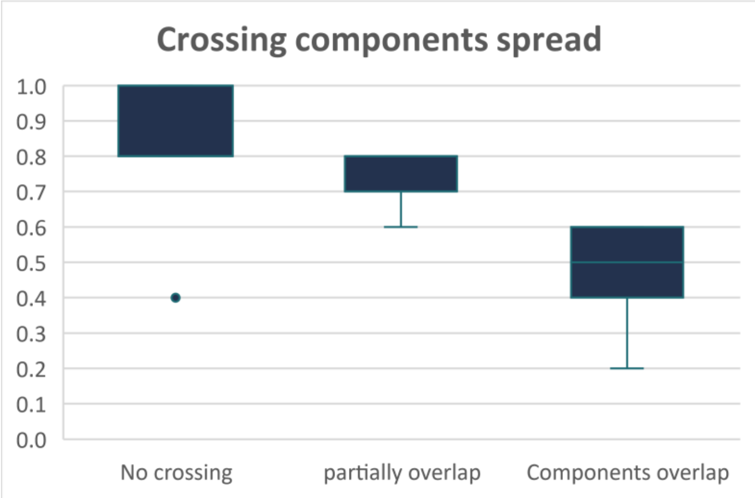

Figure 92: The spread of the crossing components scores given by the respondents

Table 96: Testing the crossing of components scores

Values	No crossing	Partially overlap	Components overlap
Q2	0.8	0.8	0.5
μ	1.0	0.4	0.1
s_x	0.250	0.089	0.167
n_x	5	5	5
t	-1.826	10	5.35
$t_{\alpha=0.32,v}$	0.505	0.505	0.505
$t_{\alpha,v} < t$	NO	YES	YES
$t_{\alpha=0.05,v}$	-2.132		
$t_{\alpha,v} < t$	YES		

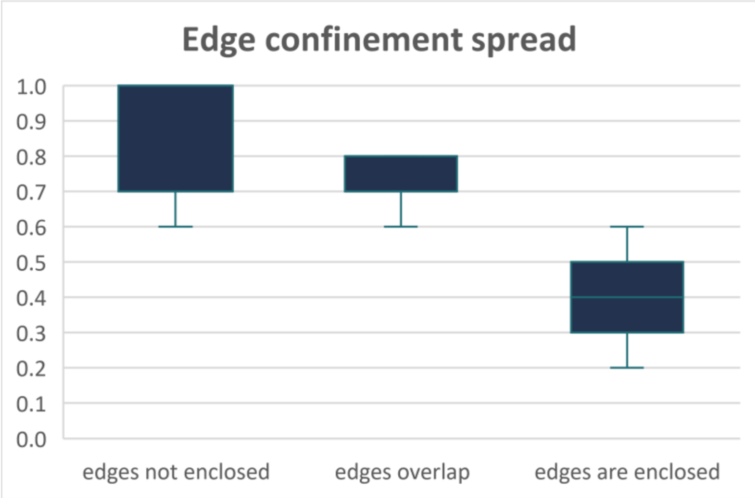

Figure 93: The spread of the edge confinement scores given by the respondents

Table 97: Testing the edge confinement scores

Values	Edges not enclosed	Edges overlap	Edges are enclosed
Q2	1.0	0.7	0.4
μ	1.0	0.8	0.1
s_x		0.0840	0.158
n_x		5	5
t		2.673	-8.485
$t_{\alpha=0.32,v}$		0.505	0.505
$t_{\alpha,v} < t$	YES	YES	NO
$t_{\alpha=0.05,v}$			-2.132
$t_{\alpha,v} < t$			NO

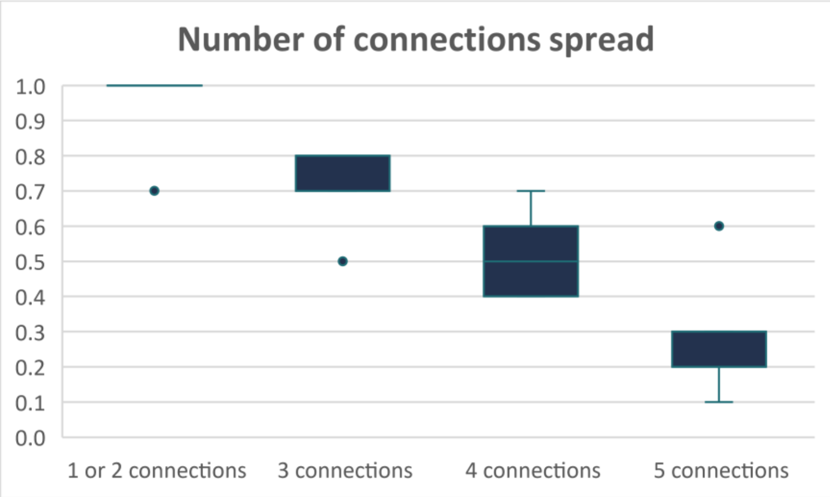

Figure 94: The spread of the number of connection scores given by the respondents.

Table 98: Testing the number of connection scores

Values	1 or 2 connections	3 connections	4 connections	5 connections
Q2	1.0	0.8	0.5	0.2
μ	1.0	0.6	0.4	0.1
s_x		0.130	0.130	0.192
n_x		5	5	5
t		3.430	1.715	1.162
$t_{\alpha=0.32,v}$		0.505	0.505	0.505
$t_{\alpha,v} < t$	YES	YES	YES	YES

H.3.2 ADJUSTMENT OF THE DEMOUNTABILITY SCORES

Some scores found in the literature are close to the given scores by the respondents but are still unreliable. The sample size of 5 respondents is minimal, causing outliers to significantly affect the standard deviation of 68% and 95%. More respondents, 300, are necessary to conclude that the score from the literature is accurate and reliable. The scores found in the literature falls within the 95% standard deviation; therefore, this research assumes that the following scores from the literature are accurate and reliable for now:

- Type of connection: Indirect connection via a third dependent element
- Accessibility: Additional operation, no damage
- Crossing components: No crossing

Other scores found in the literature deviate from the given scores by the respondents and are therefore unreliable. However, the T-test of the sample size of 5 respondents gives no problem between the respondents' scores and the literature. The scores found in the literature are correct for a standard deviation of 68% and 95%. More respondents, 300, are necessary to conclude that the scores from the literature are not accurate and reliable. The scores given by the respondents have a slight deviation; therefore, this research assumes that the following scores given by the respondents are accurate and reliable for now:

- Type of connection: Indirect connection with a third chemical material
- Crossing components: Partially overlap each other
- Crossing components: Completely overlap each other

The last option for unreliable scores is a score found in the literature that does not correspond with the score given by the respondents. In addition, based on the sample size of 5 respondents, the score found in the literature is not correct, with a standard deviation of 68% and 95%. However, the sample size is minimal; more respondents, 300, are necessary to conclude that the score from the literature is not accurate and reliable. This research assumes that the following scores given by the demolition contractors are accurate and reliable for now:

- Edge confinement: Edges completely enclosed

Table 99: Adjusted demountability scores

	Demountability	score
Type of component	Direct chemical connection	0.1
	Indirect connection with third chemical material	0.2
	Direct connection with additional fixing element	0.8
	Indirect connection via a third dependent element	1.0
Accessibility	Accessible	1.0
	Accessible with an additional operation that causes no damage	0.8
	Accessible with an additional operation that causes damage	0.4
	Not accessible, total damage of components	0.1
Crossing components	No crossing	1.0
	partially overlap each other	0.8
	Components overlap each other over the complete component length	0.5
Edge confinement	Component edges are not enclosed	1.0
	Component edges overlap	0.8
	Component edges are enclosed	0.4
Number of connections	1 or 2 connections	1.0
	Three connections	0.6
	Four connections	0.4
	Five connections	0.1

H.4 Physical safety score

The structural engineers, demolition contractors, and contractors do not have knowledge about the physical safety of the components in terms of deterioration, damage and the residual lifespan. These practitioners are not certified to make statements about a visual inspection. Therefore, the scores given by this research are not reliable and accurate. A detailed survey for inspectors indicates whether the chosen scores are reliable and accurate. This research assumes the following score for now:

Table 100: Scores for the residual lifespan

	years	score
Residual lifespan	≥ 40 years	1.00
	≥ 30 years	0.8
	≥ 15 years	0.60
	≥ 10 years	0.30
	< 10 years	0.10

The condition of the load-bearing components defines the residual lifespan.