Circular building foundations

A structural exploration of the possibilities for making building foundations contribute to a circular economy

Master's thesis
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Preface

This thesis was written to finish the Structural Engineering track within the Building engineering master, at the Faculty of Civil Engineering and Geosciences of the Delft University of Technology. The research was conducted between September 2018 and June 2019 and was facilitated by Aronsohn consulting engineers in Rotterdam.

Since I heard and read about the exhaustion of finite natural resources and environmental degradation due to pollutants, I have been interested in developments that counteract these disturbing trends. This interest led to a bachelor's thesis about the reuse of empty buildings. Now, three years later, I have examined the structural possibilities for making building foundations contribute to a circular economy. A circular building foundation is challenging and, until now, often not considered. After the literature study and establishing a new framework, theory was put into practise through a case study.

I would like to thank the graduation committee, who consisted of M. Korff, R.E.P. de Nijs and S. Pasterkamp, of Delft University of Technology and B.B. Scholten of Aronsohn consulting engineers. Their supervision and knowledge have contributed to consistent research progress.

In addition, I want to thank J. Teunizen and M. van Vliet of Alba Concepts, who gave me the opportunity to use the assessment method developed by this company. Also, thanks to P. Noomen of IMd consulting engineers, J.B. Cordes of Ballast Nedam and G. Visser of VolkerInfra for sharing information about the circular building projects in which they have been involved. Their experiences were of great use.

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Abstract

This research investigated how foundations of buildings can become circular and thus contribute to a circular economy. A circular economy strives to close biological and technical cycles to minimise the use of materials and energy. The technical cycle, where foundations belong, is divided into subcycles. Recycling of materials and reuse of products are the most relevant of these subcycles. Reuse of products is preferred because it requires less material and energy than recycling. Circular value can also be obtained by longer and consecutive cycles.

Reuse is facilitated by flexibility. Forms of flexibility are versatility, changeability and expandability. For building foundations, versatility and changeability are distinguished. However, a certain level of expandability should be incorporated in both forms of flexibility. Within the circular economy, many design methods, known as Design for Excellence, have been developed. The tools Design for Disassembly and Design for Adaptability help to design buildings for changeability and versatility, respectively. Corresponding assessment methods have been developed. Some methods are complex and require considerable data. An easy-to-use method suitable for the assessment of foundations was sought and found: Alba Concept.

To define circular foundations, the traditional foundations of buildings are a starting point. A distinction is made between deep and shallow foundations. Often, a deep foundation consists of piles, caps and beams. Shallow foundations are divided into pad, strip and raft foundations. Many design criteria and requirements apply to foundations. This research focuses on design criteria related to the building, soil and construction. Furthermore, three design requirements are considered: transfer of load, minimization of settlements and resistance to environmental degradation.

The theory of a circular economy is relatively new, and practical experiences are limited. To inventory circular, or at least sustainable, foundation principles, the internet and literature were searched. Interviews with stakeholders of circular buildings also provided useful insights. Existing examples, like The Green House in Utrecht and the temporary court in Amsterdam, were studied. In the first case, the lightweight structure and good soil conditions made it possible to construct a shallow foundation of blocks and plates. All elements can be disassembled and reused. The second building has, in spite of the name, a less temporary appearance. Given the loads and soil conditions, a deep foundation was required. The beams and caps will be disassembled and reused for the same building. The foundation piles will be left unused at the building site. In this case, the level of circularity can be improved.

In this research, four foundation variants were studied by combining deep and shallow foundations with versatility and changeability. Based on the soil condition, loads, future scenario, function and desired level of flexibility, the desired type of foundation can be determined. This determination is captured in a concise flowchart. Hereafter, a design guideline can be followed. The following design criteria are distinguished: material, dimension, load bearing capacity, connection and transportation. One should strive for longevity, standardization and uniformity. These terms are linked to the material, element and system levels, respectively. Because the assessment method of Alba Concepts focuses on changeability and buildings in general, it was modified. The alternative method is based on the new concept and enables better assessment. This method focuses on circular foundations in particular and values changeable, as well as versatile, designs.

To determine whether the theoretical concept of circular foundations indeed leads to foundations that are more circular than the traditional ones, two case studies were conducted. The projects concern the Meander Medical Centre in Amersfoort and the clinical training centre of the Radboud University in Nijmegen. These buildings required a deep and shallow foundation, respectively. For both projects, a changeable and versatile foundation was designed. This resulted in four circular foundations, which were assessed by the Alba Concepts' method and the alternative method. Independent of the assessment method, the traditional foundations have a low level of circularity, around 0.2 on a scale of zero to one. Because Alba Concepts focuses on changeability, the versatile foundations obtained a similar result. The changeable foundations result in a higher level of circularity, approximately 0.3 and 0.7. The type of connection and presence of foundation piles cause this difference. Based on the alternative method, all circular foundations score around 0.7 due to the adjusted indicators.

Finally, the structural similarities, differences, challenges, preconditions and feasibility are discussed on the basis of the design criteria and requirements. A versatile foundation appeared to be similar to a traditional one. Differences and challenges arise in case of changeable foundations. For example, the standards of dimensions and connections must be determined. Despite the disassembly, the strength, stiffness and stability must be maintained. Also, the reusability of foundation piles can be improved. More generally, finding a balance between uniformity and freedom of form is both important and challenging. Circular foundations require precise documentation of characteristics and availability. The theoretical concept has to be further developed and supported by the building industry. Eventually, practice should reveal whether foundations are more frequently reused, thus contributing to a circular economy.

Altogether, the assessment methods indicate that the traditional foundation can be more circular with some achievable changes. Foundations must be designed for versatility or changeability. Depending on the chosen form of flexibility, decisions have to be made regarding materials, dimensions, connections, load bearing capacity and transportation. One must strive for longevity, standardization and uniformity at the material, element and system level, respectively. Regardless of the building, adding a certain degree of circular value to the foundation is always possible but requires willingness and innovative thinking. This cultural change is not simple, but it will be beneficial.

Samenvatting

Dit rapport dit gaat in op de mogelijkheden om funderingen van gebouwen circulair te maken, en dus te laten bijdragen aan een circulaire economie. Een circulaire economie probeert de biologische en technische kringlopen te sluiten, om zodoende het materiaal- en energieverbruik te minimaliseren. De technische kringloop, waartoe de fundering behoort, is onderverdeeld in subcycli, waarvan recycling van materialen en hergebruik van producten zijn de meest relevante subcycli. Hergebruik wordt geprefereerd, omdat dit minder materiaal en energie vereist dan recycling. Circulaire waarde kan worden verkregen door lange en opeenvolgende gebruikscycli.

Hergebruik wordt gefaciliteerd door flexibiliteit. Vormen van flexibiliteit zijn polyvalentie, veranderbaarheid en uitbreidbaarheid. Voor funderingen van gebouwen is gekeken naar polyvalentie en veranderbaarheid. Echter, een zekere mate van uitbreidbaarheid moet in beide andere vormen van flexibiliteit aanwezig zijn. Voor een circulaire economie zijn veel ontwerprichtlijnen, aangeduid als Design for Excellence, ontwikkeld. De ontwerprichtlijnen Design for Disassembly en Design for Adaptability bieden houvast bij het ontwerpen van gebouwen voor respectievelijk polyvalentie en veranderbaarheid. Er zijn overeenkomstige beoordelingsmethoden ontwikkeld, waarvan sommige methoden complex zijn en veel data vereisen. Er is gezocht naar een eenvoudig te gebruiken en aan te passen methode voor de beoordeling van funderingen. De methode van Alba Concepts voorzag hierin.

Om circulaire funderingen te definiëren wordt de traditionele fundering als uitgangspunt genomen. Er is onderscheid gemaakt tussen een fundering op palen en een fundering op staal. Vaak bestaat een fundering op palen uit balken, poeren en palen. De fundering op staal is onderverdeeld in poer-, strook- en plaatfunderingen. Er gelden veel ontwerpcriteria en -eisen voor funderingen. Dit onderzoek focust op ontwerpcriteria die gerelateerd zijn aan de bovenbouw, ondergrond en bouw. Daarnaast worden er drie eisen in beschouwing genomen, namelijk de overdracht van belasting, het minimaliseren van zettingen en de weerstand tegen milieuschade.

De theorie van de circulaire economie is relatief nieuw en de praktijkervaring is beperkt. Er is een inventarisatie gemaakt van circulaire, of op zijn minst duurzame, funderingsconcepten, door te zoeken op internet en in literatuur. Daarnaast zijn inzichten verkregen door interviews met betrokkenen van circulaire bouwprojecten. Er zijn bestaande voorbeelden onderzocht, zoals The Green House in Utrecht en de tijdelijke rechtbank in Amsterdam. In het eerste geval maakten de lichtgewicht hoofddraagconstructie en goede grondslag een fundering op staal mogelijk. De funderingsblokken en -platen kunnen worden gedemonteerd en hergebruikt. Het tweede gebouw heeft, ondanks de naam doet vermoeden, geen tijdelijke uitstraling. Gezien de belastingen en grondslag was een fundering op palen noodzakelijk. De balken en poeren kunnen worden gedemonteerd en hergebruikt voor hetzelfde gebouw. De palen zullen waarschijnlijk ongebruikt achterblijven op de bouwlocatie. De mate van circulariteit kan in dit geval worden verbeterd.

In dit onderzoek zijn vier funderingsvarianten bestudeerd, door het combineren van een fundering op staal en op palen met polyvalentie en veranderbaarheid. Op basis van de grondslag, belasting, toekomstscenario, functie en gewenste mate van flexibiliteit kan het gewenste type fundering worden bepaald. Deze bepaling is gevat in een beknopt stroomdiagram. Hierna kan een ontwerprichtlijn worden gevolgd. Er moeten keuzen worden gemaakt met betrekking tot materiaal, afmetingen, draagvermogen, verbindingen en transport. Hierbij moet worden gestreefd naar een lange levensduur, standaardisatie en uniformiteit. Deze begrippen zijn gelinkt aan respectievelijk het materiaal-, element- en systeemniveau. Omdat de beoordelingsmethode van Alba Concepts is gericht op veranderbaarheid en gebouwen als geheel, is de methode aangepast. De alternatieve methode is gebaseerd op het nieuwe concept van circulaire funderingen en voorziet in een betere beoordeling. De methode richt zich specifiek op funderingen en waardeert zowel veranderbare als polyvalente ontwerpen.

Om te bepalen of het theoretische concept voor circulaire funderingen in praktijk resulteert in funderingen die meer circulair zijn dan de traditionele funderingen, zijn twee case studies uitgevoerd. Het betreft het Meander ziekenhuis in Amersfoort en het klinisch trainingscentrum van de Radboud Universiteit in Nijmegen. Deze gebouwen zijn gefundeerd op palen en op staal. Voor beide projecten is een veranderbare en polyvalente fundering ontworpen. Dit heeft geresulteerd in vier circulaire funderingen, die zijn beoordeeld met de methode van Alba Concepts en de alternatieve methode. Ongeacht de beoordelingsmethode scoren de traditionele funderingen slecht met een circulariteitsniveau van circa 0,2 op een schaal van nul tot één. Omdat de methode van Alba Concepts is gericht op veranderbaarheid, resulteert dit voor de polyvalente funderingen in een vergelijkbare score. De veranderbare funderingen scoren hoger met een resultaat van ongeveer 0,3 en 0,7. Het verschil komt door het type verbinding en de aanwezigheid van funderingspalen. De aangepaste indicatoren in de alternatieve methode zorgen ervoor dat alle circulaire funderingen op basis van deze methode circa 0,7 scoren.

Tot slot zijn de constructieve overeenkomsten, verschillen, uitdagingen, randvoorwaarde en haalbaarheid besproken, op basis van de ontwerpcriteria en -eisen. De polyvalente fundering lijkt op de traditionele fundering. Verschillen en uitdagingen doen zich voor bij de veranderbare fundering. Zo is het de vraag wie de standaard bepaalt met betrekking tot afmetingen en verbindingen. Ondanks de losmaakbaarheid moeten sterkte, stijfheid en stabiliteit gegarandeerd blijven. Ook kan de herbruikbaarheid van funderingspalen worden verbeterd. In het algemeen is het vinden van balans tussen uniformiteit en vormvrijheid belangrijk en uitdagend. Circulaire funderingen vereisen precieze documentatie van eigenschappen en beschikbaarheid. Het concept moet verder worden ontwikkel en moet een breed draagvlak krijgen in de bouwsector. Uiteindelijk zal in de praktijk moeten blijken of funderingen vaker worden hergebruikt en dus bijdragen aan een circulaire economie.

Al met al tonen de beoordelingsmethodieken aan dat traditionele funderingen meer circulair kunnen zijn door een aantal uitvoerbare wijzigingen. Zo moeten funderingen worden ontworpen voor polyvalentie of veranderbaarheid. Afhankelijk van de gekozen flexibiliteit moeten er beslissingen worden genomen met betrekking tot materiaal, afmetingen, draagvermogen, verbindingen en transport. Hierbij moet worden gestreefd naar een lange levensduur, standaardisatie en uniformiteit op respectievelijk materiaal-, element- en materiaalniveau. Ongeacht het type gebouw is het altijd mogelijk om een zekere mate van circulaire waarde aan de fundering te geven. Dit vereist bereidwilligheid en een innovatieve manier van denken. Deze cultuuromslag is niet simpel maar zal wel nuttig zijn.

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Glossary

BCI	Building circularity index
BoM	Bill of Materials
BIM	Building information modelling
BREAAM	Building Research Establishment Environmental Assessment Method
C2C	Cradle to Cradle
COBie	Construction Operations Building Information Exchange
CPG	CirculariteitsPresetatie Gebouw
CUR	Civieltechnisch Centrum Uitvoering en Research
DfAD	Design for Adaptability
DfD	Design for Disassembly
DfX	Design for Excellence
DI	Disassembly index
ECI	Element circularity index
EMF	Ellen MacArthur Foundation
EPS	Expanded polystyrene
ERI	Element reusability indicator
GPR	Gemeentelijke Praktijk Richtlijn
IFD	Industrieel, Flexibel en Demontabel bouwen
LCA	Life-cycle assessment
LCC	Life-cycle costing
LEED	Leadership in Energy & Environmental Design
MCI	Material circularity index
MI	Material index
mLCA	Multi life-cycle assessment
MRI	Material recyclability indicator
NAP	Normaal Amsterdam Peil
PCI	Product circularity index
RI	Reusability index
SCI	System circularity index
SRI	System reusability indicator
TLC	Technical life-cycle
ULC	Use life-cycle

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1. Introduction

1.1 Rationale

Due to environmental degradation, exhaustion of finite natural resources, growth of population and urbanization, sustainability has become increasingly important. These worldwide trends require other methods of production and consumption. A circular economy is one way to cope with these trends. This type of economy is based on closed material cycles, renewable energy and system thinking. Value retention and limiting the amount of waste are of great importance (Het Groene Brein, n.d.(a)). Implementing the philosophy of a circular economy contributes to a sustainable world. Circularity is a relatively new topic; many research studies have been conducted on this topic in the last few years, and the Ellen MacArthur Foundation (2013a) has played a driving role. Many studies are related to the technical aspects, as well as process and financial related aspects of a circular economy.

Life is dynamic and facilitated by a statically built environment (Durmisevic, 2006). In other words, static buildings do not support a dynamic way of living. To meet continuously changing requirements and wishes, the built environment must be able to change as well. However, in most cases, this type of change is difficult due to the inability to change buildings' systems and elements. The way we design and construct buildings makes recycling and reuse often difficult or even impossible, leading to demolishment, which results in large amounts of waste. At the same time, new valuable materials and energy are needed. This take-make-dispose way of living is known as the linear economy (Het Groene Brein, n.d.(b)). Although ultimate circularity is theoretically and practically infeasible (Potting, Hekkert, Worrell, & Hanemaaijer, 2017), a transition toward a circular economy is needed to minimise waste. Based on the philosophy of a circular economy, structural research into the possibilities of making buildings circular has already been conducted. However, these studies mainly focused on the superstructure instead of the substructure. Often, foundations have been neglected. Research into this particular part of the building is required to avoid unnecessary waste from foundations and the ground filling with old, unused foundations.

1.2 Objective

Translating a linear economy into a circular economy offers many opportunities for the environment and worldwide system, companies and citizens. The following opportunities have been defined by the Ellen MacArthur Foundation (2015a):

For the environment and worldwide system

- Carbon dioxide emissions
- Primary material consumption
- Land productivity and soil health
- Reduction in negative externalities

For companies

- Profit opportunities
- Reduced volatility and greater security of supply
- New demand for business services
- Improved customer interaction and loyalty

For citizens

- Increased disposable income
- Greater utility
- Reduced obsolescence (pp. 12-15)

Ministries (2016) of the Dutch government published a report with a nationwide program to make the Netherlands circular in 2050. The program's main goal is to efficiently recycle materials without emitting harmful pollutants. Products need to be designed for reuse, without loss of value. As mentioned in the report, the need for a circular economy arises from an increasing demand for raw materials and fossil energy, dependence on other countries and climate change. These developments require another approach of dealing with materials and energy. A transition toward a circular economy creates jobs and economical profit, reduces greenhouse gas emissions and creates a safe and healthy environment (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016).

The ministries (2016) defined five priorities: biomass and food, plastics, manufacturing industry, building industry and consumer goods. These priorities are important for the Dutch economy, have a significant environmental footprint and are willing to translate from a linear economy. In the Netherlands, one of these priorities, the building industry, uses 50% of the raw material, 40% of the energy and 30% of the water. About 40% of the waste and 35% of the carbon dioxide is produced by the building industry (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016).

Although circularity is a broad concept that can be applied to many industries, including the housing and non-residential building industry, just a few buildings have been constructed based on this principle, and more knowledge is required. Most research and projects focused on the superstructure and neglected the substructure. Research into circular foundations is needed to apply the circularity concept to the whole building project. To translate from a linear to a circular foundation approach, the goal is to investigate how to define, design and assess circular buildings, especially foundation systems. By adjusting traditional foundations into circular ones and checking the structural and circular performances, insight should be generated into how to deal with foundations in a circular economy. In this way, building foundations can contribute to a sustainable world.

1.3 Research questions

To achieve the objective, a main research question and additional sub questions have been formulated. The main research question, to be addressed in the thesis, is the following: ‘How can building foundation become (more) circular, using traditional foundation principles as a starting point?’ To answer this question, the following sub questions need to be answered:

1. How is the circular economy defined? (Chapter 2)
2. What are existing design guidelines and assessment methods for circularity? (Chapter 2)
3. What are the characteristics of traditional building foundations? (Chapter 3)
4. What are existing sustainable or circular foundation principles? (Chapter 4)
5. How do the adjusted foundations perform on circularity and structural issues? (Chapter 7)

The first two sub questions focus on circularity. The first question provides insight into the definition and characteristics of the circular economy and its difference from a linear economy. Designing for circularity and assessing circularity are examined when answering the second sub question. These sub questions are answered in Chapter 2.

The third and fourth sub questions relate to foundations. An overview of the commonly used building foundations, accompanied by their structural characteristics and general design criteria and requirements, is given in Chapter 3. Traditional building foundations proved themselves and give a clear and an application-orientated starting point. In Chapter 4, the current sustainable or circular foundation principles are reviewed. In addition, experiences from the first circular building projects are gained.

In Chapter 5, a new theoretical framework for circular foundations is formulated. To implement this framework and verify the concept, a case study was conducted. The traditional foundation of two existing projects was adapted to circular variants. The projects and corresponding foundations are described in Chapter 6. In chapter 7, the circularity and structural performances are reviewed. Here, the fifth sub question is answered. This chapter clarifies whether the new concept leads to more circular and structurally feasible building foundations. In Chapter 8, the conclusion and recommendations are presented.

1.4 Methodology

Figure 1 presents the thesis process, which includes the analysis, synthesis, simulation and evaluation. The analysis is divided into two parts: one focusing on circularity to answer the first two sub questions and one focusing on foundations, answering the third sub question. In the synthesis, the theoretical framework for circular foundations is elaborated to be determined how circular foundations can be defined, designed and assessed. Also, the case study’s projects are described and the associated traditional foundations are adjusted to circular alternatives. In the simulation and evaluation, the adapted foundations are checked on basis of the circularity index, and structural considerations are made. Finally, the conclusion and recommendations are presented.

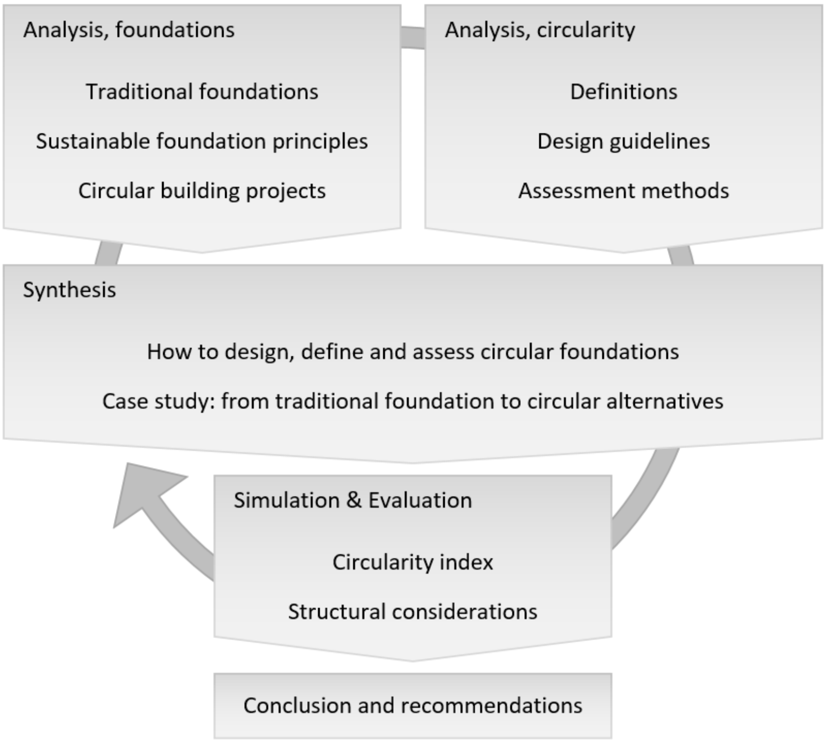


Figure 1. Methodology

To further define the scope of the research the following restrictions are formulated:

A. Process and financial related aspects of the transition from linear to circular foundations are not captured in this thesis. This research focuses on the technical aspects related to the possibilities of making building foundations circular.
B. Foundations of housing and residential buildings are considered since the author has a background in building engineering. Foundations of other civil structures, like hydraulic structures and infrastructure, are excluded.
C. Limiting the time spent on the circularity assessment method is desired. Research should reveal whether it is possible to use an (modified) existing assessment method or whether a new method is needed. If a new assessment method must be developed, it should be a rather simple method.
D. Traditional building foundations, which are commonly used in the Netherlands, are the starting point of the research. The possibilities to make these foundations circular should be, as much as possible, within the boundaries of current knowledge and experience.
E. The focus of loads is vertical compression loads, which is usually the highest type of load to be taken by the foundation. Special issues, like extreme horizontal or vertical tensile forces and earthquakes, are not considered.
F. This report focuses on the implementation of circular characteristics in new designs. Therefore, the paper does not discuss the reuse of existing foundations. However, reusing existing foundation systems is important. By reusing existing foundations, the lifespan is extended, and the use of new materials and energy is avoided. Reuse also reduces the building site being filled with new foundations.

2. Circularity

This chapter concerns circularity and is divided into three parts. First, the circular economy is defined; second, the way one designs for circularity is described; and third, the methods to assess circularity are investigated. At the end of each section, a conclusion and discussion are provided to determine how the information can be related to foundations.

2.1 Define

To define circularity, a division is made between a description of a circular economy, including definitions, and frameworks and models, which support the circularity economy. Hereafter, the differences between circular and linear economies and the schools of thought are described. The latter also includes the driving ways of value creation in the system of a circular economy.

2.1.1 Description

Although the term circularity has existed for some time, this concept has garnered much attention in the last couple of years. This attention was mainly initiated by the MacArthur Foundation (2013a). A few years ago, this non-profit organisation described the concept of a circular economy. In this way, the foundation tried to compose a coherent framework, based on other schools of thoughts, to create broad awareness and support.

Figure 2 provides the system diagram of the circular economy suggested by the MacArthur Foundation (2013a). This system diagram consists of three parts: input, biological and technical cycles, and output. At the top, material and energy enter the system. Here, use of toxic and finite natural resources must be avoided and the use of renewable material and energy has to be pursued. Emission of harmful substance into soil water and air must be limited. The valuable cycles of biological (left) and technical (right) materials concern a major part of the circular economy. Materials and products should remain in these cycles as long as possible for their optimal use. At the bottom of the system, loss of valuable products, materials and energy should be minimised. This approach involves new business models and asks for broad and systematic cooperation (Rood & Hanemaaijer, 2017).

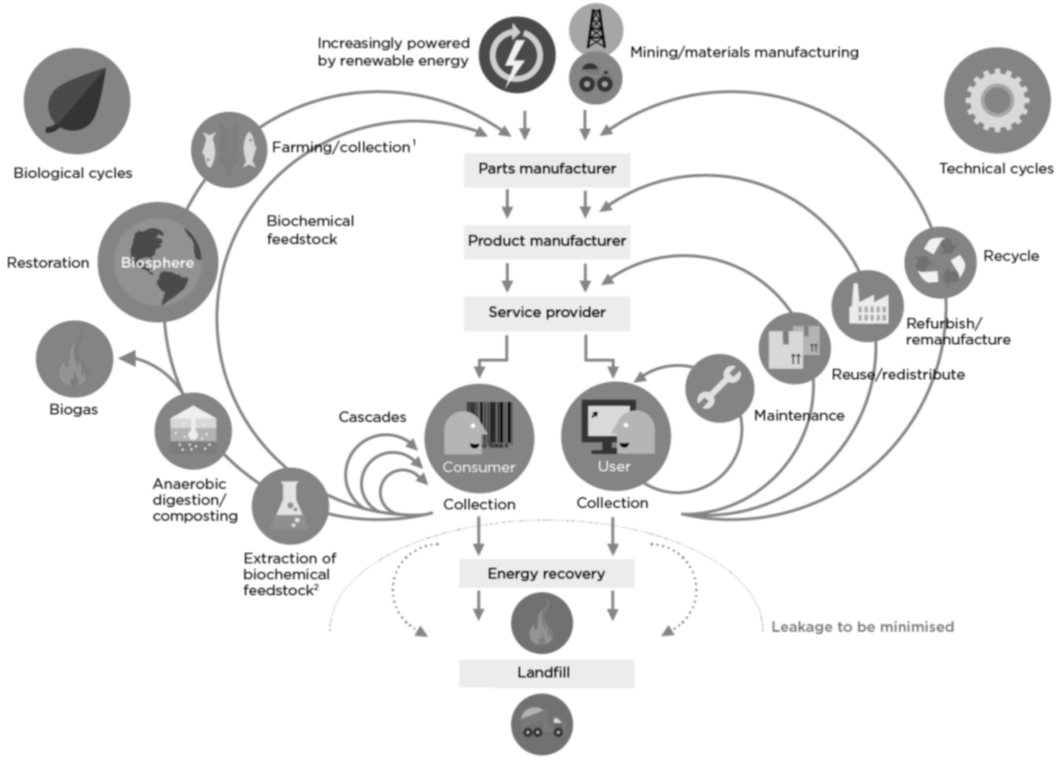


Figure 2. System diagram of a circular economy (Ellen MacArthur Foundation, 2015b, p. 8)

Since the MacArthur Foundation (2015a) has an initiating and leading role in this concept, much information can be gained from this organisation's published reports. Below, descriptions of the technical and biological cycles and the five key principles on which the circular economy is founded, formulated by the MacArthur Foundation (2015a), are provided:

> A. The technical cycle involves the management of stocks of finite materials. Use replaces consumption. Technical materials are recovered and mostly restored in the technical cycle.
> B. The biological cycle encompasses the flows of renewable materials. Consumption only occurs in the biological cycle. Renewable (biological) nutrients are mostly regenerated in the biological cycle. (p. 7)

> 1. Design out waste: In a circular economy, waste does not exist, and is designed out by intention. Biological materials are non-toxic and can easily be returned to the soil by composting or anaerobic digestion. Technical materials . . . are designed to be recovered, refreshed and upgraded, minimising the energy input required and maximising the retention of value (in terms of both economics and resources).
> 2. Build resilience through diversity: A circular economy values diversity as a means of building strength. Across many types of systems, diversity is a key driver of versatility and resilience. . . . Similarly, economies need a balance of various scales of businesses to thrive in the long term. The larger enterprises bring volume and efficiency, while the smaller ones offer alternative models when crises occur.
> 3. Rely on energy from renewable resources: The energy required to fuel the circular economy should be renewable by nature, in order to decrease resource dependence and increase systems resilience (to oil shocks, for example). This will be further enabled by the reduced threshold energy levels required in a circular economy.
> 4. Think in systems: In a circular economy, systems-thinking is applied broadly. Many real-world elements, such as businesses, people or plants, are part of complex systems where different parts are strongly linked to each other, leading to some surprising consequences. In order to effectively transition to a circular economy, these links and consequences are taken into consideration at all times.
> 5. Waste is food: In a circular economy, prices act as messages, and therefore need to reflect full costs in order to be effective. The full costs of negative externalities are revealed and taken into account, and perverse subsidies are removed. A lack of transparency on externalities acts as a barrier to the transition to a circular economy. (pp. 7-8)

In the term 'circular economy', the word 'circular' refers to closing the biological and technical material cycles. The word 'economy' refers to aspects related to financing and processes. This report focuses on the circularity aspects of closing the technical and biological cycles. The Ellen MacArthur Foundation (2013a) defined the concept of a circular economy as follows:

> A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models. (p. 7)

In addition to the MacArthur Foundation's definition, many other organisations, companies and researchers have tried to define the circular economy concept. Recently Kirchher, Reike and Marko (2017) analysed more than a hundred definitions. Based on all these definitions, they tried to formulate one that contains the most important, recognized characteristics of a circular economy. Ultimately, Kirchherr et al. (2017) gave the following definition of a circular economy:

> A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. (pp. 224-225)

Similar research was conducted by Geissdoerfer, Savaget, Bocken and Hultink (2017). They investigated the relationship between the concept of the circular economy and sustainability. Another aim of the research was to determine the main similarities and differences between these concepts. The researchers found that 'the circular economy is viewed as a condition for sustainability, a beneficial relation, or a trade-off in literature' (p. 767). Furthermore, a variety of similarities and differences were determined. Based on many other research studies, Geissdoerfer et al. (2017) defined sustainability and the circular economy as follows:

> Sustainability is the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations. . . . A circular economy is a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. (p. 759)

2.1.2 Supporting frameworks and models

The second definition was systematically composed by analysing all definitions on core principles, aims and enablers. Herein, several models can be recognised, like the triple bottom line framework, systems perspective and R-framework. Kirchherr et al. (2017) applied these models since they observed that they were frequently mentioned in the studied definitions. This use indicated a shared recognition of the importance of the models as a fundamental part of a circular economy.

The triple bottom line framework, which is part of the aims, is illustrated in Figure 3. This framework represents the elements People, Planet and Profit. Therefore, the framework is also known as the 3P model. These aspects reflect social equity, environmental quality and economic prosperity, respectively. The elements should be equally combined to obtain sustainable development. If one element gains more attention, the other two will suffer. In addition to these three dimensions, a time dimension is added. This fourth dimension reflects the future generation, as the end of the definition describes.

The systems perspective and R-framework belong to the core principles. For the transition from a linear to circular economy, a fundamental system shift is necessary. This transition should take place at three levels: the micro, meso and macro. According to the definition, these levels represent products, companies, consumers (micro level), eco-industrial parks (meso level) and city, region, nation and beyond (macro level). A systems perspective is visualised in Figure 4. The concept can be used to divide a subject into levels of ascending/descending order and identify a hierarchy.

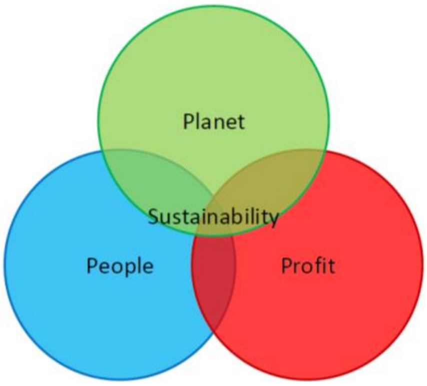


Figure 3. Triple bottom line framework (3P)

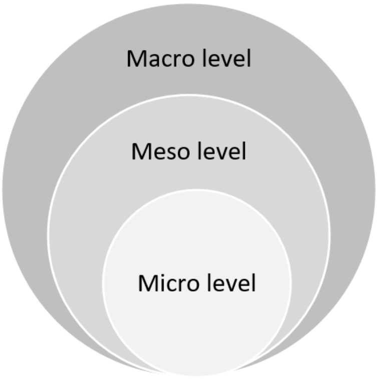
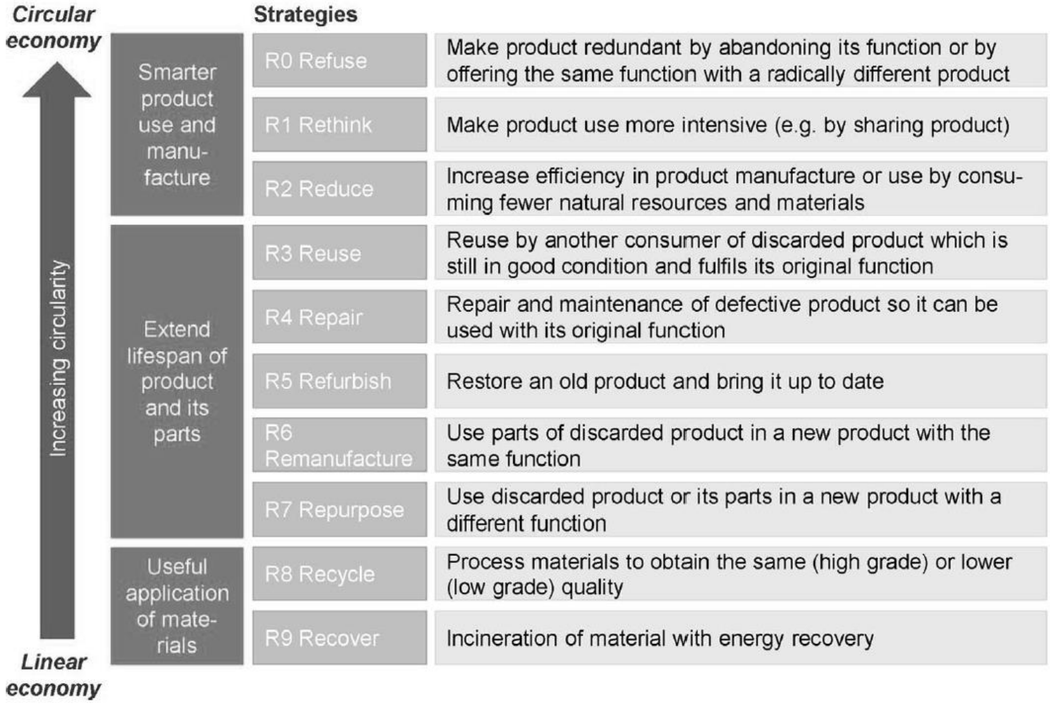


Figure 4. Systems perspective

The definition contains priority levels of circularity. An overview of all distinguished circularity levels is provided in Figure 5. Many of these levels can be recognised in the circular economy's technical cycles. Inner circles correspond to higher levels of circularity. The levels are mainly determined by energy and material use and functionality: the use period should be maximised and the amount of material and energy should be minimised. As formulated by Potting et al. (2017), the following rule can be used: 'Higher level of circularity is equal to fewer natural resources and less environmental pressure' (p. 5). Figure 5 presents the R9 framework, which is the most extensive. The levels of circularity are subdivided into three strategies that can be linked to the design process, product level and material level. As an alternative to the R9 framework, smaller frameworks exist, like the R3, R4 and R6 frameworks. The R3 framework focuses on reduce, reuse and recycle and can be recognised in the definition of Kirchherr et al. (2017).



	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 5. Levels of circularity (9R) (Kirchherr et al., 2017, p. 224)

2.1.3 Differences between circular and linear economies

Knowing the definition of a circular economy, the main differences between it and the linear economy can be discussed. The linear economy is based on take, make and dispose, as visualised in Figure 6. In this flow, technical and biological materials are mixed, causing the vast majority of materials to end as waste. This practice requires new raw materials and fossil fuel for the production of new products (3R reinmagineers, n.d.). Depletion of finite natural resources and the emission of harmful substances are maintained.

According to the Ellen MacArthur Foundation (2013a), an important distinction between the linear and circular economy concerns the difference between efficiency and effectiveness. From an environmental perspective the focus of the linear economy is on eco-efficiency. As formulated by the Ellen MacArthur Foundation, this focus means minimising the volume, velocity and toxicity of material flows but does not change the linear process, resulting in a tremendous amount of waste. Because materials are not designed for recycling, the small amount of reused material is downcycled. Downcycling reduces the material's quality and usability and maintains the short term, cradle-to-grave system (Ellen MacArthur Foundation, 2013a).

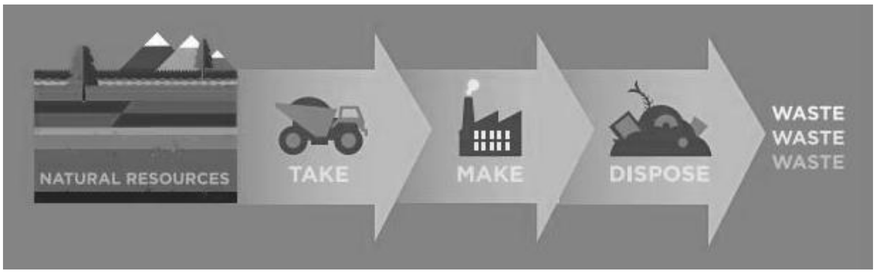


Figure 6. The principle of a traditional linear economy (3R reinmagineers, n.d.)

A circular economy is based on optimal use of energy and material: reduce, reuse and recycle. This economy focuses on eco-effectiveness. Products should be designed for reuse and recycling of associated material. The product's relation to the environment is of great importance and economic growth can be achieved. Materials should be upcycled, so they maintain their quality and gain information over time. This practice encourages a long term, cyclical, cradle-to-cradle system (Ellen MacArthur Foundation, 2013a). These fundamental differences are summarised in Table 1.

	Linear economy	Circular economy
Roadmap	Take-make-dispose	Reduce-reuse-recycle
Focus	Eco-efficiency	Eco-effectiveness
System boundaries	Short term, purchase to sale	Long term, multiple cycles
Reuse	Downcycling	Upcycling, cascading
Business model	Products	Services

Table 1. The fundamental differences between a linear and circular economy (Het Groene Brein, n.d.(b))

From a business model perspective, a linear economy is based on selling products. Products undergo changes of ownership and after usage are disposed. In a circular economy, the product manufacturer remains the owner and sells the product as a service. Subsequently, several consumers can be the product user. Manufacturers maintain the product's serviceability (Het Groene Brein, n.d.(b)).

2.1.4 Schools of thought and value creation

The concept of a circular economy has been developed by several schools of thoughts. An overview of these schools of thought is given below. The corresponding descriptions are cited from Het Groene Brein (n.d.(c)) and the Ellen MacArthur Foundation (2013b):

A. Regenerative Design: The idea of regenerative design, developed by American professor John T. Lyle in the seventies, is that processes within all systems renew or regenerate their own sources of energy and materials they consume. All needs of society are fulfilled within the limits of nature. (Het Groene Brein, n.d.(c))

B. Performance Economy: Walter Stahel coined the vision of an economy in loops, including the principles of product-life extension, long-life goods, reconditioning activities and waste prevention. Selling services instead of goods is an important notion in his thinking: one pays for the performance products deliver. This resulted in the notion of 'performance economy'. (Het Groene Brein, n.d.(c)) It also insists on the importance of selling services rather than products. (Ellen MacArthur Foundation, 2013b, p. 30)

C. Cradle to Cradle (C2C): In the cradle-to-cradle model, developed by Michael Braungart, materials involved in industrial and commercial processes are considered to be nutrients for both technical solutions as biological reutilisations. Design is literally from cradle to cradle - in the design process, the whole lifecycle of the product and its materials are considered. Technical nutrients should not have components that harm the environment, and biological nutrients should be biodegradable. (Het Groene Brein, n.d.(c)) Cradle to Cradle framework focuses on design for effectiveness in terms of products with positive impact, which fundamentally differentiates it from the traditional design focus on reducing negative impacts. (Ellen MacArthur Foundation, 2013b, p. 30)

D. Industrial Ecology: Industrial Ecology is the study of material and energy flows through industrial systems. (Het Groene Brein, n.d.(c)) This approach aims at creating closed-loop processes in which waste serves as an input, thus eliminating the notion of an undesirable by-product. Industrial ecology adopts a systemic point of view, designing production processes in accordance with local ecological constraints whilst looking at their global impact from the outset, and attempting to shape them so they perform as close to living systems as possible. (Ellen MacArthur Foundation, 2013b, p. 31)

E. Blue Economy: The Blue Economy, initiated by Gunter Pauli, is an economic philosophy that gains knowledge from the way natural systems form, produce and consume. This knowledge is applied on challenges that we face, finding solutions for local environments with specific physical or ecological characteristics. (Het Groene Brein, n.d.(c))

F. Biomimicry: Biomimicry is an approach by Janine Benyus, inspired by nature. Biomimicry imitates nature's designs and processes for solutions in human society. (Het Groene Brein, n.d.(c)) She thinks of it as 'innovation inspired by nature'. (Ellen MacArthur Foundation, 2013b, p. 31)

G. Permaculture: Australian ecologists Bill Mollison and David Holmgren coined the term 'permaculture' in the late seventies, defining it as 'the conscious design and maintenance of agri-culturally productive ecosystems, which have the diversity, stability and resilience of natural ecosystems'. (Ellen MacArthur Foundation, 2013b, p. 31)

The Ellen MacArthur Foundation (2015a) has defined different methods of value creation in the circular economy. The foundation distinguishes the power of the inner circle, circling longer, cascaded uses across industries and pure, non-toxic, and easier to separate inputs and designs. Figure 7 illustrates the four sources of value creation by which the circular economy is driven. Each of these sources can be recognised in the circular economy system diagram. The Ellen MacArthur Foundation (2015a) provided the following explanations of the four sources of value creation:

1. The power of the inner circle refers to the idea that the tighter the circle, the more valuable the strategy. Repairing and maintaining a product . . . preserves most of its value. If this is not possible anymore, individual components can be reused or remanufactured. This preserves more value than just recycling the materials. Inner circles preserve more of a product's integrity, complexity, and embedded labour and energy.
2. The power of circling longer refers to maximising the number of consecutive cycles and/or the time in each cycle for products (e.g., reusing a product a number of times or extending product life). Each prolonged cycle avoids the material, energy and labour of creating a new product or component. For products requiring energy, though, the optimal serviceable life must take into account the improvement of energy performances over time.
3. The power of cascaded use refers to diversifying reuse across the value chain . . . substituting for an inflow of virgin materials into the economy in each case.
4. The power of pure inputs, finally, lies in the fact that uncontaminated material streams increase collection and redistribution efficiency while maintaining quality, particularly of technical materials, which in turn extends product longevity and thus increases material productivity. (p. 8)

The power of…

…the inner circle

…circling longer

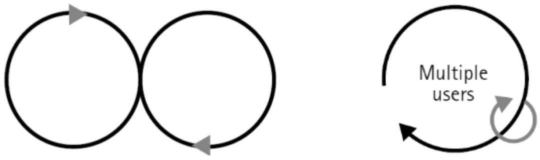
…cascaded uses across industries

…pure, non-toxic, easier to separate inputs and designs

Figure 7. Sources of value creation in the circular economy (Ellen MacArthur Foundation, 2015a, p. 8)

Similar sources of value creation have been formulated by other researchers, like Lacy, Keeble, and McNamara (2014), who distinguished four areas of value creation, as visualised in Figure 8. Cascading and longer cycles are similar to the previously defined sources of value creation. Lacy et al. (2014) explained the areas of value creation as follows:

1. Lasting resources: Breaking the link between resource scarcity and economic activity by using only resources that can be continuously regenerated for productive use.
2. Liquid markets: Eliminating idle time of products in the markets in order to grow the number of users that gain benefit from the same volume of goods.
3. Linked value chains: Minimizing resource value destruction in a value chain by reclaiming and linking up waste outputs as useful inputs into a next life production process.
4. Longer life cycles: Keeping products in economic use for longer to satisfy a greater demand and provide more utility without needing additional natural resources. (p. 6)



Lasting resources Liquid markets

Linked value chains Longer life cycles

Figure 8. Areas of value creation in the circular economy (Lacy et al., 2014, p. 6)

2.1.5 Conclusion and discussion

Whereas the Ellen MacArthur Foundation (2013a) has made an important contribution to the definition of the circular economy and drawn attention to the concept, the definition of Kirchherr et al. (2017) is more complete because, through systematic research, the most important and widely supported aspects are included. The definition addresses the triple bottom line framework, system perspective and R-framework. Related to foundations, the R-framework is the most important part of the definition. Although the framework can be expanded, reduce, reuse and recycling are the most important levels of circularity. These levels focus on reducing the number of materials and amount of energy, reusing products, and recycling material. These goals can also be applied to the foundation system, its elements and the associated materials. Using reduce, reuse and recycling, the amount of waste can be minimised. This point is the main difference between a circular economy and the current, linear economy, which is characterised by enormous amounts of waste (Het Groene Brein, n.d.(b)).

In a circular economy, value can be created in different ways. For foundations, the following are of most interest: the inner circle, longer cycles and consecutive cycles (Ellen MacArthur Foundation, 2015a). The most value can be created in the inner circle, which means that reusing the foundation system or its elements is better than recycling the material. Generally, recycling would require more material and energy-consumption than reuse. Cycle length should be maximized and consecutive to optimise utility. Longer and consecutive cycles avoid unnecessary use of new material and energy. Thus, foundations have to be used for a long time and/or repeatedly. These value creation methods are suitable to consider when designing, in this case, building foundations. How to design for a circular economy is discussed in the following section.

2.2 Design

Flexibility

Durmisevic (2006) states that designing for transformable structures results in sustainable designs, the fundamental goal of a circular economy. High structural transformation capacity results in high flexibility and thus low environmental impact. This is presented in Figure 9. Flexibility is an important condition for sustainability and thus a circular economy. The tremendous amount of waste is the result of the current static built environment, which cannot facilitate a dynamic way of life. Durmisevic argues that transformation capacity depends on a structure's disassembly potential. Making a structure demountable creates adaptability, reuse and recycling. This idea is visualised in Figure 10. Disassembly is the key factor for transformable buildings. The lower the disassembly potential, the lower the adaptability, reuse and recycling potential, resulting in low reversibility, so irreversible structures. Therefore, disassembly, adaptability, reuse and recycling are key factors in what Durmisevic (2018) calls reversible, or circular, buildings.

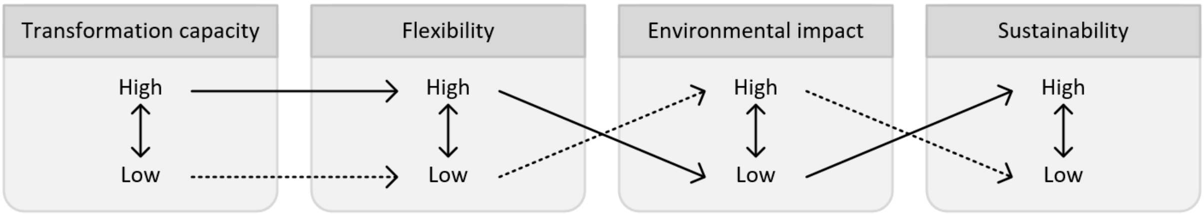


Figure 9. Relationship between transformation capacity and sustainability (Durmisevic, 2006, p. 96)

Transformable buildings are described by three dimensions: structural, spatial and material/element transformation. The subsystems represent the technical, functional and physical functions, respectively. Structural transformation relates to the replaceability and reconfiguration of a building's systems and its components. Spatial transformation concerns the adaption of space. Transformation of materials/elements relates to the possibilities of separation and thus element reuse and material recycling (Durmisevic, 2006). The mutual relations and characteristics of the three dimensions of building transformation are illustrated in Figure 10. The dimension of time has been added to reversible buildings. Time causes changes to buildings, which are not designed for one function. Equally, materials are not designed for one application. Therefore, buildings can be seen as material banks (Durmisevic, 2018).

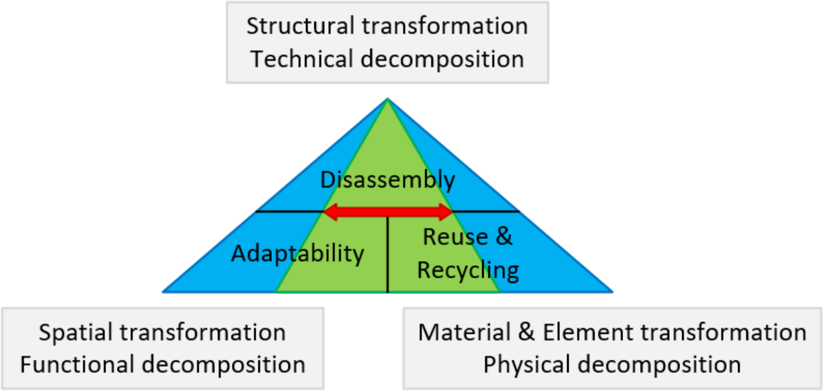


Figure 10. Three dimensions of building transformation (Durmisevic, 2018, p. 24)

Durmisevic (2006) assumed that buildings are transformable, or reversible, if they consist of interdependence and exchangeable systems, components and elements. She linked the functional, technical and physical domains of a building via interdependency and exchangeability to seven disassembly factors. These factors should to be considered when designing for disassembly. Thus, the decomposition and disassembly factors are interconnected by interdependency and exchangeability.

Lifespan
There are several types of building lifetimes. The most important are economic, technical and functional lifetimes (Durmisevic, 2006). If desired, other lifetimes, like the aesthetic, can be identified. This research focuses on the technical and functional lifetimes, as presented in Figure 11. Whereas the technical lifetime is related to the technical state of a building, the functional lifetime is related to its use. As dynamic life and static built environments conflict, the technical and functional lifetimes correspondingly conflict. In many cases, the technical lifetime is longer than the functional lifetime. While the desired function continuously changes, the building remains technical healthy.

The service life is the balance between the technical lifetime (supply) and the functional lifetime (demand). Often, these lifetimes are unbalanced, resulting in a short service life, which is consequently not sustainable. This imbalance can be related to the economic lifetime, displayed in Figure 11. This lifetime ends when the technical state does not meet the functional requirements (Durmisevic, 2006). Measurements need to be taken, like maintenance or refurbishment, which are often financially undesirable. Since buildings are not designed for reuse or recycling, this cost leads to vacancy or demolishment.

Although the financial aspect is not part of the research, the case study in Fischer's (2019) report is interesting. She looked at the financial aspect of different foundation lifespan scenarios. Scenario A concerned investing in a new foundation each 50 years in a period of 150 years. Scenario B focused on an additional investment at year 0 to extend the lifespan to 150 years. Scenario A appeared to be more expensive and less sustainable than scenario B. In scenario C, an additional investment facilitated a lifespan of 150 years and interim expansion of the building. Then, scenario A was cheaper than scenario C. However, from an environmental point of view, additional investments are more sustainable since they reduce the use of finite natural resources and pollutant emissions.

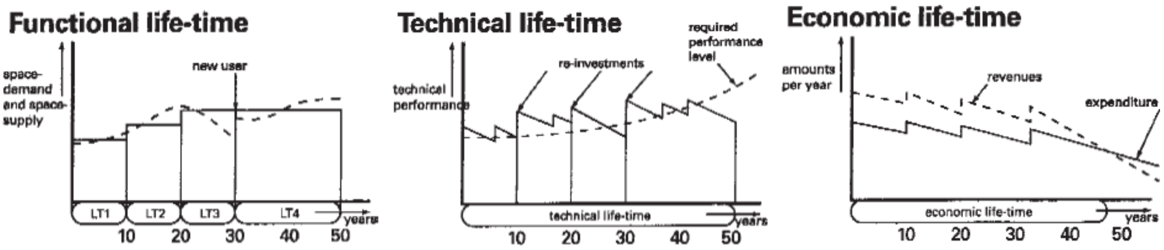


Figure 11. Functional, technical and economic lifetime (Durmisevic, 2006, p. 65)

Paesschen (2011) investigated the relationship between the lifespan and desired flexibility. She distinguished three forms of flexibility: changeability, expandability and versatility. Changeability concerns physically changing the system, expandability refers to expanding the system and versatility focuses on multiple usages of the same system. Based on lifespan prediction and desired level of flexibility, four scenarios were distinguished. A lifespan under fifty years was determined to be short, whereas a lifespan over fifty years was determined to be long. Short and long lifespans are linked to unstable and stable locations, respectively. If the function is subjected to changes, flexibility is required; otherwise, a static building will suffice.

1. Short lifespan, static
2. Short lifespan, flexible
3. Long lifespan, static
4. Long lifespan, flexible

Each scenario requires other decisions, which are explained by Paesschen (2011). For a short lifespan, a slender, a lightweight and demountable structure is desired. The difference between static and flexible is related to the dimensions and reuse or recycling. For a static structure, elements have project-specific dimensions and materials should be recyclable. A flexible structure requires project independent dimensions and elements that can be reused. Projects with a long lifespan have a surplus of load bearing capacity, permanent connections and materials with a long technical lifespan. The structural layer should be independent of the other building layers. Again, the difference between a static and flexible structure is the dimensions. A static structure is dimensioned for a specific project. A flexible structure has generic dimensions, which can be applied to different projects (Paesschen, 2011).

Levels and layers

In contrast to traditional buildings, which are considered a composition of elements, a hierarchy of subassemblies should be recognised in transformable buildings (Durmisevic & Brouwer, 2015). Disassembly must be represented at any level of the hierarchy, as illustrated in Figure 12. From the highest to the lowest level, the building, system, component, and material/element levels are determined. Construction takes place from the lowest to the highest level, and conversely, deconstruction takes places from the highest to the lowest level. The building is composed of systems, each with a main building function. A collection of components form a system. Each component can have another function to facilitate the overall system's function. Components are built from elements and materials. Here, the same functional relationship can be applied.

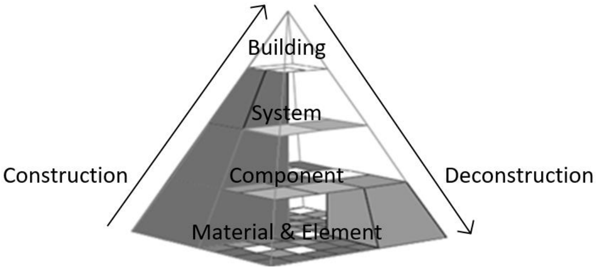


Figure 12. Hierarchy of subassemblies (Durmisevic & Brouwer, 2015, p. 7)

The structural, spatial and material/element transformation effect all subassemblies, namely building, system, component and element. Structure represents the components and systems, and space represents the building, resulting in a hierarchy with the material/element level at the bottom, the structure level in the middle and the space level at the top (Durmisevic & Brouwer, 2015). The more these layers are interconnected, the more a building is fixed, and thus the less a building is decomposable. A representation is provided in Figure 13.

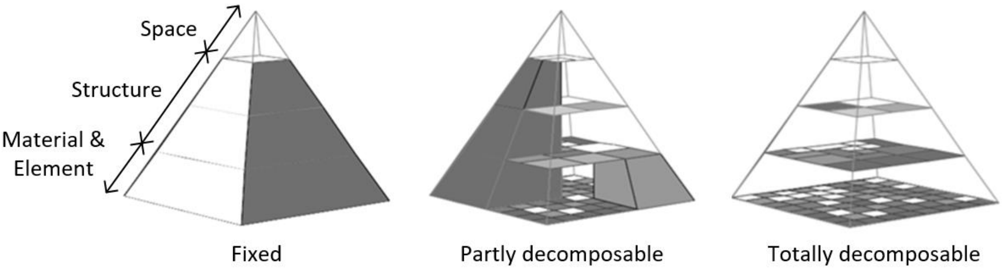


Figure 13. Three principles of integration in buildings (Durmisevic & Brouwer, 2015, p. 18)

A building can also be divided in different systems based on functionality. A building consists of six layers, each with its own function and lifecycle (Brand, 1994). By avoiding technical, physical and functional 'connections' between the systems, and designing each layer to be flexible, the systems can be optimally used. If the building layer has a long lifecycle, adjustments are more difficult. The six building layers, elaborated by Brand (1994), are illustrated in Figure 14.

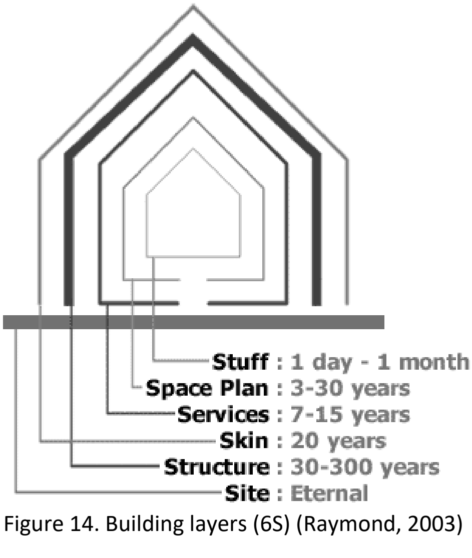


Figure 14. Building layers (6S) (Raymond, 2003)

2.2.1 Design for Excellence (DfX)

Because the circular economy is a broad system with several components, levels and sources of value creation, many design tools exist. Each of the design tools tries to give the designer clear guidelines for (a specific part of) circularity design. Moreno, De los Rios, Rowe, and Charnley (2016) analysed literature on Design for Excellence (DfX) methods. Here, 'excellence' is an interchangeable value. Based on this analysis they made an overview of all existing DfX methods that focus on the circular economy. These tools are categorized based on the DfX approach, circular design strategy and design focus. The table in Appendix 1, on page 87, provides the taxonomy. The DfX approaches are for resource conservation, slowing resources loops and whole systems design. Moreno et al (2016) described the corresponding circular design strategies as follows:

1. Design for circular supplies: This strategy focuses mainly on the biological cycles and refers to thinking of 'waste equals food' in which resources are captured and returned to their natural cycle without harming the environment.
2. Design for resource conservation: This strategy focuses on both the technical and biological cycles and uses a preventative approach in which products are designed with the minimum of resources in mind.
3. Design for multiple cycles: This strategy focuses on both the technical and biological cycle and refers to design aimed at enabling the longer circulation of materials and resources in multiple cycles.
4. Design for long life use of products: This strategy focuses on the technical cycle and refers to extending the utilisation of a product during its use through extending its life and offering services for reuse, repair, maintenance and upgrade, or by enhancing longer-lasting relationships between products and users through 'emotional durable design'. Furthermore, changing the ownership of products through services could enhance longer utilisation of products and, therefore, move to a sharing system.
5. Design for systems change: This strategy covers the whole spectrum of value creation for both biological and technical cycles and refers to design thinking in complex systems as a whole and between its parts to target problems and find innovative solutions. (p. 10)

2.2.2 Design for Disassembly (DfD)

Design for (re)manufacturing, disassembly and reassembly is the DfX method that focuses on disassembly. As mentioned, disassembly is an important principle in designing for circularity. The DfX tool focusing especially on disassembly is known as Design for Disassembly (DfD). A design guideline for DfD was written by Guy and Ciarimboli (n.d.). Guy and Ciarimboli provided the following descriptions of the ten key principles they defined:

a. Document materials and methods for deconstruction: As-built drawings, labelling of connections and materials, and a 'deconstruction plan' in the specifications all contribute to efficient disassembly and deconstruction.

b. Select materials using the precautionary principle: Materials that are chosen with consideration for future impacts and that have high quality will retain value and/or be more feasible for reuse and recycling.

c. Design connections that are accessible: Visually, physically, and ergonomically accessible connections will increase efficiency and avoid requirements for expensive equipment or extensive environmental health and safety protections for workers.

d. Minimize or eliminate chemical connections: Binders, sealers and glues on, or in materials, make them difficult to separate and recycle, and increase the potential for negative human and ecological health impacts from their use.

e. Use bolted, screwed and nailed connections: Using standard and limited palettes of connectors will decrease tool needs, and time and effort to switch between them.

f. Separate mechanical, electrical and plumbing (MEP) systems: Disentangling MEP systems from the assemblies that host them makes it easier to separate components and materials for repair, replacement, reuse and recycling.

g. Design to the worker and labour of separation: Human-scale components or conversely attuning to ease of removal by standard mechanical equipment will decrease labor intensity and increase the ability to incorporate a variety of skill levels.

h. Simplicity of structure and form: Simple open-span structural systems, simple forms, and standard dimensional grids will allow for ease of construction and deconstruction in increments.

i. Interchangeability: Using materials and systems that exhibit principles of modularity, independence, and standardization will facilitate reuse.

j. Safe deconstruction: Allowing for movement and safety of workers, equipment and site access, and ease of materials flow will make renovation and disassembly more economical and reduce risk. (p. 6)

Akinade et al. (2017) tried to identify critical success factors for DfD. An initial literature study resulted in a list of fifteen success factors, which could be divided into three broad categories: material-related factors, design-related factors and human-related factors. Below, the categories, together with the underlying success factors, are quoted from the paper of Akinade et al. (2017):

Human related factors

a. Adequate communication
b. Providing the right tools
c. Providing adequate training

Design related factors

d. Design for offsite construction
e. Use modular construction
f. Use open building plan
g. Use layering approach
h. Use standard structural grid
i. Use retractable foundation

Building materials related factors

j. Specify durable materials
k. Avoid secondary finishes
l. Use bolts/nuts joints
m. Avoid toxic materials
n. Avoid composite materials
o. Minimise building elements
p. Consider material handling (p. 5)

Literature studies and focus groups by Akinade et al. (2017) resulted in a list of almost fifty factors, which were further analysed. The analysis revealed five underlying factor groups: stringent legislation and policy, deconstruction design process and competencies, design for material recovery, design for material reuse and design for building flexibility. The factor groups indicate that not only design factors are important; legislation, policy, process and competencies are also significant. An overview of the five factor groups and associated factors is provided in Appendix 2 on page 88. Additionally, depending on the relationship between the technical and functional lifetimes, different DfD criteria, defined by Durmisevic (2006), are provided.

In the second half of the past century, the need for demountable structures rose. Load bearing structures of steel or timber are rather easy to disassemble, due to associated type of connections. Until then, mainly cast-in-situ concrete buildings were constructed, so possibilities for disassembling concrete load bearing structures were few. A committee of inquiry was created by *Civieltechnisch Centrum Uitvoering en Research* (CUR) to investigate the preconditions and design criteria for demountable concrete structures. Eventually, this committee resulted in the recommendation 134, *Demontabel bouwen* (Van den Boogaard, 1990).

In 1999, the government launched *Industrieel, Flexibel en Demontabel bouwen* (IFD), a programme to accelerate a transition to reusable building systems and elements. The approach focused on users, offering them flexibility by industrial produced and demountable systems (Geraedts, 2011). After a couple years, Geraedts (2011) evaluated this program. He concluded that those involved were not capable of implementing the concept because of several issues. First, many people were not familiar with the concept. This lack of general support did not contribute to the concept's implementation. Second, the building industry was, in most cases, technically and organisationally not able to make projects successful. From a technical point of view, the overall concept was not sufficiently developed to support the innovative idea. Also, the cooperation and organisational aspects, like cost, time and quality, were insufficient. Hereafter, no broad evaluation occurred. As a result, this concept never became a success.

2.2.3 Design for Adaptability (DfAD)

In addition to disassembly, adaptability, reuse and recycling are important terms in Durmisevic's (2018) framework. She assumed that adaptability, reuse and recycling follow from disassembly. However, it is possible to focus on adaptability instead of disassembly. The DfX method or tool Design for Adaptability (DfAD) is not explicitly mentioned in the taxonomy. However, DfAD is a type of flexibility, which is part of design for upgradeability and flexibility. The following key principles of DfAD are formulated by Moffatt and Russell (2001):

1. Independence: Integrate systems (or layers) within a building in ways that allow parts to be removed or upgraded without affecting the performance of connected systems.
2. Upgradability: Choose systems and components that anticipate and can accommodate potential increased performance requirements.
3. Lifetime compatibility: Do not encapsulate, or strongly interconnect short lifetime components with those having longer life times. It also may be advantageous to maximize durability of materials in locations where long lifetimes are required, like structural elements and the cladding. Durable claddings and foundations can greatly facilitate adaptability, often tipping the scale in favour of conversion over demolition.
4. Record keeping: Ensure that information on the building components and systems is available and explicit for future use. It will assist effective decision making with regard to conversion options and prevent costly probing exercises. (pp. 7-8)

Based on building practise, Moffatt and Russell (2001) defined features facilitating the key principles as follows:

a. Durability: Repair, maintenance and replacement periods, especially for the structure and shell especially
b. Versatility: The shape of the space lends itself to alternative use.
c. Access to services: Dropped ceilings, raised floors, central cores that provide easy access to pipes, ducts, wires and equipment
d. Redundancy: Structural elements can bear larger loads that were originally imposed.
e. Simplicity: The absence of complex systems vital for the continued operation of the building.
f. Upgradability: Systems and components that accommodate increased performance.
g. Independence: Features that permit removal or upgrade without affecting the performance of connected systems.
h. Building information: Records of drawings, specifications and design limits that assist in future economic analysis of renovation and expansion. (p. 9)

Bouwend Nederland

The organisation Bouwend Nederland (Van der Veen & Pesschier, 2017), the Dutch association of building and infrastructural companies, tried to provide practical information and advice on circular design. Bouwend Nederland was involved in the Dutch ministries' program to be circular by 2050. The organisation sees opportunities in reducing material use and choosing materials with the lowest environmental impact. Additionally, designs should be adaptive and flexible for long lifespans and circular, focused on recycling materials.

Bouwend Nederland focuses on materials. Reducing materials means designing a lightweight structure without concessions to a building's lifespan. Additionally, one should use prefabricated elements with standardized dimensions to reduce the waste. Elements must be made of materials with a low environmental impact. Different calculation methods can be used to identify the impact. For efficient material recycling, Bouwend Nederland emphasises the need for material passports, like Madaster. Furthermore, this umbrella organization pays attention to design. Designs must be adaptive, flexible and circular. Adaptive and flexible structures are suitable for other functions or can be used longer by the same user. Circular design aims for recycling and reuse of materials and elements at a high level. This means reusing elements directly on another project or recycling materials as a source for new elements. To be suitable for reusability, designs must be modular and disassemble.

2.2.4 Conclusion and discussion

Buildings are seen as a hierarchy of subassemblies (Durmisevic & Brouwer, 2015) and consist of several layers (Brand, 1994). The foundation is a building system, consisting of components, or elements, that are further composed of materials. The most common foundation elements are piles, caps, beams, pads, strips and rafts. These are made of concrete, steel or timber, the most common building materials. The foundation is part of the structure, which mainly functions to transfer loads. This building layer has a relatively long lifespan, compared to the other systems. However, for foundations, the functional lifespan is often shorter than the technical lifespan. In many cases, foundations are still in good technical conditions, even after decades of use. Thus, foundations should be designed more flexibly to extend their functional lifespan. The type and level of flexibility depends on the stability of the building location and the function.

Flexibility seems crucial for creating circular designs (Durmisevic, 2006). The subassemblies and building layers should not be interconnected; otherwise, inflexibility will cause waste. Of the types of flexibility, changeability, expandability and versatility (Paesschen, 2011), only changeability and versatility were studied for foundations. Given the requirements of a foundation and its apparently permanent connection to the site, a versatile foundation is clearly necessary. A versatile foundation remains in the same location and can support different buildings. Although the need for changeability is not obvious, within the circular economy, it is seen as the most promising approach. Investigating the possibilities for foundations is interesting. A changeable foundation would be a system of demountable elements that can be reused together or separately at different locations. These two approaches are also mentioned in Bouwend Nederland's (2017) report. Expandability is a form of flexibility, which should be incorporated in both approaches. For versatility, expandability should be added to the whole system. For changeability, expandability focuses on the elements, whereby each element should facilitate a certain load range.

Many DfX methods exist for designing a circular economy (Moreno et al., 2016). Each tool focuses on another aspect, but these tools have similarities. The design methods can also be used differently, based on expected technical and functional lifespans. Each form of flexibility can be combined with a certain DfX tool. Design for Disassembly matches changeability, while Design for Adaptability matches versatility. These design tools contain similar principles. While the DfD tool pays extra attention to demountable connections, the DfAD method focuses especially on redundancy (Guy & Ciarimboli, n.d.; Moffatt & Russell, 2001).

The CUR recommendation and IFD program indicate that designing reusable buildings has been important for some time (Geraedts, 2011; Van den Boogaard, 1990). Unfortunately, the concept has never been completely implemented. This scenario also threatens the circular economy, and thus design of circular foundations. Considerable research into the technical and organisational aspects has been completed. Now, mainly change in thinking and willingness are the crucial factors for success.

2.3 Assess

Hobbs (2018) suggested assessment of circular buildings, as visualised in Figure 15. The assessment of circularity depends on values, on the one hand, and information or data, on the other hand. Circular buildings should incorporate environmental, economic and social value. To assess the environmental and economic value, the life-cycle assessment (LCA) and life-cycle costing (LCC) have been developed. For social value, such a general analysis has not yet been developed. A building must be designed to be practically suitable for reuse or recycling. This is facilitated by several Design for Excellence methods. Corresponding assessment methods have been developed, such as those which assess the circularity on the basis of Design for Disassembly and Design for Adaptability. These circular assessment methods, and life-cycle assessment, are further elaborated in the following subsections.

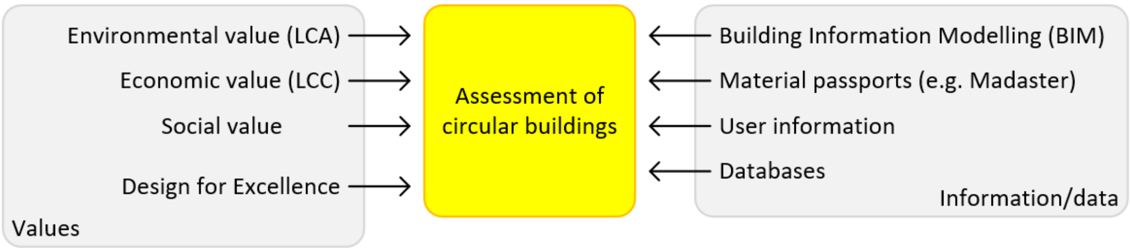


Figure 15. Overview of circular building assessment (Hobbs, 2018)

The level of circularity is also assessed on the available information, including building information modelling (BIM), material passports (like Madaster), user information and databases. In the last few years, BIM's importance has grown. Via BIM, different stakeholder models can be combined to extract information and avoid problems. Also, technical, physical and functional characteristics can be added to the digital environment. In this way, the characteristics and relations of elements and systems become clear and contribute to design for circular purposes. In recent years, the time, money and operation dimensions have been added to the traditional three dimensions of height, width and depth. Jensen and Sommer (2018) wrote an extensive book about building a circular future and suggested reuse to be the seventh dimension to enable reuse of elements and systems. Material passports are necessary to know which materials are used in a certain project. Their location, characteristics and values are collected into a material passport, making it possible to reuse elements or recycle materials, and thus reducing material and energy waste. During a building's use, the user can add information about the conditions, changes and utility. This information might be useful for the upcoming lifecycles and could facilitate upcycling instead of downcycling. Also, databases in which all foundation systems and elements, together with the availability, are recorded specifically contribute to the reuse of foundations.

2.3.1 Life-cycle assessment

The life-cycle assessment assesses the environmental impact of a product from cradle to grave. This life cycle includes four phases: production, construction, use and maintenance, and end of life. Processes in these phases cause environmental impact, like exhaustion of finite natural resources, emission of harmful substances and land use. A general life-cycle assessment consists of four steps: determining of the goal, inventorying environmental impacts, assessing the effects and interpreting the results. First, the assessment method's goal and setup is determined. Then, the environmental impacts are listed, distinguishing the inflow of energy and materials, and outflow, like emissions, for each life cycle phase. Hereafter, the environmental impacts are assessed, classified and scored. This score might be normalised and weighted. Finally, the score is interpreted, and the influence of assumptions can be determined.

Several environmental assessment methods, based on the life-cycle assessment, measure building sustainability. The most popular method in the Netherlands is the Building Research Establishment Environmental Assessment Method (BREAAM), which originates from the United Kingdom (BREEAM, n.d.). In other countries, similar assessment methodologies exist, like Green Star, developed in Australia (GBCA, n.d.), and Leadership in Energy and Environmental Design (LEED), developed in the United States (USGBC, n.d.). These assessment methods provide nationally recognised and valued certificates.

Example of assessment method
Nibe is an organisation specialised in sustainable investigation, advice and design. In that context, the company has developed a method to determine the environmental and health impact of building products, based on the LCA. For each product, the environmental and health information is described.

The model distinguishes seven environmental classes, which are divided in subclasses a, b and c. Class one is the best choice, whereas class seven is an unacceptable choice. Classes three and above are seen as an acceptable choice. The subclasses indicate the first, second and third preference in a class. The environmental impacts are divided into four knowledge categories: emissions, exhaustion, land use and pollution. Each environmental impact is expressed in an equivalent unit, which can be converted to a shadow cost. Also, general product characteristics, like the mass, lifespan and waste scenario, are listed (Nibe, n.d.-a). Additionally, the *Bron tot Bron* (B2B) factor was added. This factor is an indicator of the extent to which the product meets the C2C principle. Four categories are used to determine the factor: material health, material reutilization, renewable energy use and water stewardship. The fifth category, social responsibility, was not considered due to lack of information (Nibe, n.d.-b).

The health information was categorized into four life-cycle phases (raw material, production, construction and use and demolition/waste) and four health criteria (physical agents, chemical agents, biological agents, ergonomics and safety). For each phase, the health effects are indicated. The use phase is the longest and thus most valued (Nibe, n.d.-c).

2.3.2 Circularity assessment method
In recent years, some methodologies, which include circularity, have been developed. The municipality of Amsterdam proposed a methodology in *Roadmap Circulaire Gronduitgifte* (Roemers & Faes, 2017). Developers of *Gemeentelijke Praktijk Richtlijn* (GPR), another method to determine building sustainability allowed for one to measure circularity, using *CirculariteitsPrestatie Gebouw* (CPG) (Mak & Quelle-Dreuning, 2017). Also, the Ellen MacArthur Foundation (2015b) and companies, like Alba Concepts (2018), have developed methods to calculate a circularity index.

In the roadmap compiled by the municipality of Amsterdam, four principles of circular buildings are defined: reduction, synergy, production and purchase, and management. Additionally, five themes are distinguished: materials, adaptability and resilience, water, energy, and ecosystems and biodiversity. Based on the four principles and five themes, 32 criteria were determined, which influence the level of circularity (Roemers & Faes, 2017). However, this number of criteria and the scoring system create a complex, difficult to understand method. Furthermore, due to the large diversity in criteria, gathering all the needed information is difficult. Furthermore, critics say that some of the weighting is quite subjective. Also, a main circularity indicator is missing (Schut & Van Leeuwen, 2018).

The CPG is an extension of the GPR. The index is divided into five main strategies: use available materials and products, use renewable resources, minimise environmental impact, create value for a long cycle and create conditions for future cycles (Mak & Quelle-Dreuning, 2017). Within this framework, the CPG is calculated from circular material use and *DuurzaamheidsPrestatie Gebouw*, which consists of the *MilieuPrestatie Gebouw* and *EnergiePrestatie Gebouw*. As a result, this method is also rather complex and requires data not easily available. This method is also lacking a clear circularity indicator (Schut & Van Leeuwen, 2018).

The Ellen MacArthur Foundation (2015b) defined a circularity index. To calculate the circularity index, the material flows and utility are considered. First, the amount of linear and circular material flow is calculated. The linear and circular material flows should be minimised and maximised respectively. The diagram presented in Figure 16 represents the materials flows. Secondly, the utility takes into account the technical and functional lifetime. If desired, the product and system circularity can be calculated based on an indicator. The whole calculation can be seen in Appendix 4, on page 94. Figure 55 provides the same diagram, whereas the textual explanation of the different flows is changed to symbols used in the calculation. The result ranges from zero to one. Fully linear products use virgin materials and end up in landfills or are burned. Using recycled or reused materials that can be recycled or reused results in fully circular products. These two extremes result in a material index of zero and one, respectively.

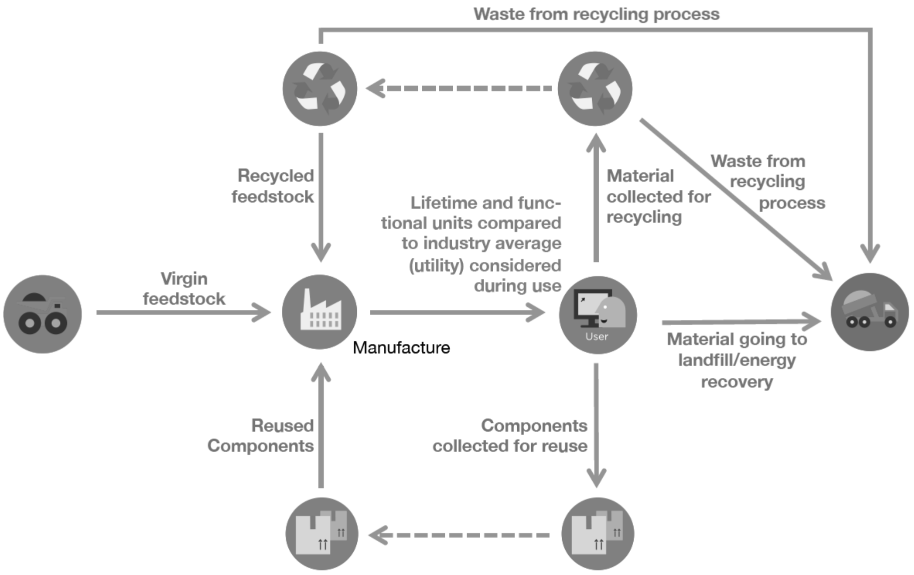


Figure 16. Diagram representation of material flows (Ellen MacArthur Foundation, 2015b, p. 19)

Schut and Van Leeuwen (2018) examined possibilities of measuring building circularity. They concluded that a LCA or circularity index, as proposed by the Ellen MacArthur Foundation (2015b), is most suitable for determining the level of circularity. Both analyses require comparable data, like the origin and future of materials and their lifespan. When several cycles are considered, a few LCA's can be calculated and summarized, resulting in a multi life-cycle assessment (mLCA). Another possibility is to perform one LCA and consider several lifecycles in the use phase. Other assessment methods, like those of GPR and the municipality of Amsterdam, are complex, laborious and lack a clear circularity indicator.

The circularity index is part of the method developed by Alba Concepts (2018). This method has a clear structure and is transparent, which makes it easy to complete. Because of the method's clarity and transparency, this method is further explained in the following subsection. In addition to the circularity index, some circularity indicators are defined in Alba Concepts' method. The method considers disassembly the most important design criteria for circularity. Therefore, Alba Concepts' method is an example of a circularity assessment method based on DfD. In the subsequent subsection, a circularity assessment method, based on DfAD, is described. In this case, no extensive preliminary investigation was performed because the investigation was already completed by Geraedts (2016), who developed his own clear and transparent method.

2.3.3 Circularity assessment method based on DfD

Development
The first version of this assessment method was descried in Verberne's (2016) master's thesis. The researcher's aim was to establish a method to assess building circularity. In addition to Ellen MacArthur Foundation's (2015b) material circularity index, he distinguished the product, system and building circularity index. The mass, the six building layers of Brand (1994) and the seven disassembly indicators, as defined by Durmisevic, Ciftcioglu and Anumba (2006), were used to calculate the circularity indices. The indicators are included in Appendix 2, on page 88. The indicators are calculated in a framework of drivers and preconditions.

The indicators and building layers were fuzzy variables. Fuzzy logic is a concept in which values can be any number from zero to one. This concept is useful to define a variable when this variable is not completely false (zero) or true (one) (Open Universiteit Nederland, n.d.). Each variable has different gradations to which a value between zero and one is assigned, in this case representing the level of circularity. The lower the value, the more linear the variable. Thus, zero corresponds to completely linear, while one corresponds to completely circular.

In consultation with Alba Concepts, Van Vliet (2018) wrote a master's thesis in which he revised the first version of the assessment method, resulting in a second version of the method. The number of indices and circularity indices were reduced, and the building layers were omitted from the method. Additionally, the framework was further elaborated. These changes improved the clarity and practical applicability of the assessment method. The current version of the assessment method is explained in the following section.

The circular economy is a relatively new concept and in full development. As mentioned, several methods to assessing building circularity are being developed. One nationally recognized method currently does not exist. However, building lifecycle assessment, which has been around longer, widely uses the BREEAM assessment method. This method is a well-known and provides valuable certificates. Several initiatives aim to set up a national assessment method for building circularity. Currently, Alba Concepts works with other companies and organisations to develop such a method (Stolk, 2018).

Calculation

Alba Concepts' assessment method elaborates on the assessment methods purposed in Verberne's (2017) and Van Vliet's (2018) master's theses. Alba Concepts distinguishes indicators, boundary conditions and drivers, which relate to the quantitative assessment of circularity. These factors were determined by literature studies, interviews with experts and expert panels. Subsequently, these indicators, boundary conditions and drivers were captured in a conceptual model, as presented in Figure 17. In Table 2, the drivers for accelerating the transition toward a circular economy and preconditions, which need to be considered when designing for circularity, are defined. The drivers and preconditions are important but do not directly influence the level circularity. This level is determined by the material use and disassembly.

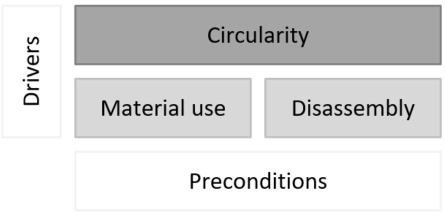


Figure 17. Conceptual model of circularity (Alba Concepts, 2018)

Drivers	Preconditions
Material scarcity	Toxicity
Residual values	Emission of harmful substances
Image	Exhaustion of finite natural resources

Table 2. Drivers and preconditions of circularity (Alba Concepts, 2018)

Figure 18 illustrates the assessment method's structure. Successively, the product circularity index (PCI), element circularity index (ECI) and building circularity index (BCI) are calculated. The PCI consists of the material index (MI) and disassembly index (DI). The MI depends on the material scenarios, lifespans and mass. The DI depends on the type of connections and the accessibility of the connections. The ECI consists of the reusability index (RI) and disassembly index (DI) and is based on the following theory: 'an element is a clustering of products which are inseparably linked. When the connection is demountable and damage remains limited, the clustering ends and the elements are recovered' (Alba Concepts, 2018). Based on the masses, the BCI can be calculated. Hereafter, the three circularity levels are further explained.

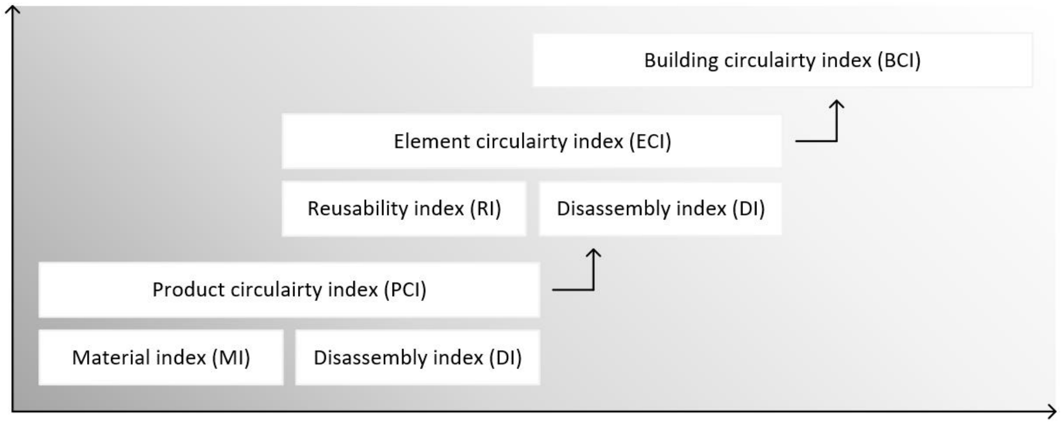


Figure 18. Framework of the assessment method

Product circularity indicator
To calculate the material index, based on the Ellen MacArthur Foundation (2015b) formula, Alba Concepts (2018) identified four origin and future material scenarios, presented in Table 3. The material's origin scenario can be new, reused, recycled or biobased. Future material scenarios are landfill, combustion, recycling and reuse. New material and material loss, resulting from landfill and combustion are considered linear and lower the circularity index. For a material's future scenario, Alba Concepts consults the Nibe database.

	Origin of material (%)		Future of material (%)
A1	New material; first life	B1	Landfill
A2	Reused material; second hand	B2	Combustion
A3	Recycled material; recyclate	B3	Recycling
A4	Biobased material; renewable	B4	Reuse

Table 3. Origin and future of materials

Material's technical and functional lifespan, presented in Table 4, also have to be known to calculate the material index. The technical lifespan relates to the material's quality and level of strength, stiffness and stability. The functional lifespan refers to changes in requirements of building codes, aesthetics and use. A high material index is obtained if the technical lifespan is equal to or longer than the functional lifespan. If the material cannot fulfil the functional requirements, it has sufficient technical value to be recycled or reused. If the technical lifespan is much shorter than the functional lifespan, the material index rapidly lowers. In most cases, Alba Concepts chose to enter the same number of years for the technical and functional lifespans. Often, the lifespans are hard to predict and differences between the technical and functional lifespan may largely affect the outcome.

	Lifespan (y)
TL	Technical lifespan; how long does the material technically last?
FL	Functional lifespan; how long can functional requirements been met?

Table 4. Technical and functional lifespans

As mentioned, Alba Concepts believes disassembly is the most important indicator for circularity. Therefore, the material index is multiplied by the disassembly index, which is based on the connection type and accessibility of the connection. These are considered fuzzy variables, for which gradations are distinguished. The subdivision and corresponding values, taken from Durmisevic et al. (2006), are presented in Table 5 and Table 6. For each product the connection to the underlying product is judged. The disassembly index is obtained using the average of both values. Then, the product circularity index is calculated by multiplying the material and disassembly indices.

1. Connection type	
Dry connection	1.0
Connection with additional elements	0.8
Direct integral connection	0.6
Soft chemical connection	0.2
Hard chemical connection	0.1

Table 5. Fuzzy values, connection type

2. Accessibility of connection	
Accessible	1.0
Accessible with additional operations, causing no damage	0.8
Accessible with additional operations, repairable damage	0.6
Accessible with additional operations, with much damage	0.4
Not accessible, total damage to both elements	0.1

Table 6. Fuzzy values, accessibility of connection

Element circularity index & building circularity indicator

Several products together form an element. Generally, when a product’s disassembly index is lower than 0.4, the product forms an element with the underlying product. To calculate the element circularity index, the reusability and disassembly index have to be determined. To calculate the reusability, the formula of the material index is used. To determine the material scenarios at the element level, the weighted average of the products is calculated. If the material scenario, based on the weighted average, differs from the actual scenario at the element level, the scenario can be manually changed. Thus, the weighted average based on the scenarios, defined at product level, is overruled. The lifespans at the element level are defined as the minimal technical and functional lifespan of the corresponding products. Again, the disassembly index is determined, this time for the element in relation to the underlying element. The element circularity level is obtained by multiplying the reusability and disassembly indices.

A building consists of several elements. The share of an element in a building is considered when determining the building’s circularity index. This index is the weighted average of the element circularity index. The share of the element in a building is determined by the mass.

2.3.4 Circularity assessment method based on DfAD

Development

In recent years, Geraedts has conducted extensive research into the assessment of buildings adaptive capacity. After a comprehensive literature study and bringing together expert panels, 147 indicators, with corresponding assessment values, were defined. These indicators were subdivided based on several criteria. For example, Geraedts distinguished between the user (demand) and owner (supply) and identified rearrange, extension and rejection flexibility, which in turn can be described by spatial/functional and construction/technical characteristics. These findings were published in version 1.0 of the assessment method (Geraedts, Remoy, Hermans, & Van Rijn, 2014). The authors provided the following definition: ‘The adaptive capacity of a building includes all characteristics that enable it to keep its functionality during the technical life cycle in a sustainable and economic profitable way withstanding changing requirements and circumstances’ (p. 2).

In consultation with different steering groups, the research continued to develop an assessment method that could be used in the construction practise. The number of indicators was reduced to 83 and weighting factors were added. To increase the clarity, the indicators were divided into the building layers defined by Brand (1994): site, structure, skin, services and space. Stuff is not taken into account. This renewed assessment method was published as version 2.0 (Geraedts & Prins, 2015). In addition, version 2.0 ‘light’ was being developed, in which the number of indicators was further reduced to 17. These were the most important indicators.

Hereafter, the assessment method was further developed in two research projects. The method was evaluated by developing school and office buildings. This research's conclusions and recommendations were used to define the most important indicators for school buildings and offices buildings. Of the 44 indicators left, 21 applied to schools, 35 applied to offices and 17 were part of the 'light' version. The revision of these 44 indicators was published in an updated version 3.0 (Geraedts & Prins, 2016). In version 4.0, the indicators were split into 12 general applicable indicators and 32 specifically applicable indicators, depending on the project type and the involved developer (Geraedts, 2016).

Calculation

In this section, the assessment method calculation is explained based on the 12 generally applicable indicators as defined in the latest version. As stated, the indicators are divided into building layers. Some building layers are divided in sublayers. An overview of building (sub)layers and indicators is provided in Table 7. The subdivision of the indicators is included in Appendix 3, on page 93.

	Layer	Sub-layer		Performance indicator	Weighting
1	Site		1	Expandable site/location	1
2	Structure	Measurements	2	Surplus of building space/floor space	4
			3	Surplus of free floor height	4
		Access	4	Access to building	2
		Construction	5	Positioning obstacles/columns in load	3
3	Skin	Façade	6	Façade windows to be opened	1
			7	Daylight facilities	2
4	Services	Measure & Control	8	Customisability/controllability	3
		Dimensions	9	Surplus of facilities shafts and ducts	4
			10	Modularity of facilities	2
5	Space	Functional	11	Distinction between support – infill	4
		Access	12	Horizontal access to building	3

Table 7. Overview of the generally applicable indicators

For each performance indicator, an assessment value (V) is determined. This value ranges from 1 to 4, whereby 1 indicates a low adaptive capacity and 4 indicates a high adaptive capacity. The corresponding weighting factor (F), included in Table 7, also ranges from 1 to 4. Subsequently, the flexibility score (S) is calculated by summing the results of the assessment value and weighting factor multiplication for all performance criteria. This is captured in the formula below:

$$S = \sum_{i=1}^{12} V_i \cdot F_i \tag{1}$$

Given the assessment values and weighting factors, a theoretical minimum and maximum score can be determined. Based on these values, five flexibility classes are distinguished, ranging from not flexible at all to excellent flexibility. The classes and corresponding scoring range is displayed in Table 8. Therefore, based on the score, one can determine the flexibility class, and thus the level of flexibility, and compare the results of different projects.

	Class	Score range
1	Not flexible at all	12 to 48
2	Hardly flexible	49 to 85
3	Limited flexibility	86 to 122
4	Very flexible	123 to 159
5	Excellent flexibility	160 to 192

Table 8. Flexibility classes and corresponding scores

2.3.5 Conclusion and discussion

To determine the environmental impact of buildings, a life-cycle assessment can be performed. This method considers the different lifecycle phases: the production phase, construction phase, use and maintenance phase, and end-of-life phase. Nibe is an example of an organisation that determines the environmental and health impact of building products based on the LCA. In recent years, other assessment methods, which take circularity in account, have been developed. General circularity assessment methods for buildings, like *Roadmap Circulaire Gronduitgifte* and *CirculariteitsPrestatie Gebouw*, are complex, laborious and lack a clear circularity indicator (Mak & Quelle-Dreuning, 2017; Roemers & Faes, 2017). Other methods, like that of Alba Concepts (2018) and Geraedts (2016), are based on a specific DfX tool. For example, Alba Concepts (2018) and Geraedts (2016) use the DfD and DfAD method, respectively. The methods are clear, easy to use and require a limited amount of data.

Alba Concepts' (2018) framework consists of drivers and preconditions. Within the drivers and preconditions of a circular economy, the product, element and building circularity index is calculated. This requires masses, material scenarios, lifespan predictions and information on the connections since disassembly is seen as the key to circularity. The material index, as defined by the Ellen MacArthur Foundation (2015b), is the starting point of the assessment method. Finally, a value between zero (completely linear) and one (fully circular) is obtained. The method of Geraedts (2016) focuses on adaptability and is based on another type of calculation. For each building layer, as defined by Brand (1994), performance indicators, with corresponding assessment values and weighting factors, are defined. These indicators are multiplied and summed, resulting in a total score. The level of flexibility can be determined by the score range.

To assess the circularity of foundations, Alba Concepts' (2018) assessment method seems most suitable. The method is not defined too specifically, thus appropriate for a variety of products and especially applicable to changeable foundations because it focuses on disassembly. The assessment method of Geraedts (2016) focuses on adaptability and seems most suitable for versatile foundations. However, the performance criteria are specified for each building layer. Characteristics of, for example, the skin and services, are not relevant when only assessing the foundation. Because of the more general applicability, Alba Concepts' method was chosen for this study. Additionally, this method can be adjusted to an alternative assessment method, which contains indicators that value disassembly and adaptability. Both types of foundations can be assessed using this method. Assessing all foundations with the same method enables accurate comparisons.

2.4 Overall conclusion

This chapter investigated how circularity can be defined, designed, and assessed and discusses how it relates to foundations. A circular economy tries to close material cycles and distinguishes the biological and technical cycles. Foundations are part of the technical cycle, which is divided into sub cycles. Recycling materials and reusing products are the most important of the sub cycles. When minimizing the use of material and energy, reuse is preferred instead of recycling. Additionally, circular value can be obtained by long use and consecutive reuse.

Reuse can be achieved by flexibility to facilitate our dynamic way of living. In the linear economy, the static build environment lacks flexibility, resulting in a tremendous amount of waste. Versatility and changeability are forms of flexibility that might be suitable for foundations. The third form of flexibility, expandability, should be guaranteed in both versatile and changeable foundation. In a circular economy, several design methods have been developed and are known as Design for Excellence. When designing for versatility and changeability, design tools Design for Adaptability and Design for Disassembly are useful.

To assess the level of circularity, several methods have been developed. Some assessment methods correspond to the design methods. For example, Alba Concepts' method is suitable for assessing changeable buildings and Geraedts' is suitable for assessing adaptable buildings. In contrast to other methods, these methods are clear and easy to use. Because the indictors in Geraedts' method focus on the whole building, Alba Concepts' method was chosen for this study. In Alba Concepts' method, the indicators are more generally defined, making the method more suitable for assessing the foundation only. Eventually, an alternative method will be developed, which will enable assessment of changeable, as well as versatile, foundations.

3. Traditional foundations

This chapter discusses the classification and design aspects of foundation. The first section provides a classification of building foundations. Deep and shallow foundations are explained. Given the wide diversity of pile types and the complexity of reusing them, foundation piles are discussed. Hereafter, some remaining topics are elaborated to clarify retaining walls and connections. The content of the first section is prominently from Brouwer (1998). The second section describes the design aspects of foundations. These aspects concern the design criteria and requirements. Finally, problems that occur when reusing foundations are listed, together with possible solutions.

3.1 Classification

A building generally consists of the superstructure and substructure. The superstructure is the upper part of the building, above ground level, and is carried by the substructure. Load bearing elements, like floors, beams, columns and walls, are part of the superstructure. These elements transfer loads to the substructure. The substructure is the building part below ground level and includes the basement, if present, and the foundation. The foundation transfers the load to the soil. All elements discussed are considered part of the foundation. In Figure 19, the different building parts are illustrated.

Foundations come in a variety of forms. Figure 20 distinguishes deep and shallow foundations, the most common building foundations. Shallow foundations are positioned directly on top of the subsoil and transfer loads to a soil layer near the ground surface. If the load bearing soil layers are located at a greater depth, a deep foundation is used. A deep foundation is generally composed of foundation piles, pile caps and foundation beams. Shallow foundations can be pad, strip and raft foundations. Deep and shallow foundations are further elaborated in the subsections.

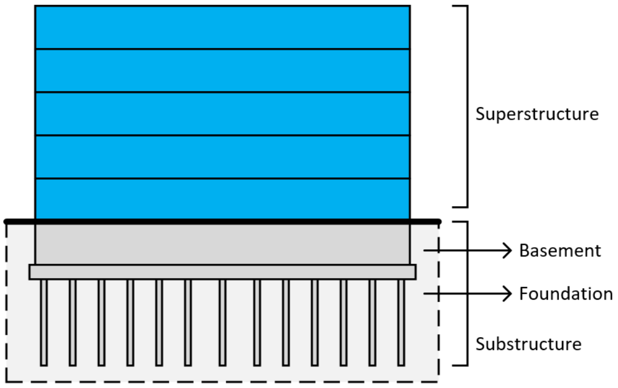


Figure 19. Illustration of the building parts

'Special' types of foundations are compensated foundation and piled raft foundation. For a compensated foundation, the ground is excavated. The weight of the soil is approximately equal to the weight of the building. Since the ground stresses remain almost identical a shallow foundation can be constructed. Because a significant amount of soil must be removed a compensated foundation is often combined with a basement. A shallow and deep foundation can also be combined in a piled raft foundation. This foundation type combines the load bearing principles of both foundation types. The raft transfers loads to the upper soil layer and the piles transfer loads to the lower soil layers. This is an efficient way of transferring loads to the soil.

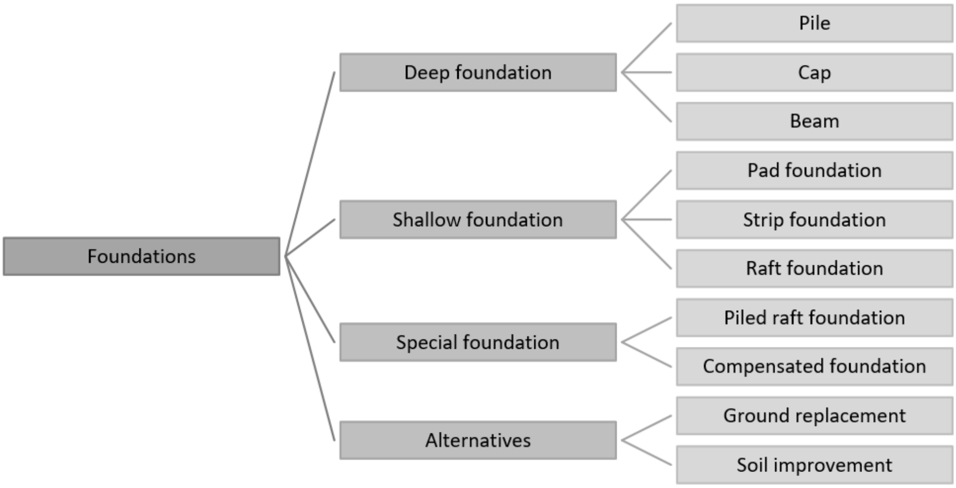


Figure 20. Subdivision of foundations (geometry)

Alternatively, ground replacement or soil improvement can be applied. Both aim to strengthen the soil in order to make a shallow foundation. When ground replacement is applied, weak top layers are replaced by a layer of sand to transfer the load to deeper, load bearing soil layers. Settlements due to compressible top layers are avoided. Another method to avoid these settlements is soil improvement, which can be accomplished by compacting the soil layers with vibration machines or injecting cement or chemical substances.

The choice between a shallow or deep foundation depends on several factors. From a technical point of view, the soil properties and loads from the building are most important. Figure 21 illustrates cumulative thickness of week soil layers, like clay and peat. Common foundations in the Netherlands transfer loads from the building to sand layers. In the eastern part of the country, these load bearing sand layers are located near the ground surface. Thus, in most cases, a shallow foundation satisfies. In the western part of the Netherlands, these strong sand layers are located at a greater depth. Compressible, weak soil layers of peat and clay are between the sand layers and ground surface, requiring a deep foundation. Generally, deep foundations can take more load than shallow foundations. Therefore, this type of foundation is more suitable for multi-story and high-rise buildings. Shallow foundations can resist fewer loads and are most applicable to single-story or low-rise buildings.

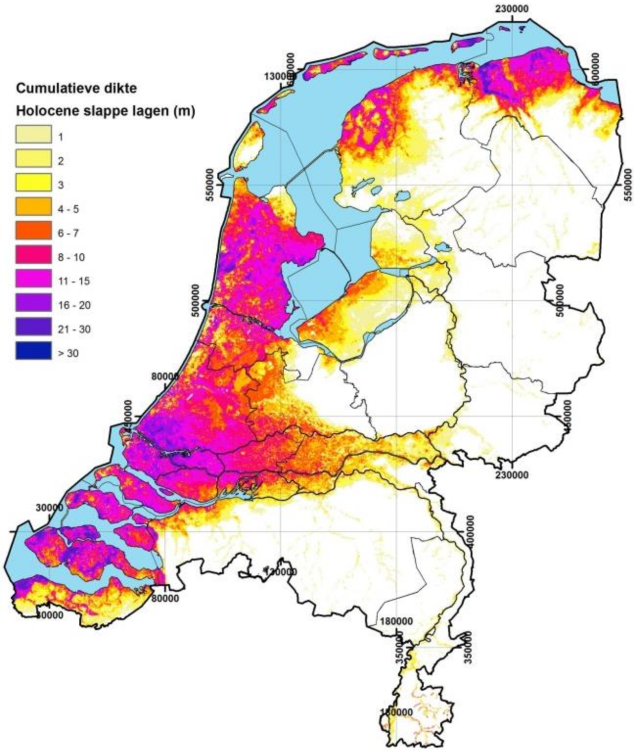


Figure 21. Thickness (m) of weak Holocene layers (TNO, 2014)

In addition to soil properties and building loads, other factors might influence the foundation decision-making. One might consider costs, resistance to lateral forces and risk of settlements. Deep foundations may be complex and require more labour and money. Construction of shallow foundations may be easier and less expensive but are prone to settlements. In addition, shallow foundations are less capable of resisting horizontal loads. Deep foundations have better performance against settlements and lateral loads. Also, relationships with the environment (like available space, noise and vibrations) can play an important role. However, in most cases, money determines the choice for a foundation type.

Houses in the western part of the Netherlands, with topsoil layers of clay and/or peat, have pile foundations, often combined with foundation beams. Non-residential buildings, with more floor levels and thus higher loads, use piles and caps for transferring loads to the sand layers. In the eastern part of the Netherlands, most buildings can be built on shallow foundations.

3.1.1 Deep foundations

Foundation piles

The most important characteristics of foundation piles are presented in Figure 22 and explained in this section. Foundation piles can be made of different materials. Before 1960, wooden piles were mainly used. Then, different types of concrete piles were developed, combined with reinforcement and/or steel tubes. Reinforcement is mainly applied to restrain bending moments, shear forces and tension.

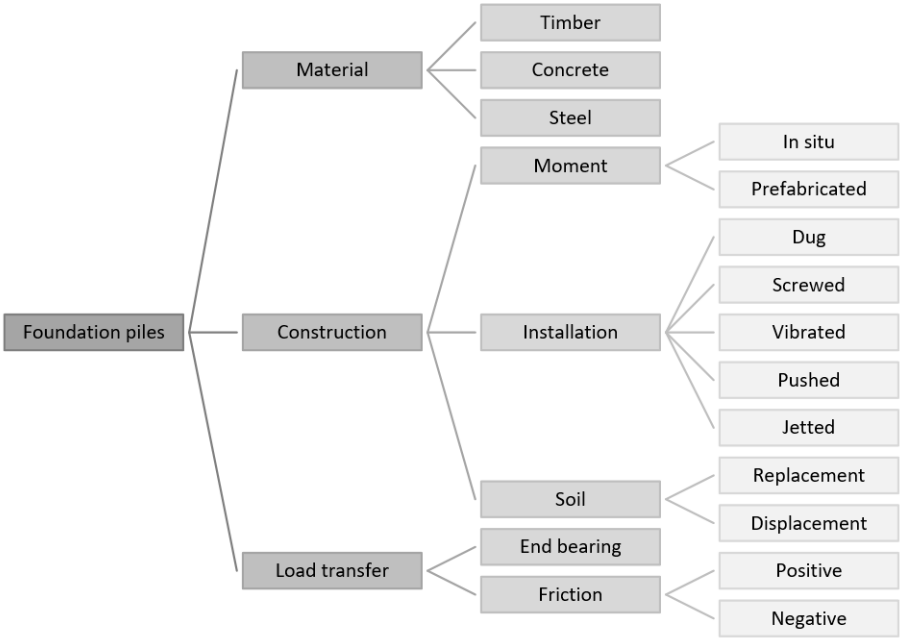


Figure 22. Subdivision of piles (characteristics)

Piles can be prefabricated or constructed on site and can be dug, pushed, driven, vibrated, screwed or jetted into the ground. Prefabrication or in situ construction of the pile depends on the chosen materials. Several considerations should be made when selecting the installation method, like the production of noise and vibrations. Depending on the surroundings, these effects might be undesirable. Construction of foundation piles can occur with or without ground displacement. For non-displacement piles, the soil is removed from the ground and transferred to the surface, thus loosening the soil. Meanwhile, displacement piles push the soil outwards, which leads to more compacted ground. This process has a positive influence on the load bearing capacity of the soil and avoids the necessity to transport soil.

Depending on the type of soil layers, piles are supported by end bearing or skin friction. When the end of the pile is located in a layer of sand or gravel, this layer provides most load bearing capacity. Another possibility is deriving load bearing capacity from skin friction, such as when piles are only located in weaker homogeneous soil layers. However, in most cases, piles will be supported by a combination of end bearing and skin friction.

The most commonly used foundation piles are wooden piles, prefabricated concrete piles and cast-in-situ piles:

A. Wooden pile: Traditionally wooden piles are combined with a masonry foundation. Usually a concrete pile cap is applied to modern wooden piles. These piles are still applied to lightweight buildings, like single-story and storage buildings. The tops of wooden piles must be located below ground water level to avoid rotting of the timber.
B. Prefabricated concrete pile: This is currently the most commonly used foundation pile. Traditional reinforcement or prestressed concrete is used to strengthen the concrete pile. Reinforcement is applied to resist bending moments (occurring when transporting and hoisting the pile), tensile forces (due to pile driving) and horizontal forces (as a result of ground pressure). These forces can also be imposed by the superstructure. In contradiction to the wooden and cast-in-site piles, these piles are squared instead of circular. Nowadays, coupling piles exists. The prefabricated concrete piles can be connected by a steel pin connection, but this does not often occur.
C. Cast-in-situ piles: For this type of foundation pile, different construction techniques can be used to make a shaft in the ground, for example, by using a bentonite slurry or a (temporary) steel tube. Reinforcement is subsequently applied and concrete is poured. Since each pile is fabricated at the construction site, the pile length can easily be varied. Because the shaft will not be completely smooth, the pile is able to resist tensile forces. Reinforcement should then be adequately applied. Additionally, most construction methods are free of vibrations and noise. Many construction methods exist for this foundation pile. Commonly used cast-in-situ piles are the vibrated and screw piles.

Smienk (2016) provides a table listing the wooden pile, prefabricated concrete pile and a series of cast-in-situ piles. Also, a steel tube, hollow or filled with concrete, is part of this overview. For each foundation pile, environmental aspects are assessed, like lifespan, removability, end-of-life scenario, material reduction and vibrations. Although the lifespan of a wooden pile might be limited, all other piles are built to last. Technically, all piles can be removed. Removal is easiest for steel tubes and prestressed concrete piles. Whereas steel tubes can be reused, concrete piles are often recycled, giving the risk of damage. Due to skin friction and risk of insufficient reinforcement, removing cast-in-situ piles is more difficult. More generally, loosening soil conditions and seepage risk must be considered. Therefore, the foundations piles are often left when the building is demolished. Material reduction can be achieved by prefabricated piles, piles with ground displacement, and a sophisticated foundation design. For a selected number of pile types, Smienk (2016) inventoried the emission of carbon dioxide per pile, based on an assumed soil profile. This calculation indicates that the amount of carbon dioxide emission can significantly differ up to a factor of five.

Pile cap and foundation beam

To distribute the loads from the building among the foundation piles, pile caps and foundation beams are used. Pile caps distribute point loads, often from columns, to the foundation piles. Pile caps can distribute the loads over two, three or four foundation piles, but six, eight or more pile caps also exist. Foundation beams normally support line loads of walls and distribute the loads among the foundation piles. The piles can be at regular centre-to-centre distances or positioned at arbitrary distances. The configuration of the caps and beams are visualised in Figure 23.

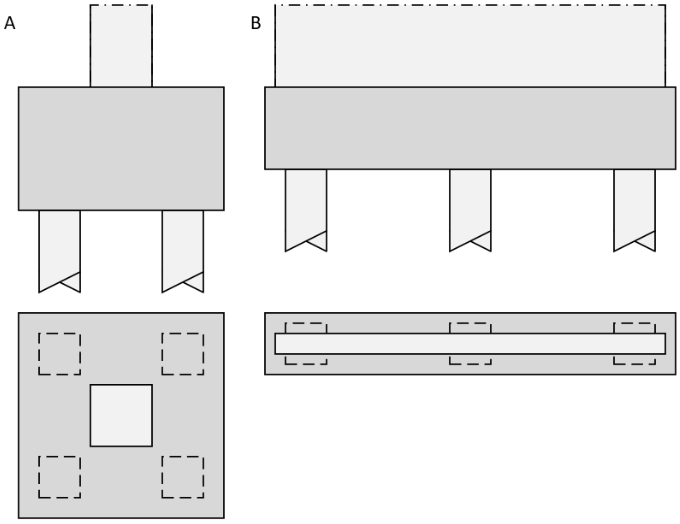


Figure 23. Pile cap (A) and foundation beam (B) principle

Foundation beams are commonly used for single-story and low-rise buildings, like residential buildings, to support the facades and partitioning walls, if applicable. Pile caps are mainly used for multi-storey and high-rise buildings like offices and apartment blocks. These types of buildings are characterised by a column-based floorplan. Combinations are common, for example, when foundation beams span from one cap to another.

In the past, when wooden piles were common, timber and masonry were used to transfer the loads from walls, columns and floors to the foundation piles. Today, all caps and beams are made of reinforced concrete. The elements can be constructed cast-in-situ or prefabricated. Given the chance of rot and corrosion of wood and steel, these materials are avoided. Otherwise, investing in thorough protection is crucial. Additionally, more solid and stiff foundations can be constructed using concrete. If the pile cap is sufficiently high, the normal force of the columns is transferred via compression struts. The foundation beams are subjected to bending moments and shear forces. When applied as continuous beams, both hogging and sagging bending moments occur. This requires appropriate application of reinforcement in the top and bottom of the beam. However, when applying continuous beams, deflections are constrained.

3.1.2 Shallow foundations

Shallow foundations, depicted in Figure 24, can be subdivided in pad, strip and raft foundations. A pad foundation consists of several circular or rectangular blocks that support columns. Stepped or sloped pad foundations can be used to spread loads. Strip foundations are similar but support walls or a row of columns, which are positioned close to each other. Thus, pad and strip foundations are used for point and line loads, respectively. In general, a raft foundation is a slab underneath the entire building area that spreads the load from the load bearing elements, like columns and walls, over the whole ground surface.

Due to the varying soil conditions in the Netherlands, a shallow foundation is often rejected. Load bearing capacity is in many cases no problem, but risk of settlements scares decision makers. Small, equal settlements are acceptable, but large and/or uneven settlements are undesirable. These settlements can be avoided by homogeneous distribution of loads and a stiff foundation. Compared to a pad or strip foundation, a raft foundation prevents differences in settlements between building parts and can be strengthened by beams or ribs. Thus, loads can be better taken or spread.

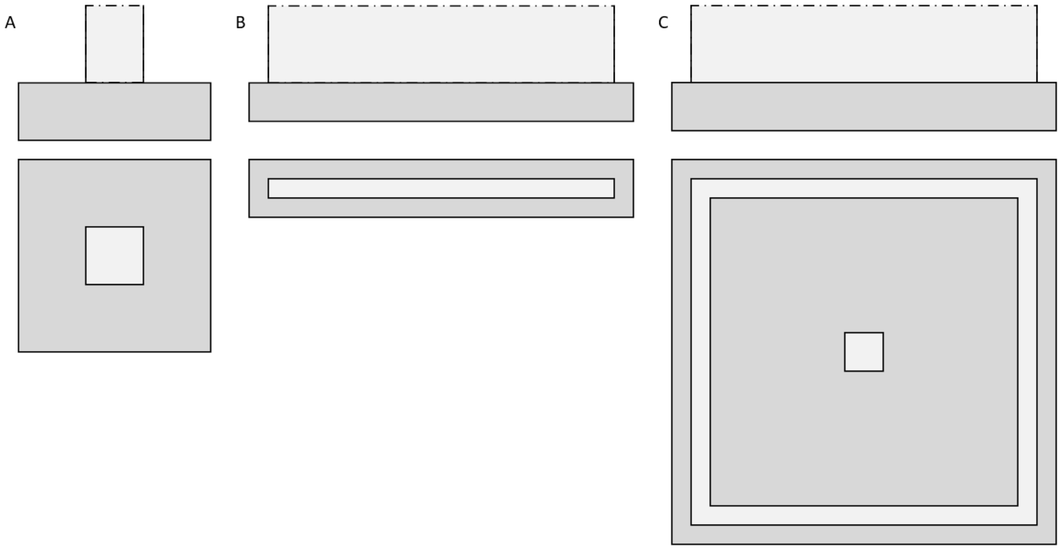


Figure 24. Pad foundation (A), strip foundation (B) and raft foundation (C)

In the past, strip foundations were made of masonry and tapered from the construction level toward the structural elements, like walls and floors. Nowadays, all types of shallow foundations are made of concrete. The shallow foundation is always constructed on top of a load bearing soil layer near ground level. Above this soil layer of sand is usually a mixed layer of clay and peat. The compressible soil layers require ground replacement and soil improvement. The upper soil layer of clay and peat is excavated and, if necessary, replaced by sand. Before constructing the foundation elements, the ground is levelled and compacted.

3.1.3 Remaining topics

Below, some remaining topics are addressed. Several retaining wall types are described in the first subsection. Although retaining walls have requirements other than traditional building foundations, they can offer interesting design principles. In the second subsection, different types of connections are discussed. The type of connection is important, especially for a changeable foundation. For a versatile foundation, the type of connection is a minor detail.

Retaining walls

Retaining walls are mainly used for building pits. Although retaining walls have additional requirements, they are useful to consider. A number of retaining walls can be disassembled and reused, which is an important design goal of changeable foundations. In that context, soldier pile walls, sheet piles and L-elements are described below. To complete the overview, walls of foundation piles and diaphragm walls are also described. The soldier pile wall and sheet piles are displayed in Figure 25.

A. Soldier pile walls: This type of retaining wall consists of steel profiles with planks of timber or concrete in between. Different construction methods can be used to position the steel I-profiles. When the building pit is excavated, the planks are positioned in between the profiles' flanges. Afterward, the profiles can be removed by vibration. Therefore, the steel profiles, as well as the wooden or concrete planks, can be reused. However, this type of wall can only be applied if no groundwater is present.

B. Sheet piles: Sheet piles are commonly made of steel. Steel sheet piles exist in different rolled profiles and are pushed or drilled into the ground. When the construction activities are finished, the sheet piles can be removed and reused. This type of retaining wall can be used when ground water is present. Wooden sheet piles are only used for low quays. Ground anchors can be used to support the retaining wall and avoid rotations due to water and ground pressure. The anchors consist of steel bars, which are embedded in concrete. Ground anchors are a permanent solution that cannot be removed without demolition.

C. L-elements: This type of retaining wall consists of several prefabricated L-shaped elements positioned next to each other. An element consists of a foundation plate and a wall. The soil above the foundation plate, which needs to be retained, also supplies resistance to the element's rotation. This type of elements can also be used for storage facilities at ground level.

D. Foundation piles and diaphragm walls: The piles were previously mentioned in this chapter, but they can also be used to construct retaining walls. Unlike the other retaining walls, this type of retaining cannot be disassembled and reused. Figure 26 displays the method of constructing a retaining wall from foundation piles and diaphragm walls. First, foundation piles or diaphragm walls are constructed at a regular centre-to-centre distance. Second, the intermediate space is filled with another series of foundation piles or diaphragm walls. Often, the piles or walls are not perfectly aligned, resulting in a rough course of the retaining wall.

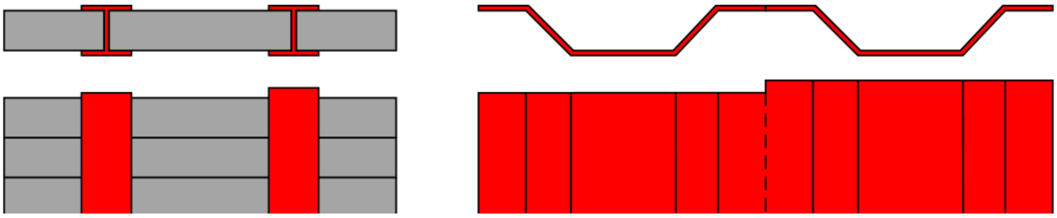


Figure 25. The soldier pile wall (left) and sheet piles (right)

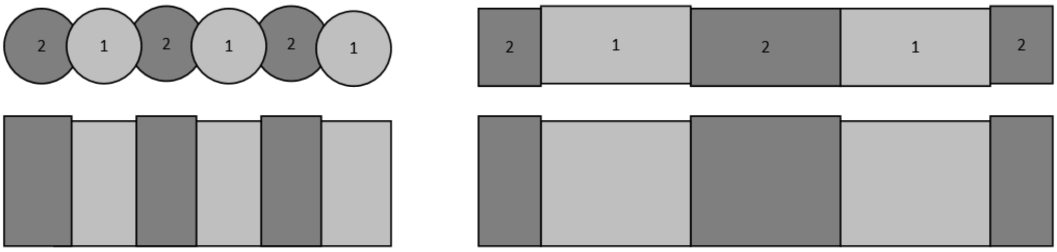


Figure 26. Retaining walls of foundation piles (left) and diaphragm walls (right)

Connections

The type of connection is important for changeable foundations. Therefore, different types of connection are described in this section. Connections are divided into dry and wet. Another distinction is made between horizontal (beam or floor) and vertical (column or wall) connections. In Figure 27 and Figure 28, some typical examples are provided. These examples are assumed to be the most commonly used types of connections.

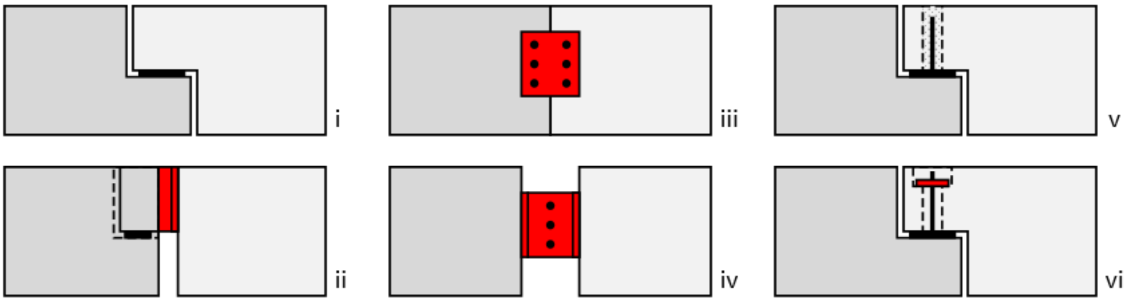


Figure 27. Horizontal connections, beams and floors

Dry connections
For dry connections, no liquids, such as mortar or concrete, are used. Often additional elements, like bolds and pins, are used to connect the elements. The advantages of dry connections are time and money: no hardening time and the construction is not labour-intensive. However, this type of connection is less solid than wet connections.

Connection i in Figure 27 and Figure 28 illustrate dry connections without additional elements. This type of corbel is a typical beam connection. The pit foundation for columns is uncommon. These connections are suitable for normal and shear forces. Bending moments and torsion are difficult to resist. Dry connections can also be realised by adding steel plates, bolts and pins. Examples are provided in the middle of Figure 27 and Figure 28. Many variants exist. Depending on the size, thickness and number of steel plates and bolts, bending moments or torsion can be taken. Connection vi represents a variant with a rod positioned in a gain and fixed afterward.

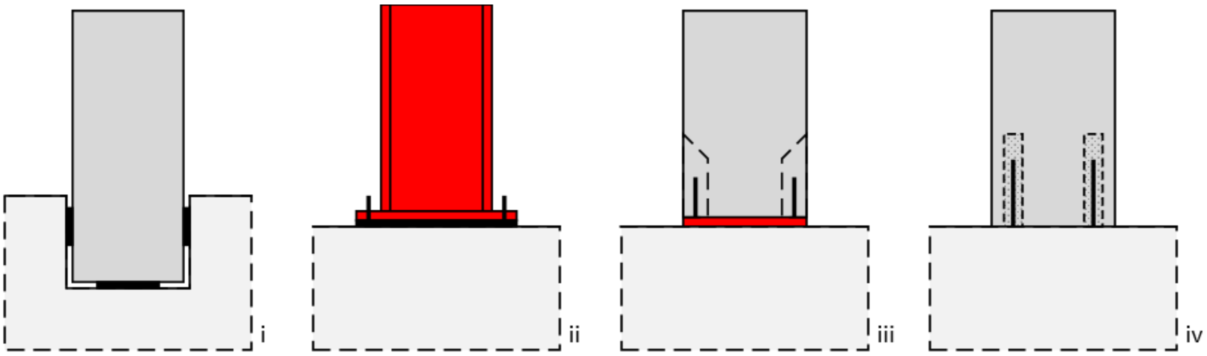


Figure 28. Vertical connections, columns and walls

Wet connections
Liquids are used to create wet connections, which make them labour intensive and require hardening time. However, solid connections can be realised. It is possible to make them air or watertight, which might be another advantage. A well-known connection is used in cast-in-situ concrete, whereas the elements, which can be any shape, are connected as depicted in Figure 29. Generally, reinforcement protrudes from phase 1. Reinforcement in the concrete, casted in phase 2, overlaps the protruding reinforcement. Alternatively, couplers are used to connect the reinforcement of the second phase to the reinforcement of the first phase.

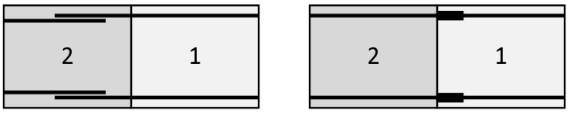


Figure 29. Cast-in-situ connection with (right) and without (left) couplers

Another type of wet connection is a grouted connection. Connection v in Figure 27 and iv in Figure 28 illustrate this connection. One of the elements contains a gain, while the other element contains a protruding rod. The rod can be positioned in the gain, which is afterward filled with grout. This is another way to create a rather solid connection.

In conclusion, the main difference between wet and dry connections is the labour-intensity, hardening time and strength of the connection. However, the execution of the connections is most important. Dry connections use bolds, plates and pins, which make the connection easy to disassemble. This is critical for the reusability of elements and systems of changeable foundations. Wet connections of concrete or mortar might cause considerable damage. However, for versatile foundations, wet connections are not a problem since the foundation will be permanent. To inventory the type of connections the books of Engström et al. (2008) and Ogden and Henley (1996) are used.

3.2 Design aspects

When designing a foundation, many criteria and requirement have to be considered. In the first subsection, an overview of the criteria is given, while in the second, the most important requirements are provided. Currently, when one strives to reuse a foundation, problems ensue. These problems are listed in the third subsection. However, possible solutions are also considered.

3.2.1 Criteria

A multitude of design criteria from Van Tol et al. (2005) is specified below. The criteria are grouped into building, subsoil, environment, building site, construction and building physics.

Building

- Structural concept
- Consequence classes and loads
- Building masses and dilatations
- Desired strength, stiffness
- Special loads (tensile or horizontal)

Subsoil

- Load bearing capacity
- Ground water level
- Settlement-sensitive layers
- Negative friction

Environment

- Allowable vibrations and noise
- Lowering of ground water level
- Foundation method of abutments
- Boundary conditions of building pit

Building site

- Dimensions and accessibility
- Obstacles in soil
- Sloping surface
- Preparations

Construction

- Possibilities
- Time
- Risks
- Organisation

Building physics

- Waterproofness
- Thermal bridges
- Thermal insulation
- Harmful substances
- Airtightness

The foundation can be designed based on the criteria. For this research, the design criteria related to the building, soil and construction are most important. Design criteria related to the environment, building site and building physics are of minor interest.

3.2.2 Requirements

The main requirements, applicable to a traditional foundation, are defined as follows:

1. Transferring loads: The foundation transfers the load from the superstructure to the soil layers. These are mainly vertical compression loads but can also be vertical tensile loads, horizontal loads, or even loads due to earthquakes. As mentioned, these types of loads are not considered.
2. Minimising settlements: Due to loads and compressible soil layers, buildings settle. The amount of settlement strongly depends on the foundation. Even settlements, relative to the environment, do not result in significant problems. However, uneven settlements between building parts can result in serious issues. Damage will occur due to cracking, and the foundation’s structural integrity and the building might be affected. Cracks in basement floors or walls can easily result in leakage.
3. Resisting environmental influences: The foundation is in permanent contact with the soil. In most parts of the Netherlands, the ground water level is near the ground surface. The foundation, and especially a basement, must withstand this presence of soil and water over a long period of time. The concrete should be of sufficient quality to protect the reinforcement. Also, steel and timber elements must be protected.

3.2.3 Reuse problems and solutions

When trying to reuse foundation system, many problems are faced. In many cases these problems ensure that the foundation is not reused, and a new foundation is constructed. However, reusing materials and elements is one of the main goals in a circular economy. Below the main occurring problems when reusing foundations are enumerated. After general problems, additional problems depending on the type of reuse (changeability or versatility) are given. Hereafter problems, specifically applying to the removability of foundation piles, are given. Solving the problems might result in better reusability in building practise. For each problem, possible solutions are formulated.

General problems

- Lack of information (e.g., availability, characteristics): Without adequate data storage, information can be indirectly gained via conditions of the superstructure and signs of settlements. However, this data is often not sufficient. Many digital systems and programs are being developed to save data and information, such as BIM, material passports, user information and databases, as mentioned. Digitizing and saving data should be one of the preconditions of designing for circularity.
- Not suitable for the new purpose (e.g., positioning, geometry, load bearing capacity): Anticipating other applications should be part of the design guidelines. This can be achieved by standardizing elements and creating uniform foundation systems. Standardized elements facilitate a load range and repeating them in a uniform system offers flexibility in load transfer.
- New, stricter design requirements: In the future, new and stricter design requirements, for example, related to the material class and protection, might be enforced. By applying appropriate materials classes and protection, better than now required, one can anticipate these requirements. These requirements can also be part of a design’s guidelines. For example, requirements from the Eurocode, which are related to time, might be extrapolated to a design period of 200 years.
- Environmental degradation of materials: The foundation is at the interface of the building and soil for a long period of time. Ground water especially affects the quality of the material and thus the elements. Steel elements and reinforcement are sensitive to corrosion, while wood is sensitive to rotting. In turn, concrete could crumble. As stated, elements should be appropriately designed with high-quality materials and protection. The quality cannot drop below an acceptable level. In practise, concrete seems to be the most suitable material resisting the presence of ground (water). Use of wood and steel is avoided.
- Inspection and maintenance are difficult: Since the foundation is embedded in the ground and located underneath other elements, like floors, walls and columns, it is not accessible during the use phase. For this reason, design and construction of the foundations needs to be completed carefully. If possible, the foundation can be designed to be suitable for intermediate inspections and maintenance. This design aspect is most important for versatile foundations since the elements of changeable foundations can be checked in between use phases. Generally, no settlement indicates proper functioning of the foundation.

Additional problems for changeability

- Foundations are solid, cast-in-situ systems: Whether this is a problem depends on the type of flexibility. Versatile foundations are static and can be made cast-in-situ. Changeable foundations require dry instead of wet connections. These connections make it possible to disassemble the system and reuse the elements at the same locations or elsewhere.
- Transportation is difficult due to large and heavy elements: To make transportation of foundation elements easy, the elements should be lightweight and small. Preferably, elements have to be within the mass and dimensions ranges transportable by trucks, without extra measures. The mass and dimensions are important for changeable foundations and does not hold for versatile foundations.

Additional problems for versatility

- The function of the building site dramatically changes: Changes in the building site's function are not problematic for changeable foundations since those can be replaced. However, problems occur with versatile foundations. Relatively small changes in the building geometry, number of levels and live loads on floors can be implemented, but changing from low-rise to high-rise buildings, from a building to a public space, or a radical change of geometry might be problematic. One should only choose a versatile foundation when it is likely that the function of the building site will roughly remain the same in the future. Of course, the future is unpredictable, so for great uncertainty, a changeable foundation can be chosen.

Problems occurring when removing foundation piles

- Seeping and loosening of soil conditions: Removing a foundation pile might cause seepage due to perforation of water retaining clay layers and loosening of soil conditions. Therefore, steel piles instead of concrete of wooden foundation piles are preferred. Steel piles significantly reduce the risk of seeping and loosening of the soil conditions. However, the load bearing capacity dramatically reduces as well, limiting the practical applicability. It is possible to remove wooden or concrete foundation piles with a special deconstruction method. A steel tube is positioned around the pile and drilled downward. When the pile is pulled up, the lower part of the shaft is filled with clay to avoid seeping. The remaining part is filled with sand, after which the casing is removed, and the ground can by mechanically compacted (Van Schie, n.d.). However, the soil is still affected, so whether this method results in an acceptable condition is questionable. Based on the current state of knowledge and experience, leaving the foundation piles is often the best option.
- Damage to the foundation pile due to compression or tensile force: When a concrete foundation pile is pulled up, high tensile forces might cause it to break. Furthermore, clamping the pile top might cause crushing due to high compression forces. By applying appropriate reinforcement or prestressing, this can be avoided. Another option is to use steel or wooden piles, which do not cause this problem.

3.3 Conclusion

Traditional building foundations form the basis of the practical applicability of potential circular foundations. The main difference is between deep and shallow foundations. Deep foundations are commonly composed of piles, caps and beams. Several foundation piles exist, each with its own characteristics. Shallow foundations can be subdivided in pad, strip and raft foundations. Additionally, retaining walls, connections and current problems when reusing foundations were described. Retaining walls can be of interest to changeable foundations due to reusability. Also, the type of connection is of special importance to changeable foundations. This is not of interest to versatile foundations.

Finally, the design aspects were considered. Many design criteria apply to foundations. This research focuses on design criteria related to the building, subsoil and construction. Three main requirements were defined: transferring loads, minimising settlements and resisting to environmental influences. Also, problems currently occurring when reusing foundations were listed. Solutions were proposed and will be processed in a new framework, described in the upcoming chapters. Risk of seepage and loosening of the soil conditions when removing foundation piles are problems that are difficult to solve given the current state of knowledge.

4. Circular foundations in practise

In this chapter, practical applications of circular foundations are reviewed. In the first section, internet and literature on circular foundation principles are discussed. These can be general foundation principles or concepts developed by companies. Based on the gathered knowledge, the level of circularity is determined. Some of these principles were used in the first circular building projects, which are described in the second section. In interviews, these projects' stakeholders were asked about their experiences regarding the design and construction of circular buildings, with a special interest in the foundation.

4.1 Principles

The internet and literature were searched to inventory the circular, or at least sustainable, foundation principles currently used in the building industry. This search led to a list of principles, subdivided into several groups, for the overall foundation concepts, materials, integrated functionalities and elements. As stated, the level of circularity was determined. A distinction was made between reduce, reuse and recycle, known as the 3R framework. Hereafter, another assessment was completed. Based on Alba Concepts' framework, whether the principle has intrinsic circular characteristics or whether the characteristics are seen as precondition was determined. The descriptions and assessment of all concepts are presented in Appendix 5, on page 96. This section provides an overview of the results.

The aim of the general foundation concepts, such as a shallow instead of deep foundation, piled raft foundation and floating foundation, is to reduce the amount of material and energy used in foundation construction. Within the 3R framework, this is the highest goal. However, in the Alba Concepts' framework reduction is a precondition and thus does not directly result in a high level of circularity. An expandable foundation does have characteristics which facilitate reusability. Although reuse is a lower level of circularity in the 3R framework, such a design would obtain a better score when assessed with Alba Concepts' method.

Regarding materials, mainly recycling, rather than reuse, was considered. The traditional materials concrete, steel and wood are recyclable. Production and recycling of concrete and steel require considerable energy, but developments are currently taking place to reduce this amount of energy. Although recycling is the lowest level in the 3R framework, like reuse, recycling obtains a high score in Alba Concepts' framework. For example, wood is a biobased material, and the production and recycling of timber elements require less energy. Traditionally, steel and wood elements have been more suitable for reuse, giving their demountable connections. However, risk of rotting and corrosion must be considered. Using expanded polystyrene, Xiriton and bacteria aim for a reduction of material, but the applicability in the building industry is questionable and under development. Assessing these materials in the Alba Concepts' framework would probably result in a lower score.

Determining the best reusable or recyclable, and thus the most circular, building material is difficult. The level of circularity depends on several factors, such as the availability, production process, method of application, maintenance and the subsequent way of reuse and recycling. New technologies and approaches have to improve steel and concrete reuse and recycling processes. Recycling of traditional building materials currently requires considerable energy and may result in downcycling and thus loss of value. In general, the choice of materials should be an integral and well considered, as is mentioned by Crielaard, Vorstman, Kerkstra, Luijten and Schutte (2018).

Integration of functionalities, like concrete core activation and water storage, creates additional value, for example by more efficient use of materials and production of renewable energy. This integration is a form of reduction since the initial required amount of material and energy is reduced. Like the overall foundation concepts, this method is the highest level of circularity in the 3R framework. However, integration does not directly result in a high level of circularity, according to Alba Concepts' framework. The same holds for the energy piles and hollow piles, which aim to reduce energy and material, respectively.

The steel piles, demountable beams, modular blocks and plates, and pad systems can be disassembled and reused. In the framework of Alba Concepts disassembly is seen as the driving principle for circular designs. Therefore, these elements are highly valued. The level of circularity in the 3R-framework is reuse, thus in between reduce and recycling. This type of element is also used in the foundations of the temporary court in Amsterdam, The Green House in Utrecht and the circular viaduct in Kampen. Those projects are discussed in the following section. Demountable concrete foundation beams, and similar pile caps, are used in the deep foundation of the temporary court in Amsterdam. Concrete blocks and plates are part of the foundation of The Green House. Steel sheet piles are used at Kampen for the foundation of the circular viaduct. Many of these foundation principles were also listed by Gispert (2015) in her research on prefabricated foundations for room module buildings. This application also highlights the limited applicability since the load bearing capacity is restricted.

In general, several foundation principles have been developed to make the building industry more sustainable. However, many principles involve reduction of material and energy use. Although reduction is better ranked in the 3R framework, it is a precondition in Alba Concepts' framework. Reducing the material and energy use does not determine whether the elements or systems are physically recyclable or reusable. Some of the principles do involve characteristics that facilitate recycling or reuse. Unfortunately, a general concept is missing, and some principles are only suitable for temporary or lightweight buildings. A concept for long lasting and heavier buildings still needs to be found. Additionally, the reusable principles are primarily based on changeability. A versatile strategy is not convincingly represented.

4.2 Projects

Although the circular economy philosophy is relatively new and further knowledge and experience have still to be collected, a few projects have been built based on circularity. Interviewing these project stakeholders offered practical insights into circular building design and construction. Below five projects are briefly described. For three projects, employees of the involved contractor or engineering firm were interviewed.

XX, Delft

Despite their long technical lifespan, many office buildings are demolished due to their short service life. Changing demands and high refurbishing costs often result in vacant offices. This situation inspired J. Post to adjust the technical lifespan of an office to the economical and functional lifespan. The aim was to apply materials that would be mouldered or could be reused (without or with minor alternations) or recycled after twenty years. Thus, easily demountable connections and pure materials were applied. The number of materials was minimised and materials with excessive quality were avoided. Additionally, the building had to be flexible and comfortable. The result was XX, an office building in Delft completed in 1999. This information was obtained from Hooijmans (2009). Figure 30 displays the office building.

Figure 30. View of XX, Delft (Hooijmans, 2009)

The two-story office's hybrid load bearing system consists of timber columns and beams supported by steel frames. The column-based structure offers an open space that can be arranged at will. Connections consist of steel plates, pins and bolts. The façade is composed of glass panels with blinds to control the light and temperature. The channels for air treatment are made of cardboard. The timber was varnished rather than coated. The concrete foundation piles and hollow core slabs at ground level are made with 20% recycled aggregate. The insulation and finishing layers are detachably fitted. The first floor consists of a timber frame, filled with sand, for creating enough sound insulation. If desired, the first floor can be disassembled to create one open space. This description is based on the overview of the Waste and Recources Action Plan (n.d.). Figure 31 illustrates some elements and connections.

Figure 31. Structural elements and connections (Tissink, 2018; Hooijmans, 2009)

The building has existed for twenty years and is still in good condition (Tissink, 2018). Only the wooden window frames have been painted to maintain their appearance. Furthermore, radiators have been installed in the building because the climate control worked differently than expected. Twenty years ago, the design was controversial, but the concept and appearance meet the current philosophy and aesthetics. Also, tracking of materials was suggested, a precursor of today's material passport.

Circl, Amsterdam

Cricl (2017) is an initiative of ABN AMRO bank. The headquarters of the bank are located in the business district Zuidas in Amsterdam. A pavilion, with catering and meeting facilities, was planned right in the front of the office. Due to a lack of sustainable aspects, the initial design was rejected, and new plans were made. This resulted in a circular building design, visualised in Figure 32, with better sustainability characteristics. CIE architects and BAM were involved as the architect and contractor, respectively.

Figure 32. View of Circl, Amsterdam (de Architect, 2017)

Unfortunately, the foundation underneath the pavilion was already realised and thus not executed based on circular principles. The substructure consists of a single-layered basement, with a height of two traditional floor levels and supported by foundation piles. The basement and piles are made of 30% recycled concrete. Generally, the foundation is completely linear and, despite the recycled material, has almost no circular characteristics. The superstructure, however, has circular characteristics. The main load bearing structure and floor are made of timber elements connected with bolts. Also, the other building layers, like the skin, stuff and services, are circular. The information above was obtained during a telephone call with a representative of ABN AMRO bank on Tuesday 30 October 2018.

Temporary court, Amsterdam

The Amsterdam court consisted of several buildings that had reached the end of their lifespan, no longer fulfilling usage and comfort requirements. Therefore, a large part of the court complex was demolished and a new court was designed and constructed. Since this process takes several years, a temporary court was built (Figure 33), so the court could continue operating. The temporary court's construction is circular, which makes it possible to disassemble the structure, including the foundation (made of prefabricated elements), and rebuild it at another location (De Danschutter, Noomen, & Oostdam, 2017).

Figure 33. View of the temporary court, Amsterdam (Duurzaam Gebouwd, 2016)

Architect Cepezed, engineering firm IMd consulting engineers and contractor Du Prie were part of the consortium DPCP, which designed and constructed the project. During a conversation on Tuesday 13 November 2018, P. Noomen, a structural engineer at IMd consulting engineers, was interviewed. The interview transcript is provided in Appendix 6, page 101. Figures for the main load bearing structure and structural details are included here as well.

The Green House, Utrecht

The Green House, situated in Utrecht, was part of the tendering process of the adjacent building. The companies involved in the project designed and constructed a circular building in line with the function of the pavilion, a place that supports a transition toward a circular economy and new innovations. A rendering of the circular building is displayed in Figure 34. The foundation is made of demountable Stelconplates and Legioblocks.

Figure 34. View of The Green House, Utrecht (Albron, 2018)

The building was designed and built by architect Cepezed, engineering firm Pieters Bouwtechniek and contractors Strukton and Ballast Nedam. J.B. Cordes, a project manager at Ballast Nedam, was interviewed. He answered the interview questions via emails, dating Friday 9 and Thursday 13 November 2018. The translated answers are provided in Appendix 6, page 101. Figures for the main load bearing structure and structural details of the foundation are provided here as well.

Circular viaduct, Kampen

Recently, the first circular viaduct was built (Robbe, 2019). The stakeholders focused on disassembly and reuse of elements and did not particularly pay attention to the origin and waste scenario of the material. The structure is composed of prefabricated concrete tubes 2.5 metres long, 1.5 metres wide and 1.0 metre high. The modules are connected by prestressing and shear keys. The 5 mm thin joints are filled with mortar for strong collaboration of the modules. Pictures of the modules, prestressing and shear keys are displayed in Figure 35. The foundation is made of sheet piles. All elements can be disassembled and reused, except the mortar.

Figure 35. Structural elements and connections (Kamper Nieuws, 2018; Van Hattum en Blankevoort, 2019)

Designing modules for 200 years means the elements can be used for a long period of time without producing waste, creating reusability and sufficient quality. Normally, infrastructural works are designed for 100 years, but sometimes do not last for more than 30 or 40, as a result of changing demands. Designing modules for a lifespan of 200 years is accomplished by applying a thicker concrete cover and choosing a higher concrete class. These improvements should allow the elements to last for at least 200 years (Tissink, 2019). A brief interview was conducted with G. Visser, a senior specialist at VolkerInfra. The interview questions were answered via email on Monday 4 February 2019 and are provided in Appendix 6, page 101.

Discussion

As mentioned, considerable waste is produced when a building's functional, economic and technical lifespans do not coincide. This problem was tackled at the XX office in Delft. The technical lifespan was adapted to the functional and economical lifespans. Materials and elements with lower value could be used, and by designing for disassembly, these materials can be reused or recycled. This method avoids unnecessary use of energy and high-quality materials or elements. By choosing a limited technical lifespan, and thus raw low-value materials, one can best focus on recycling. Generally, reuse requires high-quality elements to last a long time. This concept can be recognised at the circular viaduct at Kampen. For longevity, a better concrete class was chosen, and additional concrete covering was applied.

The Green House in Utrecht and the temporary court in Amsterdam are of interest regarding the current method of designing and constructing circular foundations. From both projects, disassembly appeared to be an important design aspect. Disassembling must facilitate reuse of foundation elements. Despite the demountability the temporary court does not look like a circular building. This is admirable since designing a circular building might end in a building with a fragile and temporary appearance. However, the temporary court looks like a traditional, solid building. The most important lesson of this project lays in the reusability of the elements. The elements are designed to be disassembled, but since they are project-specific, they can only be used for the same building. In this case, that use is the purpose and therefore not a problem, but it may be an issue in many other cases. Using project-specific elements for another building would require many adaptations to the system or a building that is fully adapted to the foundation. Since this is not desirable or practically feasible, one should anticipate the following cycles. This requires a certain degree of standardization. Since precast foundation elements are not new, the design of the foundation was rather traditional. Incorporating more flexibility would transform the foundation into a more circular one.

In contrast to the cap and beams, the foundation piles are not designed for disassembly. The piles are likely left at the building site after disassembling the above structure. Removing piles is difficult and causes undesirable loosening of the soil conditions and risk of seepage. Presumably, the piles in this project will not be reused. If the piles are left unattended, recycling will not take place, resulting in waste and obstacles in the soil. This project demonstrates the recycling or reuse of foundation piles can be improved. Application of steel piles, like the sheet piles in the foundation of the circular viaduct, might be an alternative. However, the applicability for buildings is limited. Designing a permanent, piled (raft) foundation suitable for different buildings is another possibility. However, this method requires a considerable investment. Generally, designing for circularity requires a significant investment, and in many cases, the client is not willing to pay. The transfer from linear to circular buildings should be imposed by the government. Possibly, this is the only way to create a circular economy. For example, the temporary court and The Green House are government-owned projects. To goal to construct a circular building fundamentally influences the design process. Therefore, circularity has to be considered from the beginning of the project. Otherwise, circular values cannot be fully embedded in the design, as with Circl in Amsterdam.

In contrast to the temporary court, The Green House has a more temporary appearance. However, the lightweight structure and appropriate soil conditions enabled a shallow foundation design. Here, the challenges of the foundation piles could be avoided. The Stelconplates and Legioblocks, used in combination with soil improvement, can be easily disassembled and reused. Instead of different caps and beams, similar plate and block modules could be used. After disassembly, the modules can be used for any other project and an empty building site remains. Based on the temporary court and The Green House, designing a circular shallow foundation, instead of circular deep foundation, appears easier.

4.3 Conclusion

Practical experience with circular foundations is currently limited since the theory of the circular economy is relatively new. To understand the circular, or at least sustainable, foundation concepts in practice, internet and literature were studied. Many concepts focus on material and energy reduction. Within the framework of Alba Concept this criterion is seen as a precondition so does not directly influence the level of circularity. Only a few concepts have characteristics that aim for recycling and reuse. The reusable concepts are based on changeability and lightweight buildings. Hardly any concepts are based on versatility, nor are they suitable for heavier buildings.

Useful insights were obtained in interviews with stakeholders of circular building projects. The Green House in Utrecht and the temporary court in Amsterdam are of the most interest. Due to the lightweight structure and appropriate soil conditions, a shallow foundation was sufficient for The Green House. The blocks and plates can be disassembled and individually reused for other projects. The temporary court, which has a less temporary appearance than The Green House, has a deep foundation. This choice was necessary because of the heavy loads and soil conditions. The beams and caps can also be disassembled but can only be reused for the same building. The piles will be left at the building site. Thus, there is room for improvement.

5. Circular foundations

This chapter discusses a new theoretical framework for circular foundations. Design guidelines and a conceptual elaboration of the defined circular foundation types are presented in sections 1 and 2. In the third section, an alternative assessment method is elaborated. This method focuses on the assessment of circular foundations and is based on the content provided in the first two sections.

5.1 Design guidelines

Two types of the foundations related to flexibility: (1) dynamic and changeable and (2) static and versatile. In addition, depending on the building loads and soil conditions, shallow or deep foundations can be chosen. Combining these pairs of foundation systems results in four foundation types, presented in Table 9. Changeable foundations consist of a collection of modules that can be easily disassembled and reused. A versatile foundation is a permanent system suitable for different applications and defined by three subtypes.

	Deep foundation	Shallow foundation
Versatility	Type 1, three subtypes	Type 3, three subtypes
Changeability	Type 2, collection of modules	Type 4, collection of modules

Table 9. Four foundation types

To choose the right foundation type, the flowchart displayed in Figure 36 can be followed. Based on the loads and soil conditions, one must determine whether a deep or shallow foundation is needed. Then, a versatile or changeable foundation can be chosen based on the future scenario of the function and location of the building. The versatile foundation is divided into three types and corresponding levels of flexibility. In addition to flexibility, the choice of a subtype depends on the type of building. Types 1.2 and 3.2 might be more applicable to single-story buildings, like housing and industrial buildings, while types 1.1, 1.3, 3.1 and 3.3 might be more suitable for multi-story buildings, like offices and apartment blocks. For a changeable foundation, a selection of proposed modules can be used.

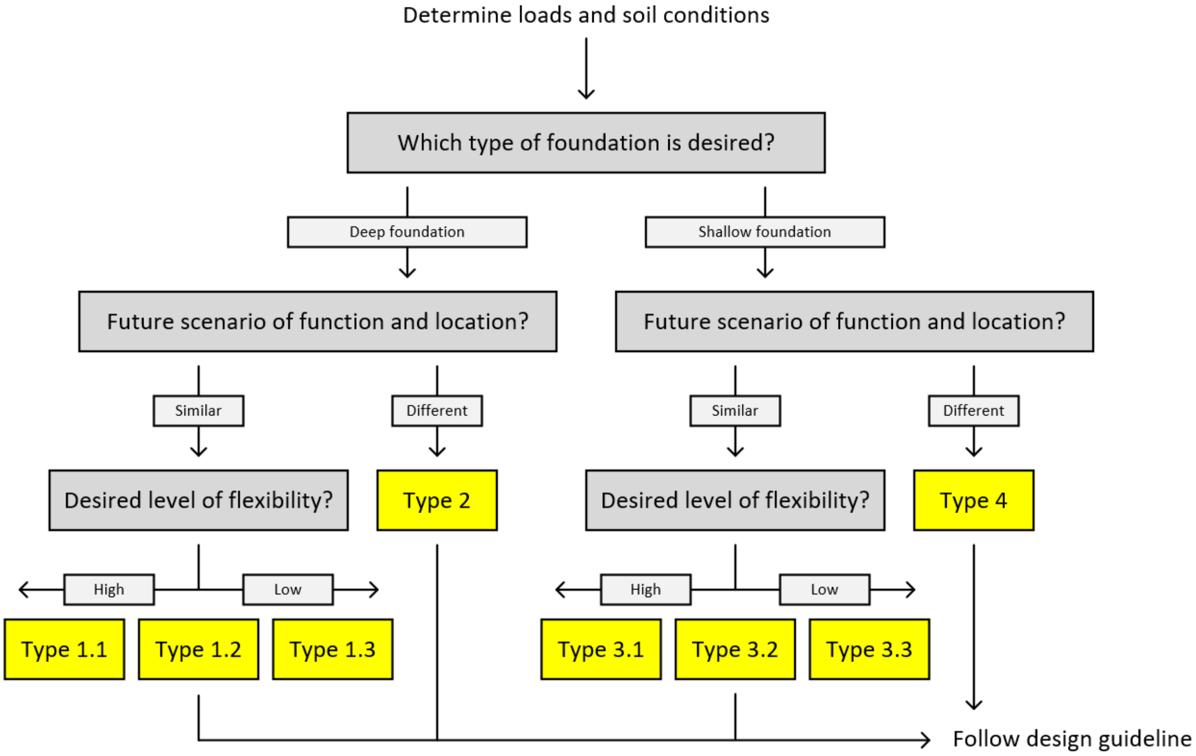


Figure 36. Flowchart for choosing the foundation type

When the desired foundation type is known, the foundation systems can be designed. The following topics need to be considered when designing a foundation: materials, dimensions, load bearing capacity, connections and transportation. The guidelines are based on longevity, standardization and uniformity to create long and consecutive lifecycles. These terms can be applied to each topic but, more specifically, relate to the material, element and systems levels, respectively. These levels are considered in foundations. An overview of this concept is provided in Figure 37. Longevity relates to appropriate material classes and protection to create long lasting design. Standardization concerns developing a selected number of different modules and connections, and the associated materials, to improve interchangeability. Longevity and standardization also benefit the load bearing capacity. Uniformity concerns the repetitive application of centre-to-centre distances, modules and connections in the total foundation system to benefit the reusability and create flexibility in the load bearing capacity.

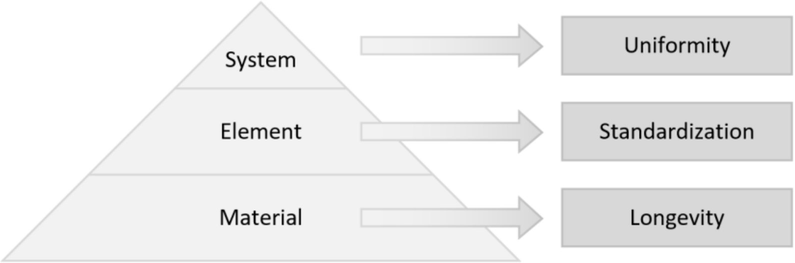


Figure 37. Hierarchy and corresponding design goal

Materials
Considering the requirements of a foundation, using traditional building materials is unavoidable. In the short term, it is not expected that another materials replace the traditional building materials. Therefore, steel, concrete and timber should be used in a thoughtful way. When designing for 200 years of reusability, sufficient quality should be obtained, and design should be sustainable for a long period of time.

Creating long lasting designs requires more attention and other decisions than conventional building and foundation design. For example, one should choose at least steel class S355 and concrete classes C30/37 and C60/75 for in situ and prefabricated concrete, respectively. For timber, the right soft and hard wood class should be chosen. In addition to the material class, materials should be adequately protected. To protect the reinforcement in the concrete elements, the covering can be increased, a concrete mix with higher resistance against penetration can be chosen, or a coating can be applied (Visser & Siemes, 2010). Also, steel and timber can be protected in different ways, like coating or protecting elements. Prefabrication offers controlled conditions to create high quality. If constructed cast in situ, extra attention must be paid to the execution.

Dimensions
The foundation elements' dimensions can be rounded to, for example, 50 or 100 mm. By doing so, one can create redundancy and a limited number of modules, which benefits interchangeability and thus reusability. The overall foundation system should have a grid with a multiplication of 0.3 m, or if possible 0.6 or 1.2 m. This makes it possible to design centre-to-centre distances of 3.6, 4.8 or 7.2 m, which are widely used in the building industry. Choosing a grid, and thus creating regular supports for load bearing elements, makes it easier to reuse the foundation systems or the associated elements. Randomly designed foundation systems and elements are more difficult to reuse.

Load bearing capacity
The load bearing foundation elements should have sufficient load bearing capacity to carry the design loads and facilitate expandability. Live loads can be recalculated from a standard design period of 50 years to a design period of 200 years. Choosing appropriate material classes and protection, as well as rounding the element dimensions, also result in additional load bearing capacity. Whereas elements of a changeable foundation must facilitate a certain load range, a versatile foundation system has to support different buildings. Thus, for versatile foundations, additional load bearing capacity is more important.

Connections
For changeable foundations, connections should allow for easy construction and disassembly, without causing damage. Dry connections can be executed with or without additional elements, like bolts, screws and pins. Wet connections, such as grouted rod in gain connections, also allow for reuse and are of particular interest to create solid connections in foundations. It is important to create connections that facilitate stiff and stable foundations to minimise settlements and rotations. Since versatile foundations are not replaced, general cast-in-situ connections can be used. Like in traditional foundations, these connections allow for solid foundation systems. Removal without causing considerable damages is not possible.

The connections between the foundation and superstructure should preferably be dry, in case of changeable or versatile foundations. In both cases, one must be able to replace the superstructure, including the load bearing structure (e.g., floors, columns, walls), the installation (e.g., piping), skin (e.g., facade elements) and interior (e.g., partition walls, flooring).

Transportation
The maximum weight of a truck (vehicle and load) is 50,000 kg. Assuming a vehicle of approximately 20,000 kg leaves a load of 30,000 kg, which corresponds to approximately 300 kN. Concrete has a weight of 25 kN/m^3, so 12 m^3 of concrete elements can be transported without special measurements. The dimensions of the truck load are restricted to approximately 12.5 m in length, 2.5 m in width and 2.5 m in height (RDW, 2012).

5.2 Conceptual elaboration

In the following subsections, the four defined foundation types are explained at a conceptual level.

5.2.1 Type 1: Deep foundation, versatility

A deep foundation seems suitable for versatility. A versatile foundation is defined as a static foundation that is one solid system and suitable for different superstructures. Since it seems practically undesirable to remove the foundation piles (due to seepage and disturbed soil conditions), permanent foundation piles and versatile foundations are logical. In practice, this type of foundation is similar to traditional foundations, but versatile foundations focus on longevity, standardization and uniformity. Additional load bearing capacity should facilitate expandability. The layout should be a grid with repetitive elements.

Three types of versatile foundations are illustrated in Figure 38. These types depend on the function and loads of the building and the soil conditions. Type 1.1 consists of a thick slab, supported by foundation piles in a regular grid. The load bearing elements, either a column or a wall, can be positioned anywhere. Loads can always be distributed and transferred to the piles. This type of foundation is most suitable for high-rise buildings with a small building plot, high loads and irregular positioning of the load bearing elements.

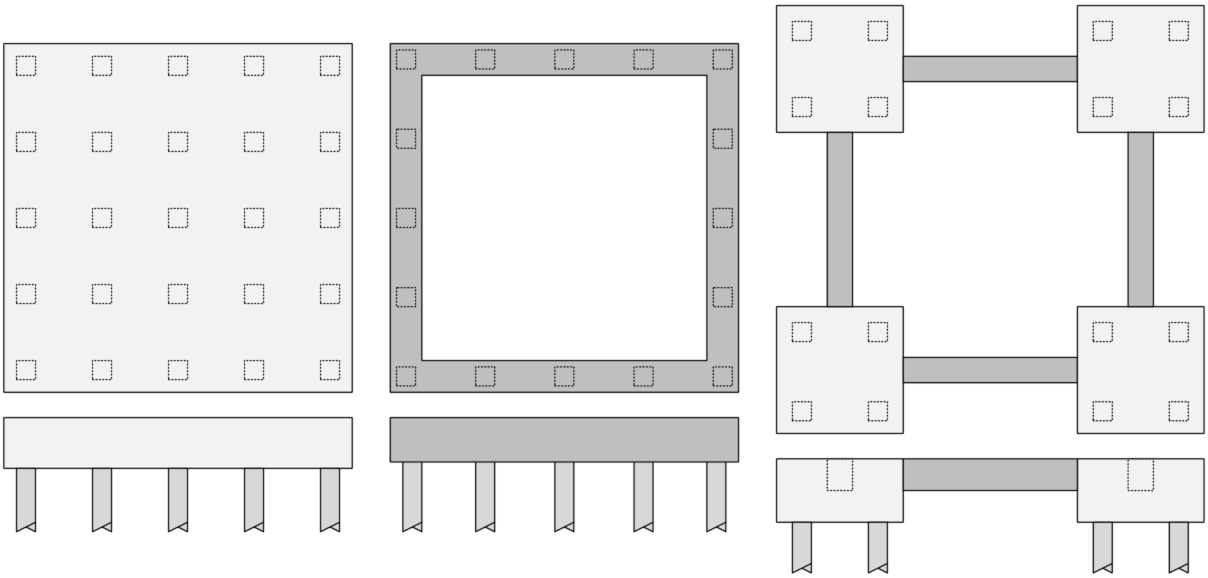


Figure 38. Different types of versatile pile foundation; from left to right, type 1.1, 1.2 and 1.3

For types 1.2 and 1.3, the load supporting elements are placed at larger distances. Type 1.2 has beams supported by foundation piles at repeating centre-to-centre distances. Type 1.3 uses caps supported by a number of foundation elements. For stability, the caps are interconnected by beams. Of course, combinations are possible. Point and line loads from columns and walls must be positioned at the beams and caps, respectively. In addition to high-rise buildings and high loads, these foundation types are suitable for lower loads, and thus for low-rise buildings. They are also more suitable for larger building plots but require regular positioning of load bearing elements. Type 1.2 is appropriate when the loads within the building are low and uniformly spread about the building plot, like housing. Extreme concentrate loads are difficult to resist and can be better taken by type 1.3.

Overall, the distance between the foundation piles increases, and the load bearing capacity of the intermediate regions reduces. This involves a reduction of the flexibility concerning the positioning of load bearing elements, like columns and walls.

5.2.2 Type 2: Deep foundation, changeability

A changeable, deep foundation is much more challenging than a versatile deep foundation. Logically, a changeable deep foundation would consist of foundation piles, pile caps and foundation beams that can be disassembled. When applying solid, demountable connections, this feature is achievable. Specifically, the pile cap and foundation beams can be designed and constructed in this way. However, the foundation piles are an issue. As mentioned, removing the foundation piles is rather difficult and creates serious problems. Seepages can occur, and the soil conditions are disturbed. Therefore, in this thesis, the foundations piles are considered before the total concept is described.

Table 10 presents the characteristics of different foundation piles: steel piles (e.g., steel profiles, sheet piles and helical piles), wooden piles and concrete piles, of which variants exist. For each foundation pile, the relative load bearing capacity was determined. Whether the pile is renewable and whether removing the pile causes seepage and disturbed soil conditions were also considered. The load bearing capacity and chance of seepage and disturbed soil conditions when removing the pile are of most interest. Ideally, a pile with high load bearing conditions without risk of seepage and disturbed soil conditions is desired. Unfortunately, this combination does not exist.

	Risk of seepage and disturbed soil conditions	Load bearing capacity	Renewable
Steel piles	No	Low	No
Wooden piles	Yes	Medium	Yes
Concrete piles	Yes	High	No

Table 10. Comparison between foundation piles

The steel piles cause no, or limited, risk of seepage and disturbed soil conditions but have low load bearing capacities. Sheet piles and steel profiles only have load bearing by skin friction. The end bearing capacity is negligible. On the contrary, the wooden or concrete piles have higher load bearing capacities, but removal causes a chance of seepage, and the soil is left disturbed. A significant advantage of the wooden pile is the material's renewability. If removing a concrete pile and avoiding the mentioned problems were possible, it might be beneficial to choose connection piles (Bennenk, 2001). This pile type is compiled of smaller elements, which are suitable for disassembly and transportation. At another location, the piles can be reconstructed. The length of the pile can be adjusted to the soil conditions and loads.

If the loads of the superstructure are low, steel piles are an appropriate choice. Without notable problems, these piles can be removed and reused. For higher loads, wooden or concrete piles are inevitable. As suggested, disadvantages of removing foundation piles can be solved. However, whether the technique is sufficient is questionable. If it is sufficient, the method increases the reusability of foundation piles. For now, it is assumed that the technique is practically undesirable, and steel and wooden piles do not have sufficient load bearing capacity. Thus, concrete piles are used and not removed. A possibility is to apply demountable beams and caps and leave the piles in place. The foundation system should be designed so reuse of the piles is possible. Therefore, a grid with logical centre-to-centre distances for the piles, beams and caps is needed. The positioning of piles underneath caps deserves extra attention. Figure 39 illustrates the interchangeability of two-, three- and four-pile caps.

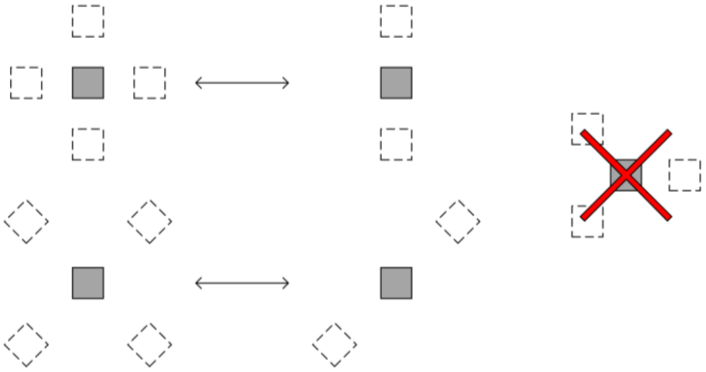


Figure 39. Interchangeability of two-, three- and four-pile piers

Two-pile and four-pile piers can be interchangeable in permanent foundation piles. The positioning of the foundation piles for three-pile caps does not coincide with the positioning of two or four foundation piles. For the two- and four-pile caps, two geometries can be distinguished: (1) the foundation piles are located in the vertical and horizontal symmetry lines of the column and (2) the foundation piles are rotated 45 degrees and coincide with the diagonal symmetry lines of the column. A more specific visualisation of these options is provided in Figure 40. To retain equal beam lengths and promote the reuse of beams, the positioning of the corbel remains the same between the four- and two-pile caps.

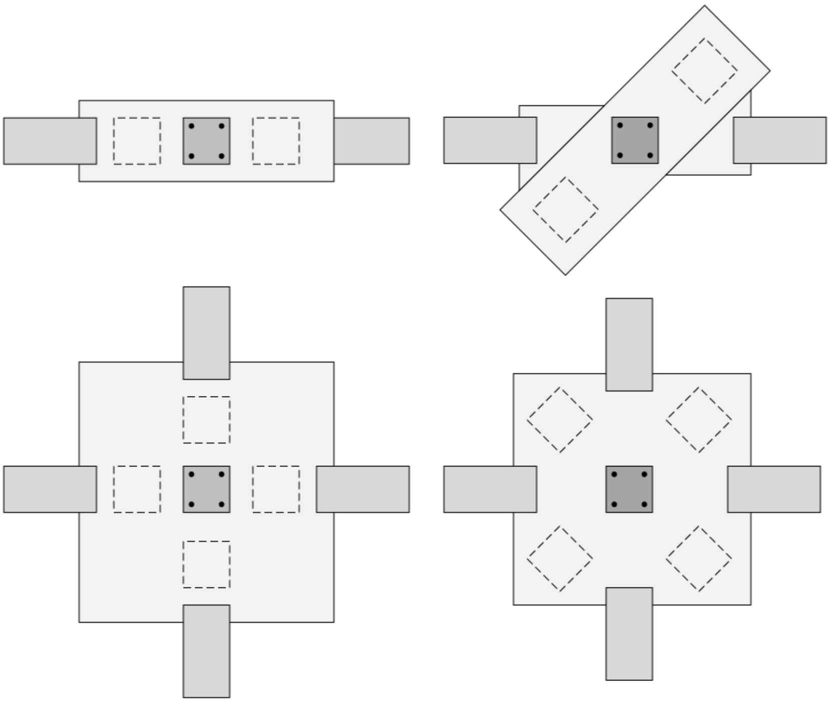


Figure 40. Interchangeable two- and four-pile caps, option 1 (left) and option 2 (right)

For option 1, the beam-to-cap connections interfere with the cap-to-pile connections. This interference allows for the combination of these connections, as depicted in Figure 41. For tolerances and reusability, however, keeping the connections separated is preferred. These connections can be dry or wet connections. If the structural integrity can be guaranteed, it might be even possible to apply no additional elements. Designing and constructing a cap like this will create difficulties in the amount and anchoring length of reinforcement at the location of the corbel. This problem does not occur in option 2. However, to keep the same beam length, a 'special' corbel has to be created for a two-pile cap. Additionally, the two-pile cap only fits if the beams are 'continuous' at both sides. A 90-degree corner requires another positioning of the corbel. Despite the challenges, the second option was chosen for this study.

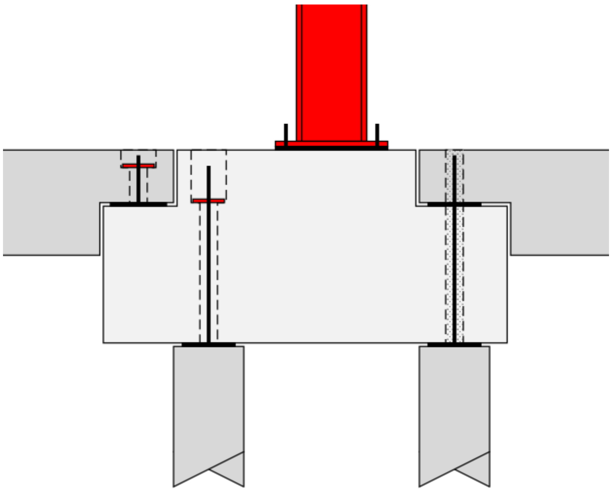


Figure 41. Connections that may or may not coincide

To promote cap and beam reuse, standardized dimensions and connections should be implemented. When completely different dimensions and connections are used in the circular building industry, interchange and reuse of the foundation elements over several lifecycles are difficult. A stock of (varied) standardized elements should be established. Defining standard dimensions and connections is challenging and who defines the dimensions and connections to be used in changeable pile foundations is in question. This could be the government or market leaders, for example.

Table 11 and Table 12 suggest some standardized cap modules. For the two-pile and four-pile caps, three types are specified, facilitating a range of pile cross sections. Prefabricated concrete piles of 180, 220, 250, 290, 320, 350, 380, 400, 420, 450 and 500 mm squared are presumed. These dimensions are standard in Dutch building practise. Prefabrication in controlled conditions provides quality, and one knows exactly what goes into the ground. The foundation piles should be installed carefully and precisely, on the one hand, to coincide with the location of the connection and, on the other hand, to avoid undesirable damage and forces.

The width and length are determined by the centre-to-centre of the piles and the distance from the pile centre to the edge of the cap. The centre-to-centre distance is at least three times the diameter. The other distance should be at least 500 mm. The width and length are rounded to a multiple of 300 mm. An exception is the width of the two-pile caps, which is rounded to a multiple of 100 mm. The length of the two-pile cap depends on the diagonal distance between the piles. The height is chosen so the load transfer from the column to the piles is at a minimum angle of 45 degrees. The results are also rounded to a multiple of 100 mm.

	Width (mm)	Length (mm)	Height (mm)	Pile range (mm)
A	1000	2700	1000	180 to 320
B	1100	3300	1100	320 to 420
C	1200	3900	1200	420 to 500

Table 11. Dimensions of two-pile caps

	Width (mm)	Length (mm)	Height (mm)	Pile range (mm)
A	2100	2100	1000	180 to 320
B	2400	2400	1100	320 to 420
C	2700	2700	1200	420 to 500

Table 12. Dimensions of four-pile caps

Table 13 presents the three variants for the beams, which were determined similar to the piles. The height is rounded to a multiple of 300 mm. The width is two-thirds of the height, resulting in a multiplication of 200 mm. The length of the beams depends on the centre-to-centre distance of the caps. If the beams are supported by piles, the length can be a multiple of the piles' centre-to-centre distance. The number of different modules is limited by ensuring that two- and four-pile caps can be interchanged without needing another beam length. Both cap and beam modules are conceptual proposals. Further research may result in other dimensions and a larger variety.

	Width (mm)	Height (mm)
A	400	600
B	600	900
C	800	1200

Table 13. Dimensions of foundation beams

5.2.3 Type 3: Shallow foundation, versatility

In contrast to a versatile deep foundation, a versatile shallow foundation is not obvious. A shallow foundation is suitable for a changeable foundation. The absence of foundation piles, which is challenging for a changeable deep foundation, is decisive. Like the versatile deep foundation, the versatile shallow foundation is similar to the traditional shallow foundation. As mentioned, the differences are in the additional focus on longevity, standardization and uniformity.

Three types of versatile shallow foundations are suggested based on the reasoning presented in the previous subsection. Differences are in the flexibility of load bearing elements’ positioning and the type of load, low versus high loads and relatively distributed versus concentred loads. The slab type 3.1 (Figure 42) offers great flexibility in positioning of the load bearing elements. For type 3.2, the location of the point and line loads is restricted to the stiffened grid of the thinner slab. Alternatively, foundation type 3.3 consists of individual parts that carry line or point loads. These strips and pads might be positioned at regular distances and are equal type elements. The foot of the elements is at a lower construction level than the other types. Also, in this case, the larger the distances between the load carrying foundation parts, the lower the load bearing capacity of the intermediate parts. Thus, the flexibility in location and type of loads reduces.

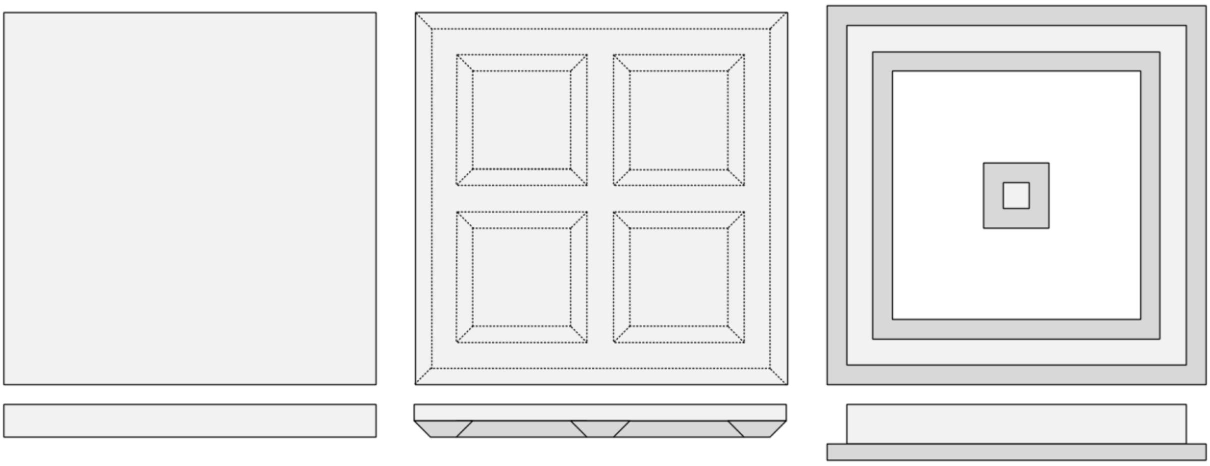


Figure 42. Different types of versatile raft foundation. From left to right, type 3.1, 3.2 and 3.3

5.2.4 Type 4: Shallow foundation, changeability

Due to the absence of foundation piles, a shallow foundation is suitable for changeability. An example of a changeable shallow foundation is presented in Figure 43. This concept consists of blocks and plates, which can be made as a series of modules. With different blocks and plates, one could compose any foundation systems, from pads and strips. Pads can be constructed by individually stacking modules, whereas a strip is created by repeating the modules. If, for stability reasons, the elements need to be interconnected, several connections could be applied, such as shear keys, rod in gain connections or connections composed of steel plates and anchors.

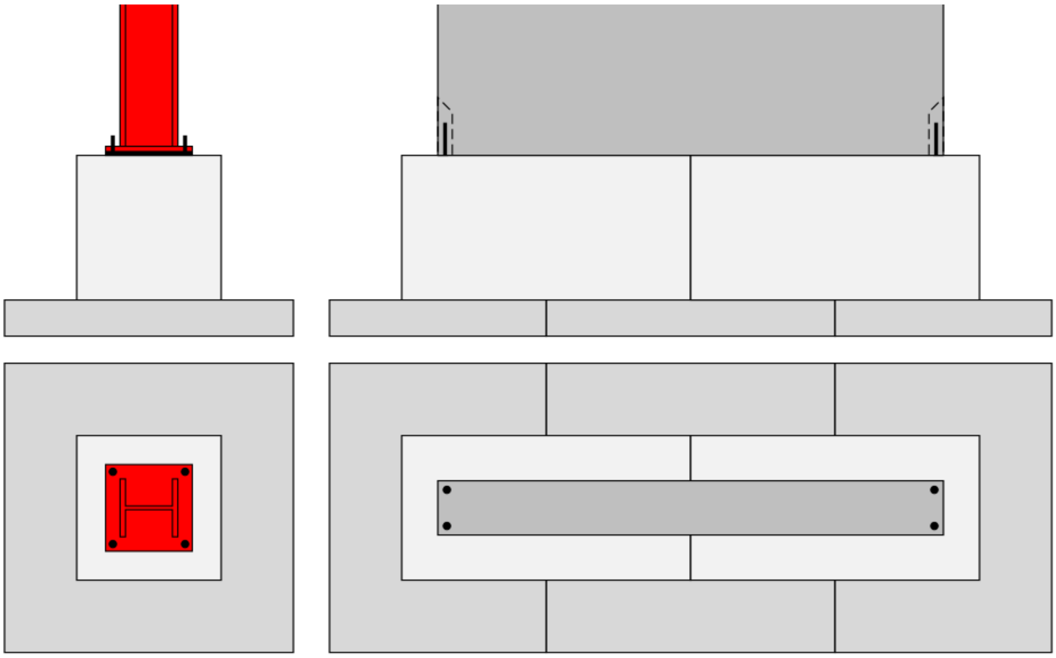


Figure 43. Side and top view of the changeable shallow foundation concept, pad (left) and strip (right)

Using the same kind of elements and connections would strongly improve the foundation elements' reusability. As stated, who decides the dimensions and quality of the elements and connections is questionable, but for now, the dimensions of the block are assumed to be a multiple of 300 mm. If desired, an intermediate step of 150 mm can be applied. This step could also be implemented for the plate dimensions. For the thickness, a multiple of 50 mm could be used.

Columns and walls can be directly positioned on top of the block, which is, in turn, supported by the plate. Different configurations support the floor. The first option is to position the floor directly on the subsurface. The distributed floor load is directly taken by the soil. The second option is to support the floor elements by strip foundations, thus a series of blocks and plates. This line load will be taken by the subsurface. The third option is to add beams spanning between pad and/or strip foundations. Via these locations, point loads are transferred to the soil.

By positioning the floor elements directly on the subsurface, there is no crawlspace. Thus, the floor elements have direct contact with the soil, which causes thermal bridges and a chance of material degradation. Connecting the floor elements to create a solid and stable plate is difficult, and the floor is prone to uneven settlements. If the floor spans, a crawl space can be realised. This crawl space reduces the risk of thermal bridges and material degradation. Connecting the elements to create a solid and stable foundation is easier and avoids uneven settlements. However, the loads are more concentrated in lines or points. Therefore, the load bearing capacity of the pads and strips needs to be sufficient. All variants are possible and involve advantages and disadvantages. One should make a careful decision based on the loads, soil conditions and building lifespan.

5.3 Alternative method

The method of Alba Concepts states disassembly is decisive for circularity. However, for foundations, adaptability is a promising form of flexibility. This difference is the main reason to adjust Alba Concepts' method. By adapting the indicators, the new method values not only changeable, but also versatile, foundations. Additionally, some changes were made concerning the determination of material scenarios and lifespan. In the first subsection, the overall framework is explained. The second subsection discusses the indicators.

5.3.1 Framework

The diagram presented in Figure 44 provides the underlying model of the alternative method. On the left, material, which can be new, non-virgin or biobased, enters the system. Using the material, elements and systems are made. After use, the materials can leave the system on the right. This is loss of value and thus a linear material flow. Alternatively, in a circular economy the materials, elements and systems cycle. For this method, a distinction is made between recycling and reuse. Reuse concerns elements and systems, whereas recycling refers to materials. Reuse can occur through changeability and versatility. Roughly speaking, changeability means reusing individual elements, whereas versatility entails reuse of the whole system.

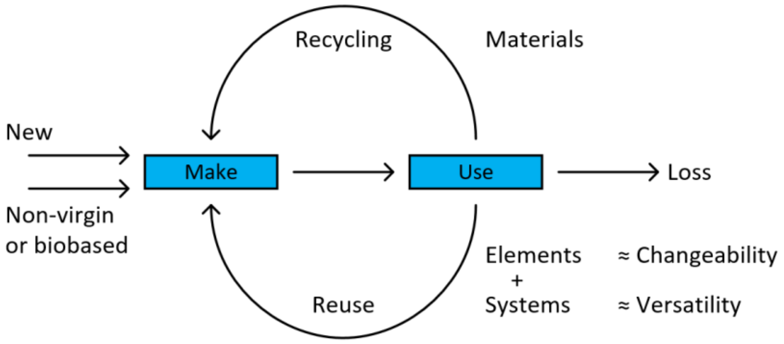


Figure 44. Schematic overview of underlying model

The result of the method is a value between zero and one, which corresponds to linearity and circularity. As with the indicators, fuzzy logic (Open Universiteit Nederland, n.d.) can be applied. This application is illustrated in the first graph of Figure 45. The horizontal axis indicates the circularity index and the vertical axis represents the truth value. A truth value of one is completely true, and a truth value of zero is completely false. When the circularity index is zero, the design is completely linear, and when the circularity index is one, the design is completely circular.

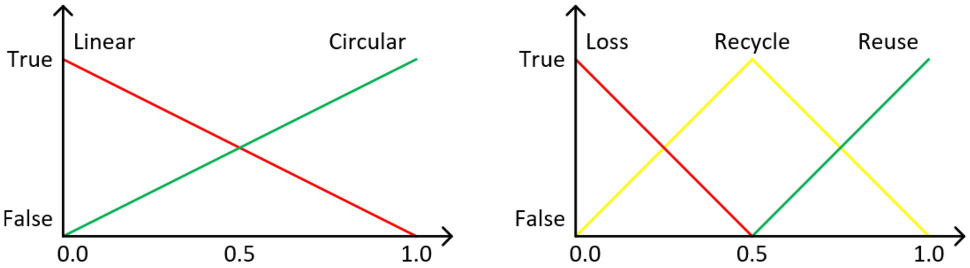


Figure 45. Different distribution of membership functions

When distinguishing recycling and reuse, these levels should be reflected in the method's outcome. Therefore, circularity is subdivided into recycling and reuse. Logically, loss is linear, and recycling is a lower level of circularity than reuse. This is illustrated in the second graph of Figure 45. A design characterised by loss, recycling or reuse should obtain a score approaching zero, half and one, respectively.

Figure 46 presents the framework of the new method. This framework broadly follows Alba Concepts' framework (2018). In addition to material scarcity, residual value and reputation, pollution should be one of the drives since one generally desires an environment without air, water and ground pollution. Adequate documentation is added to the preconditions because data is an important precondition for the reuse or recycling of materials, elements and systems. In many cases, if the availability of products and their characteristics are unknown, recycling material is hard or will not take place.

Because this research only considers the foundation, the building level was changed to the system level. Moreover, the product level was changed to material level. These changes better represent the considered subassemblies. Thus, the circularity index was determined at the material, element and system levels. The Ellen MacArthur Foundation (2015b) formula remained the starting point of the calculation. Thereafter, the indices were calculated based on the masses and corresponding indicators. The indicators are specified for each level and indicate the recyclability of materials and reusability of elements and system. An overview of the formulas and parameters for both methods are provided in Appendix 7, on page 110.

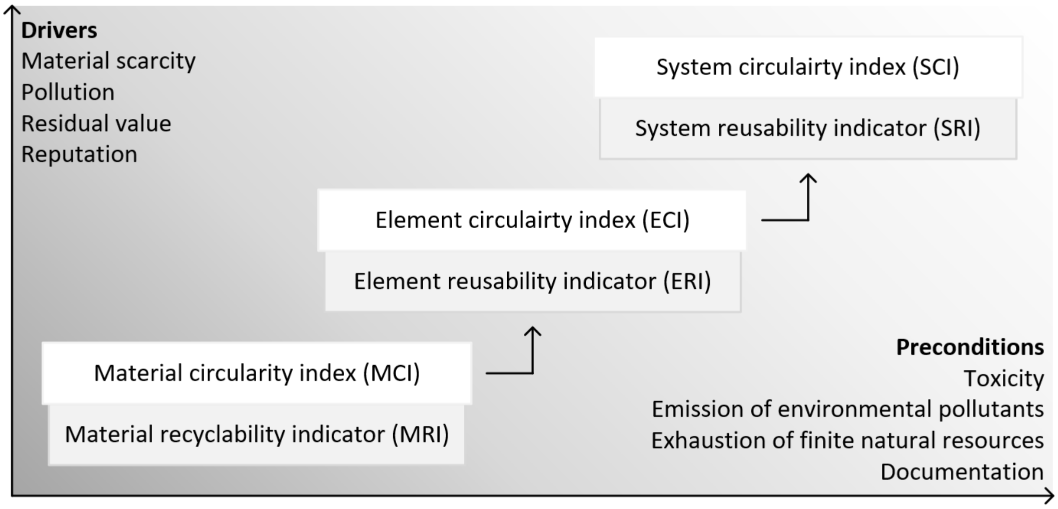


Figure 46. Framework for the new assessment method

In Table 14 and Table 15, the material scenarios and lifespan distinguished in the alternative method are presented. In Alba Concepts' (2018) method, four origin scenarios and four future scenarios are defined. In the alternative method, these scenarios are reduced to two and three, respectively. The origin scenario includes new material and non-virgin or biobased material. Reused, recycled and biobased materials were combined into one value because reused and recycled materials are non-virgin material and biobased material is renewable. The alternative method identifies three future scenarios: loss, recycling and reuse. Therefore, landfill and combustion are seen as loss of material and energy and thus combined into one value. As visualised in Figure 45, recycling should result in a lower value than reuse. However, to retain the formula of the Ellen MacArthur Foundation (2015b), that values recycling and reuse equally, the difference in assessment is not incorporated here. To value recycling and reuse differently the fuzzy values at the material level were reduced, compared to fuzzy values at element and system level.

	Origin of material (%)		Future of material (%)
A1	New	B1	Loss
A2	Non-virgin or biobased	B2	Recycling
		B3	Reuse

Table 14. Origin and future of materials

In contrast to the original method, the share of reuse and the technical and functional lifespans are determined at the element level instead of the product level. This step partially corresponds with the original method, whereas the reuse scenario could be adapted at the element level and the minimal lifespan of the individual products was taken for the lifespan of the element. In the author's opinion, the lifespans and reuse can be better defined at the element level, as displayed in Figure 44. Whereas Alba Concepts commonly equalizes the technical and functional lifespan, in this method, the lifespans may differ because that kind of steering is undesirable. In many cases, the technical and functional lifespans are not equal. For foundations, the functional lifespan is often shorter than the technical lifespan.

	Lifespan (y)
TL	Technical lifespan; how long does the material technically last?
FL	Functional lifespan; how long can functional requirements been met?

Table 15. Technical and functional lifespan

The subsequent indices were calculated based on the indicators and masses. The details are presented in Appendix 7, on page 110. In the original method, the connections' type and accessibility are the determining indicators for recycling and reuse. Although these factors are important for recycling and changeable reuse, they are less important for versatile reuse. In addition, reuse is characterised by other indicators. Demountable or not, if an element or system is too project specific is difficult to reuse, resulting in combustion or landfill. Other important indicators are the quality, dimensions, expandability, diversity and grid. These new indicators, specifically defined for foundations, were formulated based on the design guidelines presented earlier in the report. Recycling is considered at the material level and reuse is considered at element and system level.

At the element level, the contribution of the indicators depends on the future scenario. Thus, the reusability indicator weighs more when the main goal is to reuse elements. If one aims to recycle most materials, the recyclability indicator weighs more. If losses occur, this share is valued as completely linear. At the system level, the indicator is only charged on the share that will be reused. Since reuse is more circular than recycling, the latter should have a lower result. Aiming for reuse of elements or systems should result in high scores.

5.3.2 Indicators

In Alba Concepts' method, a high circularity index can be obtained by assessing products and element to be recyclable or reusable, together with demountable and accessible connections. In addition to these indicators for recyclability and reusability, other indicators are relevant. These indicators should apply to versatile systems. The connection type and damage are retained at the material level. At the element level, new indicators are formulated. The third indicator at this level differs between changeable and versatile foundations. At the system level, new indicators are also defined. An overview of all indicators is provided in Table 16. In Table 17 through Table 24, the fuzzy variables are defined. All indicators are explained below.

Level	Recycling	Reuse
Material	Material recyclability indicator (MRI) 1. Connection type 2. Damage	
Element		Element reusability indicator (ERI) 1. Quality 2. Dimensions 3. Damage *or* Expandability
System		System reusability indicator (SRI) 1. Diversity 2. Grid

Table 16. Overview of the circularity levels, building levels and corresponding indicators

Material recyclability indicator (MRI)

In the method of Alba Concepts the connection type and accessibility are considered at the product level, which is equal to the material level in the alternative method. This consideration concerns the connection between the materials. This connection should be easy to disassemble with minimal operations and damage to separate and recycle the materials.

To recycle materials, the type of connection is important. The more easily the materials can be separated, the better the materials can be recycled. Direct integral or chemical connections make it difficult to separate materials. Therefore, this indicator is retained in the new method. The soft and hard chemical connections are combined into one fuzzy value. Furthermore, the fuzzy values are slightly reduced to lower the final circularity index regarding recycling because recycling is seen as less valuable than reuse.

1. Connection type	
Dry connection	0.8
Connection with additional elements	0.6
Direct integral connection	0.4
Chemical connection	0.2

Table 17. Fuzzy values, connection type

Also, the fuzzy variable of the accessibility was retained but changed. Because accessibility is a vague description, this term was removed and changed to damage. Whether or not the connection is accessible, the ultimate damage is decisive. If the materials are seriously damaged, recycling them might not be possible, resulting in loss of material and energy, which must be avoided. Again, since recycling is less valuable than reuse, the fuzzy values are slightly reduced.

2. Damage	
No operations and damage	0.8
Additional operations, no damage	0.6
Additional operations, limited damage	0.4
Additional operations, much damage	0.2
Additional operations, total damage	0.1

Table 18. Fuzzy values damage, at material level

Element reusability indicator (ERI)
At the element level in the Alba Concepts' method, the connection type and accessibility are judged. However, these indicators do not match the defined forms of flexibility, especially versatility. Only the adjusted accessibility indicator, as defined at the material level, was retained at the element level in the new method. This indicator is only used for the changeable foundation. For both forms of flexibility, new indicators are defined.

Adequate material classes and protection should be applied to ensure that the elements last for a long period of time. Additionally, adequate material classes and protection improve the load bearing capacity. The minimal required material class and protection are the lowest level of quality possible. One level or two levels better is rewarded with higher fuzzy values, for example, by choosing a higher concrete, steel or timber class or adding additional concrete cover, steel coating or timber protection.

1. Quality	
Better material class and protection (2 levels)	1.0
Better material class and protection (1 level)	0.7
Standard material class and protection	0.5

Table 19. Fuzzy values quality

In addition to the material class and protection, the element dimensions are important for both versatile and changeable foundations. Element dimensions should not be rounded to arbitrary number since this makes them difficult to reuse, especially for changeable foundations. A limited amount of differently dimensioned element makes it easier to create an interchangeable system of elements. Limiting the use of different elements in a system also improves flexibility in sense of load bearing capacity. This also applies to a versatile foundation. Thus, elements should be rounded to, for example, 50, 100 or 300 mm. Using standard elements that are widely used and supported in building industry results in a high fuzzy value.

2. Dimensions	
Standard element in building industry	1.0
Rounded to multiple of 300 mm	1.0
Rounded to multiple of 100 mm	0.6
Rounded to multiple of 50 mm	0.4
Arbitrary rounding of dimensions	0.1

Table 20. Fuzzy values, dimensions

The revised accessibility of the connection at the material level was also applied at element level. As stated, whether the connection is accessible does not matter; the amount of damage after disassembly is most important. In this case, the fuzzy values are not reduced as one would expect this indicator to only be applied to changeable foundations.

The type of connection was not considered at the element level because judging a chemical connection as bad if it can be easily disassembled and reconstructed is not desirable. The required time and energy have only a small share in the overall project. At the material level, this measurement is important because it involves more work to separate materials than to separate elements and might be crucial for recycling.

3. Damage	
No operations and damage	1.0
Additional operations, no damage	0.8
Additional operations, limited damage	0.6
Additional operations, much damage	0.4
Additional operations, total damage	0.1

Table 21. Fuzzy values, damage, at element level

The expendability indicator only applies to the versatile foundation and was not considered for changeable foundations. By choosing appropriate material classes, protection and dimensions, the modules within the changeable foundation facilitate a certain load range. If a smaller load must be transferred, another module can be chosen. This practice is not possible for a versatile foundation. Therefore, additional load bearing capacity is judged separately. The additional load bearing capacity might be limited due to material classes, protection and dimensions to facilitate expandability. Thus, accounting for higher loads to facilitate expandability might be desirable, depending on the project and future expectations.

3. Expandability	
> 40% additional load bearing capacity	1.0
> 20% additional load bearing capacity	0.7
No additional load bearing capacity	0.5

Table 22. Fuzzy values, expendability

System reusability indicator (SRI)

The system level in the alternative method is comparable to the building level in Alba Concepts' method. In the latter method, no indicators are considered. Indicators were defined in the alternative method. The new indicators are explained in the following paragraphs.

To improve the reuse potential, a system should contain the same elements, concerning dimensions, connections and quality. Using different modules and connections makes reuse of elements or the systems more difficult. It is also not beneficial for the transfer of loads and sustainability. Repeating the same principles ensure better flexibility.

1. Diversity	
> 70% similar	1.0
40-70% similar	0.7
10-40% similar	0.4
< 10% similar	0.1

Table 23. Fuzzy values, diversity

Repetition of logical centre-to-centre distances are required to create repeated elements and have load bearing capacities at regular positions. This makes it easier to reuse the elements of a changeable foundation and reuse a versatile foundation system. Constructing another building on top of an existing foundation is less challenging with repeated elements and centre-to-centre distances than constructing one on top of an arbitrarily designed foundation. A grid is defined as (repeating) centre-to-centre distances, which are a multiple of 0.3 m in both directions.

2. Grid	
> 80% of foundation system	1.0
> 50% of foundation system	0.7
> 30% of foundation system	0.4
No grid	0.1

Table 24. Fuzzy values, grid

5.4 Conclusion

Dividing foundations into (1) deep and shallow and (2) versatile and changeable results in four circular foundation types. The versatile foundation's three subtypes differ in the level of flexibility, related to the positioning of load bearing elements, like columns and walls. The choice of subtype also depends on the type of building. The changeable foundations consist of a collection of modules. Each circular foundation was described at concept level.

A flowchart was proposed to determine the desired foundation type on the basis of the soil conditions, loads, future building site scenario and the desired level of flexibility or building type. Depending on the chosen foundation type, decisions must be made concerning the design criteria: material, dimension, load bearing capacity, connection and transportation. When designing, one should strive for longevity, standardisation and uniformity. Although these terms are inextricably linked, the goals correspond to the material, element and system, level respectively.

An alternative method, a variation of Alba Concepts' assessment method, enables better assessment of circularity and circular foundations. This alternative method incorporates design criteria, goals and levels, as well as acknowledging changeability and versatility as ways to create circular value. The method also makes a clear distinction between recyclability and reusability. The formula, as defined by the Ellen MacArthur Foundation, is the start of the calculation. The definitions of the material scenarios and lifespans were changed to better represent the underlying model. Hereafter, the circularity indices were calculated based on masses and indicators. Compared to the original method, the indicators were adapted and extended with new ones.

6. Case studies

To check the theoretical framework developed in previous chapter, and determine its practical usability, two case studies were conducted. Two projects of Aronsohn, one involving a deep foundation and one a shallow foundation, were chosen. For both projects, the traditional foundation was adjusted to circular variants, which were versatile and changeable. The four circular foundations correspond to the four circular foundation types defined in the previous chapter. To check whether the new designs are more circular than the traditional ones, the assessment method of Alba Concepts and the alternative method were applied. The application of the methods is presented in the next chapter.

The first project concerns the Meander Medical Centre in Amersfoort, which has a deep foundation. This project is detailed in the first section. In the second section, the second project is described. This project concerns the clinical training centre of the Radboud University in Nijmegen, which has a shallow foundation. For both projects, general project information, as well as data concerning the main load bearing structure, loads and geotechnics, are provided. In the subsections, the traditional and circular foundations are explained. Drawings of all foundation variants are included in Appendix 8, on page 112. In Appendix 9, on page 113, the Bill of Material (BoM) is presented for each foundation. The inventories of the elements and masses are needed in the next chapter. If no reference is given, the information was retrieved from Aronsohn's internal documents.

6.1 Project 1

The Meander Medical Centre in Amersfoort opened in 2013 and replaced the two old hospitals located elsewhere in the city. The building complex, displayed in Figure 47, covers an area with a length of approximately 230 m and a width of around 190 m. The complex has a floor area of about 113,000 m^2. Depending on the building section, low-rise (four levels) and high-rise (nine levels) exist.

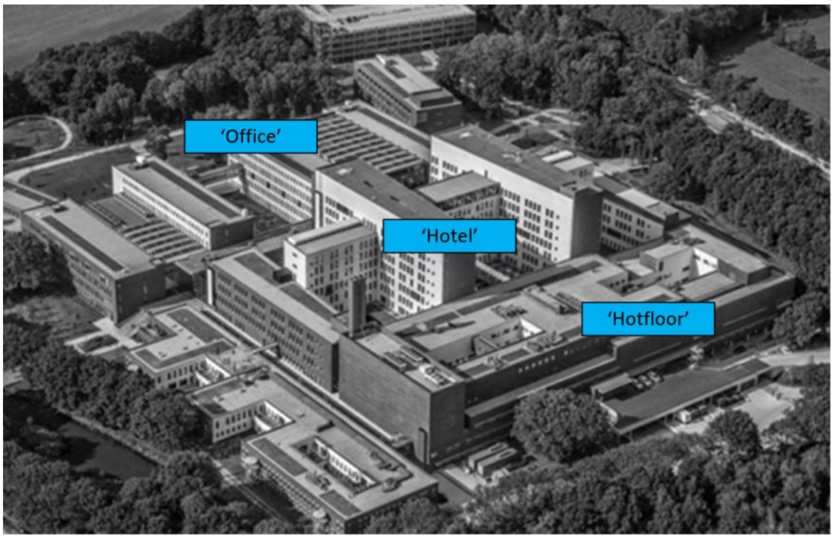


Figure 47. View of the Meander Medical Centre (STZ-ziekenhuizen, n.d.)

To avoid expensive functional adaptions during use and create enough residual value afterward, flexibility was an important design aspect. The designers considered recesses and change in function. The medical centre is divided in three parts: hotfloor, hotel and office. Each part has its own function (surgical and diagnostic, nursing department and outpatient clinics) that determine the characteristics of the building part. Underneath the whole complex, a parking garage is realised at ground level. This information is taken from Aronsohn (n.d.).

Main loadbearing structure
For this case study, half of the hotfloor was chosen. The chosen area has a floorplan of approximately 70 x 40 m^2, and the number of levels varies from three to six. The main load bearing system is made of prefabricated concrete façade elements, columns and reinforced plank floors or hollow core slabs. At ground level, hollow core slabs of 260 or 320 mm are used. On the other levels, reinforced plank floors of 250 or 300 mm are applied. Between the columns, concrete beams of 1200 x 500 mm^2 support the floor. Circular concrete columns of 450 mm are used on the lower levels. On the upper levels, circular concrete columns of 325 mm are applied. The load bearing façade elements are 200 mm thick. A small portion is made of steel beams and columns, consisting of several HEA and HEB profiled columns, beams and bracings.

Loads
At ground level, concrete columns and walls transfer the loads to the foundation. The live loads vary from 4.0 kN/m^2 to 10.0 kN/m^2, including partition walls, if applicable. The dead load depends on the chosen pressure and finishing layers and the chosen steel profiles and concrete elements. In the calculation, consequence class 2 was used.

Geotechnical research
From the ground level, varying between 0.5 and 1.3 m above NAP, the following soil layers were identified:

A. To approximately 5.5 to 7.0 m below NAP: mainly sand, locally thin layers of clay and peat
B. To approximately 8.0 to 12.0 m below NAP: sand, regularly interrupted by clay and peat layers
C. To approximately 16.0 to 19.0 m below NAP: clay, containing a considerable amount of sand
D. To at least 29.0 m below NAP: solid to extremely solid sand

The ground water level varies around NAP. Considering the size of the building loads, a deep foundation, to the deepest sand layer, was advised. After financial consideration, Vibro piles were chosen. Foundation piles with a diameter of 410 or 510 mm were applied, resulting in a load bearing capacity of 2000 and 2700 kN, respectively. The Vibro piles reach a depth of 18.5 or 19.0 m below NAP.

6.1.1 Traditional foundation

The deep foundation is composed of foundation piles, pile caps and foundation beams. The foundation piles are circular Vibro piles, whereas the caps and beams are made of cast-in-situ concrete. Almost all piles have a diameter of 410 mm. All beams have a width of 650 mm and a height ranging between 700 and 1600 mm. In addition to pile caps with varying dimensions, two-, three- and four-pile caps are repeated. The two- and three-pile caps are 650 mm wide, 2200 or 3500 mm long and 1380 or 1580 mm high. The four-pile cap has the dimensions 2200 x 2200 x 1000 mm^3. The connections between the foundation elements are cast-in-situ. The connection to the prefabricated column and wall elements is designed as a grouted rod in gain connection.

6.1.2 Circular foundation

Given the loads and soil conditions, a deep foundation is required. Therefore, the left of the flowchart (Figure 36) is relevant. The medical function of this site should remain for a long time. The design of the superstructure facilitates expandability and use by other functions. Foundation type 1, a versatile foundation, is most suitable. Because of the walls and columns, the foundation can be designed as a combination of subtypes 1.2 and 1.3. In addition to the versatile foundation, a changeable foundation, composed of modules, will be designed.

Versatile foundation
The floorplan of the building is adjusted to 44.0 x 67.2 m^2. In the blue zones, the centre-to-centre distances are equalized to 6.6 m in one direction and 5.1 in the other direction. In the red zone, the centre-to-centre distances in one direction are equalised to 5.1 m. In the other direction, the centre-to-centre distances remain 3.0, 6.0 and 5.4 m. Finally, the centre-to-centre distances in the green zone are equalized to 5.1 m in both directions. Consequently, the courtyard has a length of 32.4 m and a width of 10.2 m. The zones are indicated in Figure 48.

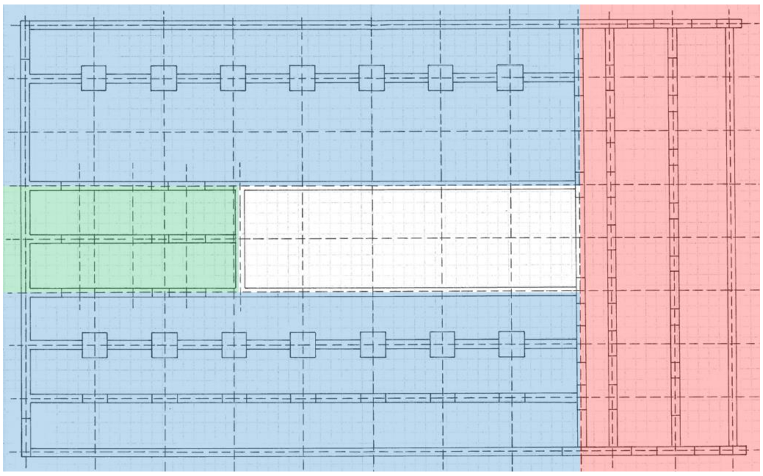


Figure 48. Floorplan indicating the blue, red and green zone

The dimensions of the two-, three- and four-pile caps remain almost the same. The following was changed:

- Rotating the cap at location F2b and B9
- Applying a three- instead of two-pile cap at axis 3c
- Applying a four- instead of three-pile cap at H7
- Adding a two-pile cap at J12 and three-pile caps at A1 and J9 and axis 11

Some other changes were also made. The dimensions of the four-pile caps at axes 9 and 10 were equalized. At axes D, E and F, three identical six-pile caps were applied. In the versatile foundation, only foundation piles with a diameter of 410 mm were applied. When the cap type changes, the number of piles will also change. The position of the piles underneath the beams changed from varying centre-to-centre distances to repeated centre-to-centre distances. Three beam types are distinguished, but one beam type is applied per axis.

Changeable foundation

The geometry and centre-to-centre distances of the changeable foundation are the same as defined for the versatile foundation. Instead of cast-in-site piles, prefabricated piles of 420 x 420 mm^2 were assumed. The variety of caps was further reduced to four types, taken from the modules defined in Table 11 and Table 12. All the two-pile caps were rotated. Subsequently, the position of the piles also changed. All three-, six- and rectangular four-pile caps of the versatile foundation were changed to squared four-pile caps. The piles underneath these caps are assumed to be squared 320 mm. In addition, the two-pile caps at B9, D9, H9, A12 and J12 were changed to four-pile caps because of the 90-degree angles between beams. The beam types result from the two chosen profiles, taken from of the modules listed in Table 13 and the centre-to-centre distances of the caps and piles.

6.2 Project 2

The clinical training centre of the Radboud University is composed of three buildings, indicated as U1, U2 and U3 in Figure 49. The clinical training centre is part of the faculty of medicines and houses several rooms for educational purposes. The medical library and study areas are located in building section U1. Building section U2 contains the main entrance and several education rooms. Building section U3 accommodates a lecture hall, with an approximate capacity of 300 people (Radboudumc, n.d.).

The -1 level of the buildings coincides with the courtyard, which adjoins each building part. The 0 level coincides with the surrounding ground level. Thus, the walls along the perimeter of the building plot have to resist ground pressure. Underneath U2 is a basement and corridor at the -2 level. The corridor connects several buildings of the Radboud University and Radboud University Medical Centre.

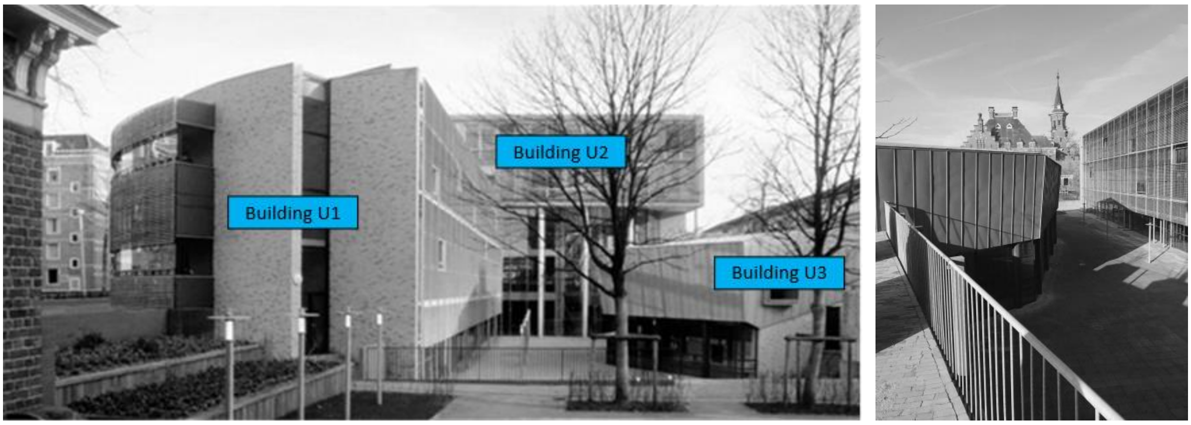


Figure 49. View of the clinical training centre (EGM Architecten, n.d.; Van Schaik, 2019)

Main loadbearing structure

In this case study, building section U3 is explained. Building sections U1 and U2 were not considered. Building section U3 is two levels high, with a length and width of approximately 45 m and 22 m, respectively. The tribune is made of steel profiles and composite floors with a thickness of 180 mm. Steel HEA120 columns and HEB140 beams support the tribune and transfer the loads to the foundation. The perimeter of the building is constructed of concrete walls with a thickness of 200, 250 or 300 mm and circular concrete columns with a diameter of 300 mm. The columns are situated at the lowered courtyard. The walls must retain the ground at the other side of the lecture hall and adjacent space. The roof is made of steel trusses or concrete with a thickness of 350 mm.

Loads

At ground level, concrete columns and walls transfer the loads to the foundation. The columns and walls result in point and line loads. The live load of 4.0 kN/m^2, including partition walls when applicable, was considered. The dead load depends on the chosen pressure and finishing layers, steel profiles and concrete elements. Consequence class 2 was chosen.

Geotechnical research

From the ground level, at 30.5 m above NAP, the following soil layers were identified:

A. To approximately 27.5 to 27.0 m above NAP: loose to moderate solid sand, locally clayey/salty
B. To at least 18.5 m below NAP: solid sand, locally thin layers of clay and peat

The ground water level is assumed to be approximately 8.0 m above NAP. The soil conditions indicate a shallow foundation seems appropriate. Depending on the foundation elements' thickness, the engineers assumed a level of construction around 26.0 m above NAP. Varying the dimensions of the foundation elements and the ground covering, the load bearing capacity of several strip and pad foundations were calculated. Load bearing capacities up to 600 kN/m and 2400 kN can be reached.

6.2.1 Traditional foundation

The building has a shallow foundation of strips and a pad, with a cast-in-situ floor in between. Strips of 1000 x 450 mm^2 support the steel structure of the tribune in the U3 building. The concrete columns at the courtyard are supported by a lowered strip of 1000 x 400 mm^2. The retaining walls are also supported by strips of 1000 x 450 mm^2. A single column is supported by a pad with a width and length of 2000 mm and a height 450 mm. A beam 490 mm wide and 390 mm high is positioned at the connection to the adjacent building section. The cast-in-situ floor has a thickness of 250 or 300 mm.

6.2.2 Circular foundation

In the flowchart in Figure 36, the right path has to be followed since the loads and soil conditions indicate that a shallow foundation is possible. From a circularity point of view, foundation type 4 seems the best choice. The building's function is likely to change in the future, requiring another floor plan and perhaps involving much higher loads. The current relatively low loads and angular floor plan lend themselves to a changeable foundation. The modules can be disassembled and removed when higher loads and a different floor plan are desired. In addition to the changeable foundation, which is most suitable, a versatile foundation was composed. Foundation type 3.2 seems the most logical choice. The walls and columns can be supported by the thickened floor strips. Applying these strips underneath the tribune provides flexibility in positioning the supporting structure.

Versatile foundation

The building floorplan changed due to the added centre-to-centre distances between the strips and pads and adapted angles. In the lecture hall, the centre-to-centre distances are 3.6 and 7.2 m. The positioning of the columns at axes D, E and F changed to centre-to-centre distances of 3.0, 3.6 and 4.2 m. The centre-to-centre distances in the adjacent space are 3.6 and 5.1 m. As a result, the column position slightly changed. All angles are multiples of 22.5 degrees.

All strips are 1200 mm wide and 450 mm high. The strip along the courtyard is lowered, and 900 x 150 mm^2 was added to the cross section. At the passage to the adjacent building section, a beam with a cross section of 450 x 450 mm^2 is situated. The pad is squared 2100 x 2100 mm^2 and kept 450 mm high.

Changeable foundation

The floorplan, with the adapted centre-to-centre distances and angles, remains the same. However, the foundation itself is made of several block, plate and beam modules. The floor is additionally supported at axes B, J and H.

The pads underneath the columns are squared 1200 x 1200 mm^2 and have a thickness of 150 mm. Underneath the walls, the plates have a rectangular shape of 1200 x 1800 mm^2. The blocks underneath the columns are 600 x 600 x 600 mm^3. The beams in between the columns and underneath the walls have a cross section of 600 x 600 mm^2. The lengths of the beams depend on the position. Recesses of 150 x 300 mm^2 in the blocks and beams provide space to support the floor elements. The blocks and beams along the courtyard have a height of 900 mm. At angles other than 90^0, special blocks and beams are needed. The retaining wall consists of modules with a foot of 1200 x 150 mm^2. The wall, with a console of 150 x 300 mm^2, is positioned on top of the foot.

6.3 Conclusion

In this chapter, the case study was described. For both projects, a versatile and changeable foundation was designed as an alternative to the traditional one. The goal of the caste study is to check whether the theoretical concept of circular foundations indeed leads to foundations that are more circular than traditional foundations. For the case study, two projects were chosen. The first is the Meander Medical Centre in Amersfoort, which has a deep foundation. The other project is the clinical training centre in Nijmegen, which has a shallow foundation.

Changes related to the material, connections, load bearing capacity and transportation were not expressed in the floorplans and assumptions were made for these design criteria. These assumptions are discussed in the following chapter. Changes related to dimensions were visually expressed in the floorplan and described in this chapter. Generally, standardisation and uniformity of element sizes and centre-to-centre distances in the system should enable better reusability in the future. For the versatile foundation of project 1, repeating centre-to-centre distances of 5.1 and 6.6 were applied. The diversity of caps and beams was reduced. The same changes are applied to the changeable foundation. However, the two-pile cap orientation was changed. Other than these two-pile caps, only squared four-pile caps were applied. The design for the versatile foundation of project 2 is similar to the design of the traditional foundation. The main difference is the repeated centre-to-centre distance of 3.6 m. All angles are multiples of 22.5 degrees. The changeable foundation follows the same structure but is built from demountable modules of plates, blocks and beams.

7. Performance

In this chapter, the performance of the traditional and circular foundations for the two projects described in the previous chapter is discussed. First, the circularity index was calculated using Alba Concepts' method and the alternative method. In the second section, structural issues are considered, specifically the design criteria and requirements.

7.1 Circularity index

The circularity index determination based on Alba Concepts' method is presented in subsection 7.1.1 and on the alternative method in subsection 7.1.2. This determination was performed for the traditional, versatile and changeable foundations for both projects. After the input explanation, the output is presented and discussed. An overview of both methods' input and output are included in Appendices 10 (page 116) and 11 (page 119), respectively. The masses, resulting from the six different foundations, are discussed in Appendix 12 on page 122.

The assessment methods focus on concept and do not require in-depth information. Therefore, concrete and reinforcement are not separately considered as this consideration would be too labour intensive, and it is difficult to determine the exact amount of reinforcement. This choice was not expected to significantly influence the result, because the parameters (material scenario and lifespans) of reinforcement would be quite similar to concrete. So, the elements are considered to be made of one material, indicated as reinforced concrete. Thus, the product level in Alba Concepts' method and the material level in the alternative method were not considered because they provide the same results as the element level.

7.1.1 Alba Concepts

Input

For the input, the material origin and future, technical and functional lifespan, and the connection type and accessibility have to be determined. Below, these three topics are explained for the traditional foundations.

1. Material origin and future: Assuming a traditional method of constructing, the origin of the material is 100% new, for both projects. For the medical centre in Amersfoort, 100% reuse is assumed. Because of the open floorplan and expandability, the building can be reused for a second functional lifespan. The material of the university building in Nijmegen is assumed 95% recycled. Of the total material, 5% will end in a landfill since waste will be produced during the recycling process. Despite the lecture hall's potential reuse as theatre, office or restaurant, demolition is most likely.
2. Technical and functional lifespan: The technical lifespan is assumed to be 100 years. After this period, the elements will be deteriorated and no longer fulfil the building standards. A functional lifespan of 50 years is assumed for the medical centre and university building. Hereafter, the functional requirements and wishes will be changed.
3. Connection type and accessibility: In general, the foundations of both projects are cast in situ, resulting in hard chemical connections accessible with additional operations, which cause significant damage. For the medical centre in Amersfoort, this this applies to the beam-to-cap and cap-to-pile connection. The same characteristics are apparent in the pile-to-soil connection since removing piles is difficult and involves special operations to limit negative consequences. The same characteristics also apply to the strips of the university building in Nijmegen. The pad-to-soil connection is assumed to be dry and accessible without additional operations.

The input for both versatile and changeable foundation is explained below.

1. Material origin and future: The elements were assumed to be produced in a responsible manner, using 30% recycled material, which is currently the usual percentage. This amount of recycled content is allowed without client permission or adjustments of the calculation rules (Mebin, 2017). The other 70% of content is new. The versatile foundations are totally reused, and therefore, the material future is assumed to be 100% reused. The changeable foundation is predominantly reused. For project 1, 10% of the pills were assumed not reusable and will be landfill. All caps can be reused, whereas 10% of the beams are non-modular elements, which will be recycled. For project 2, 10% of the plates and blocks and 20% of the beams were assumed to be non-modular elements and will be recycled.
2. Technical and functional lifespan: The functional lifespan of the foundations remains 50 years. By adequately designing and constructing the elements and system, the technical lifespan is assumed to be 150 years. In the traditional situation, materials are recycled after one functional lifespan, regardless of whether those materials are technically suitable to reuse. Often, reuse is not possible because elements and systems are not designed for this purpose. When designed well, the circular foundation could be used three times.
3. Connection type and accessibility: The versatile foundation connection characteristics are the same as in the traditional variant. For the changeable foundations, the characteristic of the pile and plate-to-soil connections remain the same. The grouted rod in gain connections of beam-to-cap and cap-to-pile are classified as soft chemical connections and accessible with additional operations, without causing damage. The beam, block and plates are interconnected with additional elements, which are accessible with additional operations, without causing damage.

Output

The assessment method provides three circularity indices, varying between zero (linear) and one (circular). Since the element consists of one product, reinforced concrete, the product and element circularity index are the same. Therefore, only the element and building circularity index are presented in Table 25 and Table 26. Because the changeable foundation of project 2 does not contain strips and pads, the circularity index at the element level is not given. Plates, blocks and beams cannot be compared one-to-one to stripes and pads. Figure 50 displays a bar graph with the building circularity indices.

	Traditional	Versatile		Changeable	
Piles	0.19	0.22	+0.03	0.22	+0.03
Caps	0.19	0.22	+0.03	0.45	+0.26
Beams	0.19	0.22	+0.03	0.45	+0.26
Total	0.19	0.22	+0.03	0.31	+0.12

Table 25. Circularity index and differences, element and building level, project 1

For project 1's output, the circularity indices of the traditional and versatile foundations are low and the same for all elements. The circularity index is significantly low as a result of the type and accessibility of the connections. The cast-in-situ connections and characteristics of the foundation piles are poorly classified. The results of the traditional and versatile foundations slightly differ due to their material scenarios and technical lifespan. Since the other parameters remain the same, the difference is small.

The changeable foundation obtained better results than the other foundation types. However, the level of circularity is still limited. The foundation piles remain a limiting factor. The characteristics of the grouted rod in gain connection, used to connect the caps and beams, increase the level of circularity. Despite this increase, the result remains low. Although the grouted rod in gain connection can be easily demounted, it is classified as a soft chemical connection, lowering the circularity index. The indicator should be adjusted, or another type of solid connection should be developed and applied. This finding is also true for the foundation piles. To increase the circularity index of the pile, the indicators have to be adjusted, or the piles should be more easily removable. This new method requires an adequate solution for seepage and loosening of the soil conditions.

	Traditional	Versatile		Changeable	
Strip	0.19	0.22	+0.03	n/a	n/a
Pad	0.76	0.90	+0.14	n/a	n/a
Total	0.20	0.23	+0.03	0.74	+0.54

Table 26. Circularity index and differences, element and building level, project 2

For project 2, the traditional and versatile foundations obtained a low circularity level. The majority of the foundation consists of strips, which have a low circularity index. The share of the pad, with a high circularity index, is limited. The mutual differences between the traditional and versatile foundation are minimal. This difference is due to the material scenarios and technical lifespan. When designing a changeable foundation of modules the index strongly increases. Due to the type of connection and the accessibility, the circularity index remains high and is not rapidly lowered, unlike the other foundations types.

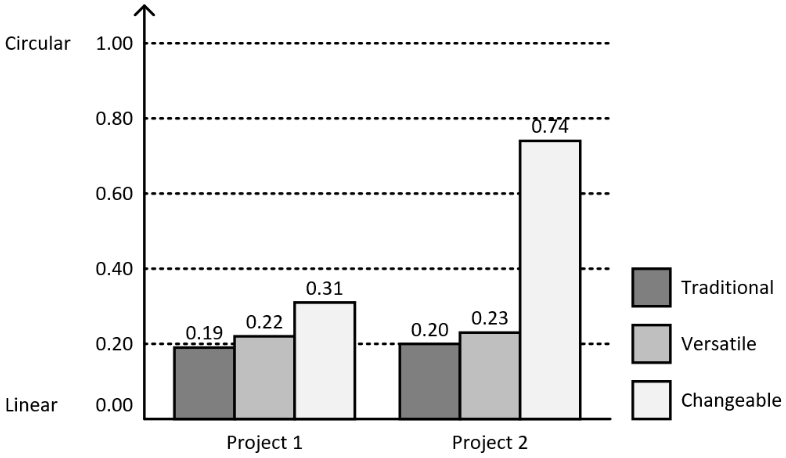


Figure 50. Building circularity index of foundation variants in case studies

7.1.2 Alternative method

Input
Although the material scenarios and lifespans are partly defined at another level, the alternative method input remains the same as the input of Alba Concepts' method. The main difference concerns the indicators. The material recyclability index is equal for each foundation. The connection between the concrete and reinforcement is considered a chemical connection. The materials can be separated with additional operations, resulting in limited damage and ensuring recycling. The element reusability index and system reusability index are not separately explained for each foundation. Details are provided in the appendix. Generally, the circular foundations score better on quality, dimensions, damage, expandability, diversity and grid.

Output
The new method provides material, element and building circularity indices. Like the Alba Concepts' indices, the alternative method's indices vary between zero (linear) and one (circular). Since the element is made of one material, reinforced concrete, the material circularity index was considered irrelevant. Therefore, Table 27 and Table 28 only display the element and building circularity index. Again, the circularity indices at the element level of the changeable foundation for project 2 are not provided. The bar graph, which illustrates the building circularity indices, is presented in Figure 51.

	Traditional	Versatile		Changeable	
Piles	0.57	0.72	+0.15	0.62	+0.05
Caps	0.47	0.60	+0.13	0.75	+0.28
Beams	0.34	0.60	+0.26	0.70	+0.36
Total	0.34	0.66	+0.32	0.66	+0.32

Table 27. Circularity index and differences, element and system level, project 1

Both circular foundations obtained a considerably better level of circularity compared to the traditional foundation. The versatile and changeable foundations' circularity indices are equal. For the versatile foundation, the circularity index of the caps and beams is slightly lower than the circularity index of the piles. This difference is caused by the rounding of dimensions. For the changeable foundation, the circularity of the piles is lower due to removability and the assumed landfill when reusing the foundation. In both circular variants, the increase in circularity is the highest for the beams because of the arbitrary rounding of dimensions in case of the traditional foundation.

	Traditional	Versatile		Changeable	
Strip	0.22	0.72	+0.50	n/a	n/a
Pad	0.22	0.72	+0.50	n/a	n/a
Total	0.22	0.72	+0.50	0.67	+0.45

Table 28. Circularity index and differences, element and system level, project 2

The level of circularity for the circular foundations are almost equal and both significantly higher than the circularity of the traditional foundation. As stated, this is the result of the adjusted indicators and the fact that the elements and system perform better at each indicator.

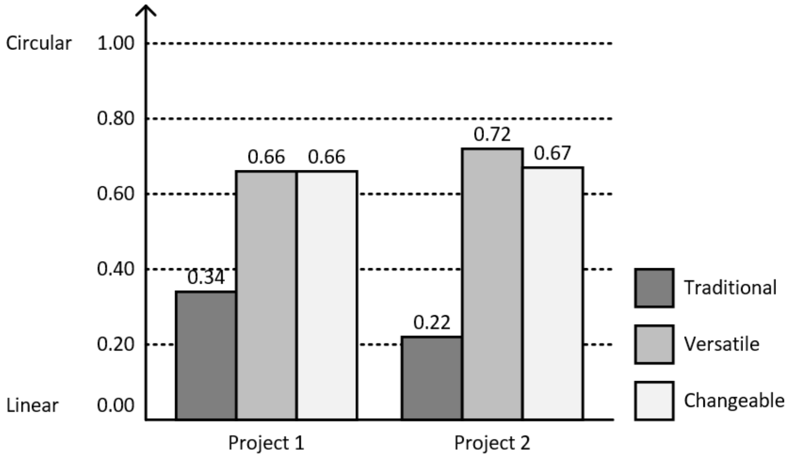


Figure 51. System circularity index of foundation variants in case studies

7.1.3 Comparison

The calculation for the alternative method is similar to the calculation used in the assessment method of Alba Concepts. As a starting point, the circularity at the material level was calculated using the formula as proposed by the Ellen MacArthur Foundation. Hereafter, the indices were calculated based on the indicators and masses. The number and kind of indicators differ from the indicators used in Alba Concepts' method. The results are presented in Figure 52.

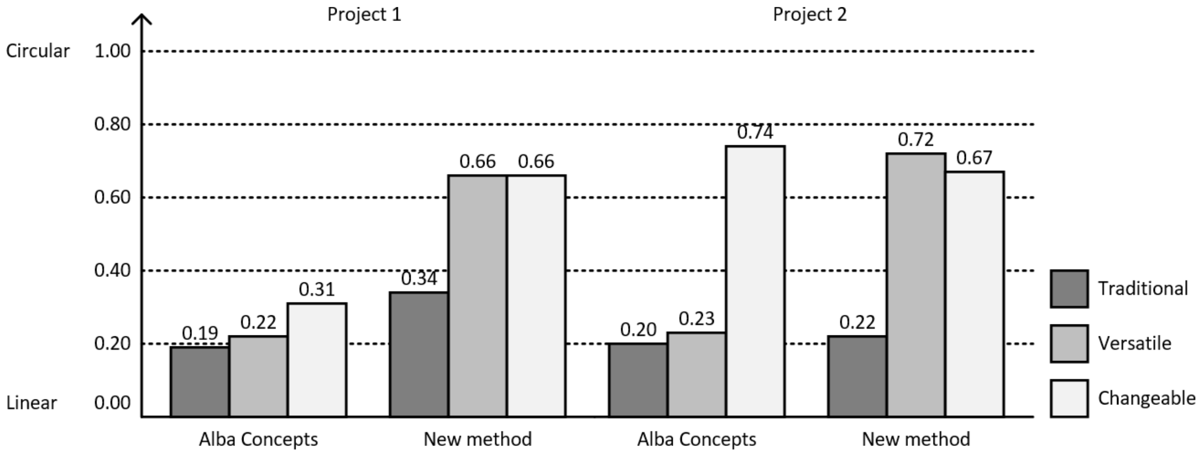


Figure 52. Comparison between the circularity indices of the assessment methods

For Alba Concepts' method, the traditional foundations obtained a comparable, low score of approximately 0.2. The alternative method provided slightly better results, but the score is still relatively low. Only project 1's traditional foundation scored significantly better, with a score of about 0.3. This score is a result of the repeated elements and centre-to-centre distances.

Like the traditional foundations, the versatile foundation obtained a low score of approximately 0.2, based on Alba Concepts' method because this method is based on changeability. Using this method, the connections are poorly assessed. The newly defined indicators of the alternative method resulted in a much better score for the versatile foundations of around 0.7. The type of connections is no longer considered for the versatile foundation, ensuring a higher level of circularity.

Based on Alba Concepts' method, the changeable foundations obtained a considerably better score than the traditional and versatile foundations. The changeable foundation of project 2 had a particularly high score of 0.7. Given a score of 0.4, project 1's changeable foundation did not completely succeeded in Alba Concepts' method because of the elements' connection type and elements' accessibility. This was corrected in the alternative method. Then, both foundations obtained a level of circularity of approximately 0.7.

Based on the alternative method, the circular foundations' circularity index is about 0.7. Figure 53 provides graphs presented in Figure 45. In the first graph, a circularity index of 0.7 indicates a foundation system that is 70% circular and 30% linear. The circularity index in the second graph, in which three circularity levels are distinguished, gives a truth value of 0.4 for reuse and of 0.6 for recycling. This indicates that the foundations are more suitable for recycling than for reuse, which is not the case.

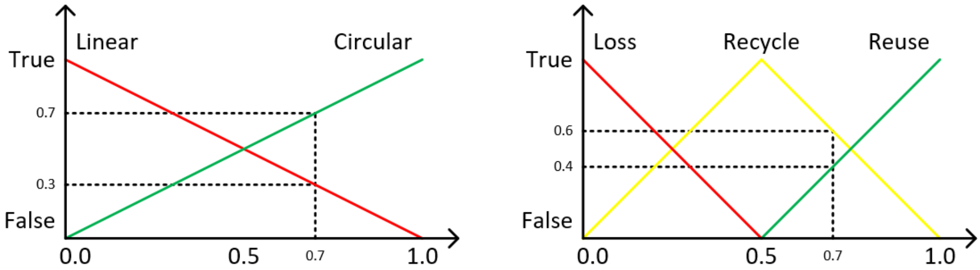


Figure 53. Different distribution of membership functions, with results from the case study

To align the level of circularity and the distribution of the membership functions, the domains of the fuzzy values were adjusted, as illustrated in Figure 54. Based on this graph, a circularity index of 0.7 indicates a foundation that is 67% reusable and 33% recyclable. However, whether this result sufficiently reflects the foundation is unclear. A large part of the foundation is arguably suitable for reuse and a small part will be lost. Therefore, this model might not be the best choice. Another model might be more suitable to make a distinction between loss, recycling and reuse, based on the final outcome. This option can be investigated in subsequent research.

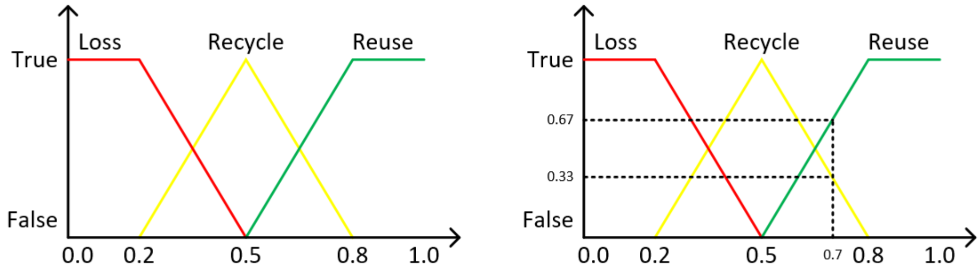


Figure 54. Alternative distribution of membership functions, with results from the case study

7.2 Structural considerations

In this section, the structural issues, divided into design criteria and requirements, are discussed. The design criteria are complemented with process-related topics: design process, (re)construction process and documentation. For each aspect, the similarities and differences between a traditional and circular foundation are reviewed. Furthermore, the challenges, preconditions and feasibility are considered.

7.2.1 Design criteria

In this subsection, the design criteria materials, dimensions, connections, load bearing capacity and transportation, as defined in Chapter 3, are considered. These topics are complemented with design and (re)construction process and documentation. The indented text discusses the experiences from the case study.

Materials

With the current state of knowledge, building materials other than the traditional ones (concrete, steel and wood) are unlikely to be used for foundations in the short-term. Therefore, circular foundations will also be made of concrete, steel or wood, despite the enormous amount of energy used to produce and protect these materials. However, the materials have been used for decades, so extensive research has been conducted on them, providing a plethora of theoretical knowledge and practical experience. In addition, further techniques can be developed to reduce the amount of energy required to produce these materials.

As stated, quality is important at the material level. For currently used materials, quality entails appropriate material classes and protection, resulting in higher material classes than the traditional design, as well as additional protection. Time will tell if this additional quality is enough to reuse elements or systems several times. Although adding quality is feasible, more sustainable techniques are desired.

> In the case studies, foundations were explained at the element and system levels. No in-depth consideration was made at the material level. For the traditional foundations, standard material classes and protection were assumed. For the circular foundations, one level better than the minimal required material class and protection was considered.

Dimensions

In traditional foundations, dimensions can be arbitrary, which creates a large variation in modules, grids and load bearing capacity. Element dimensions must be rounded to 50, 100 or 300 mm to create redundant elements and uniform load bearing capacities within a system. For changeable foundations, modules promote interchangeability and thus reuse. A grid must have regular centre-to-centre distances, which are a multiple of 0.3, to create commonly used dimensions of, for example, 3.6, 4.8 and 7.2 m. This approach improves the flexibility of a foundation's modules and system.

> For the case studies, the element dimensions were rounded to 50, 100 or 300 mm, thus reducing the variety of elements. Rounding also improved the elements', as well as the system's, load bearing capacity, by repeating the elements. If the grid did not have many repeated elements and centre-to-centre distances with a multiple of 0.3 m, it was possible to incorporate. The geometry and layout of the building slightly changed. This consideration, the extent to which a design can differ from the (traditional) building design, remains difficult. The author strived for repetition in elements and centre-to-centre distances and at the same time for few changes to the original building design. Therefore, considering some important design guidelines, the traditional building design methods can coincide with circular foundation designs.

Connections

Most foundations are made cast in situ, so wet connections are used. This type of connection can also be used in versatile foundations. For changeable foundations, other types of connections should be applied. To reuse the element, the connections should be easily demountable, without causing damage. Compared to the wet connections in cast-in-situ foundations, this type of connection can be less strong and stiff, which undermine the foundation's load bearing capacity and stability. Therefore, one should pay special attention to those connections. Within the system, standardized connections should be repeated as often as possible to ease interchangeability.

> Like the traditional foundation's connections, the versatile foundation's connections are cast in situ, so nothing changes. The connections in the changeable foundation differ. For the university building, connections with additional elements were assumed, which should be sufficient given the small dimensions and forces. Because the dimensions and forces are larger for the medical centre, grouted rod in gain connections are likely required. By drilling, this connection can be demounted without causing damage to the element itself. Further research should be performed to design wet connections, which are easier to disassemble. However, it is challenging to make dry connections that are as strong, stable and stiff as wet connections.

Load bearing capacity

Traditionally, each element and system has a load bearing capacity specifically adapted to the building loads. By focusing on the load bearing capacity, elements and systems can serve a range of loads. This focus improves the flexibility and thus reusability. Adequate load bearing capacity has been realised by choosing high-quality materials, rounding element dimensions and repeating elements in regular grid. For versatile foundations, the load bearing capacity requires additional attention. Depending on the future, additional load bearing capacity for the system might be desired. The elements of the changeable foundations service a specific load range. If the load radically changes, another module should be used.

> Adequate load bearing capacity has been created through appropriate decisions concerning the quality and dimensions. For the changeable foundations, modules were applied. The chosen module depends on the indicated estimated load. For the versatile foundation, extra attention was paid to the load bearing capacity. For project 1, the elements' dimensions were retained since relatively high floor loads were already considered. The elements' dimensions in project 2 were increased to create additional load bearing capacity, assuming this capacity was limited. In both cases, the elements were repeated in the system, and the grid was adjusted to a regular one.

Transportation

The traditional and versatile foundations are static, permanent foundations that are not moved or transported between functional lifespans. In contrast, the changeable foundation is demountable and dynamic. The dimensions and mass of the elements used in this type of foundation are restricted by the transport options. Although larger and heavier elements can be applied, limiting the dimensions and mass to a maximum that does not require additional measures seems ideal.

> Intermediate transportation of foundation elements is not relevant for the traditional and versatile foundation but does matter for the changeable foundation. For both projects, the elements are within the maximum transportable dimensions and mass. The shallow foundation elements in the university building are small and lightweight. The deep foundation elements in the medical centre are large and heavy due to the number of levels and floor loads. Because of the dimensions and mass of the individual elements, one or two elements at a time can be transported without additional measures. However, whether this situation is desirable from an environmental perspective is unclear.

Design process

The design process focused on quality, standardization and uniformity. These goals might be restrictions on the design process. However, although each building, and thus foundation, is unique, there are also many similarities. Thus, freedom in design may not be restricted. The case studies indicate, with some simple changes, the traditional foundation and building can preserve their original shape and layout. In addition to the reusability, choosing adequate material quality and element standardization, the safety can be increased. Applying uniformity in the foundation system reduces the number of calculations. Only the normative aspects must be checked. Reusing a versatile or changeable foundation might seem easy because existing systems and elements are used so fewer decisions need to be made. However, the designer is restricted to the existing systems and elements and must align the building to the foundation.

Implementing quality and standardization is simple; striving for uniformity within the system is more difficult. The designer must search for repetition, on the one hand, and a freedom in building geometry and layout, on the other hand. The geo-engineer, structural engineer and architect should find a balance. As stated, each foundation is unique and uniformity might be difficult to find, but if one is willing, one can find some repetition, even within a free geometry and layout.

Designing a new versatile foundation or changeable foundation is more difficult than designing a traditional foundation. One must account for various design criteria. Designing for successive functional and technical lifespans is difficult because the currently chosen material class, protection, dimensions and type of connections influence the long-term reusability. The decisions have to be widely supported in the building industry. The question of who establishes the overall principles, such as geo-engineers, the contractors, the government or market-leaders, remains. Geo-engineers and contractors have the knowledge to determine which principles are theoretically and practically feasible. However, with so many companies, a consensus may be difficult. Perhaps, then, this is a task for market leaders. Government guidelines or rules are also possible. However, the government may not have enough practical knowledge for the task. Widely supported principles are not easily defined. Theoretical principles have to be proven in practise. Iterations might be necessary to come to a final concept, but only when reusing the foundation one can determine whether the foundation is truly reusable.

> The case studies' design process was challenging because estimating the desired standardizes dimensions and connections was difficult. Achieving an accurate estimation at the element level was particularly complex due to the lack of experience and without in-depth calculations. At system level, the level of uniformity had to be considered. These considerations included to what extent the layout and geometry of the (traditional) building could be adapted to create more uniformity in the foundation. This step might be easier when the standards are established. Then, one can make a choice within the standards, and the main challenge is to align the building and foundation, searching for a balance between uniformity and variation.

(Re)construction process
The construction of a versatile foundation does not differ from a traditional foundation. Both are often constructed cast in situ. A changeable foundation consists of prefabricated elements to construct quality elements. These elements are connected on the building site. The foundation system must be constructed carefully to avoid damage to elements and limit undesirable loads or settlement. Whereas disassembly and rebuilding are not relevant for traditional and versatile foundation, these steps are important for changeable foundations. Connections, whether dry or wet, should be easily demountable. Demounting should be completed carefully to avoid damage. When reusing the element in another system, the connections should easily reconnect the elements.

Documentation
Traditionally, the drawings, calculations and reports are documented on paper, and now, mainly in company servers. Tracing the final documents to determine how the foundation was constructed is often arduous. In many cases, the characteristics (like material class, reinforcement, concrete cover, dimensions, load bearing capacity, construction level) of the executed foundation are unknown. In a circular economy, appropriate documentation is crucial. If the information cannot be traced, in many cases, the foundation is demolished. Thus, each foundation system and element, together with its characteristics, has to be documented. This data should be collected in a database that is freely accessible to involved companies, like geo-engineering firms, structural engineering firms and contractors. Furthermore, the temporarily unused elements and systems that are waiting for new users must remain in this database. In this way, designers can directly see what is available for reuse. Changes should be recorded in the database.

7.2.2 Requirements

This subsection considers the requirements listed in Chapter 3, concerning transferring of loads (strength), minimising settlements (stability and stiffness) and resisting environmental influences. Because the projects are conceptual considering each foundation separately is unnecessary.

Transferring loads: strength

For strength, thus transferring the loads, the connections, elements and system are considered. Overall, a circular foundation's elements' and systems' load bearing capacity will be higher than a traditional foundation's. As mentioned, this capacity is achieved through high-quality material, standardization and uniformity of elements in the foundation system. Assuming the versatile foundation is cast in situ and has solid, strong connections, the performance is comparable to the traditional foundation. A changeable foundation's connections have to be easily demountable, which is a weak spot. These connections might be sensitive to failure when constructed incorrectly. Thus, connections require attention to their design and construction. Additionally, the elements are prefabricated and more interrupted than the continuous elements in other foundation types. This influences the element's behaviour, like the deflection.

Minimising settlements: stability and stiffness

Dutch soil is sensitive to settlement because of the presence of compressible soil layers. Transferring loads is important, but limiting the settlements may be more important. If the foundation and building settle as a whole, the total structure can be tilted, or particular parts can settle more than others. This settlement can be the result of an instable foundation system, differences in stiffness or lack of stiffness. Due to the different modules, and thus the number and type of connections, a changeable foundation may be less stiff and stable than the traditional and versatile foundation. For a changeable foundation, special attention should be paid to this phenomenon.

Resisting environmental influences

Using steel seems desirable because it results in more light-weight structures and connections, which can be more easily disassembled than concrete. However, steel is prone to corrosion even when galvanised. Additionally, during the use time, the elements and connections are not accessible for inspection. This factor is the same for wood, which also seems an ideal choice since it is renewable and therefore circular. However, wood is prone to rotting, despite timber protection measures. Intermediate checking of the wood is rarely possible. Therefore, concrete remains the most suitable material for foundations. With concrete, one can create solid foundation systems that are strong, stable and stiff, resistant to the environmental influences. Application of concrete is not a problem for a versatile foundation and its connections. For a changeable foundation's connections, other materials are preferred for easier disassembly. If other materials are applied, strong protection and a limited number of prone materials must be implemented.

7.3 Conclusion

A total of six foundations (two traditional and four circular) were assessed using the method of Alba Concepts and the alternative method. The Alba Concepts' method is based on disassembly, resulting in a low level of circularity for traditional and versatile foundations. A result around 0.2 was obtained. The changeable foundations obtained a better result, especially those of project 2, which scored about a 0.7. With a score of approximately 0.3, the changeable foundation of project 1 is not very circular. This results from the proposed type of connection and the presence of foundation piles.

Based on the alternative method, the traditional foundations scored similarly. Whereas project 2's foundation scored approximately 0.2, project 1's scored a bit better, approximately 0.3, as a result of the repeated modules and centre-to-centre distances. All circular foundations had a relative high level of circularity, around 0.7. In this case, the versatile foundations performed well because the type of connection and damage when disassembled were not considered. In addition, project 1's changeable foundation obtained a high score because the type of connection was not taken into account. Only the amount of damage when disassembled was relevant. According to the alternative method's results, the versatile and changeable foundations are 70% circular and 30% linear.

Finally, the structural similarities, differences, challenges, preconditions and feasibility were discussed based on the design criteria and requirements. From a structural point of view, a versatile foundation is similar to a traditional foundation. However, the changeable foundation significantly differs from the traditional one. For example, who determines the standards for dimensions and connections is not clear. Regarding disassembly, special attention should be given to the strength, stiffness and stability of the elements and system. Now, positioning of the foundation piles is not seen as linear, but this view can be called into question. Further investigation must improve the reusability of foundation piles.

Through achievable changes, traditional foundation can be made more circular. One should find a balance between uniformity and freedom of form. Although weighing design freedom against uniformity for future reusability can be complex, even with total freedom of form, uniformity can be applied. Circular foundations require strong documentation of their characteristics and availability. This concept should be further developed. When broad support among the building industry is gained, practice will reveal whether foundations are indeed more circular.

8. Conclusion

The purpose of the research was to investigate how building foundations can be made circular. Traditional foundations formed the basis of the investigation. To answer the main research question, the author examined how circularity is defined, designed and assessed. Additionally, existing circular foundation principles and experiences from the first circular building projects have been searched. Based on the gathered knowledge, a theoretical framework for circular foundations was described. This framework includes the definition of the circular foundations and the associated design guidelines. Additionally, an alternative assessment method was developed. This method is a variant of Alba Concepts' framework and should enable better assessment.

In a case study, the defined foundation types, design guidelines and assessment methods were applied to two projects. For both projects, a versatile and changeable foundation was designed. Based on the Alba Concepts' assessment method, the traditional and versatile foundations obtain a level of circularity of around 0.2 on a scale of zero (linear) to one (circular). The versatile foundations scored slightly better than the traditional ones. Alba Concepts' method focuses on disassembly, which results in a higher score for the changeable foundations. Projects 1 and 2 scored 0.3 and 0.7, respectively. The alternative assessment method also acknowledges versatility as a form of flexibility. Although the result of the traditional foundations remained low, all circular foundations scored a circularity level of approximately 0.7.

The case study indicates that the projects' traditional foundations were assessed as more circular when they had been changed based on the defined foundation types and design guidelines. Thus, to facilitate a circular economy, foundations can be made reusable. Reuse can be achieved by flexibility. For foundations, flexibility can be obtained by versatility and changeability. Flexibility by expandability must be incorporated in both other forms of flexibility. Distinguishing deep and shallow foundations results in four types of circular foundations. The desired type of foundation can be determined based on the soil conditions, loads, future scenario and level of flexibility. After choosing the right type, the foundation can be designed, paying attention to materials, dimensions, connections, load bearing capacity, transportation and documentation. One should strive for longevity, standardization and uniformity at the material, element and systems levels, respectively.

The new approach demonstrates that, with number of changes, traditional foundations can be considerably more circular. From a structural viewpoint, versatile foundations do not significantly differ from traditional foundations. Thus, attention should be paid to the changeable foundation. For example, the standardised element dimensions and connections must be determined. Despite the disassembly, the structural integrity has to be retained. Moreover, reusability of foundation piles, which are part of changeable foundations, is a challenge. Finding a balance between uniformity, for better reusability, and freedom of form, to meet current needs applies to all circular foundations. Furthermore, documentation of characteristics and availability of foundation elements and systems is essential. Designing circular foundations requires willingness and a change in thinking by all stakeholders. An important role and cooperation is reserved for (geo-)engineers, architects and contractors. The concept needs to be further elaborated, and the feasibility has to be further explored. When the main part of the building industry supports the concept and the application is feasible, practise will reveal whether this concept of circular building foundation is a success. Until then, designers can translate buildings to a more sustainable world by looking for long and consecutive use of foundations. Although this practice requires willingness and creative thinking, it will produce benefits.

8.1 Discussion

The definition of a circular foundation, and the corresponding assessment method and guidelines, is based on the author's knowledge and interpretation, as well as a select amount of information gained from practical experiences. The verification was limited to two case studies. As the number of available definitions, assessment methods and guidelines of circularity indicate this topic is open for discussion, and thus different opinions. Although the information in this research was carefully composed and formulated, further verification of this approach is desired.

To determine the level of circularity, the Alba Concepts' assessment method was used. This method is prominently based on changeability, as a form of flexibility for circularity. The changeable foundation, with easily accessible and demountable connections, indeed results in a high level of circularity. When using grouted connections instead of bolted connections, which is desirable for foundations, the result rapidly decreases. Also when applying foundation piles, which are difficult to remove, the result decreases. In addition to changeability, this research also indicates versatility as a promising form of flexibility. As expected, versatile foundations result in a low level of circularity, comparable to traditional foundations. The Alba Concepts' method seems most suitable for products that are part of the superstructure. However, due to the different requirements and forms of flexibility, the method is not (fully) suitable for foundations. As a first step, an alternative, but similar, assessment method was proposed. The method was not extensively detailed because developing a completely new method was not the aim of the research. Therefore, the results of this assessment method should not be interpreted strictly. The mathematical format of the method and chosen indicators, as well as the way these indicators can be measured, need to be reviewed. For example, quantities and unities to determine the fuzzy value for each indicator are missing. These factors were determined on intuition and variant comparisons. Regardless, the alternative method fit better with the concept of circular foundations, and the changeable as well as versatile foundations obtain high levels of circularity.

8.2 Recommendations

Based on the conclusion and discussion, recommendations were formulated. The first recommendations focus on further research. In the second subsection, recommendations are given for practical implementation. In the last subsection, a recommendation is provided for who want to design circular foundations in the short-term.

8.2.1 Research

Detailed structural research
This research was conducted on a conceptual level. For a better understanding, an in-depth investigation into the structural design, (re)construction and behaviour of elements and system is required. Further research is needed to investigate the influence of adjustments on strength, stiffness and stability of the foundation elements and system. Developing new principles may be needed to retain the desired level of integrity, especially for changeable foundations. Additionally, the possibilities for better reusability of foundation piles can be explored in further research. Currently, removing foundation piles is difficult and involves loosening of soil conditions and risk of seepage. Since the versatile foundation is similar to the traditional, these recommendations are of limited importance to these types of foundations.

Further investigation into feasibility
This research has not considered financial and business models, and associated ownership or responsibilities. In further research, the feasibility of circular foundations, focusing on the financials and business models, can be investigated. This research can be performed for all lifecycle stages, like design, construction, use, maintenance and reuse or recycling. Furthermore, the research can determine which business models are desired, whether circular foundations are financially attractive, and how this can be achieved.

This research focused on the reuse of elements and systems at the end of a lifecycle to reduce the required amount of material and energy. The environmental influence and share of the other lifecycle stages, like the design and construction process, usage, maintenance and transportation, was not considered. Changing from a traditional to circular approach might cause challenges.

Reusable foundations initially require an additional investment of money, material and energy. However, determining whether the additional investment is justified is complex because predicting whether the added flexibility will be used in the future is difficult. New developments might make the investment in flexibility superfluous, which would mean that unnecessary amounts of material and energy have been used. Currently reused foundations could be more easily reused when they are designed according to the approach presented in this report. If this is not the case, retaining the traditional approach, combined with accurate documentation, may be most appropriate. Then, reuse can be facilitated by hidden load bearing capacity, efficient use of load redistribution in the superstructure and targeted adjustment to the foundation. This strategy might require less material and energy than the suggested circular approach. Additionally, designers would have more freedom of form. Predicting the actual use of flexibility in the future and comparing the circular approach to a more traditional one are of great interest.

If this approach for reuse of foundations is not more circular than the traditional approach, an alternative approach might be proposed. For example, designers might focus on recycling instead of reuse. Then, the recycling process should be optimised, avoiding toxicity, exhaustion of finite recourses and emission of pollutants. This optimisation would enable more design freedom because ‘restrictions’, as defined in the design guidelines, lapse.

8.2.2 Practise

Setting up a documentation system
Within the building industry, a documentation system should be established to facilitate the reuse of foundations. This database should contain all relevant information on the foundation elements and system, like the dimensions, materials, load bearing capacity, type of connection and construction and disassembly methods. Interim adjustments and findings must be recorded. In the database, all stored, and thus directly available, systems and elements should be listed and accessible for potential new users and stakeholders, like geo-engineers, structural engineers, contractors and architects. The requirements for such a documentation system should be investigated.

Generally supported approach
A concept widely supported by all stakeholders needs to be developed. The definitions, design guidelines and assessment method in this research can be further improved, elaborated and verified. In consultation with stakeholders, a promising concept, based on everyone’s knowledge and experiences, can be formalised. Using a theoretically verified and widely supported concept improves feasibility and avoids failure. This point is specifically important for changeable foundations. Using one concept in the building industry benefits interchangeability and thus reusability. However, the chosen approach for circular foundations ultimately needs to be verified in practice. Likewise, the structural implementation and documentation system need practical verification. Practise should reveal whether the concept satisfies the requirements. For foundations, this clarification will take time and patience.

8.2.3 Starting tomorrow

Despite the need for further research and the practical challenges, putting circular foundations into practise is now feasible. First, one must determine the desired foundation using the four defined foundations types, based on the loads, soil conditions, expected future scenario and the desired level of flexibility. The preferred foundation type also depends on the building type. For this, the flowchart in Figure 36 can be used.

Once the right foundation type is chosen, the foundation can be designed. The designer should focus on reusability and then pay attention to recyclability. Creating reusable elements and systems is both important and challenging. With current techniques, recycling traditional building materials is already possible. When designing the materials, dimensions, load bearing capacity, connections and transportation must be considered. Decisions are based on the chosen type of flexibility. The load bearing capacity is important to versatile foundations, whereas connections and transportation are important design criteria for changeable foundations. Furthermore, disassembly should occur without compromising structural integrity.

More generally, one should strive for longevity, standardisation and uniformity at the material, element and system levels. This goal means choosing the right material classes and protection for longevity, specifying a limited number of standardized modules and connections and applying them repeatedly in a system with regular centre-to-centre distances. No standards have currently been set by the building industry. Therefore, designers must try to make logical choices. One can determine the degree of uniformity by the desired freedom of form, finding a balance between the two: freedom of form should fulfil the current building needs and uniformity should improve long-term reusability.

Using current techniques, foundations can be made (more) circular, independent of the flexibility type. However, reusability of concrete foundation piles in a changeable foundation is limited. These piles are hard to remove and cause an undesirable loosening of soil conditions and risk of seepage. If the loads allow, steel piles, like sheet profiles, sheet piles and helical piles, or timber piles are preferred. Steel piles are easier to remove without causing undesirable side effects, and timber piles are desired because of wood's renewability.

After designing, foundations must be constructed precisely and carefully to avoid structural side effects and damage. The characteristics of foundations should be properly documented. Reports, calculations, drawings and models needs to be digitally saved in databases. For changeable foundations, not only the characteristics, but also the methods of construction and disassembly are important. Over time, changes and findings must be recorded. To facilitate reuse, the availability of elements and systems, together with their main characteristics, should be accessible to potential new users. Currently, no national documentation directive on foundations exists. Thus, this documentation must currently be completed in-house, and companies and investors should remain in contact.

In general, to design for circularity, all stakeholders have to be involved and support the main goal. This requires willingness and innovative thinking. However, carefully considering cycles of foundations, whether reuse or recycling, can create a more sustainable world.

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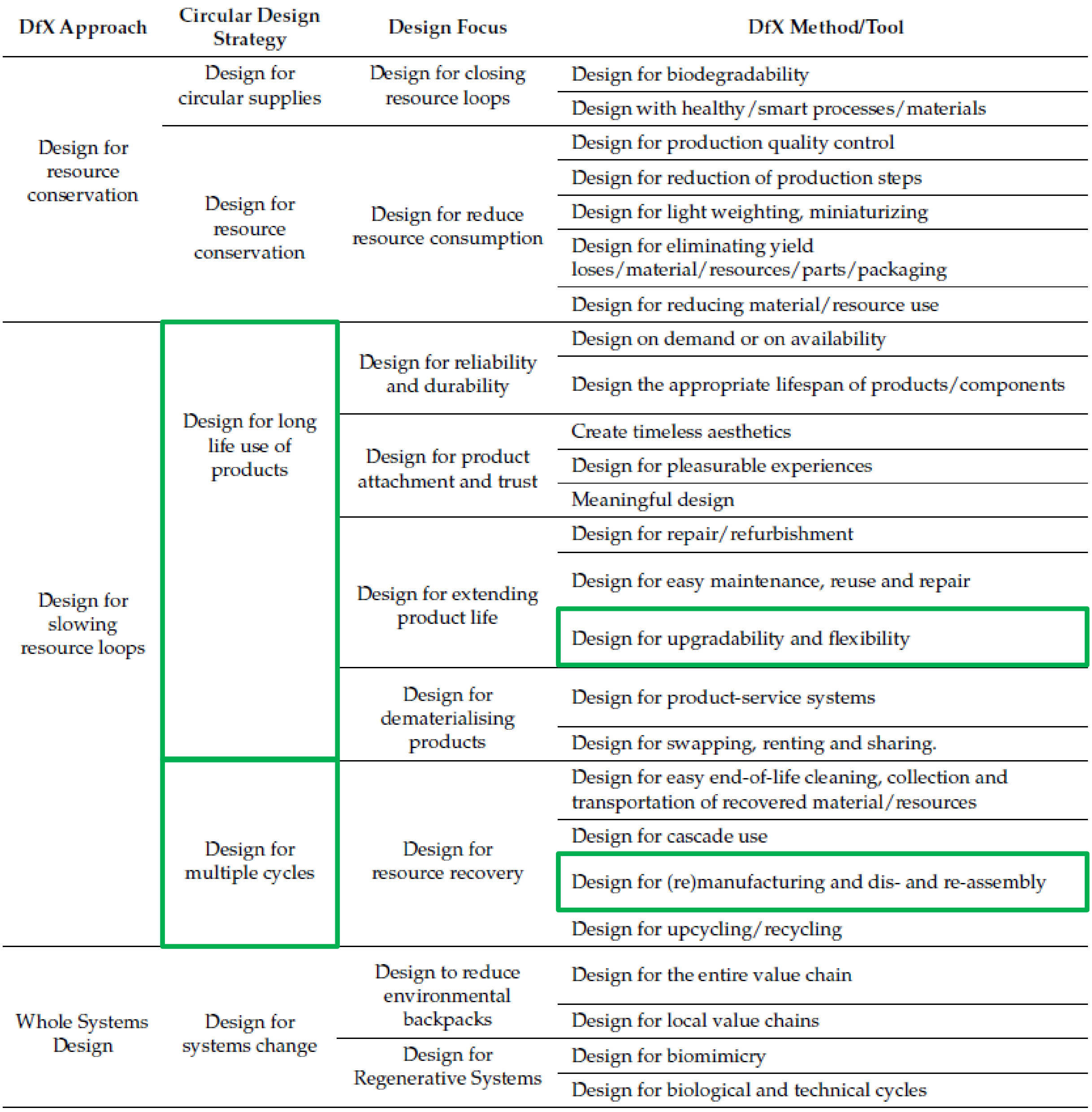
Appendix 1: Taxonomy of DfX approaches

In Table 29 the taxonomy of DfX approaches, elaborated by Moreno et al. (2016), is presented.



DfX Approach	Circular Design Strategy	Design Focus	DfX Method/Tool
Design for resource conservation	Design for circular supplies	Design for closing resource loops	Design for biodegradability
			Design with healthy /smart processes/materials
	Design for resource conservation	Design for reduce resource consumption	Design for production quality control
			Design for reduction of production steps
			Design for light weighting, miniaturizing
			Design for eliminating yield loses/material/resources/parts/packaging
			Design for reducing material/resource use
Design for slowing resource loops	Design for long life use of products	Design for reliability and durability	Design on demand or on availability
			Design the appropriate lifespan of products/components
		Design for product attachment and trust	Create timeless aesthetics
			Design for pleasurable experiences
			Meaningful design
		Design for extending product life	Design for repair/refurbishment
			Design for easy maintenance, reuse and repair
			Design for upgradability and flexibility
		Design for dematerialising products	Design for product-service systems
			Design for swapping, renting and sharing.
	Design for multiple cycles	Design for resource recovery	Design for easy end-of-life cleaning, collection and transportation of recovered material/resources
			Design for cascade use
			Design for (re)manufacturing and dis- and re-assembly
			Design for upcycling/recycling
Whole Systems Design	Design for systems change	Design to reduce environmental backpacks	Design for the entire value chain
			Design for local value chains
		Design for Regenerative Systems	Design for biomimicry
			Design for biological and technical cycles

Table 29. Taxonomy of DfX approaches (Moreno et al., 2016, p. 7)

Appendix 2: DfD design guidelines

Table 30 shows the DfD design guideline, based on three lifecycle scenarios, taking into account the use life-cycle (ULC), technical life-cycle (TLC) and three levels, as defined by Durmisavic (2006).

	Scenario 1 ULC < TLC			Scenario 2 ULC > TLC			Scenario 3 ULC = TLC		
	Building level	System level	Material level	Building level	System level	Material level	Building level	System level	Material level
Define use strategy for the building	X			X			X		
Define functional decomposition of the building through the specification of fixed and changeable parts of the building	X								
Develop life cycle coordination matrix in order to define the point of disassembly	X	X		X	X				
Design complex structures which can change functionality in the course of time	X	X							
Design base element as an intermedier between systems, components and elements	X	X	X		X	X			
Design base element of each system and components	X	X			X				
Optimize the structural grid to materials in order to the most efficient use of material properties and therefore use less material	X	X		X	X		X	X	
Provide sufficient information about the building/ systems configurations their reconfiguration possibilities and their capacity for reconfiguration, reuse and recycling	X	X	X	X	X	X	X	X	X
Provide separation between major building functions such as load-bearing structure, façade, installations, partitioning elements and finishing	X			X					
Define material levels following the functional decomposition		X							
Cluster materials into subassemblies according to their functionality, use life cycle, material, technical life cycle		X							
Cluster materials into subassemblies according to material, technical life cycle					X			X	
Create separation between the element with different functional and life cycle expectances by using separate construction systems		X			X				
Define an open hierarchical structure by avoiding functional and assembly relations between different functional groups		X			X				
Design an open building system whose elements are independent and exchangeable		X			X				
Use modular dimensional systems that are compatible with other systems		X			X				
Base element/intermediary should be the most durable elements within the clusters		X	X		X	X			

Use pre-assembled assemblies for the reason of faster and easier construction on the building site. In this way building, systems or components will be disassembled in two phases on the building site and in the workshop. This results into greater control of the material flow.	X		X		X	
Define the building through the building sections that could be independently produced and assembled	X	X	X	X	X	X
Define building systems suitable for repetitive manufacturing processes while retaining variation and irregularity	X			X		
The connection between two independent clusters, should be suitable for their easy decomposition and reuse	X	X	X	X		
Use light weight components which are easy to handle and transport	X			X	X	
Use small size components which are part of larger assembly in order to increase the possibility of variations	X					
Design connections between changeable components to withstand multiple disassembly and reuse of well-engineered base elements and intermediary between changeable components	X	X				
Use minimum number of different types of fasteners connection geometries	X	X	X	X	X	X
Provide tolerances to allow disassembly of individual parts	X	X	X	X	X	X
Parallel assembly should replace sequential assembly in order to allow disassembly of single part without disruption to other parts and for faster disassembly		X		X		X
Keep all components separated avoiding penetration into other component or system		X		X		
Provide accessibility to the component s with shorter life cycle		X		X		
Mechanical connections should replace chemical connections		X		X		X
Provide intermediary between base elements which belong the different clusters		X		X		X
The clusters should be assembled in systematically order that is suitable for maintenance and replace ability		X		X		
Assembly sequences should be designed with respect to type of material, its performance and life cycle		X		X		
The connections within the cluster should be suitable for recovery or recycling of single part		X		X		X
Provide material information		X		X		X
Assembly sequences should be designed with respect to type of material						X
Avoid using composite materials unless they can be recycled without creating negative impact on the environment		X		X		X

Table 30. DfD-guideline for the different lifecycle scenarios (Durmisevic, 2006, pp. 272-274)

Table 31 to Table 33 show the seven disassembly factors, divided in the functional, technical and physical domain, as defined by Durmisevic et al. (2006).

Systematisation	Structure and material levels	Components	1.0
		Elements/components	0.8
		Elements	0.6
		Material/element/component	0.4
		Material/element	0.2
		Material	0.1
	Clustering	Clustering according to the functionality	1.0
		Clustering according to the material life cycle	0.6
		Clustering for fast assembly	0.3
		No clustering	0.1

Functional decomposition	Functional separation	Separation of functions	1.0
		Integration of functions with same life cycle	0.6
		Integration of functions with different life cycle	0.1
	Functional dependence	Modular zoning	1.0
		Planed interpenetrating for different solutions	0.8
		Planed interpenetrating for one solution	0.4
		Unplanned interpenetrating	0.2
		Total dependence	0.1

Table 31. Fuzzy variables, functional domain (Durmisevic et al., 2006, pp. 5-6)

Life cycle coordination	Use*	Long – Long *or* Short – Short	1.0
		Long – Short	0.8
		Medium – Long	0.5
		Short – Medium	0.3
		Short – Long	0.1
	Technic*	Long – Long *or* Short – Short *or* Long – Short	1.0
		Medium – Long	0.5
		Short – Medium	0.3
		Short – Long	0.1
	Size*	Big/small element – Long life cycle	1.0
		Small element – Short life cycle	1.0
		Big component – Short life cycle	0.4
		Big component – Long life cycle	1.0
		Material – Long life cycle	0.2
		Big element – Short life cycle	0.1
		Material – Short life cycle	0.1

Relational pattern	Position and type of relations	Vertical	1.0
		Horizontal in lower zone	0.6
		Horizontal between upper and lower zone	0.4
		Horizontal in upper	0.1
	Base element specification	Base element intermediary between systems	1.0
		Base element on two levels	0.6
		Element with two functions	0.4
		No base element	0.1

Table 32. Fuzzy variables, technical domain (Durmisevic et al., 2006, pp. 5-6)

Assembly	Assembly direction	Parallel	1.0
		Stuck assembly	0.6
		Base element in stuck assembly	0.4
		Sequential sequence base element	0.1
	Assembly sequence*	Component – Component	1.0
		Component – Element	0.8
		Element – Component	0.6
		Element – Element	0.5
		Material – Component	0.3
		Component – Material	0.2
		Material – Material	0.1
Geometry	Product edge	Open linear	1.0
		Symmetrical overlapping	0.8
		Overlapping on one side	0.7
		Unsymmetrical overlapping	0.4
		Insert on one side	0.2
		Insert on two sides	0.1
	Standardization	Pre-made geometry	1.0
		Half standardised geometry	0.5
		Geometry made on the construction side	0.1
Connections	Type	Accessory external connection or system	1.0
		Direct connection with additional fixing devices	0.8
		Direct integral connection with inserts	0.6
		Direct integral connection	0.5
		Accessory internal connection	0.4
		Filled soft chemical connection	0.2
		Filled hard chemical connection	0.1
		Direct chemical connection	0.1
	Accessibility to fixings and intermediary	Accessible	1.0
		Accessible, additional operation, no damage	0.8
		Accessible, additional operation, reparable damage	0.6
		Accessible, additional operation, damage	0.4
		Not accessible, total damage of bought elements	0.1
	Tolerance	High tolerance	1.0
		Minimum tolerance	0.5
		No tolerance	0.1
	Morphology of joint	Knot (3D connections)	1.0
		Point	0.8
		Linear (1D connections)	0.6
		Service (2D connections)	0.1

Table 33. Fuzzy variables, physical domain (Durmisevic et al., 2006, pp. 5-6)

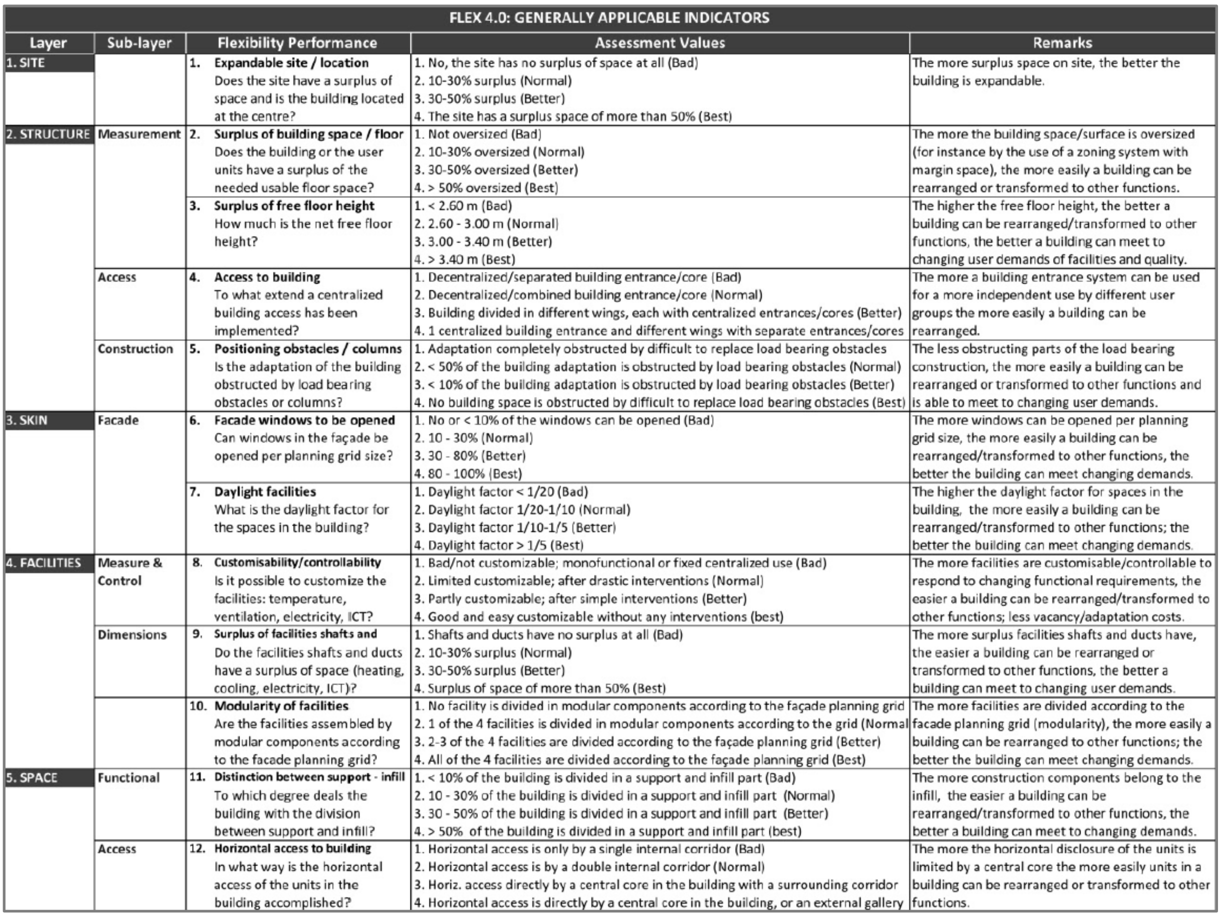
* The first term refers to the part that is assembled first and the second term refers to the part that is assembled second.

Below, the DfD factors, subdivided in five groups, are listed, cited from the paper of Akinade et al. (2017).

1. Stringent legislation and policy
    - Award of more points for building deconstructability in sustainability appraisal
    - Government legislation to set target for material recovery and reuse
    - Project contractual clauses that will favour building material recovery and reuse
    - Legislation to make deconstruction plan compulsory at the planning permission stage
2. Deconstruction design process and competencies
    - Improved education of professionals on design for building deconstruction
    - Effective communication of disassembly needs to other project participants
    - Effective pre-design disassembly review meetings
    - Design conformance to codes and standards for deconstruction
    - Early involvement of demolition and deconstruction professionals during design stage
    - Production of a site waste management plan
    - The use of BIM to estimate end-of-life property of materials
    - Preparation of a deconstruction plan
    - The use of BIM to simulate the process and sequence of building disassembly
    - Production of COBie [Construction Operations Building Information Exchange] to retain information of the building components
3. Design for material recovery
    - Use bolted joints instead of chemical joints such as gluing and nail joints
    - Avoid composite materials during design specification
    - Design foundations to be retractable from ground
    - Specify building materials and components with long life span
    - Specify lightweight materials and components
    - Use joints and connectors that can withstand repeated use
    - Minimise the number of components and connectors
    - Minimise the types of components and connectors
4. Design for material reuse
    - Knowledge of end-of-life performances of building materials
    - Avoid toxic and hazardous materials during design specification
    - Making inseparable products from the same material
    - Avoid specifying materials with secondary finishes
    - Specify materials that can be reused or recycled
    - Design for steel construction
5. Design for building flexibility
    - Use open building system for flexible space management
    - Using of interchangeable building components
    - Design for modular construction
    - Design for preassembled components
    - Design for the repetition of similar building components
    - Ensure dimensional coordination of building components
    - Separate building structure from the cladding
    - Standardising building form and layout
    - Use standard structural grid
    - Structure building components according to their lifespan (Akinade et al., 2017, p. 9)

Appendix 3: DfAD assessment method

The general applicable indicators to determine the adaptive capacity of buildings, as defined in the DfAD assessment method of Geraedts (2016), are given in Table 34.



FLEX 4.0: GENERALLY APPLICABLE INDICATORS

Layer	Sub-layer	Flexibility Performance	Assessment Values	Remarks
1. SITE		1. **Expandable site / location** Does the site have a surplus of space and is the building located at the centre?	1. No, the site has no surplus of space at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. The site has a surplus space of more than 50% (Best)	The more surplus space on site, the better the building is expandable.
2. STRUCTURE	Measurement	2. **Surplus of building space / floor** Does the building or the user units have a surplus of the needed usable floor space?	1. Not oversized (Bad) 2. 10-30% oversized (Normal) 3. 30-50% oversized (Better) 4. > 50% oversized (Best)	The more the building space/surface is oversized (for instance by the use of a zoning system with margin space), the more easily a building can be rearranged or transformed to other functions.
		3. **Surplus of free floor height** How much is the net free floor height?	1. < 2.60 m (Bad) 2. 2.60 - 3.00 m (Normal) 3. 3.00 - 3.40 m (Better) 4. > 3.40 m (Best)	The higher the free floor height, the better a building can be rearranged/transformed to other functions, the better a building can meet to changing user demands of facilities and quality.
	Access	4. **Access to building** To what extend a centralized building access has been implemented?	1. Decentralized/separated building entrance/core (Bad) 2. Decentralized/combined building entrance/core (Normal) 3. Building divided in different wings, each with centralized entrances/cores (Better) 4. 1 centralized building entrance and different wings with separate entrances/cores	The more a building entrance system can be used for a more independent use by different user groups the more easily a building can be rearranged.
	Construction	5. **Positioning obstacles / columns** Is the adaptation of the building obstructed by load bearing obstacles or columns?	1. Adaptation completely obstructed by difficult to replace load bearing obstacles 2. < 50% of the building adaptation is obstructed by load bearing obstacles (Normal) 3. < 10% of the building adaptation is obstructed by load bearing obstacles (Better) 4. No building space is obstructed by difficult to replace load bearing obstacles (Best)	The less obstructing parts of the load bearing construction, the more easily a building can be rearranged or transformed to other functions and is able to meet to changing user demands.
3. SKIN	Facade	6. **Facade windows to be opened** Can windows in the façade be opened per planning grid size?	1. No or < 10% of the windows can be opened (Bad) 2. 10 - 30% (Normal) 3. 30 - 80% (Better) 4. 80 - 100% (Best)	The more windows can be opened per planning grid size, the more easily a building can be rearranged/transformed to other functions, the better the building can meet changing demands.
		7. **Daylight facilities** What is the daylight factor for the spaces in the building?	1. Daylight factor < 1/20 (Bad) 2. Daylight factor 1/20-1/10 (Normal) 3. Daylight factor 1/10-1/5 (Better) 4. Daylight factor > 1/5 (Best)	The higher the daylight factor for spaces in the building, the more easily a building can be rearranged/transformed to other functions; the better the building can meet changing demands.
4. FACILITIES	Measure & Control	8. **Customisability/controllability** Is it possible to customize the facilities: temperature, ventilation, electricity, ICT?	1. Bad/not customizable; monofunctional or fixed centralized use (Bad) 2. Limited customizable; after drastic interventions (Normal) 3. Partly customizable; after simple interventions (Better) 4. Good and easy customizable without any interventions (best)	The more facilities are customisable/controllable to respond to changing functional requirements, the easier a building can be rearranged/transformed to other functions; less vacancy/adaptation costs.
	Dimensions	9. **Surplus of facilities shafts and** Do the facilities shafts and ducts have a surplus of space (heating, cooling, electricity, ICT)?	1. Shafts and ducts have no surplus at all (Bad) 2. 10-30% surplus (Normal) 3. 30-50% surplus (Better) 4. Surplus of space of more than 50% (Best)	The more surplus facilities shafts and ducts have, the easier a building can be rearranged or transformed to other functions, the better a building can meet to changing user demands.
		10. **Modularity of facilities** Are the facilities assembled by modular components according to the facade planning grid?	1. No facility is divided in modular components according to the façade planning grid 2. 1 of the 4 facilities is divided in modular components according to the grid (Normal 3. 2-3 of the 4 facilities are divided according to the façade planning grid (Better) 4. All of the 4 facilities are divided according to the façade planning grid (Best)	The more facilities are divided according to the facade planning grid (modularity), the more easily a building can be rearranged to other functions; the better the building can meet changing demands.
5. SPACE	Functional	11. **Distinction between support - infill** To which degree deals the building with the division between support and infill?	1. < 10% of the building is divided in a support and infill part (Bad) 2. 10 - 30% of the building is divided in a support and infill part (Normal) 3. 30 - 50% of the building is divided in a support and infill part (Better) 4. > 50% of the building is divided in a support and infill part (best)	The more construction components belong to the infill, the easier a building can be rearranged/transformed to other functions, the better a building can meet to changing demands.
	Access	12. **Horizontal access to building** In what way is the horizontal access of the units in the building accomplished?	1. Horizontal access is only by a single internal corridor (Bad) 2. Horizontal access is by a double internal corridor (Normal) 3. Horiz. access directly by a central core in the building with a surrounding corridor 4. Horizontal access is directly by a central core in the building, or an external gallery	The more the horizontal disclosure of the units is limited by a central core the more easily units in a building can be rearranged or transformed to other functions.

Table 34. Generally applicable indicators for the adaptive capacity of buildings (Geraedts, 2016, p. 572)

Appendix 4: Circularity index

The Ellen MacArthur Foundation (2015b) is the first to make a calculation method to determine a building's circularity index. Below, the suggested method is given. To start the calculation, the diagram in Figure 16, which represents the material flows, is transformed from a textual description into symbols (see Figure 55).

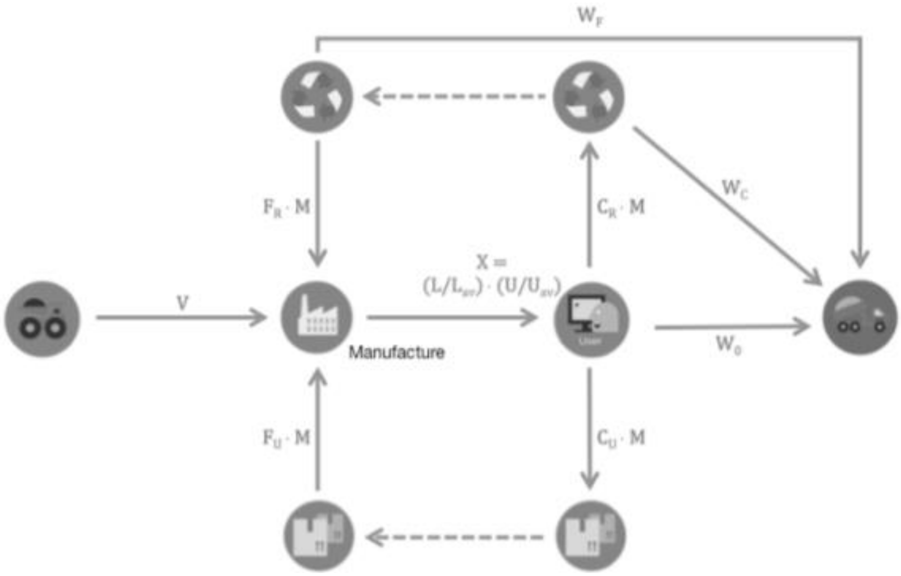


Figure 55. Diagrammatic representation of material flows (Ellen MacArthur Foundation, 2015b, p. 20)

The mass of virgin material

$$V = M(1 - F_R - F_U) \tag{2}$$

M = Mass of the finished product
F_R = Feedstock from recycled sources
F_U = Feedstock from reused sources

The mass of unrecoverable waste

$$W = W_0 + \frac{W_F + W_C}{2} \tag{3}$$

The parameters can be calculated with the formulas below:

Product waste at end of use

$$W_0 = M(1 - C_R - C_U) \tag{4}$$

M = Mass of the finished product
C_R = Mass for recycling at end of use
C_U = Mass for reuse at end of use

Quantity of waste generate to produce recycled content

$$W_F = M\frac{(1 - E_F)F_R}{E_F} \tag{5}$$

M = Mass of the finished product
F_R = Feedstock from recycled sources
E_F = Efficiency of recycling process to produce recycled content

Quantity of waste generated in the recycling process

$$W_C = M(1 - E_C)C_R \tag{6}$$

M = Mass of the finished product
E_C = Efficiency of recycling process
C_R = Mass for recycling at end of use

Note: The quantity of waste can be excluded from the calculation

Knowing the previously obtained values, the Linear Flow Index can be determined:

$$\mathrm{LFI} = \frac{\mathrm{V} + \mathrm{W}}{2\mathrm{M} + \frac{\mathrm{W_F} + \mathrm{W_C}}{2}} \tag{7}$$

In addition to the material flows, the product utility is used, transposed into a factor:

Utility

$$\mathrm{X} = \left(\frac{\mathrm{L}}{\mathrm{L_{av}}}\right)\left(\frac{\mathrm{U}}{\mathrm{U_{av}}}\right) \tag{8}$$

L = Lifetime
L_{av} = Average lifetime
U = Number of functional units during use
U_{av} = Average number of functional units during use

Utility factor

$$\mathrm{F(X)} = \frac{0.9}{\mathrm{X}} \tag{9}$$

Based on the Linear Flow Index and utility factor, the material circularity indicator can be calculated:

$$\mathrm{MCI^*} = 1 - \mathrm{LFI} \cdot \mathrm{F(X)} \tag{10}$$

$$\mathrm{MCI} = \max\{0; \mathrm{MCI^*}\} \tag{11}$$

Consider a company consisting of several departments, which are in turn comprised of a product range. The material circularity indicator for a department and the company can be calculated based on the normalising factor. The formulas are provided below.

Material circularity indicator for department D(α)

$$\mathrm{MCI_{D(\alpha)}} = \frac{1}{\mathrm{N_{D(\alpha)}}} \sum\nolimits_{\beta} \left(\mathrm{N_{R(\alpha,\beta)}} \cdot \mathrm{MCI_{P(\alpha,\beta)}}\right) \tag{12}$$

$MCI_{P(\alpha,\beta)}$ = Material circularity indicator of reference product $P_{(\alpha,\beta)}$
$N_{R(\alpha,\beta)}$ = Normalising factor of product range $R_{(\alpha,\beta)}$
$N_{D(\alpha)}$ = The total normalising factor of the department D(α)

$$\mathrm{N_{D(\alpha)}} = \sum\nolimits_{\beta} \mathrm{N_{R(\alpha,\beta)}} \tag{13}$$

Material circularity indicator for company C

$$\mathrm{MCI_C} = \frac{1}{\mathrm{N_C}} \sum\nolimits_{\alpha} \left(\mathrm{N_{D(\alpha)}} \cdot \mathrm{MCI_{D(\alpha)}}\right) \tag{14}$$

$MCI_{D(\alpha)}$ = Material circularity indicator of department D(α)
$N_{D(\alpha)}$ = Normalising factor of department D(α)
N_C = The total normalising factor of company C

$$\mathrm{N_C} = \sum\nolimits_{\alpha} \mathrm{N_{D(\alpha)}} \tag{15}$$

Appendix 5: Circularity in practise, foundation principles

By searching the internet and literature, several sustainable or circular foundations principles were found. These were general foundation principles or concepts developed by a specific company. In addition, recent developments, supported by research, are included. To provide a clear overview, a division has been made between overall foundation principles, materials, integrated functionalities and elements. Below, the main characteristics are described for each principle. After a general description, the sustainability and level of circularity are discussed.

A. Shallow instead of deep foundation
Constructing a deep foundation affects the soil conditions and requires more material and energy than a shallow foundation. The foundation piles are commonly left in the ground. When a new building is constructed, the positions of these piles need to be considered. New foundation elements must be located so they do not interfere with existing foundation piles. After each lifecycle, the soil is filled with new piles. To avoid this, a shallow foundation can be considered. On the one hand, (additional) settlements might occur; on the other hand, when removing the building, the shallow foundation can be easier reused or recycled, and an empty spot remains.

Reducing material and energy use is an important goal in a circular economy. This goal is fulfilled with a shallow foundation because a shallow foundation requires less material and energy than a deep foundation. Another goal of circular economy is recycling and reuse, which is easier for shallow foundations than for deep foundations, especially for foundation piles. In that sense, a shallow foundation offers better opportunities.

B. Piled raft foundation
A piled raft foundation combines the load bearing capacity of a raft and piles. This foundation uses the load bearing capacity of the relatively weak top layers by the raft and the load bearing capacity of the strong sublayers reached by the piles. In this way, the load bearing capacity of the soil can be ‘optimally’ used. By positioning the piles in a grid and constructing a thick raft, this foundation type can be suitable for different buildings.

Since the soil’s load bearing capacity can be used effectively, the use of material and energy can be reduced. This profit arguably cancels when extra material and energy is invested to create flexibility for different buildings. However, the flexibility can ensure that the foundation can be reused for multiple lifecycles.

C. Floating foundation
A floating foundation is a shallow foundation at a construction level which is lower than a ‘normal’ shallow foundation. In this case, the weight of the excavated soil is approximately equal to the weight of the total building, reducing the risk of settlement. In addition, the upward ground water pressure can be used to counteract the weight of the superstructure. Since a substantial part of the soil is excavated from the ground, this foundation type is usually combined with a basement.

For floating foundations, the same advantages of a shallow foundation apply. The main difference is the goal of eliminating the chance of settlements by retaining the same soil stresses. A floating foundation often contains a basement. As one interviewee indicated, developers might value the presence of a basement, which promotes the reuse of the substructure.

D. Expandable foundation
A traditional shallow or deep foundation can be designed to facilitate building expansion. By giving the foundation a relatively high load bearing capacity, the building can be expanded by a number of floor levels. Alternatively, the building’s function can be changed. Some functions require higher floor loads than others. Offering expendability involves an additional investment because constructing the foundation requires more material and energy. However, if floors can be added to the building or the function of the building can be changed, the lifecycle of the foundation is extended. Thus, the foundation can be reused, saving material and energy in the long-term.

E. Wood

Foundation piles made of timber have been used for centuries. Timber is a circular product since it is natural and renewable. When, during the life cycle of the timber products, the same amount of wood has grown elsewhere, all materials have been compensated. Additionally, carbon dioxide, which is a major contributor to the greenhouse effect, is taken from the air through timber. Compared to other materials, the production of timber elements requires considerably less energy. This energy can also be compensated by growth of wood. One must pay attention to the risk of rot when the top of the foundation pile is above the groundwater level.

Wood is renewable and thus belongs to the biological cycle. By cascading, the material can be optimally used. Because wood is renewable, reuse and recycling are less important than with other materials. If reuse of timber elements is not possible, the material is recycled, which often means downcycling; the wood fibres are used for other products with lower value. Finally, the wood is burned, which is seen as sustainable energy production.

F. Concrete & Steel

Concrete and steel are traditional building materials and have been used for decades. Building industry waste mainly consists of concrete and steel. The production of concrete and steel require considerable energy. Steel and reinforcement in the concrete can corrode, so sufficient protection must be applied. Concrete itself is well resistant to soil and water. Additionally, solid foundation systems can be constructed. Therefore, many foundations are made of concrete.

These materials are mainly recycled. Steel can be recycled by adding scrap to the production process of new steel. In this process, elements of equivalent value can be produced. Much concrete is crushed and downcycled, for example in base layers of roads. Both recycling processes consume high amounts of energy. A new technology enables more sustainable recycling of concrete (Florea & Brouwers, 2013). Traditional crushing machines break the sand and aggregates and provide non-reusable cement. A newly developed machine does not crush the sand and aggregates and produces reusable cement. This process allows for better recycling of the concrete. The process is also less energy intensive and the material can be used to produce elements of equivalent value.

Since reusing products requires less energy than recycling materials, reuse is preferred. When correctly applied, wood, concrete and steel products can be suitable for reuse. This reuse requires high-quality material classes and production, as well as standardized profiles, lengths and connections. Steel and timber elements are often bolted together, making them easy to disassemble. From a traditional point view, much concrete is cast in situ, and consequently, wet connections are applied, so reuse of concrete elements is difficult. Prefabricated concrete elements combined with dry connections offer better opportunities. However, this type of reuse is not fully supported by the building industry and is therefore limited. Regarding foundation piles, steel piles can be easily removed but concrete and wooden piles are more difficult to remove because removal causes loosening of soil conditions and risk of seepage. Steel piles are often reused, whereas concrete or wooden piles are recycled of left as waste.

G. Expanded polystyrene

Expanded polystyrene (EPS) is a plastic material and the result in a chain of chemical reactions. The majority of EPS exists as gas, which makes it a lightweight material. Due to its strong thermal and sound insulating properties, EPS is traditionally used as insulation material. Over time, EPS has acquired application within the field of infrastructural and building foundations. Blocks of EPS are mainly used in foundations of infrastructural works, for example, roads. These EPS blocks are further discussed later in the appendix. Within the building industry, several foundations systems using formwork of EPS have been developed (B-smart fundering, 2016; Hectar, n.d.). This system provides formwork during casting of concrete beams and plates and provides insulation afterward. Thermal bridges, which often occur at foundations, are reduced. In foundation beams and piles, EPS elements can be positioned in the centre of the beam, reducing the amount of concrete needed.

Due to the amount of energy and chemicals, the production of EPS is not sustainable. However, EPS can fulfil several functions, which create circular values. As formwork, EPS reduces the need for other materials, like timber, as well as the loss of energy. If applied in beams of piles, the amount of concrete is reduced. Expanded polystyrene blocks in foundations of infrastructural works can be easily removed and reused. When buildings are demolished, the embedded EPS is recycled. In general, EPS can be easily recycled, but EPS originating from the building industry contains a forbidden chemical. A new recycling process eliminates this chemical and provides recyclable polystyrene. In the future, only better recyclable EPS will be produced (Vos, 2016).

H. Xiriton

Recent research has made storing carbon dioxide in concrete possible (Duurzaam Gebouwd, 2009). Fibres of the plant species *miscanthus* are added to the concrete and absorb a considerable amount of carbon dioxide from the air. In addition, the fibres can replace a part of the traditional aggregates in concrete. Despite the material reducing characteristic, and the storage of carbon dioxide, this method's applicability is currently limited. Further investigation should improve the applicability.

I. Bacteria

The soil characteristics can be improved by bacteria. For example, SmartSoils improves the load bearing capacity of the soil by Biogrouting and Biosealing (Deltaris, 2008). For Biogrouting, bacteria and additives are injected into the soil. Sand and gravel clump together and 'stones' are formed, improving the soil's load bearing capacity. Biosealing limits the permeability of the soil, creating more reliable ground layers. This process is also achieved by injecting bacteria. The technique is still under development and only applied on a small scale.

When the bacteria and additives are biobased and sustainably applied and produced, SmartSoils can be a strong principle to reduce material and energy use. Instead of a deep foundation, a shallow foundation can be constructed, reducing the required amount of material and energy and offering better possibilities for reuse and recycling. This characteristic gives methods, like SmartSoils, a high circular potential. However, the concept must be further developed before it can be broadly used in the building industry.

J. Concrete core activation

Concrete core activation uses material mass for heating or cooling the environment. A piping system is integrated into the concrete elements. In summer, the concrete extracts heat from the environment and avoids considerable warming of the space. In winter, the concrete radiates heat and prevents extreme cooling of the space. The excess or shortage of warmth is removed or added by the piping system. In this way, the work intensity of the traditional technical heating and cooling installations can be reduced (Betonhuis, n.d.). This system can be combined with energy piles. By accumulating warmth and cold in the building, mass energy is saved. In a circular economy, this practice is a form of renewable energy, reducing the amount of energy produced with fossil fuels and optimizing material use.

K. (Rain)water storage

Storage of water, especially rainwater, is relevant in urban areas (De STRAADkrant, 2017). Due to extreme weather conditions and an increase of paved surfaces in cities, problems with rainwater drainage occur. Foundations can be used for temporary storage of rainwater. Furthermore, when dry periods happen, and water becomes scarce, foundations can storage water that can be used later. By integrating these functions, the used materials gain more value. The value creation and application is important, but rainwater storage in itself is not particularly circular. If the need for rainwater storage is caused by global warming, it is more important to stop this trend, rather than minimising the negative consequences.

L. Energy piles

Energy piles are concrete piles with ducts inside, which are connected to a heat pump. This makes heat storage or extraction possible. In winter, heat is absorbed from the soil and transferred to the building, while in summer, cooled water is transferred from the soil to the building. In autumn and spring, respectively heated and cooled water is stored (Geelen, Krosse, Sterrenburg, Bakker, & Sijpheer, 2003). As stated, while use of renewable energy and minimising energy consumption is important, it is a precondition within the circular economy. Energy piles, combined with concrete core activation in the building, can be part of a circular economy but do not directly influence the level of circularity.

M. Hollow piles

Examples of developed hollow foundations piles are the SurePile and Pluspaal (Leading Edge Only, n.d.; Hordijk, De Kok, & Klösters, 2006). The SurePile is constructed cast in situ. After drilling the temporary casing to the desired level, a steel tube is positioned in the centre. Hereafter, the concrete is poured. Although the temporary casing can be reused, the steel tube stays in place. The cavity could be used for rainwater storage or heating and cooling services. Furthermore, one can inspect and improve the load bearing capacity. The Pluspaal is a prefabricated, prestressed pile with EPS elements in its centre.

The main goal of hollow piles is to reduce material use. If it is possible to use these vacant spaces for extra functionalities, like rainwater storage or heating or cooling services, the material obtains more value. The possibility of inspection and expandability improves reusability. If the internal tube is also reused, the circular value of the SurePile will further increase. The additional advantage of the Pluspaal is the reduced energy consumption for transportation, hoisting and driving, which can be achieved through the reduced self-weight.

N. Steel piles

Steel piles come in different forms, like sheet piles, steel profiles or helical piles. Sheet piles have a U or Z profile and are commonly used for building pits, hydraulic structure and infrastructural works because of their strong ground and water retaining properties. These piles can be easily installed and removed. Unfortunately, their application in the building industry is limited, as are steel profiles and helical piles, which are only used for light-weight structures. However, they can also be easily reused. In contrast to wooden and concrete piles, loosening of the soil conditions and risk of seepage is limited. The reuse possibilities of these foundation piles may be of interest in a circular economy. The helical piles of Krinner (n.d.) are already used for the circular residential building concept developed by the company Bilt (n.d.).

O. Demountable beams

Instead of monolithic cast-in-situ concrete foundation beams, prefabricated concrete foundation beams can be used. These beams are post-tensioned at the building site to obtain a rigid system of reusable beams (Van Elle, n.d.). Like demountable prefabricated concrete foundation beams, a similar system made of steel or wooden beams can be constructed. Steel and wooden beams are suitable of demounting. Currently, these beams are only used for lightweight structures and positioned above ground level to avoid degradation, so their application is limited. Disassembly facilitates reuse, so they have a high level of circularity.

P. Modular blocks and plates

Several types of modules have been developed for various foundation-related functions. Blocks of EPS are mainly used in road foundations (Isobouw, 2017). The ground underneath the route is excavated. Subsequently, several layers of EPS blocks are constructed. By increasing the width of the layers, the load is spread. Applying this concept results in lightweight foundations and reduces the risk of (uneven) settlement.

Modular blocks and plates of concrete are commonly used in the industry. Concrete blocks, like those of Legioblock (n.d.), are mainly used for storage and retaining walls. The modules can easily be stacked. Due to the interlocking connection, no additional elements, like bolts, are needed. This type of connection facilitates easy element disassembly and reuse. Concrete plates, like those of Stelcon (2017), are prefabricated concrete slabs with steel angle profiles at the edges for protection. These types of plates are often used for temporary pavement or for more permanent pavement around industrial buildings. They can also be used as shallow foundations for lightweight buildings. Like the blocks, the plates can be easily removed and reused.

Due to the modularity and dry connections, these types of blocks and plates are suitable for reuse. They are frequently used and contribute to a circular economy. The flexibility and multiple purposes of this concept offer high potential for circular shallow foundations of buildings. A lightweight structure and strong upper soil layer are important preconditions. These types of elements have been recently used for circular building projects. Contractor Heijmans (2016) developed housing concept ‘One’, which uses Stelconplates as a shallow foundation. The foundation of The Green House consists of Stelconplates, as well as Legioblocks. For stiffness and stability, the blocks and plates are connected by bolts.

Q. Pad systems

Several companies have developed systems whereby pads are placed in a regular grid. A pad is a portable shallow foundation element. Commonly, this element consists of three subassemblies, from top to bottom: an adjuster, the pad itself and incremental packers. Different adjusters can be placed to carry wooden or steel beams. Subsequently, pads spread the load toward the incremental packers, which can overcome level differences between the supports. The Jackpad (n.d.) and Easypad (n.d.) are made of concrete and plastic and are placed directly on the ground surface. The Diamond Pier (n.d.) uses steel pins to fix the pad to the ground and spread the load. Like the block and plate modules, pad systems require lightweight structures and soil layers near ground level with sufficient load bearing capacity. Nevertheless, pads can be easily replaced. By reusing the elements or systems, this principle contributes to a circular economy.

Overview

Table 35 presents an overview of all the principles, subdivided into categories. Each principle is assessed based on the 3R framework and the framework of Alba Concepts. In the 3R framework, reduce, reuse and recycling are distinguished as the three levels of circularity. The level of circularity increases from recycling to reuse to reduce and are scored with one, two and three stars, respectively. In Alba Concepts' framework, a distinction is made between Circular (C) and Precondition (P). A precondition should be strived for but does not affect the level of circularity, such as reduce. Circular means the material, element or concept has circular characteristics that determine the level of circularity in the assessment method. This applies if the material, element or concept aims recycling or reuse.

	Category	3R framework	Framework of Alba Concepts
	Overall foundation concept		
A	Shallow instead of deep foundation	***	P
B	Piled raft foundation	***	P
C	Floating foundation	***	P
D	Expandable foundation	**	P
	Materials		
E	Wood	*	C
F	Concrete & Steel	*	C
G	Expanded polystyrene	***	P
H	Xiriton	***	P
I	Bacteria	***	P
	Integrated functionalities		
J	Concrete core activation	***	P
K	(Rain)water storage	***	P
	Elements		
L	Energy piles	***	P
M	Hollow piles	***	P
N	Steel piles	**	C
O	Demountable beams	**	C
P	Modular blocks and plates	**	C
Q	Pad systems	**	C

Table 35. Overview of all circular foundation concepts and assessments based on the frameworks

Appendix 6: Circularity in practise, project interviews

The Green House, Utrecht
Written interview with J.B. Cordes, project manager at Ballast Nedam, a Dutch contractor located in Utrecht. Answers to the questions were mailed on Friday 9 and Thursday 13 November 2018. The answers are translated from Dutch to English.

1. What were the motives to make circularity the starting point of the design?

Rijksvastgoedbedrijf [governmental real estate organization] tendered the project *PPS de Knoop* [development of a government office in Utrecht]. Part of this tender was a temporary pavilion. The contractor was responsible for the implementation of this building. The pavilion needs to be temporary (approximately 10 to 15 years) since the building site eventually will be used for permanent buildings. These permanent buildings are not developed yet. Given the temporary character of the building and the investment, circularity is chosen as a starting point of the design.

2. Which stakeholder (architect, engineer, contractor, and developer) was leading/decisive?

The contractor (Ballast Nedam and Strukton) were the developers and were leading/decisive.

3. What was the origin of information about circular building design?

Building from a circular perspective is still developing, so a clear information source does not exist yet. Eventually, all stakeholders (architect, advisor building physics, subcontractors, etc.) contributed to the knowledge. The main goal, which was defined for this project, was the reusability of materials. In this case, the pavilion can be disassembled and reconstructed at another location, or the materials can be reused elsewhere. This means dry connections, common materials without treatments, etc.

4. What is the structural concept of the superstructure? Which design criteria are used?

The main load bearing structure is made of steel. [See Figure 56.] The same profiles and lengths were used as much as possible. The first floor is made of laminated timber and plates. Timber frames are used for the facades. The roof consists of steel sheeting, which is bolted to the steel structure. The most important design criterion was to apply materials with minimal treatment or additional processing. In this way, materials remain original and can be more easily reused. The elements are calculated using the loads and lifespan of this particular application.

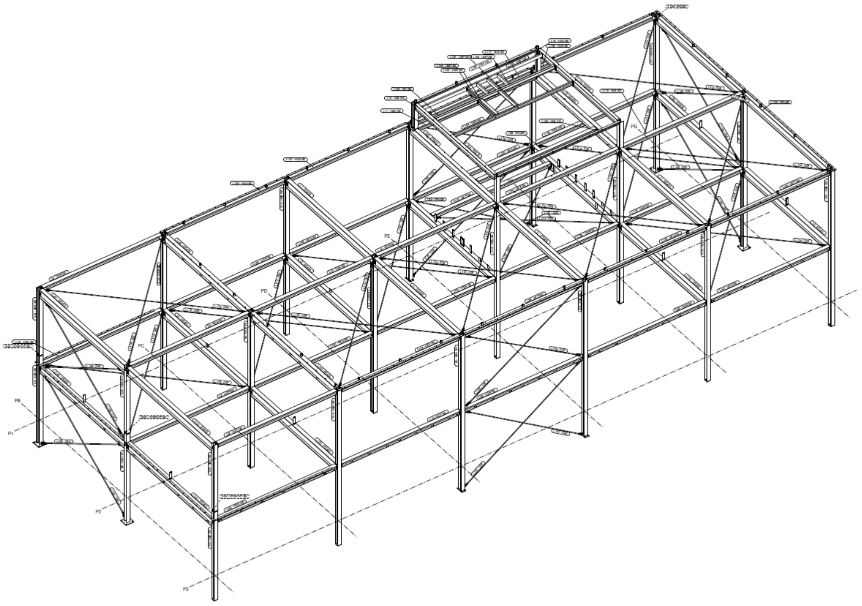


Figure 56. Main load bearing structure of The Green House, based on drawings sent by the interviewee

5. How is the substructure (foundation) executed?

The foundation is made of Stelconplates and Legioblocks, which are coupled with steel connections. [See Figure 57 and Figure 58.] No concessions could be made regarding settlements. The curtain wall at the ground floor is not able to restrain any deformations. Consequently, additional steel is applied to support the certain wall and thus eliminate undesirable consequence of settlements.

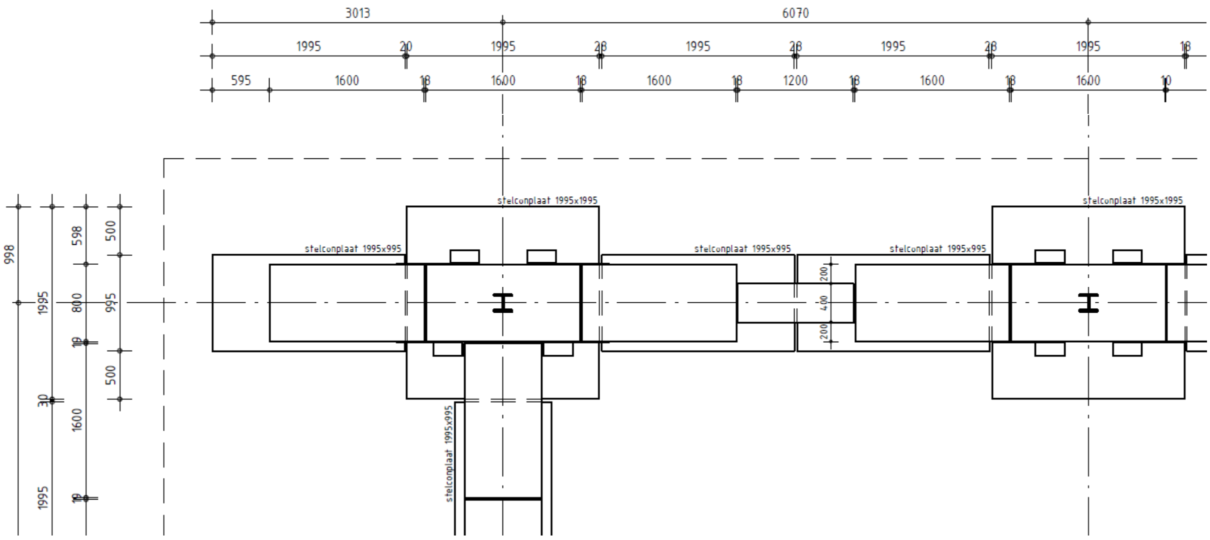


Figure 57. Foundation of The Green House (top view), based on drawings sent by the interviewee

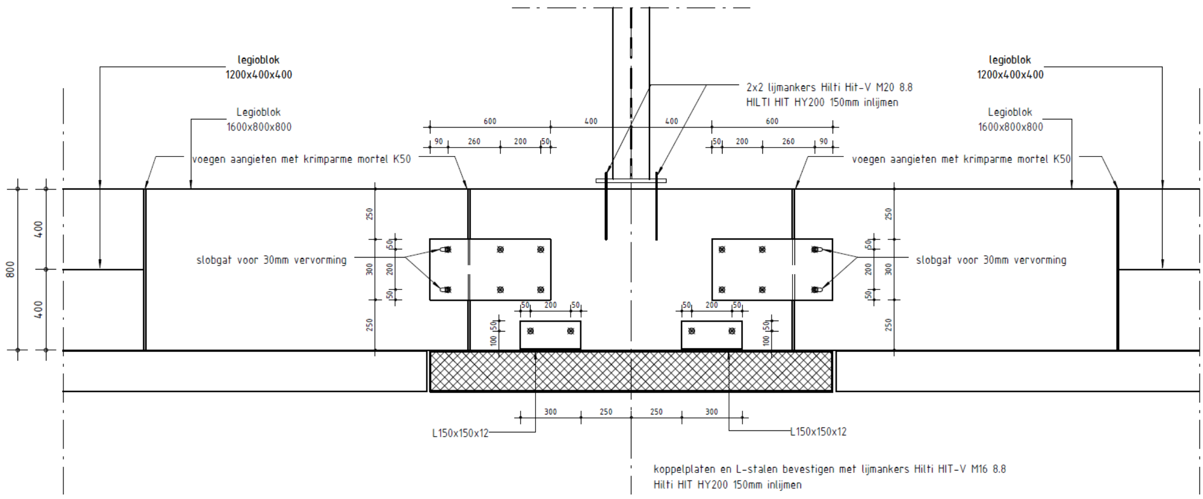


Figure 58. Foundation of The Green House (side view), based on drawings sent by the interviewee

Dutch citation from the geotechnical rapport:

> Grondverbetering: In de berekening van het draagvermogen en de vervorming is ervan uitgegaan dat onder het aanlegniveau een draagkrachtige laag aanwezig is met een dikte van minimaal 0,5 m. Rond het aanlegniveau van de fundering bestaat de bodemopbouw uit los gepakt kleihoudend zand en meer of minder zandhoudende klei. Dit houdt in dat een grondverbetering moet worden aangebracht. Bij de aangetroffen bodemopbouw wordt geadviseerd over het gehele grondvlak van de nieuw een grondverbetering toe te passen in de vorm van 0,5 m hydraulisch menggranulaat 0/40. Dit houdt in dat het grondvlak van de nieuwbouw moet worden ontgraven tot 0,7 m + NAP, vervolgens kan het menggranulaat worden aangebracht en verdicht Na plaatsing van de funderingselementen moet tot onderzijde begane grondvloer goed verdicht zand worden aangebracht. Door zowel onder de dragende constructie als de begane grondvloer een grondverbetering aan te brengen wordt voorkomen dat zettingsverschillen ontstaan tussen de vloer en de gevels.

6. What was considered during the design process of the foundation?

The design process started with prefabricated concrete beams. Subsequently, retaining wall elements were considered. Finally, the current solution was suggested.

7. What are the main challenges when designing a circular foundation?
Avoiding driven piles since their reuse can be very difficult. The use of second-hand materials has also been difficult. Everybody is very careful and thus reserved in using second-hand materials. It is difficult for engineers and governmental organisations to prove that the quality of the materials suffices. Thirdly, it is challenging to come up with solutions that are universally reusable.

8. What is the connection between the sub- and superstructure?
See the technical drawings.

9. When the project is disassembled, what is the next application?
Depending on what happens to The Green House, two options are possible. Firstly, the foundation will be re-used if The Green House is disassembled and reconstructed elsewhere. Secondly, the elements (Stelconplates and Legioblocks) will be reused separately. This can be done in the traditional way. [Figure 59 and Figure 60 show the building layers, and structural elements and connections respectively.]

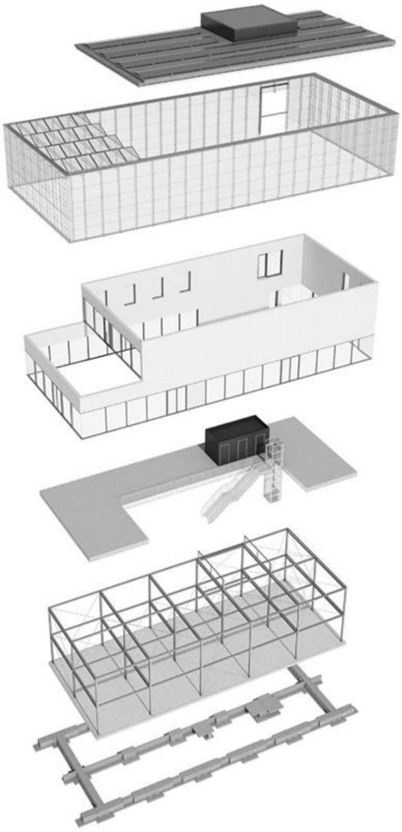


Figure 59. Building layers of The Green House (De ingenieur, 2018)

10. What problems are faced when designing for a building site with an old foundation? See previous comments.

11. Afterward, what would you do differently regarding the design and construction process? Introduce circularity earlier in the design process.

12. What is your definition of a circular foundation? [no answer was given]

13. What, do you think are the most important design criteria for a circular foundation? Adaptability, disassembly and movability, and reuse of materials.

14. What is the main difference between a circular and traditional foundation? Traditionally much concrete is cast in situ, which is all but circular. This is what we are used to, and everything is focused on this.

15. What are the upcoming challenges and opportunities for circular foundations? There is no specific idea about this.

16. Finally, do you have additional comments, tips or useful references related to this research? Perhaps a conversation with Alba Concepts is useful. They developed a circularity index, which makes it possible to determine and compare the levels of circularity.


Figure 60. Structural elements and connections in The Green House (Doomen, 2018)

Temporary court, Amsterdam
Written interview with P. Noomen, structural engineering at IMd consulting engineers, a Dutch engineering firm located in Rotterdam. Answers to the questions were given during a conversation on Tuesday 13 November 2018. The answers are translated, reformulated and restructured.

1. What were the motives to make circularity the starting point of the design?

The client tendered the project and imposed circularity as an important design criterion. The winning contractor was required to disassemble the building after five years and reconstruct the building at another location. It is not sustainable to construct a building and demolish it after five years. The client decided to tender a circular project, so at least the building is sustainable. The client saw the value and forced the contractor to build circularly. This is necessary; otherwise, the stakeholders are not willing to invest in this type of sustainability. Somebody has to pay the investment at the beginning of the process. The engineering firm wanted to use second-hand materials. However, the contractor wanted to use new materials since this is easier. It would be difficult to prove the quality of the second-hand materials.

2. Which stakeholder (architect, engineer, contractor, and developer) was leading/decisive?

See previous question.

3. What was the origin of information about circular building design?

The stakeholders had little knowledge regarding circularity. Much knowledge needed to be acquired by the involved companies. In fact, we are continuously building prototypes in the building industry. This is in contrast to the automotive industry. Here, something is being developed and produced millions of times. Each project, so each prototype, requires new input, knowledge and research into the possibilities. Everyone needed to contribute, accounting for their specialisation. Experience and literature were not available, thus we had to develop, try and think it through. From the engineering firm, much work was spent on the connection between the steel load bearing structure and hollow-core slab.

4. What is the structural concept of the superstructure? Which design criteria are used?

The main load bearing structure is made of steel, with floors of hollow-core slabs. [See Figure 61.] Normally, one would apply a topping to create horizontal stability and transferring loads to wind braces or stabilizing elements. [The left picture of Figure 63 illustrates one of the bolded connections of the main load bearing structure.]

Disassembly was the basis of the design process. Disassembly is difficult for cast-in-situ concrete and, therefore, was quickly omitted. Prefabricated concrete was a possibility. However, by using steel, slender and lightweight designs are possible. In addition, flexibility with regard to installations was important. No obstacles underneath floors were desired. To create a flat surface underneath the floors, one used many integrated steel beams between the hollow-core slabs. In this way, installations can be easily installed and changed. A disadvantage was the need to coat the steel to make it fire-resistant. Maybe the coating is damaged when disassembling the building. Repainting the steel elements might be necessary. This must be experienced later on.

The project is not documented other than traditional projects. Common calculations and drawings are stored and can be consulted at another time. It is unclear whether the project is included in a platform, like Madaster. This is of less interest since the building should be reused one-to-one.

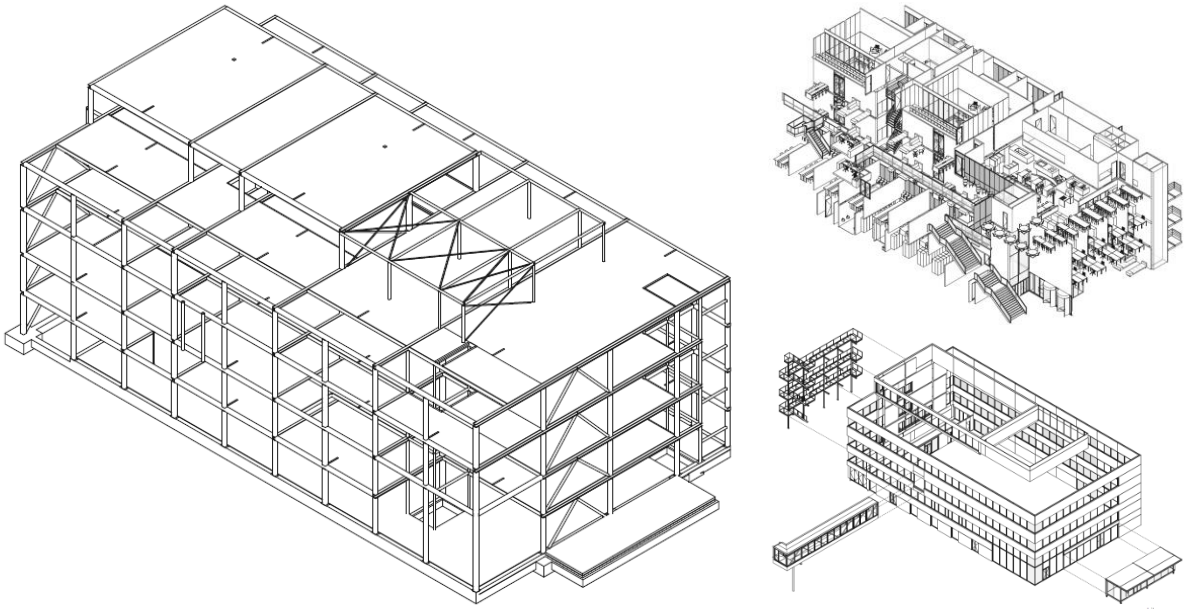


Figure 61. Building layers of the temporary court (De Danschutter et al., 2017, p. 15)

5. How is the substructure (foundation) executed?

Designing a shallow foundation was not feasible because the geotechnical basis was of insufficient quality. Also, soil improvement did not offer a solution, so foundation piles were necessary. The foundation had to be payable. Ultimately, this resulted in a relatively traditional foundation made of prefabricated foundation piles, beams and pile caps. Hollow-core slabs are positioned on top of the foundation beams and pile caps. Consequently, the foundation is constructed of individual elements.

The prefabricated concrete foundation piles are driven to the correct level. A steel bar is cast in and protrudes at the top. The pile caps are positioned on top, and the gains are poured. When disassembling, the steel bar is drilled out from the top. Thereafter, the pile cap can be removed. The same construction and deconstruction method is used for the foundation beams. A cantilever corbel is applied at the interface of the cap and beam. Theoretically, the foundation piles can be removed, but this is unrealistic. In practice, removing foundation piles is undesirable. At certain locations, piles are driven through water retaining soil layers. Water pressure underneath these layers might result in seepage when removing the piles.

Applying the foundation elements for other projects (with other geometries, loads, soil conditions, etc.) is difficult since they are specifically designed for this project. In advance, one did not consider other locations and functions. The dimensions and reinforcement were determined on the basis of this project.

6. What was considered during the design process of the foundation?

Based on the cone penetration test, it soon turned out that the upper soil layers were relatively weak. A shallow foundation was not possible. Soil improvement, to strengthen the upper soil layers, was not feasible. The load bearing soil layers were at a great depth and required foundation piles. Since the structure needed to be demountable, a prefabricated structure appeared to be suitable.

7. What are the main challenges when designing a circular foundation?

Anticipating subsequent cycles is difficult. If one knows the second location of the foundation, one can easily anticipate and combine the requirements of the first and second cycle. This can be foreseen and, for a reasonable investment, is achievable. If one does not know the next application of the elements, one must gamble. This is not always possible. Thus, making a structure demountable is possible; however, predicting the next, unknown cycles is most challenging.

For the temporary court, the foundation can be disassembled, but we did not think about the actual reusability. In practise, the foundation can only be reused in the current composition and for the current function. We did not consider other reuse opportunities in advance. This was mainly induced by costs.

8. What is the connection between the sub- and superstructure?

The steel tube columns are bolted to the pile caps in a traditional way. Dowels are cast in the pile cape. A new connection between the integrated steel beams and hollow-core slabs is developed to make it demountable. [See Figure 62.] The lower flange of the profile is widened. One makes sure that the profile cannot twist when placing and connecting the hollow-core-slabs. [The right picture of Figure 63 depicts the connection in practise.]

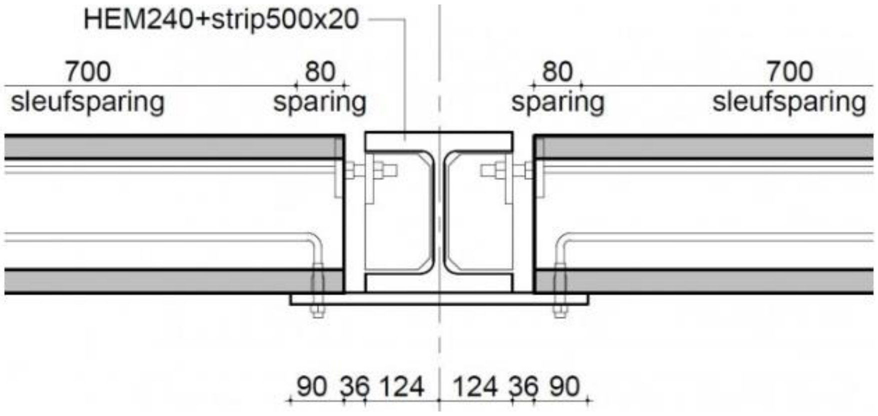


Figure 62. Connection between integrated steel beam and hollow-core slabs (Cepezed projects, 2015)

9. When the project is disassembled, what is the next application?

The foundation elements are specifically designed for this project. The pile caps and foundation beams can be disassembled and reused, albeit only for this specific project. Presumably, the foundation piles remain. When the plot is delivered, the piles will be shortened to 50 cm under ground level. If removal of the piles is desired, this pile type is most suitable. Cast-in-situ piles are more difficult to remove, unless reinforcement is present over the full pile length.

Within the foundation, pile caps for two, three or four exist. It is questionable whether another pile cape is necessary at the new location. This was not considered when designing the foundation. Ideally, the pile plan can be copied to the new location and the same number of piles can be constructed. This requires soil conditions similar to the original location.

It is possible to adjust the pile diameter; however, this is restricted by the pile distance. If the diameter increases, the pile distance must increase as well. This creates problems for the cap since the gains have fixed positions. Also, driving the piles at an angle might be challenging. Despite the fact that one is restricted by the diameter, one is not restricted to the pile type and length.

If more freedom of diameter choice is desirable, an extra investment is requested. Normally, one would position the foundation pile as close as possible to the column. This reduces the dimensions and reinforcement of the pile cap. Increasing the distance between the piles and column, to obtain more freedom of diameter choice, requires larger dimensions and more reinforcement. In this way, one can anticipate different loads and geometries. However, less flexible due to the large elements might result.

Standardization might be a potential, for example, piles caps designed for columns loads of 3000 kN, 4000 kN, 5000 kN and corresponding two-pile, three-pile and four-pile caps. The subsoil is, in most cases, critical for determining the pile type, diameter and length. Thus, a foundation made of modules is an option. One should search for a certain degree of standardization.

10. What problems are faced when designing a building site with an old foundation?
Often, the old foundation is not reused. Many foundations are cast in situ and thus consist of interconnected elements. Disassembly, for reusing elements somewhere else, is not possible. Demolishing a foundation results in rubble, and thus, the material can only be recycled. Reusing the foundation at its current location is, in many situations, not feasible. The old foundation has the wrong geometry, load bearing capacity, etc. Thus, regularly, the foundation beams and pile caps are demolished. Foundation piles are left, and their locations are measured, so they do not interfere with new foundation. The lack of information about the existing foundation is also not in favour of reuse.

More frequently, basements are reused. Developers see the (additional) value of a basement and are willing to make an extra investment and align the superstructure with the basement. However, one does not see any value in existing foundations.

11. Afterward, what would you do differently regarding the design and construction process?
Adding second-hand elements would have been interesting. The contractor was not able to achieve this within the given time. It would take much effort to recycle these materials. It was easier to use new materials. In addition, the connection between the steel beams and hollow-core slabs was hard to realise.

12. What is your definition of a circular foundation?
A foundation should be reusable one-to-one. This requires extra investments in and cogitation about the possibilities during the design process. The foundation and its elements should be flexible and suitable for different geometries and loads.

13. What, do you think are the most important design criteria for a circular foundation?
See previous questions.

14. What is the main difference between a circular and traditional foundation?
This project was no different from a traditional foundation. The way this foundation is constructed has already been done. Additional thinking about the reusability is essential. This foundation is insufficiently standardized and designed for future applications. The foundation should be made more flexible because one does not know the new location and function. The location and function should be similar to reuse this foundation. Otherwise, one must remove elements and replace them with new ones. Also, dry instead of wet connections are required. However, the description above requires a large investment.

If somebody asks to redesign the foundation, this would result in the same design. This design is the most economical one for this location. A prefabricated foundation is not new and has already been applied several times. In fact, this foundation is little circular, except the choice for prefabricated instead of cast-in-situ concrete. This makes the foundation reusable, but in reality, due to a missing philosophy, this is rarely the case.

15. What are the upcoming challenges and opportunities for circular foundations?
See previous question.

16. Finally, do you have additional comments, tips or useful references related to this research?
A contractor should work accurately, given the small tolerances and chance of damage. The contractor needs to be aware of the circular function.

Instead of pouring the connection, a galvanized steel bolted connection might be possible. This concerns a dry instead of wet connection. Perhaps keeping the elements (piles, caps and beams) loose is an option, as long as normal forces and shear forces can be transferred. Depending on the structural concept (wind bracings or other stabilizing elements) horizontal or tensile forces might occur. A bolted connection was considered, but given the uncertainty, a traditional connection of a grouted rod in gain was chosen.

For a four-pile cap, the connections to the foundation pile are not loaded by special forces since the system acts like a table. The main function of the connection is to keep the elements in place. For a two-pile cap, this function is more difficult, especially when the position of the piles deviate. In addition to the normal force and shear force, bending moments and torsion might occur. The pile cap should be designed to take these forces. Only standardizing three-pile and four-pile piers and omitting two-pile piers can be a possibility.

One can build a raft foundation supported by foundation piles. The raft foundation should be an adequately thick, reinforced plate supported by foundation piles, positioned in a certain grid. Thus, a standard centre-to-centre distance is applied. Random point and line loads can be positioned on this solid piled raft foundation. The structure acts like a plate supported by springs. This type of structure offers the most possibilities. One does not have to worry about the position loads enter the foundation. It is impossible to anticipate the changing positions of loads. In this way, different buildings, with comparable height and loads, can be built on the same foundation. Nevertheless, it is questionable whether it is worth the significant investment. A flexible, demountable system is more promising. This requires an investment as well, but to a limited extent.

A foundation is, with few exceptions, at ground level and thus in contact with water, soil and air. This makes the application of steel foundation beams challenging. Concrete is better preserved and, when enough concrete cover is applied, has a long lifespan. Galvanizing or coating the steel and regular inspections are essential. However, the latter is difficult since the beams are located underneath the ground floor. Steel is widely used in the offshore industry, so apparently, it should be possible. Nevertheless, concrete is instinctively a better and simpler solution. Environmental conditions, which affect the steel, are just a significant risk.

Figure 63. Structural elements and connections in the temporary court (Staalmakers, n.d.)

Circular viaduct, Kampen

Written interview with G. Visser, senior specialist at VolkerInfra, a Dutch contractor located in Vianen. Answers to the questions were mailed on Monday 4 February 2019. The answers are translated from Dutch to English.

1. What considerations have led to the application of sheet piles?

The application of sheet piles was feasible. In other words, the application of a pile foundation was not necessary. The sheet piles can be easily removed and reused. This contributes to the circular thoughts. It should be noted that, looking at circularity, the focus was not on the foundation. The focus was mainly on the viaduct itself. However, one pursued a foundation that was reusable as much as possible. This was possible by using sheet piles.

2. Is shaft friction only used for bearing capacity?

Yes, the end bearing capacity contributes negligibly.

3. What is the connection between the sub- and superstructure?

On top of the sheet piles, a continuously steel plate is welded. On top of this plate, rubber blocks are positioned. The concrete beams are positioned on top of these rubber blocks.

4. Which difficulties did you encounter during the design process?

Designing the foundation did not lead to problems. During the design of the road surface, some challenges were encountered, like the application of unbonded prestressed concrete, which cannot be applied according to the guidelines of *Rijkswaterstaat* [executive agency of the Ministry of Infrastructure and Water Management]. For the reusability of the structure, one consciously deviated from it, in consultation with *Rijkswaterstaat*. Also, the connection between the concrete blocks was challenging, regarding the transfer of shear forces by shear keys. The joint is designed in such a way that disassembly is possible. The joints will be open in the ultimate limit state. This was an important aspect. Fewer shear keys need to be activated. Finally, the high stresses at the introduction of the prestressing forces at the endings of the viaduct presented difficulties.

5. For what reason was a design period of 200 years chosen?

A shorter period of time would limit the reusability and therefore the circular concept. A longer period of time would result in large deviations from the Eurocode and, therefore, large uncertainties in the design.

6. In what way was one designed for 200 years (e.g., loads, materials, factors)?

This was mainly done by applying more concrete cover (+5 mm). Also, the load factors were increased for traffic, temperature, wind and fatigue. Concrete class C60/75 [instead of C35/45] was applied, but this is not special for prefabricated concrete elements.

Appendix 7: Calculation of assessment methods

		Origin scenario (%)				Future scenario (%)			
	Mass, m (kN)	New, A1	Reuse, A2	Recycling, A3	Biobased, A4	Landfill, B1	Combustion, B2	Recycling, B3	Reuse, B4
Element x	$m_x = m_a + m_b$	$A1_x = \frac{A1_a m_a + A1_b m_b}{m_a + m_b}$	$A2_x = \frac{A2_a m_a + A2_b m_b}{m_a + m_b}$	$A3_x = \frac{A3_a m_a + A3_b m_b}{m_a + m_b}$	$A4_x = \frac{A4_a m_a + A4_b m_b}{m_a + m_b}$	$B1_x = \frac{B1_a m_a + B1_b m_b}{m_a + m_b}$	$B2_x = \frac{B2_a m_a + B2_b m_b}{m_a + m_b}$	$B3_x = \frac{B3_a m_a + B3_b m_b}{m_a + m_b}$	$B4_x = \frac{B4_a m_a + B4_b m_b}{m_a + m_b}$
Product a	m_a	$A1_a$	$A2_a$	$A3_a$	$A4_a$	$B1_a$	$B2_a$	$B3_a$	$B4_a$
Product b	m_b	$A1_b$	$A2_b$	$A3_b$	$A4_b$	$B1_b$	$B2_b$	$B3_b$	$B4_b$
Element y	$m_y = m_c + m_d$	$A1_y = \frac{A1_c m_c + A1_d m_d}{m_c + m_d}$	$A2_y = \frac{A2_c m_c + A2_d m_d}{m_c + m_d}$	$A3_y = \frac{A3_c m_c + A3_d m_d}{m_c + m_d}$	$B4_y = \frac{A4_c m_c + A4_d m_d}{m_c + m_d}$	$B1_y = \frac{B1_c m_c + B1_d m_d}{m_c + m_d}$	$B2_y = \frac{B2_c m_c + B2_d m_d}{m_c + m_d}$	$B3_y = \frac{B3_c m_c + B3_d m_d}{m_c + m_d}$	$B4_y = \frac{B4_c m_c + B4_d m_d}{m_c + m_d}$
Product c	m_c	$A1_c$	$A2_c$	$A3_c$	$A4_c$	$B1_c$	$B2_c$	$B3_c$	$B4_c$
Product d	m_d	$A1_d$	$A2_d$	$A3_d$	$A4_d$	$B1_d$	$B2_d$	$B3_d$	$B4_d$
Building z	$m_z = m_x + m_y$	$A1_z = \frac{A1_x m_x + A1_y m_y}{m_x + m_y}$	$A2_z = \frac{A2_x m_x + A2_y m_y}{m_x + m_y}$	$A3_z = \frac{A3_x m_x + A3_y m_y}{m_x + m_y}$	$A4_z = \frac{A4_x m_x + A4_y m_y}{m_x + m_y}$	$B1_z = \frac{B1_x m_x + B1_y m_y}{m_x + m_y}$	$B2_z = \frac{B2_x m_x + B2_y m_y}{m_x + m_y}$	$B3_z = \frac{B3_x m_x + B3_y m_y}{m_x + m_y}$	$B4_z = \frac{B4_x m_x + B4_y m_y}{m_x + m_y}$

Table 36. Parameters and formulas, Alba concepts, part 1

	Lifespan (y)						
	Technical, TL	Functional, FL	Material index, MI	Disassembly index, DI	Product circularity index, PCI	Element circularity index, ECI	Building circularity index, BCI
Element x	$TL_x = \min\{TL_a, TL_b\}$	$FL_x = \min\{FL_a, FL_b\}$	$MI_x = 1 - \frac{A1_x + B1_x + B2_x}{2} \cdot \frac{0.9}{TL_x/FL_x}$	DI_x		$ECI_x = MI_x \cdot DI_x$	
Product a	TL_a	FL_a	$MI_a = 1 - \frac{A1_a + B1_a + B2_a}{2} \cdot \frac{0.9}{TL_a/FL_a}$	DI_a	$ECI_a = MI_a \cdot DI_a$		
Product b	TL_b	FL_b	$MI_b = 1 - \frac{A1_b + B1_b + B2_b}{2} \cdot \frac{0.9}{TL_b/FL_b}$	DI_b	$ECI_b = MI_b \cdot DI_b$		
Element y	$TL_y = \min\{TL_c, TL_d\}$	$FL_y = \min\{FL_c, FL_d\}$	$MI_y = 1 - \frac{A1_y + B1_y + B2_y}{2} \cdot \frac{0.9}{TL_y/FL_y}$	DI_y		$ECI_x = MI_x \cdot DI_x$	
Product c	TL_c	FL_c	$MI_c = 1 - \frac{A1_c + B1_c + B2_c}{2} \cdot \frac{0.9}{TL_c/FL_c}$	DI_c	$ECI_c = MI_c \cdot DI_c$		
Product d	TL_d	FL_d	$MI_d = 1 - \frac{A1_d + B1_d + B2_d}{2} \cdot \frac{0.9}{TL_d/FL_d}$	DI_d	$ECI_d = MI_d \cdot DI_d$		
Building z							$BCI_z = \frac{ECI_x m_x + ECI_y m_y}{m_x + m_y}$

Table 37. Parameters and formulas, Alba concepts, part 2

		Origin scenario (%)		Future scenario (%)			Lifespan (y)		
	Mass, m (kN)	New, A1	Non-virgin or biobased, A2	Loss, B1	Recycling, B2	Reuse, B3	Technical, TL	Functional, FL	Circularity index, CI
Element x	$m_x = m_a + m_b$	$A1_x = \frac{A1_a m_a + A1_b m_b}{m_a + m_b}$	$A2_x = \frac{A2_a m_a + A2_b m_b}{m_a + m_b}$	$B1_x = \frac{B1_a m_a + B1_b m_b}{m_a + m_b} \cdot \frac{100 - B3_x}{100}$	$B2_x = \frac{B2_a m_a + B2_b m_b}{m_a + m_b} \cdot \frac{100 - B3_x}{100}$	$B3_x$	TL_x	FL_x	$CI_x = 1 - \frac{A1_x + B1_x}{2} \cdot \frac{0.9}{TL_x/FL_x}$
Material a	m_a	$A1_a$	$A2_a$	$B1_a$	$B2_a$				$CI_a = 1 - \frac{A1_a + B1_a}{2} \cdot \frac{0.9}{TL_x/FL_x}$
Material b	m_b	$A1_b$	$A2_b$	$B1_b$	$B2_b$				$CI_b = 1 - \frac{A1_b + B1_b}{2} \cdot \frac{0.9}{TL_x/FL_x}$
Element y	$m_y = m_c + m_d$	$A1_y = \frac{A1_c m_c + A1_d m_d}{m_c + m_d}$	$A2_y = \frac{A2_c m_c + A2_d m_d}{m_c + m_d}$	$B1_y = \frac{B1_c m_c + B1_d m_d}{m_c + m_d} \cdot \frac{100 - B3_y}{100}$	$B2_y = \frac{B2_c m_c + B2_d m_d}{m_c + m_d} \cdot \frac{100 - B3_y}{100}$	$B3_y$	TL_y	FL_y	$CI_y = 1 - \frac{A1_y + B1_y}{2} \cdot \frac{0.9}{TL_y/FL_y}$
Material c	m_c	$A1_c$	$A2_c$	$B1_c$	$B2_c$				$CI_c = 1 - \frac{A1_c + B1_c}{2} \cdot \frac{0.9}{TL_y/FL_y}$
Material d	m_d	$A1_d$	$A2_d$	$B1_d$	$B2_d$				$CI_d = 1 - \frac{A1_d + B1_d}{2} \cdot \frac{0.9}{TL_y/FL_y}$
System z	$m_z = m_x + m_y$	$A1_z = \frac{A1_x m_x + A1_y m_y}{m_x + m_y}$	$A2_z = \frac{A2_x m_x + A2_y m_y}{m_x + m_y}$	$B1_z = \frac{B1_x m_x + B1_y m_y}{m_x + m_y}$	$B2_z = \frac{B2_x m_x + B2_y m_y}{m_x + m_y}$	$B3_z = \frac{B3_x m_x + B3_y m_y}{m_x + m_y}$			

Table 38. Parameters and formulas, alternative method, part 1

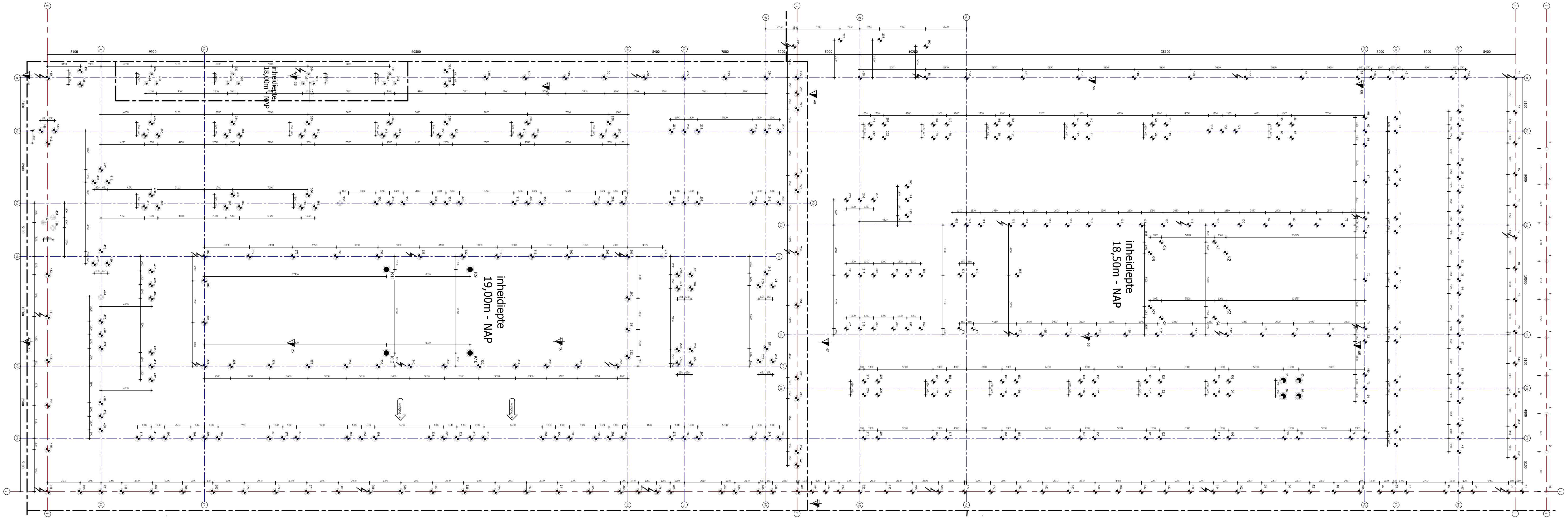
	Indicator (-)			Index (-)		
	Material recyclability, MRI	Element reusability, ERI	System reusability, SRI	Material circularity, MCI	Element circularity, ECI	System circularity, SCI
Element x		ERI_x			$ECI_x = CI_x \cdot \frac{B1_x \cdot 0.1 + B2_x \cdot \frac{MRI_a m_a + MRI_b m_b}{m_a + m_b} + B3_x \cdot ERI_x}{B1_a + B2_a}$	
Material a	MRI_a			$MCI_a = CI_a \cdot \frac{B1_a \cdot 0.1 + B2_a \cdot MRI_a}{B1_a + B2_a}$		
Material b	MRI_b			$MCI_b = CI_b \cdot \frac{B1_b \cdot 0.1 + B2_b \cdot MRI_b}{B1_b + B2_b}$		
Element y		ERI_y			$ECI_y = CI_y \cdot \frac{B1_y \cdot 0.1 + B2_y \cdot \frac{MRI_c m_c + MRI_d m_d}{m_c + m_d} + B3_y \cdot ERI_y}{B1_a + B2_a}$	
Material c	MRI_c			$MCI_c = CI_c \cdot \frac{B1_c \cdot 0.1 + B2_c \cdot MRI_c}{B1_c + B2_c}$		
Material d	MRI_d			$MCI_d = CI_d \cdot \frac{B1_d \cdot 0.1 + B2_d \cdot MRI_d}{B1_d + B2_d}$		
System z			SRI_z			$SCI_z = \frac{ECI_x m_x + ECI_y m_y}{m_x + m_y}(B3_z \cdot SRI_z + (100 - B3_z) \cdot 1.0)$

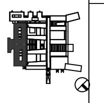
Table 39. Parameters and formulas, alternative method, part 2

Appendix 8: Foundation drawings of case studies

Foundation drawings for the project 1, the medical centre in Amersfoort, and project 2, the university building in Nijmegen, are presented on the following pages. The drawings of the traditional foundation are from the database of Aronsohn and are made using Autodesk and Revit. Hereafter, the handmade drawings of the circular foundations are provided. Below an overview of the added drawings is given:

1. Traditional foundation, project 1
    a. Pile plan
    b. Ground floor plan, part 1
    c. Ground floor plan, part 2
2. Traditional foundation, project 2
3. Versatile foundation, project 1
4. Changeable foundation, project 1
5. Versatile foundation, project 2
6. Changeable foundation, project 2





(28) Overzicht Palen HF tbv tekening					
Type paal	Aantal	Symbool	Afmeting	inheidiepte tov NAP	Peil tov NAP
in de grond gevormde grondverdringende palen (vibro)	10	⌖	ø300/330	-18500	1250
in de grond gevormde grondverdringende palen (vibro)	6	⊕	ø300/330	-19000	1250
in de grond gevormde grondverdringende palen (vibro)	12	✕	ø300/330	-18000	1250
in de grond gevormde grondverdringende palen (vibro)	238	◐	ø410/475	-18500	1250
in de grond gevormde grondverdringende palen (vibro)	205	◑	ø410/475	-19000	1250
in de grond gevormde grondverdringende palen (vibro)	4	◕	ø510/585	-19000	1250
in de grond gevormde grondverdringende palen (vibro)	4	●	ø510/585	-19000	1250

Grand total: 479

- max. optredende verticale belasting
  palen rond 300/330 Pdmax = 900kN
  palen rond 410/475 Pdmax = 2000kN
  palen rond 510/585 Pdmax = 2660kN

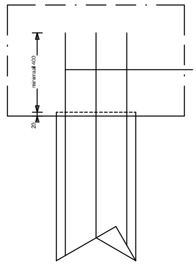
- zie rapport Tjaden S 06.112-F1, d.d. 29 april 2010

- voor onderkant fundering zie tek. 8888 / HF-1201v en HF-1202v

- aardpalen volgens opgave installateur

ϟ = palen voorzien van aarding

▽ = sondering



algemeen detail aansluiting paal aan fundering

opmerking:
bij schoorpalen is de aangegeven maatvoering t.o.v. onderkant fundering hiermee
rekening houden bij een lager gelegen bouwput e.d.

▲	datum	omschrijving	get.	gec.	gez.
G	19-08-2010	aanpassing ivm waterdichte wanden vervallen paal 343	RZ		
F	11-08-2010	palen 83-84-91-92 gewijzigd	RZ		
E	05-08-2010	palen kraanpoer K1 t/m K12+468 toegevoegd	RZ		
D	14-07-2010	paaltype aangepast op verzoek aannemer	RZ		
C	16-06-2010	palen toegevoegd, gewijzigd en gemaatvoerd	RZ		
B	18-05-2010	voor uitvoering	RZ		
A	07-05-2010	ter controle	RZ		

werk	Meander Medisch Centrum Amersfoort
onderdeel	Palenplan
architect	Atelier PRO Den Haag
schaal	1 : 100
gezien	datum

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Rotterdam Eindhoven Amsterdam

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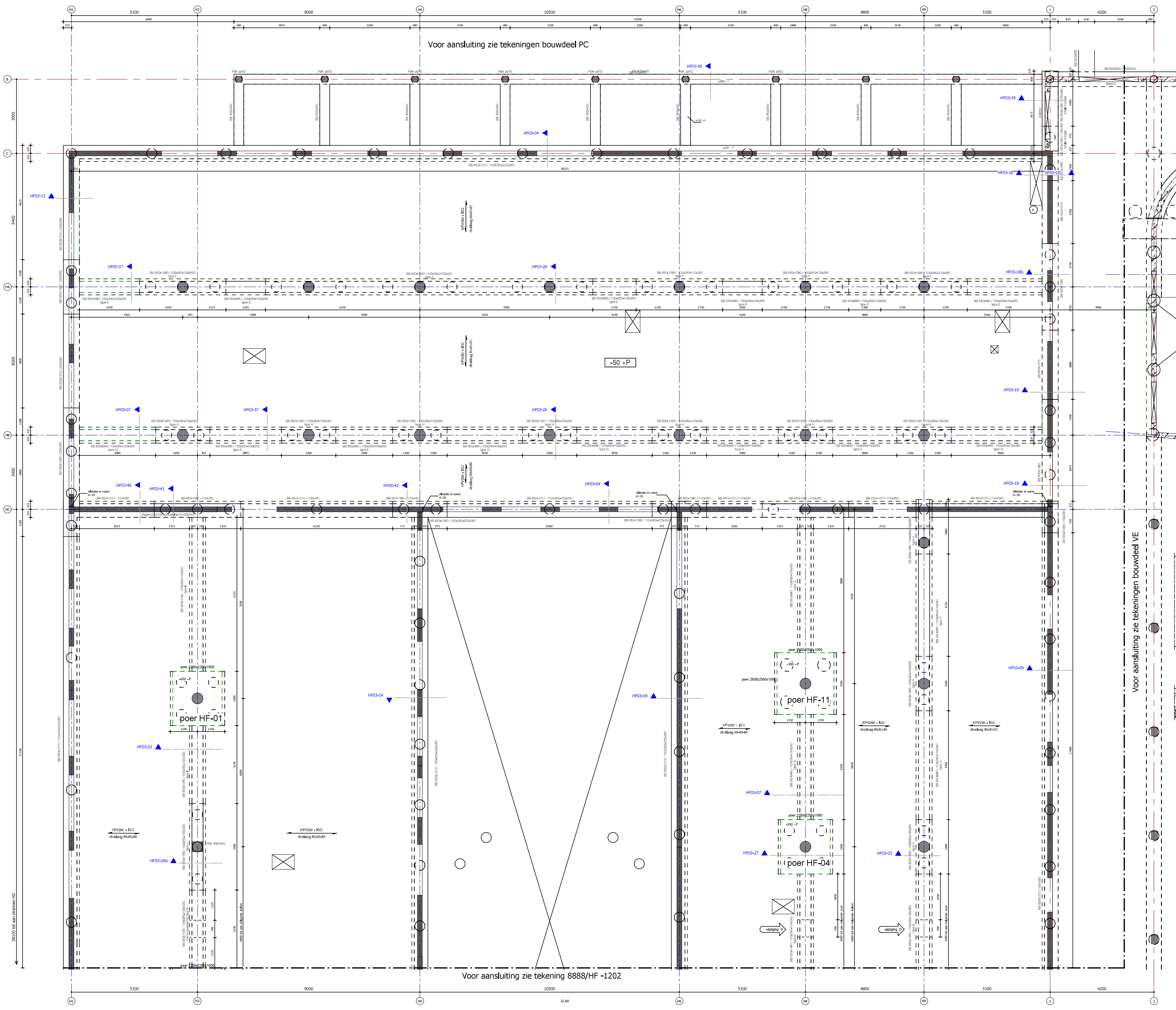
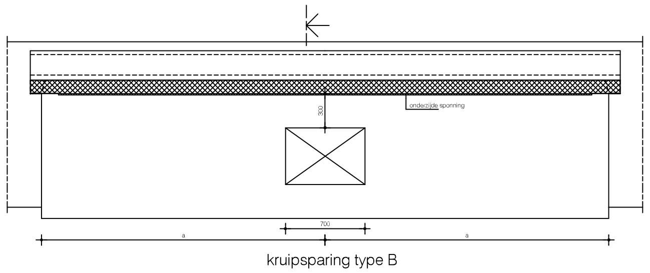
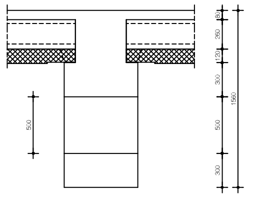
040 - 2909900
020 - 3987310
fax : 010 - 4127548
040 - 2443321
020 - 6002854
www.aronsohn.nl
rotterdam@aronsohn.nl

tekeningnummer: 8888 / HF X101v
formaat: A0+
revisie: G




kruipsparing type B
schaal 1:20


doorsnede

Afkortingen benamingen

aanduiding staalprofilering (liggers) volgens geldende staal NEN norm

Materiaalsoort:

BB	= betonbalk	LW	= kalkzandsteen lijmwerk
BF	= betonnen fundatiestrook	BPV	= breedplaatvloer
BPW	= bekistingplaatwand	PBB	= prefab betonbalk
BK	= betonkolom	PBK	= prefab betonkolom
BW	= betonwand	PBW	= prefab betonwand
GL	= gelamineerde ligger	PBV	= prefab betonvloer (bordessen/balkon/galerij)
HSB	= houtskeletbouw	PPV	= prefab plaatvloer
HK	= houten kolom	BBV	= prefab balkbodem
IHW	= betonvloer in het werk gestort	SK	= staalkolom
KM	= kalkzandsteen metselwerk	SBK	= staalkolom betongevuld
KPV	= kanaalplaatvloer	SPV	= staalplaatvloer
KV	= klimaatvloer	SPB	= staalplaatbetonvloer

Tenzij niet anders aangegeven:

- kolommen rond 450
- dragende prefab wanden d=200
- voor in te storten voorzieningen zie desbetreffende tekening.
- zie voor sparingen de desbetreffende sparingtekening.
- hoogtematen balken/poeren zijn aangegeven excl. druklaag.
- vermelden sponningdiepte in het model zijn excl. hoogte oplegnokken, in de details zijn deze goed aangegeven.
- ontbrekende maatvoering van wanden en wandopeningen volgens opgave architect.
- ravelingen t.p.v. sparingen volgens opgave leverancier. Ⓡ
- definitieve plaats van de kruipluiken te bepalen door 2MC3 in overleg met architect.

betondekking op buitenste wapening

	milieuklasse		
	1	*2*	*3*
	XC1	*XC2 en XC3 XF3*	*XA1 t/m XA3 XD3 XF4*
vloer	*15*	*25*	*30*
wand	*20*	*25*	*35*
balk, console	*25*	*30*	*35*
kolom	*30*	*35*	*40*
poer	*-*	*40*	*45*

betondekking op hoofdwapening; *voor staven Ø k ≤ 25mm C ≥ Ø k*
voor staven Ø k > 25mm C ≥ 1,5 Ø k

op de minimale betondekking een toeslag van 5mm toepassen indien er sprake is van;

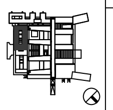
- *een nabewerkt oppervlak*
- *een oncontroleerbaar oppervlak*
- *beton met een karakteristieke sterkte kleiner dan C20/25*

Indien deze gevallen zich tegelijkertijd voordoen, moeten de toeslagen worden opgeteld.

cementsoort: CEMIII/B42,5
betonsterkte: C35/45

maten (ook peilmaten) in mm
peilmaten t.o.v. peil
peil is b.k. afgewerkte parterre vloer = N.A.P. +1250

voor details zie tekening 8888/HFX801v
voor poeren zie tekeningen 8888/HF-1301 t/m HF-1304



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D	15-09-2010	aanpassing kruipgaten/luiken	GG		
C	31-08-2010	diverse wijzigingen	GG		
B	15-07-2010	vorm definitief	GG		
A	31-05-2010	ter controle	GG		

werk: Meander Medisch Centrum
Amersfoort

onderdeel: plattegrond parterre deel 1

architect: Atelier PRO
Den Haag

schaal: 1 : 50

gezien:
datum:

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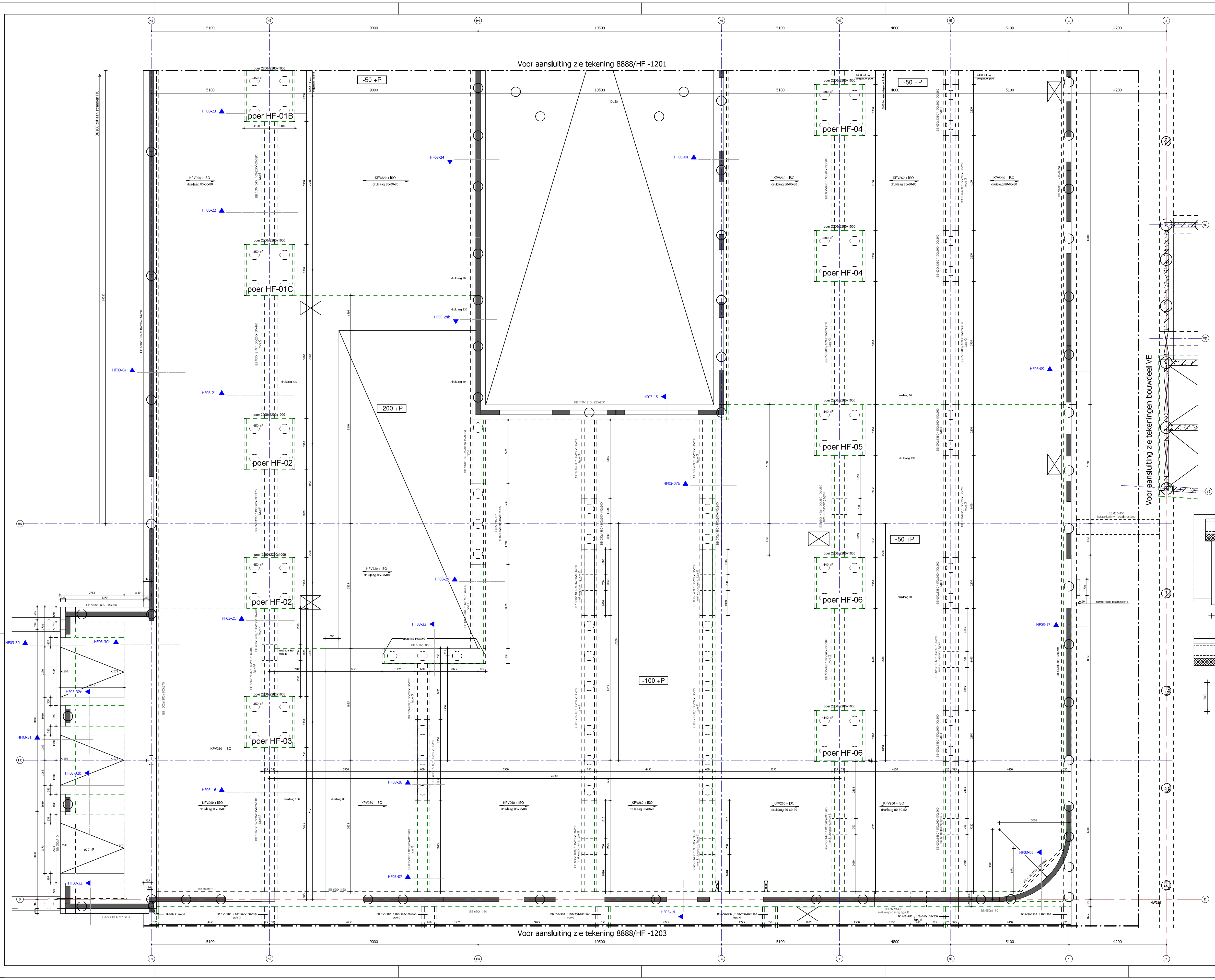
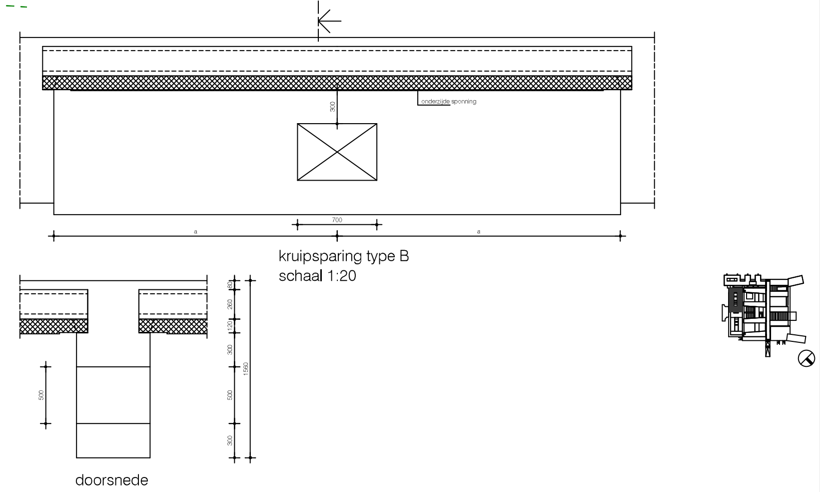
tekeningnummer: 8888 / HF-1201
formaat: A0+
revisie: D





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BK	= betonkolom	PBK	= prefab betonkolom
BW	= betonwand	PBW	= prefab betonwand
GL	= gelamineerde ligger	PBV	= prefab betonvloer (bordessen/balkon/galerij)
HSB	= houtskeletbouw	PPV	= prefab plaatvloer
HK	= houten kolom	BBV	= prefab balkbodem
IHW	= betonvloer in het werk gestort	SK	= staalkolom
KM	= kalkzandsteen metselwerk	SBK	= staalkolom betongevuld
KPV	= kanaalplaatvloer	SPV	= staalplaatvloer
KV	= klimaatvloer	SPB	= staalplaatbetonvloer

Tenzij niet anders aangegeven:

- kolommen rond 450
- dragende prefab wanden d=200
- voor in te storten voorzieningen zie desbetreffende tekening.
- zie voor sparingen de desbetreffende sparingtekening.
- hoogtematen balken/poeren zijn aangegeven excl. druklaag.
- vermelden sponningdiepte in het model zijn excl. hoogte oplegnokken, in de details zijn deze goed aangegeven.
- ontbrekende maatvoering van wanden en wandopeningen volgens opgave architect.
- ravelingen t.p.v. sparingen volgens opgave leverancier. Ⓡ
- definitieve plaats van de kruipluiken te bepalen door 2MC3 in overleg met architect.

betondekking op buitenste wapening

	milieuklasse		
	1	*2*	*3*
	XC1	*XC2 en XC3 XF3*	*XA1 t/m XA3 XD3 XF4*
vloer	*15*	*25*	*30*
wand	*20*	*25*	*35*
balk, console	*25*	*30*	*35*
kolom	*30*	*35*	*40*
poer	*-*	*40*	*45*

betondekking op hoofdwapening; *voor staven Ø k ≤ 25mm C ≥ Ø k*
voor staven Ø k > 25mm C ≥ 1,5 Ø k

op de minimale betondekking een toeslag van 5mm toepassen indien er sprake is van;

- *een nabewerkt oppervlak*
- *een oncontroleerbaar oppervlak*
- *beton met een karakteristieke sterkte kleiner dan C20/25*

Indien deze gevallen zich tegelijkertijd voordoen, moeten de toeslagen worden opgeteld.

cementsoort: CEMIII/B42,5 betonsterkte: C35/45

maten (ook peilmaten) in mm
peilmaten t.o.v. peil
peil is b.k. afgewerkte parterre vloer = N.A.P. +1250

voor details zie tekening 8888/HFX801v
voor poeren zie tekeningen 8888/HF-1301 t/m HF-1304

▲	datum	omschrijving	get.	gec.	gez.
E	25-11-2010	dockshelter aangepast	RZ		
D	15-09-2010	aanpassing kruipgaten/luiken	GG		
C	31-08-2010	diverse wijzigingen	GG		
B	15-07-2010	vorm definitief	GG		
A	31-05-2010	ter controle	GG		

werk
Meander Medisch Centrum
Amersfoort

onderdeel
plattegrond parterre deel 2

architect
Atelier PRO
Den Haag

schaal 1 : 50

gezien datum

Aronsohn Constructies
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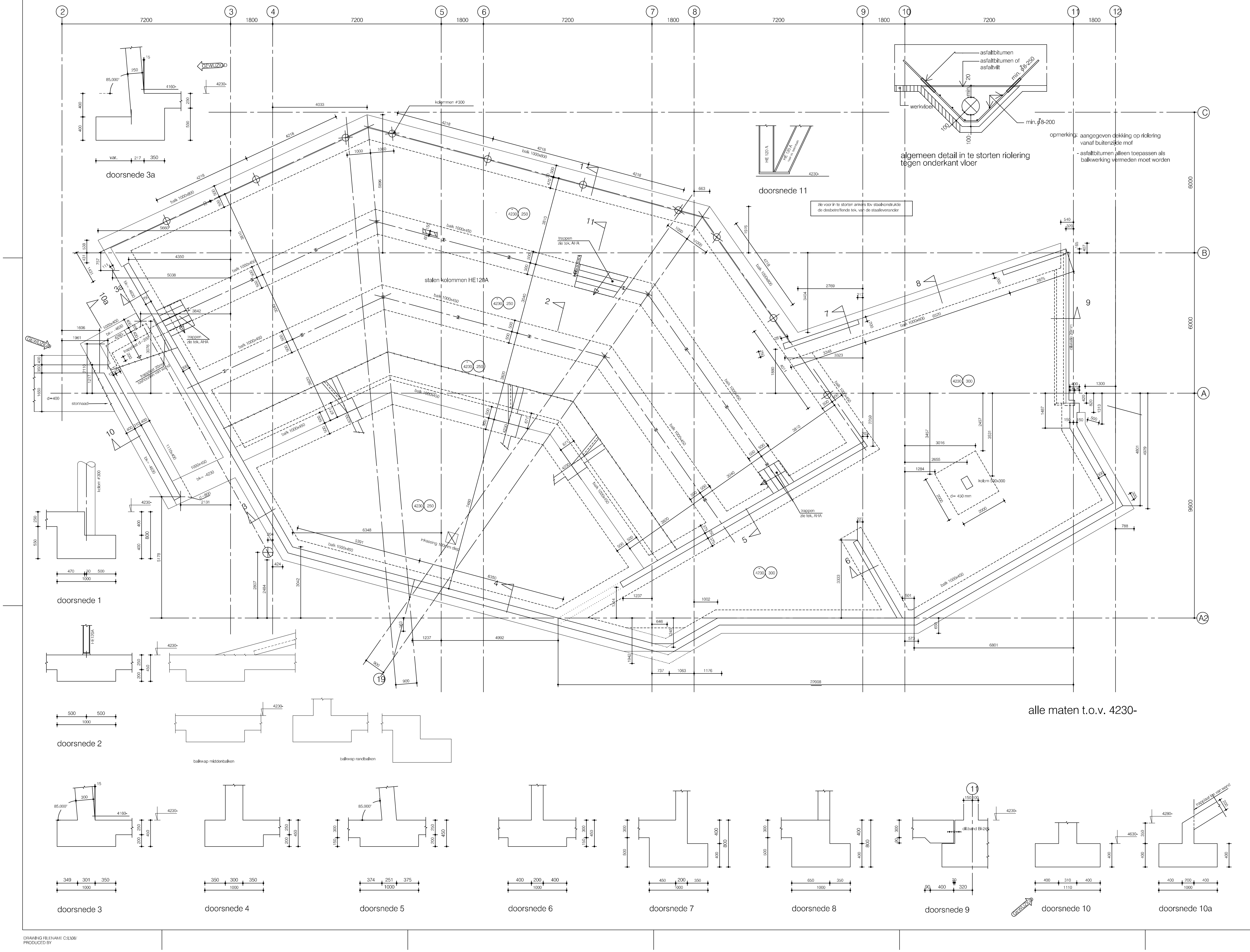
rotterdam—aronsohn.nl

tekeningnummer 8888 / HF-1202

formaat A0+

revisie E



algemeen detail in te storten riolering tegen onderkant vloer

opmerking: aangegeven dekking op riolering vanaf buitenzijde mof

- asfaltbitumen alleen toepassen als balkwerking vermeden moet worden

zie voor in te storten ankers tbv staalkonstruktie de desbetreffende tek. van de staalleverancier

alle maten t.o.v. 4230-

algemene opmerkingen

- bij aansluitingen met bestaande bebouwingen de maatvoering kontroleren en aanpassen in overleg met de konstrukteur
- voor instortvoorzieningen ten behoeve van konstrukties derden zie desbetreffende tekening leverancier

betonrenvooi

beton B35 milieuklasse 1
tbv onderdelen in binnenconditie als :
- vrijdragende vloeren incl. verzwaringen
- druklagen systeemvloeren
- verdiepingsbalken
- trappen en bordessen
- opstortingen

beton B35 milieuklasse 2 ⇦
tbv onderdelen in buitenconditie die niet met dooizouten in aanraking kunnen komen
- vloeren op grondslag
- kelderwanden
- funderingsbalken

beton B35 milieuklasse 3 ⇦
tbv onderdelen in buitenconditie die wel met dooizouten in aanraking kunnen komen

beton B45 milieuklasse 1
tbv onderdelen :
- vulbeton stalen kolommen binnen

beton B45 milieuklasse 2
tbv onderdelen :
- vulbeton stalen kolommen buiten

beton B45 milieuklasse 3
tbv onderdelen :
- vulbeton stalen kolommen buiten die met dooizouten in aanraking kunnen komen

staalsoort	laagligging
∅ = FeB 220 $\bar{\varnothing}$ = FeB 500	1^e laag van buitenaf 2^e laag van buitenaf 3^e laag van buitenaf onder resp.boven(bij vloer)

betondekking op buitenste wapening

voor staven $\varnothing_k \leqq 25$	milieuklasse 1 droog	2 vochtig	3 t/m 5 agressief
vloer $h_t < 200$	15	25	30
vloer $h_t \geqq 200$	20	25	35
wand	20	25	35
balk	25	30	35
kolom	30	35	40
poer	-	40	45

milieuklasse voor op deze tekening aangegeven onderdelen is milieuklasse: ZIE TABEL

dekking niet kontroleerbaar : 5 mm ekstra
betondekking op hoofdwapening : als $\varnothing_k \leqq 25$, C $\geqq \varnothing_k$
als $\varnothing_k > 25$, C $\geqq 1{,}5\ \varnothing_k$

cementsoort: CEM IIIB/42,5
cementklasse:

betonsterkte: ZIE TABEL
$\bar{x}_3$ bij ontkisten

maten (ook peilmaten) in mm
peilmaten t.o.v. peil
peil is b.k. afgewerkte begane grondvloer = 31.00 m+ N.A.P.

A	B	C	D	E	F	G	H	J	K	
										install. c.v.
										elektra
										liften
										luchtbeh.
										riolering
	1									advies c.v.
										elektra
										liften
										luchtbeh.
										riolering
			2	2	2					opdrachtgever
2	2	2	1	1	1					architekt
	1		1	1	1					opzichter
	4		4	4	4					aannemer
										b. en w. toezicht

Academisch Ziekenhuis Nijmegen St Radboud
Faculteit der Medische Wetenschappen

Herstructurering en (ver)nieuwbouw

32000+
7 28000+
6 24000+
5 20000+
4 16000+
3 12000+
2 8000+
1 4000+
0 P=0(31m+NAP)
-1 4160-
-2 6810-

0 1 2 3 m

	datum :	omschrijving:	get.	gek.	gez.
H					
G					
F	25-08-98	gewijzigd	MV		
E	24-04-98	gewijzigd	ds	bl	
D	08-04-98	gewijzigd	ds	bl	
C	17-02-98	diverse wijzigingen 2e kontrole	cjb	bl	
B	25-07-97	vorm	rb	evc	
A	13-06-97	ter kontrole	cjb	evc	

werk: bouwdeel M260 Onderwijscentrum
St Radboud te Nijmegen

onderdeel: plattegrond nivo -1

architekt:
EGM architecten Dordrecht
Laan der VN 9
postbus 298
3300 AG Dordrecht
telefoon 078-6330660

Nijst Idema Burger architecten
Overschiestraat 59
postbus 9261
1006 AG Amsterdam
telefoon 020-4088222

AHA
ARCHITECTENMAATSCHAP HERSTRUCTURERING AZN ST RADBOUD

schaal: 1:50,1:20
datum:
gezien:

tekening nummer: werknummer 7108/
bouwdeel U3 nivo -1 gedeelte blad A10 functie V
formaat A0
F

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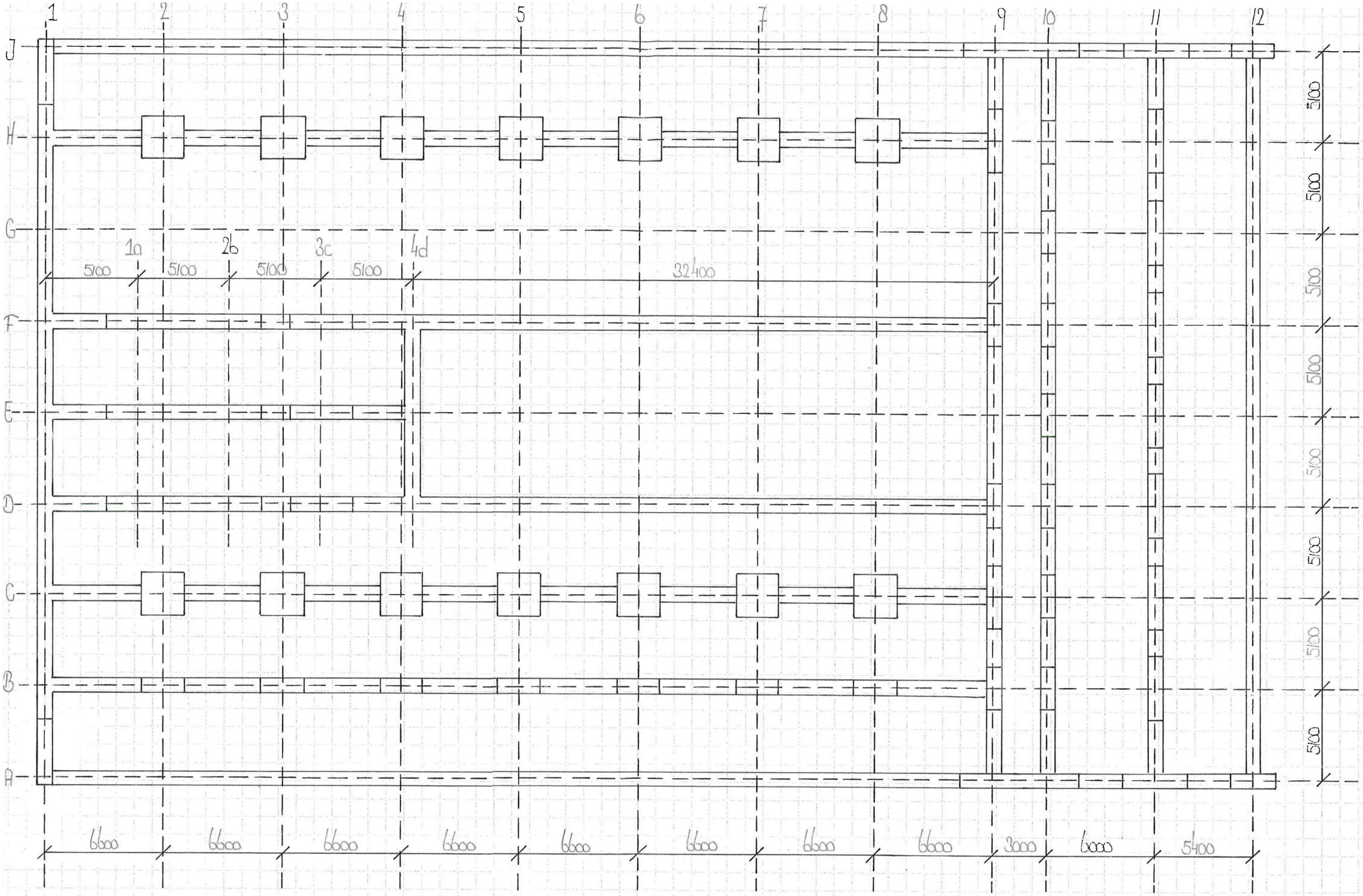
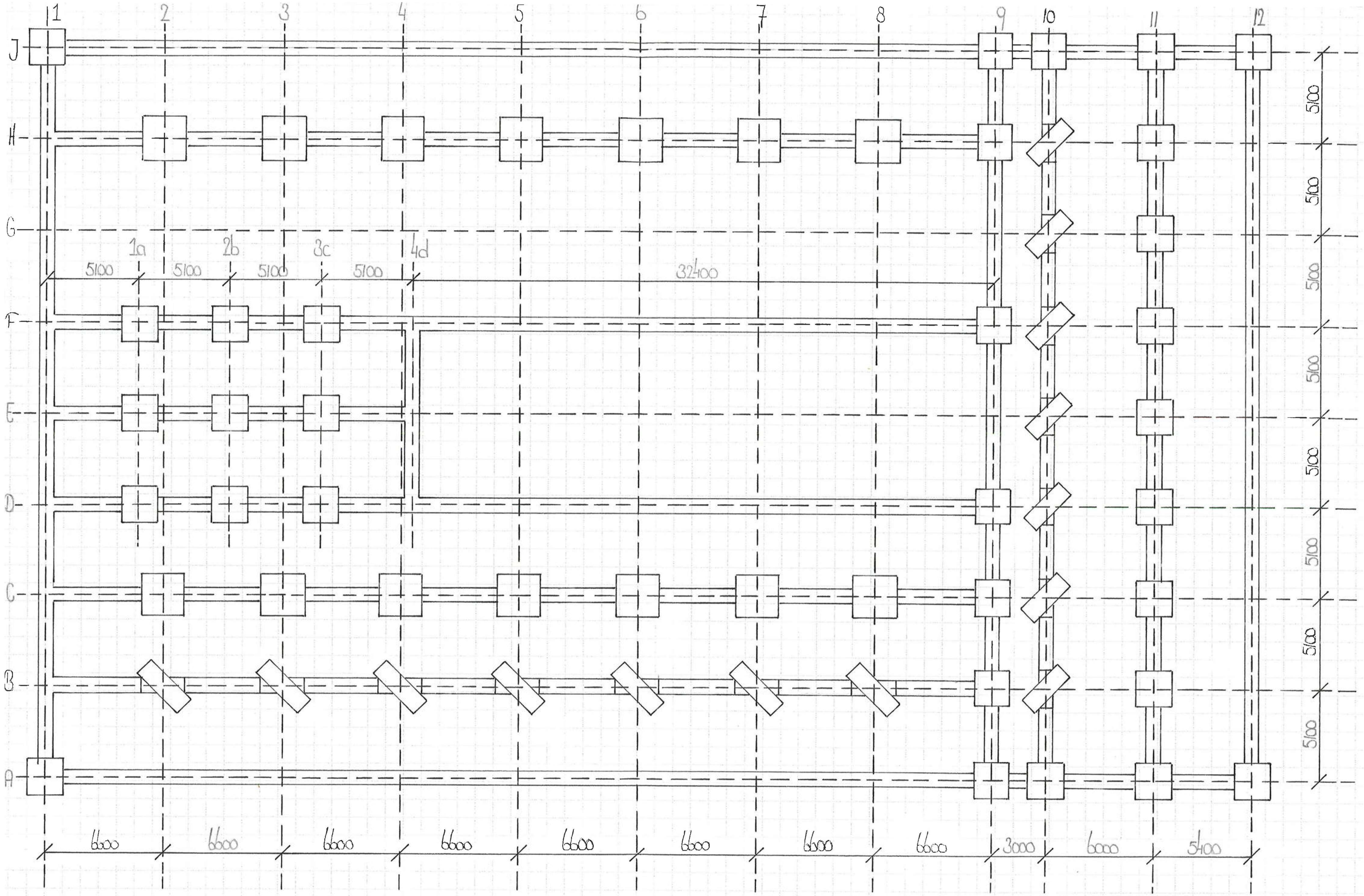


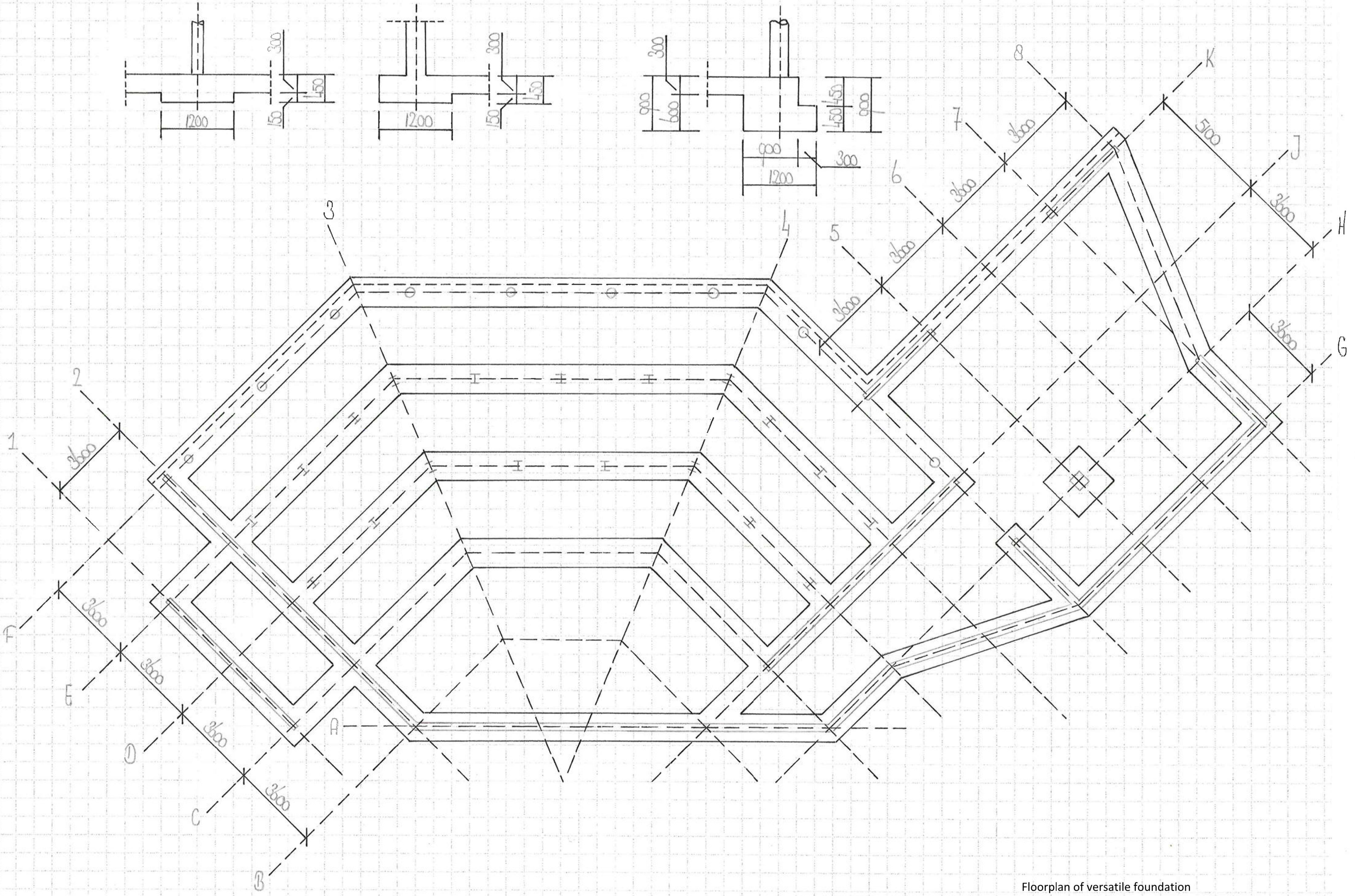
Floorplan of versatile foundation
Project 1, Meander Medical Centre

Size: A3
Scale: 1:200
Unity: mm



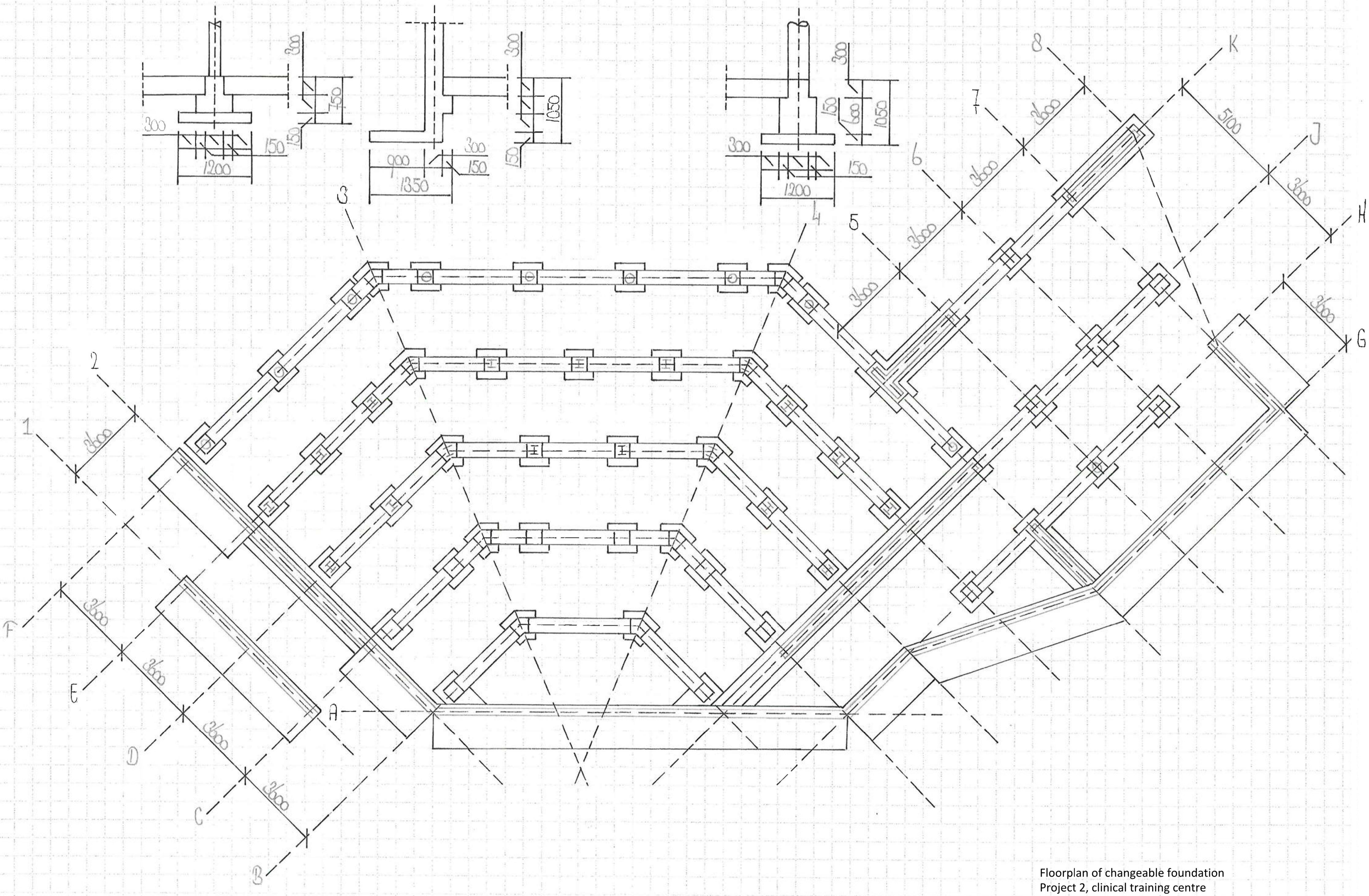
Floorplan of changeable foundation
Project 1, Meander Medical Centre

Size: A3
Scale: 1:200
Unity: mm



Floorplan of versatile foundation
Project 2, clinical training centre

Size: A3
Scale: 1:150
Unity: mm



Floorplan of changeable foundation
Project 2, clinical training centre

Size: A3
Scale: 1:150
Unity: mm

Appendix 9: Bill of Materials

Pile	Diameter (mm)	Section (m²)	Number (-)	Length (m)	Volume (m³)	Mass (kN)
X	410	0.13	225	19.75	587	14667
Y	410	0.13	12	20.25	32	802
Z	510	0.20	4	20.25	17	414
					Total	15883

Cap	Width (mm)	Length (mm)	Height (mm)	Number (-)	Volume (m³)	Mass (kN)
1 - 2 piles	650	2200	1380	21	41	1036
2 - 3 piles	650	3500	1580	11	40	988
3 - 4 piles	2200	2200	1000	12	58	1452
4 - 4 piles	2500	2500	1000	1	6	156
5 - remaining	650	29230	1580	n/a	30	750
6 - remaining	650	10600	1380	n/a	10	238
					Total	4621

Beam	Width (mm)	Height (mm)	Section (m²)	Length (m)	Volume (m³)	Mass (kN)
A	650	680	0.44	19.5	9	215
B	650	980	0.64	74.7	48	1190
C	650	1040	0.68	21.0	14	355
D	650	1160	0.75	34.2	26	644
E	650	1210	0.79	282.7	222	5558
F	650	1480	0.96	46.2	44	1112
G	650	1540	1.00	3.2	3	79
					Total	9154

Table 40. BoM, project 1, traditional foundation

Pile	Diameter (mm)	Section (m²)	Number (-)	Length (m)	Volume (m³)	Mass (kN)
X	410	0.13	257	20.25	687	17177
					Total	17177

Cap	Width (mm)	Length (mm)	Height (mm)	Number (-)	Volume (m³)	Mass (kN)
1 - 2 piles	650	2200	1400	19	38	951
2 - 3 piles	650	3500	1600	16	58	1456
3 - 4 piles	2200	2200	1000	14	68	1694
4 - 4 piles	650	6500	1400	2	12	296
5 - 6 piles	650	8600	1600	3	27	671
					Total	5068

Beam	Width (mm)	Height (mm)	Section (m²)	Length (m)	Volume (m³)	Mass (kN)
A	650	1000	0.65	192.2	125	3122
B	650	1300	0.85	268.5	227	5672
					Total	8795

Table 41. BoM, project 1, versatile foundation

Pile	Diameter (mm)	Section (m²)	Number (-)	Length (m)	Volume (m³)	Mass (kN)
X	320	0.10	138	20.25	286	7154
Y	420	0.18	159	20.25	568	14199
					Total	21353

Cap	Width (mm)	Length (mm)	Height (mm)	Number (-)	Volume (m³)	Mass (kN)
1 - 2 piles	1000	2700	1000	7	19	473
2 - 2 piles	1100	3300	1100	7	28	699
3 - 4 piles	2100	2100	1000	31	137	3418
4 - 4 piles	2400	2400	1100	14	89	2218
					Total	6807

Beam	Width (mm)	Height (mm)	Length (m)	Number (-)	Volume (m³)	Mass (kN)
A	600	900	3000	26	42	1053
B	600	900	3750	4	8	203
C	600	900	4200	18	41	1021
D	600	900	5100	6	17	413
E	600	900	8100	1	4	109
F - ctc 2100	600	1200	8400	9	54	1361
G - ctc 3000	600	1200	9000	8	52	1296
H - ctc 5100	600	1200	10200	7	51	1285
I - closure	600	1200	57000	n/a	41	1026
					Total	8934

Table 42. BoM, project 1, changeable foundation

Strip	Section (mm^2)	Section (mm^2)	Section (m^2)	Length (m)	Volume (m^3)	Mass (kN)
A	1000 x 400	470 x 400	0.59	33.3	20	490
B	1000 x 450		0.45	159.0	72	1789
C	1000 x 400	650 x 400	0.66	12.8	8	211
D	490 x 300	445 x 90	0.19	6.5	1	30
E	1110 x 400		0.44	13.4	6	149
					Total	2669

Pad	Width (mm)	Length (mm)	Height (mm)	Number (-)	Volume (m^3)	Mass (kN)
1	2000	2000	450	1	2	43
					Total	43

Table 43. BoM, project 2, traditional foundation

Strip	Section (mm^2)	Section (mm^2)	Section (m^2)	Length (m)	Volume (m^3)	Mass (kN)
A	1200 x 450		0.54	175.8	95	2373
B	1200 x 450	900 x 450	0.95	48.2	46	1139
C	450 x 450		0.20	9.4	2	48
					Total	3559

Pad	Width (mm)	Length (mm)	Height (mm)	Number (-)	Volume (m^3)	Mass (kN)
1	2100	2100	450	1	2	48
					Total	48

Table 44. BoM, project 2, versatile foundation

Block	Width (mm)	Length (mm)	Height (mm)	Number (-)	Volume (m^3)	Mass (kN)
X	600	600	600	39	8	211
Y 135°	600	600	600	10	2	54
						27
					Total	291

Plate	Width (mm)	Length (mm)	Height (mm)	Number (-)	Volume (m^3)	Mass (kN)
1	1200	1200	150	40	9	211
2 135°	1200	1200	150	10	2	54
3	1200	1800	150	20	6	162
						43
					Total	475

Beam	Width (mm)	Height (mm)	Length (mm)	Number (-)	Volume (m^3)	Mass (kN)
A	600	600	2400	4	3	86
B	600	600	2700	2	2	49
C	600	600	3000	20	22	540
D	600	600	3600	12	16	389
E	600	600	4200	2	3	76
G wall	900	450	57540	n/a	23	583
H remaining	600	600	30160	n/a	11	271
						199
					Total	2192

Table 45. BoM, project 2, changeable foundation

Appendix 10: Overview of calculation, Alba Concepts

	Disassembly Index (DI)		
	1. Connection type	2. Accessibility	Average
Traditional			
Pile	0.1	0.4	0.25
Cap	0.1	0.4	0.25
Beam	0.1	0.4	0.25
Versatile			
Pile	0.1	0.4	0.25
Cap	0.1	0.4	0.25
Beam	0.1	0.4	0.25
Changeable			
Pile	0.1	0.4	0.25
Cap	0.2	0.8	0.50
Beam	0.2	0.8	0.50

Table 46. Index, Alba Concepts, project 1

Traditional			
Strip	0.1	0.4	0.25
Pad	1.0	1.0	1.00
Versatile			
Strip	0.1	0.4	0.25
Pad	1.0	1.0	1.00
Changeable			
Plate	1.0	1.0	1.00
Block	0.8	0.8	0.80
Beam	0.8	0.8	0.80

Table 47. Index, Alba Concepts, project 2

		Origin (%)				Future (%)				Lifespan (y)		Indices (-)			
	Mass (kN)	New	Reuse	Recycling	Biobased	Landfill	Combustion	Recycling	Reuse	Technical	Functional	MI	DI	ECI	BCI
Traditional															
Pile	15883	100	0	0	0	0	0	0	100	100	50	0.78	0.25	0.19	
Cap	4621	100	0	0	0	0	0	0	100	100	50	0.78	0.25	0.19	
Beam	9154	100	0	0	0	0	0	0	100	100	50	0.78	0.25	0.19	
Total	29658	100	0	0	0	0	0	0	100	100	50	0.78	0.25		0.19
Versatile															
Pile	17177	70	0	30	0	0	0	0	100	150	50	0.90	0.25	0.22	
Cap	5068	70	0	30	0	0	0	0	100	150	50	0.90	0.25	0.22	
Beam	8795	70	0	30	0	0	0	0	100	150	50	0.90	0.25	0.22	
Total	31040	70	0	30	0	0	0	0	100	150	50	0.90	0.25		0.22
Changeable															
Pile	21353	70	0	30	0	10	0	0	90	150	50	0.88	0.25	0.22	
Cap	6807	70	0	30	0	0	0	0	100	150	50	0.90	0.50	0.45	
Beam	7767	70	0	30	0	0	0	10	90	150	50	0.90	0.50	0.45	
Total	35927	70	0	30	0	6	0	2	92	150	50	0.89	0.35		0.31

Table 48. In- and output, Alba Concepts, project 1

		Origin (%)				Future (%)				Lifespan (y)		Indices (-)			
	Mass (kN)	New	Reuse	Recycling	Biobased	Landfill	Combustion	Recycling	Reuse	Technical	Functional	MI	DI	ECI	BCI
Traditional															
Strip	2669	100	0	0	0	5	0	95	0	100	50	0.76	0.25	0.19	
Pad	43	100	0	0	0	5	0	95	0	100	50	0.76	1.00	0.76	
Total	2712	100	0	0	0	5	0	95	0	100	50	0.76	0.26		0.20
Versatile															
Strip	3559	70	0	30	0	0	0	0	100	150	50	0.90	0.25	0.22	
Pad	48	70	0	30	0	0	0	0	100	150	50	0.90	1.00	0.90	
Total	3607	70	0	30	0	0	0	0	100	150	50	0.90	0.26		0.23
Changeable															
Plate	475	70	0	30	0	0	0	10	90	150	50	0.90	1.00	0.90	
Block	291	70	0	30	0	0	0	10	90	150	50	0.90	0.80	0.72	
Beam	2192	70	0	30	0	0	0	20	80	150	50	0.90	0.80	0.72	
Total	2958	70	0	30	0	0	0	17	83	150	50	0.90	0.90		0.74

Table 49. In- and output, Alba Concepts, project 2

Appendix 11: Overview of calculation, alternative method

	Material Recyclability Indicator (MRI)			Element Reusability Indicator (ERI)					System Reusability Indicator (SRI)		
	1. Connection type	2. Damage	Average	1. Quality	2. Dimensions	3. Damage	3. Expandability	Average	1. Diversity	2. Grid	Average
Traditional											
Pile	0.2	0.4	0.30	0.5	1.0	n/a	0.7	0.73			
Cap	0.2	0.4	0.30	0.5	0.6	n/a	0.7	0.60			
Beam	0.2	0.4	0.30	0.5	0.1	n/a	0.7	0.43			
Total									0.7	0.7	0.70
Versatile											
Pile	0.2	0.4	0.30	0.7	1.0	n/a	0.7	0.80			
Cap	0.2	0.4	0.30	0.7	0.6	n/a	0.7	0.67			
Beam	0.2	0.4	0.30	0.7	0.6	n/a	0.7	0.67			
Total									1.0	1.0	1.00
Changeable											
Pile	0.2	0.4	0.30	0.7	1.0	0.6	n/a	0.77			
Cap	0.2	0.4	0.30	0.7	1.0	0.8	n/a	0.83			
Beam	0.2	0.4	0.30	0.7	1.0	0.8	n/a	0.83			
Total									1.0	1.0	1.00

Table 50. Indicators, alternative method, project 1

Traditional											
Strip	0.2	0.4	0.30	0.5	0.6	n/a	0.5	0.53			
Pad	0.2	0.4	0.30	0.5	0.6	n/a	0.5	0.53			
Total									1.0	0.1	0.55
Versatile											
Strip	0.2	0.4	0.30	0.7	1.0	n/a	0.7	0.80			
Pad	0.2	0.4	0.30	0.7	1.0	n/a	0.7	0.80			
Total									1.0	1.0	1.00
Changeable											
Plate	0.2	0.4	0.30	0.7	1.0	1.0	n/a	0.90			
Block	0.2	0.4	0.30	0.7	1.0	0.8	n/a	0.83			
Beam	0.2	0.4	0.30	0.7	1.0	0.8	n/a	0.83			
Total									1.0	1.0	1.00

Table 51. Indicators, alternative method, project 2

		Origin (%)		Future (%)			Lifespan (y)		Indicators (-)		Indices (-)	
	Mass (kN)	New	Non-virgin	Loss	Recycling	Reuse	Technical	Functional	ERI	SRI	ECI	SCI
Traditional												
Pile	15883	100	0	0	0	100	100	50	0.73		0.57	
Cap	4621	100	0	0	0	100	100	50	0.60		0.47	
Beam	9154	100	0	0	0	100	100	50	0.43		0.34	
Total	29658	100	0	0	0	100	100	50		0.70		0.34
Versatile												
Pile	17177	70	30	0	0	100	150	50	0.80		0.72	
Cap	5068	70	30	0	0	100	150	50	0.67		0.60	
Beam	8795	70	30	0	0	100	150	50	0.67		0.60	
Total	31040	70	30	0	0	100	150	50		1.00		0.66
Changeable												
Pile	21353	70	30	10	0	90	150	50	0.77		0.62	
Cap	6807	70	30	0	0	90	150	50	0.83		0.75	
Beam	7767	70	30	0	10	90	150	50	0.83		0.70	
Total	35927	70	30	6	2	92	150	50		1.00		0.66

Table 52. In- and output, alternative method, project 1

		Origin (%)		Future (%)			Lifespan (y)		Indicators (-)		Indices (-)	
	Mass (kN)	New	Non-virgin	Loss	Recycling	Reuse	Technical	Functional	ERI	SRI	ECI	SCI
Traditional												
Strip	2669	100	0	0	0	100	100	50	0.53		0.22	
Pad	43	100	0	0	0	100	100	50	0.53		0.22	
Total	2712	100	0	0	0	100	100	50		0.55		0.22
Versatile												
Strip	3559	70	30	0	0	100	150	50	0.80		0.72	
Pad	48	70	30	0	0	100	150	50	0.80		0.72	
Total	3607	70	30	0	0	100	150	50		1.00		0.72
Changeable												
Plate	475	70	30	0	10	90	150	50	0.90		0.75	
Block	291	70	30	0	10	90	150	50	0.83		0.70	
Beam	2192	70	30	0	20	80	150	50	0.83		0.75	
Total	2958	70	30	0	17	83	150	50		1.00		0.67

Table 53. In- and output, alternative method, project 2

Appendix 12: Review of the masses

The starting point of the assessment method determined the mass of the foundation elements. The overview of the masses, in Table 40 through Table 45, provides the opportunity to evaluate the required amount of material for each foundation element and system. In the circular economy, reduce is a high level of circularity, even better than reuse or recycling. Reduce is defined as a precondition so should be pursued.

Project 1

The medical centre, project 1, has a deep foundation, consisting of piles, caps and beams. In general, the total mass of the circular foundation is larger than the mass of the traditional foundation due to an increase of the piles' and caps' mass. The increases are lager in case of the changeable foundation. For the versatile foundation, the increase of mass, resulting from rounding of dimensions to 100 mm and repeating the elements in the system, is limited. The dimensions are not rounded to 300 mm since the elements already incorporate additional load bearing capacity, as a result of the high loads considered. The additional mass of the changeable foundation is significantly larger. This is the result of only applying two- and four-pile caps, turning the two-pile caps and rounding dimensions to 300 mm. These adjustments improve the reusability of the modules. In contrast, the mass of the beams decreases in both cases. Enlarging the size and number of piles and caps reduces the dimensions and thus the mass of the beams. Differences also occurred due to the slightly adapted floorplan. All numbers are provided in Table 54.

	Traditional	Circular, versatile		Circular, changeable	
Piles	15883	17177	+8.1 %	21353	+34.4 %
Caps	4621	5068	+9,7 %	6807	+47.3 %
Beams	9154	8795	-3.9 %	7767	-15.2 %
Total	29658	31040	+4.7 %	35927	+21.1 %

Table 54. Mass (kN) and difference (%) of the elements and total foundation, project 1

Table 55 presents the share of each foundation element to the total foundation, based on the mass. These numbers also indicate the increasing share of piles and caps and decreasing share of beams. The share of an element to the relevant foundation remains approximately the same. The share of the total foundation is approximately 55% to 60% for piles, 15% to 20% for caps and 20% to 30% for beams.

	Traditional		Circular, versatile		Circular, changeable	
Piles	15883	54 %	17177	55 %	21353	59 %
Caps	4621	16 %	5068	16 %	6807	19 %
Beams	9154	31 %	8795	28 %	7767	22 %
Total	29658	100 %	31040	100 %	35927	100 %

Table 55. Share (%) of the foundation element to the total foundation, based on mass (kN)

For the changeable foundation, the perimeter of the building and courtyard cannot be completed with a whole number of beam modules. Therefore, some closure elements are needed, which were assumed to be 10% of the total beam mass. These beams can be recycled but consequently require new energy. It was also presumed that 10% of the piles would not be reused. This mass will be landfill and thus loss of material. Therefore, in contrast to the versatile foundation, not all elements will be reused, and additional material and energy are needed.

Project 2

Project 2 concerns the shallow foundation of the university building. As noted in the previous project, the mass of the circular foundations is larger than the mass of the traditional foundations. In this case, the increase of mass is larger for the versatile foundation than for the changeable foundation. This difference is manly caused by the rounding of the element dimensions. The dimensions of the strips and pad of the versatile foundations are rounded to 300 mm to create additional load bearing capacity. It was presumed that the additional load bearing capacity of the traditional foundation was limited, in contrast to previous project. The elements of the changeable foundation were also rounded to 300 mm. However, this step did cause such a large increase because of the relatively small modules. These elements enable a more precise design. In both cases, differences occurred as a result of adapting the floorplan, repeating the elements and centre-to-centre distances. The masses are presented in Table 56.

	Traditional	Circular, versatile		Circular, changeable	
Strip	2699	3559	+33 %	n/a	n/a
Pad	43	48	+10 %	n/a	n/a
Total	2712	3607	+33 %	2958	+9 %

Table 56. Mass (kN) and difference (%) of the elements and total foundation, project 2

For the changeable foundation, not only closure beams are needed; closure plates and blocks are also needed to complete the foundation. It is assumed that 10% of the plates and blocks and 20% of the beams are closure elements. Presumably, these elements will not be reused, but recycled. As indicated, recycling requires more energy than reuse.

Conclusion and discussion

Generally, the total mass of the foundation increases for a circular instead of a traditional foundation design. This increase is mainly caused by rounding and repetition of dimensions and applying additional load bearing capacity. These adjustments have to improve reuse. Although this contradicts the precondition of reducing the amount of material, the extra investment can save material and energy in the future. If the elements or system can be reused several times, intermediate use of new material is avoided. Instead of constructing three times a new foundation, foundation systems or elements can be reused three times. This change saves material and energy since the extra investment is not a multiple of the traditional variant.

In the case studies, the masses depend on the load bearing capacity and rounding and repetition of dimensions. Versatile foundations require additional load bearing capacity, resulting in larger elements, thus an increase of mass. In project 1, this increase was incorporated in the traditional foundation, while in project 2, it had to be added. The increase of mass, as a result of additional load bearing capacity, does not apply to changeable foundations. Rounding dimensions ensures that modules facilitate a load range and are interchangeable. Comparing the projects demonstrates that it is easier to limit the mass when small modules are applied. When larger modules are applied, the mass quickly increases.