Building a Circular Future

3rd edition — 2018

Originally published in 2016 with support from
the Danish Environmental Protection Agency

Building a Circular Future

— 3rd Edition

Key findings

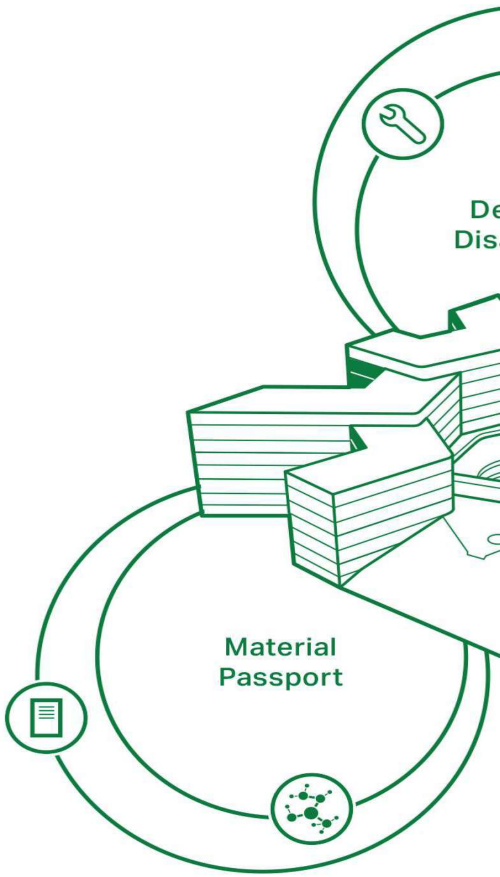
This publication thoroughly calculates the effects of Building a Circular Future on a 42.000 m² representative case study office building with a new built value of DKK 860 million.

A positive business case

Redesigning the case study building and implementing circular economy principles, turns the current demolition costs of the building into a positive business case.

Go from todays DKK 16.000.000
in demolition costs.

To a future with DKK 35.000.000
in business upside.



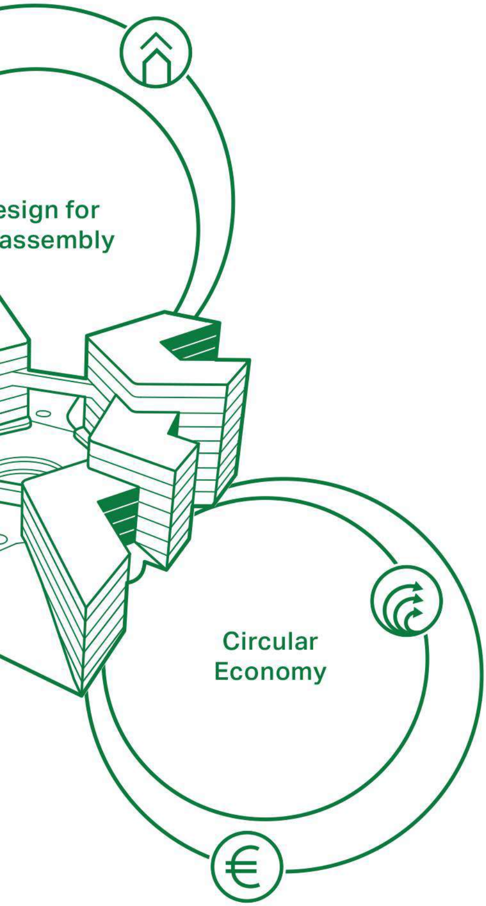
Resale earnings

The resale value of the case study compared to turn key cost. Due to resource scarcity; earnings will increase over time.

Earn 4% of the new build value
on the superstructure and envelope,
in todays material prices.

Earn 8% of the new build value
on the entire building,
in todays material prices.

Earn 16% of the new build value
on the entire building, in +50 years
in projected material prices.



Prerequisites for reuse

To prepare buildings for a circular future todays building practice has to integrate the following.

Material passport
establish functionality information at component level.

Circular Economy
implement business models that supports a circular transition.

Design for disassembly
make all joints visible, mechanical, dissolvable, similar and common.

Immediate and short term gains

Implementing circular principles creates immediate gains and a flexible building from day one.

Improved flexibility
by easier adaptation of buildings and functions.

Faster construction
by shortening drying times and optimizing workflow.

Optimized maintenance
by simple connection logic and detailed information at component level.

Introduction
— 3rd Edition

With 'Building a Circular Future', we want to challenge and rethink the way we use and reuse resources in the building industry, and ultimately eliminate the concept of waste. Since we issued the 1st edition of 'Building a Circular Future' in 2015, there has been a significant development as more and more stakeholders in the construction industry and other industries have engaged in the circular economy.

In June 2017, John Sommer presented our findings at the first World Circular Economic Forum in Helsinki with participants from 105 countries. In Denmark, Kasper Guldager was appointed as chair of the building industry section in the Danish Government advisory board for circular economy. In September 2017, the board issued their first recommendations, and the Danish Government has already taken the first initiatives for implementing a circular economy. The most important recommendations relevant to the construction industry are the following; develop a circular building code, develop material passports for buildings, base public procurement on life cycle costs and extend the use of selective deconstruction and demolition.

Since issuing the second edition of 'Building a Circular Future' in 2016, the lead authors Kasper and John have been giving lectures on the subjects discussed in the book at Columbia University, New York, Yale University, New Haven, Stanford, San Francisco and IMD Lausanne among others. Moreover, the book has been requested and explored by professionals in several different countries across the world; Australia, United States, Canada, United Kingdom, Germany, Belgium, Holland, Finland, Switzerland, Norway, Sweden and Denmark. Also in 2018, Kasper started as visiting professor of Circularity at the University of Calgary School of Environmental Design and at Delft University School of Architecture.

Respecting the positive response we have recieved following the 1st and 2nd editions, and because we believe the book still has great relevance to practitioners in the industry, politicians, academics and students interested in the subject, we have decided to reissue the book in a 3rd revised edition.

New content

The prelude before the table of contents includes new material under the chapters; Faster, Smarter and Flexible, Five Circular Business Models and The Circular Future is now. At the end of the book an additional section regarding the environmental impact has been included.

1. Faster, Smarter and Flexible. This section illustrates how design for disassembly and circular thinking provides immediate value to the owners of the Quay Quarter tower in Sydney through upcycling existing structures, installation of flexible floors and preparation for future recycling.

2. Five Circular Business Models. This section sketches out five generic business models which are applicable in part, in whole, or in combination for companies that want to develop or extend their value proposition and business model to be able to pursue circular opportunities in the construction industry.

3. The Circular Future is Now. This section provides perspectives on why there is presently a window of opportunity for companies, industries, and nations to take advantage of the opportunities the circular future provides, by differentiating their value proposition from that of their competitors and to get ahead of the competition.

The new Environmental Impact section (beginning page 243) also demonstrates how 'going circular' not only preserves the value of the materials and resources reused or recycled, but also reduces CO_2 emissions from the construction industry substantially — and why 'going circular' can thus be an important element in combating climate change.

Kasper Guldager Jensen and John Sommer

Editors and Lead Authors

Faster, smarter, flexible
— circular construction with immediate gains

The built environment plays a vital role in the global economy and can be an engine for sustainable innovation and growth. Accelerating the ongoing transition from a linear to a circular economy in the construction sector can vastly increase this potential. This section illustrates that the transition is already here. It provides up-to-date examples of large-scale material upcycling, integrated design for disassembly strategies, and new partnerships that promise to link prosperity to healthy and environmentally sustainable solutions.

The examples show how circular thinking provides immediate value for construction clients and building tenants – and how this value can scale on large projects. This is good news for a sector characterised by outsized costs and huge material volumes. For the owners of the 49-storey, 200 meter tall Quay Quarter Tower in Sydney, the upcycling of the existing structure on-site will lead to substantial economic and environmental savings. Installation of flexible floors introduces further potential gains to the project, giving client and tenants the flexibility to explore the value of social dynamism while humanising the high-rise.

The circular economy seeks to design out waste to increase the well-being of people and environments. Keeping products and materials circulating at their highest value in the construction sector requires the introduction of design for disassembly into all parts of a building. The Circle House project demonstrates that this is possible. The project brings together more than 30 companies in the Danish construction sector to create 60 housing units built entirely according to circular principles, and allowing 90% of all materials to be reused at high value.

Circle House shows the power of collaboration within the construction sector. This is crucial for turning principles into practice and releasing the value inherent in a circular economy. Partnerships reaching beyond the sector will further allow innovative companies to adopt new business models and technologies to gain a competitive advantage. The Circularity Lab shows one model for how this can be organised while simultaneously demonstrating how design, construction, materials innovation, and technology can accelerate the transition towards circular economy in the built environment.

Transform, reuse and revitalise
— quay quarter tower, sydney

Location Sydney
Year 2014
Owner AMP Capital
Architect 3XN Architects
Size 102,000 m^2

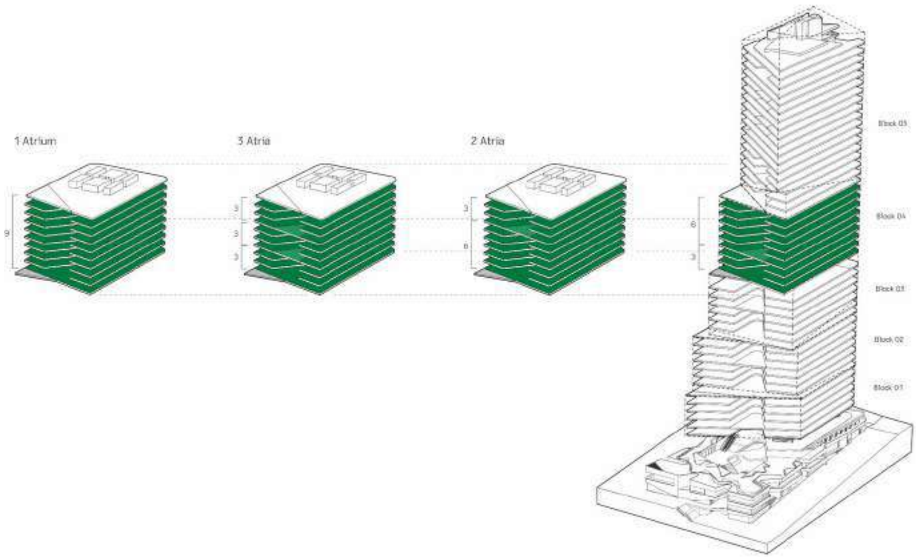
Quay Quarter Tower
In developed countries, 85% of the buildings that will be around in 2050 have already been built[a]. If we want to introduce circular economy to the built environment, we need viable strategies for how to work with existing buildings – and these strategies need to focus on both material economy and social value.

Located in Sydney, the Quay Quarter Tower shows a way forward for how we can apply circular economy principles at a significant scale on existing buildings. The redesign of the 49 story, 200 meter tall high-rise reuses substantial parts of the existing structure, while transforming the tower into a state-of-the-art office building with flexible facilities and optimised views of the harbour.

Circular Economy leads to Economic and Environmental Savings
Accounting for the existing structure, the designers and client ensured that 65% of columns, beams, and slabs, as well as 95% of structural walls were reused in the redesign of the building. This ensured that 50% of the resources required for the new tower were directly reused from the existing building.

Retaining and reusing parts of the core and structural walls, the project was estimated to save the client 130.000.000 AUD compared to a full demolition[b]. This covers substantial material costs as well as time and expenses from a costly demolition in the heart of Sydney's CBD. The 50% saving in materials also meant significant reductions in CO2 emissions for the project; a total of 7.505 tons of CO2 was saved by reusing materials[c], equivalent to 2.500 one-way flights from Sydney to Copenhagen.

Photo: 3XN Architects visualisation of how the refurbished Sydney Tower will appear from street level.



Increasing flexibility
Flexible mechanical joints prepare the structure for potential reuse in the future. The tower's five large atria areas have been designed to be highly flexible and easy to reconfigure for changing building use in the future.

Flexibility is ensured by enabling new tenants to remove or relocate the atrium floors within the void space at different levels of the atrium. The design of these partial floors utilise design for disassembly principles to ensure that they are easy to assemble without disturbing ongoing use of the building. The atria floors are made in standardised steel profiles, all joints and connections are mechanical, and all elements are dimensioned to fit within the tower's service elevators. This ensures that assembly and disassembly requires no extra scaffolding, no polluting construction techniques, and makes reconfiguration of floor plans or whole sections of the tower possible with a reduced construction time.

Expanding the Value of Circular Economy
Designing flexibility directly into the structure of the Quay Quarter Tower via design for disassembly principles is central to the social value proposition of the project. Rather than have one large volume distributed across 49 separate floors, the design utilises five volumes stacked upon each other, each connected by a large atrium. When built, the tower will not feel like a high-rise, but a vertical village that acts as a catalyst for a dynamic working environment and sense of community.

To achieve this, the designers and client have insisted on appropriating some of the most area of the tower to create light and airy spaces that increase connection, interaction, and cohesion; and thus, a sense of community. This is done from a belief that contemporary office buildings must provide more than just efficient enclosures around their tenants, and a belief that there is great value to be found in social cohesion. Adapting design for disassembly principles from circular economy has made this added social value possible, as these allow the client to trust that atria spaces can be re-configured to better fit changing tenant and user needs.

The Quay Quarter Tower expands the value of circular economy by introducing social and aesthetic concerns into the equation alongside material and construction costs. With its design, the new building looks at the 'high rise' in an entirely new way, every architectural solution aiming at creating added value for people - both the users inside the building and for the people around it. It also points towards a future where the circular economy in the built environment increasingly embraces and expands the possibilities of existing buildings while integrating flexibility, social, and aesthetic value into their business models. Quay Quarter Tower does more than upcycle an existing tower, it also *humanizes the high-rise.*

a According to the Chartered Institute of Building
b Estimated savings at time of design. Final savings is not available.
c Calculations from the Carbon Value Engineering Team at CRC Low Carbon Living

Diagram (opposite): Floor structure components designed using design for disassembly principles are used to extend the existing structure and allows for flexibility.

Image (bottom): visualisation of the proposed atrium space within the refurbished quay quarter building.

Images © 3XN Architects

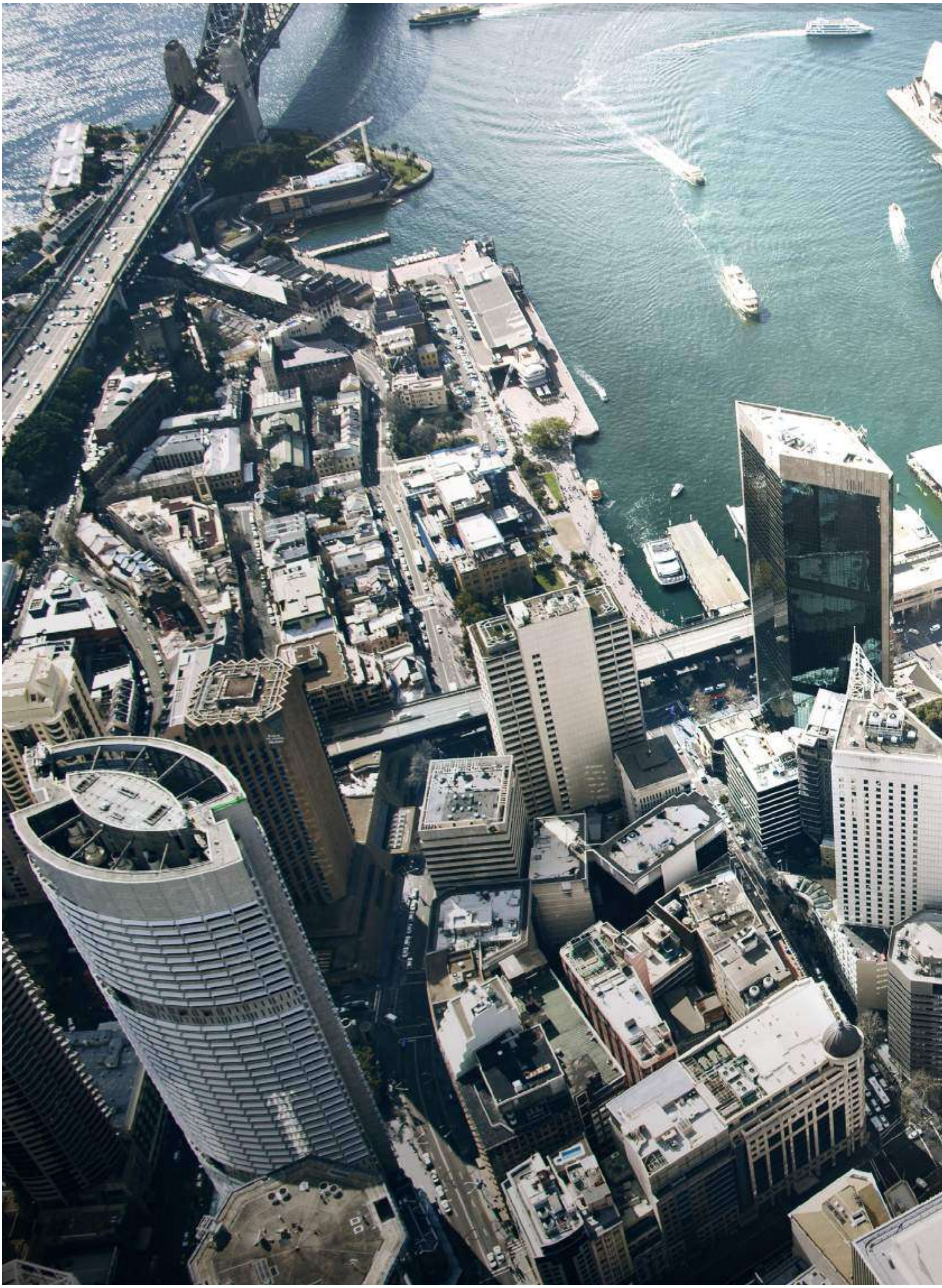


Image: An aerial view of the Quay Quarter tower.
Image © 3xn

Experimental, ambitious and inclusive
— circularity lab, san francisco

Location San Francisco
Year 2019
Owner Google
Architect 3XN Architects
Engineer Arup
Contractor Turner
Size 50 m²

Image: 3XN visualisation of how the approach to the Circularity Lab experimental pavilon will look.

Circularity Lab
The Circularity Lab asks people to imagine a world without waste while exploring the potential of design and collaboration to accelerate the transition to a circular economy. Arup, Turner Construction, and 3XN Architects along with GXN Innovation are working together with support from Google to take circular principles into the construction sector and demonstrate the power of circular design. A full-scale prototype building in the San Francisco Bay Area will illustrate the opportunities and challenges circular design brings to buildings and cities, and demonstrate design for disassembly, materials innovation, new economic models, and technical solutions.

Design Drives the Circular Economy
Design is a vital driver for the circular economy. The greatest opportunity for delivering buildings and products that fit within circular frameworks and economic models is at the design stage. Where principles and business cases are crucial for showing the possibilities inherent in the circular transition, design gives these possibilities form and substance. The power to reconfigure complex problems into new aesthetic and functional solutions is the

fundamental attraction of design; in this way design turns principles into practice, and promises into salient experiences that can show the way forward for society.

At the same time, the transition from a linear to a circular economy in the built environment requires design strategies that are scalable and reach beyond the individual instance. Applying design for disassembly and lifecycle design across urban scales is essential to building a truly circular urban environment and holds large potential gains for people, businesses, and the environment. Good design should not only provide society with exemplars for a future circular economy, it should also enable contractors to build structures faster and architects and engineers to design buildings that are smarter and more flexible for their tenants.

Make it Innovative, Make it Real
The Circularity Lab addresses the twofold challenge of circular design by advancing a striking vision of circular architecture and creating a scalable construction system for a 1:1 demonstrator to be built in the Bay Area.
The full-scale prototype building will demonstrate that circular construction is feasible and should help companies explore economic possibilities in the circular economy. One aim is to demonstrate commercially available materials and technologies, and the lab includes a variety of partners who are already engaged in the circular agenda and can deliver actual solutions.

With the Circularity Lab Call for Innovative Materials, the lab also invites companies, researchers, and backyard inventors of all stripes to submit the most exciting examples of circular products and materials for the built environment. These could be anything from roof tiles made of recycled plastic to egg cartons made of grass.

The submissions will be entered into a competition and the best entries will win a place in the opening exhibition of the Circularity Lab.

Partnerships add Competitive Advantages

The circular economy is collaborative by definition. Designing and building for disassembly and keeping materials in circulation at high value requires new partnerships in construction. Companies that understand the power of inter- and cross-sector partnerships for adapting to new business models and technologies will have a competitive advantage in the circular economy. The Circularity Lab show the construction sector what a circular economy in the built environment might look like, but it will also demonstrate how a new team of stakeholders can collaborate to accelerate the circular transition and business development.

New models for collaboration will affect the business of all companies in the construction value chain. The Circularity Lab demonstrates new ways of organising projects to enable improvements from the earliest stages of the design process. Defining new models for collaboration throughout design, procurement, construction and operations can enable circular solutions through cheaper and better project delivery, up-scaling design for disassembly, and enabling recycling of building materials at a higher value during both construction and demolition.

Image (opposite): Visualisation showing the interior of the Circularity Lab experimental pavilion, with a display of circular materials, one possible use for this space.

Image (bottom): Visualisation of the Circularity Lab experimental pavilon.

Image (top): GXN visualisation of how the Circle House demonstrator unit will look when completed.

Images (left and above): Details of the Circle House demonstrator unit, showing the use of Pretty Plastic recycled plastic tiles and Komproment ceramic shingles in combination with burnt timber cladding.

A scaleable building solution
— circle house, copenhagen

Location Copenhagen
Year 2018
Owner Lejerbo
Architects Lendager Group, Vandkunsten, 3XN Architects
Size 5.500 m^2 (Final project) and 40 m^2 (Demonstrator)

Circle House
The Circle House project, with Lejerbo as the client, is building the world's first social housing units built entirely according to circular principles, where 90% of all material can be reused at a high value. This means, among other things, that the construction can be disassembled again and the elements recycled without significant loss of value.

Background
The Circle House project consists of 60 social housing units in Lisbjerg, near Aarhus in Denmark, which is expected to be completed by 2020. In addition to serving as housing, Circle House is a scalable demonstration project that can introduce new knowledge to the construction industry about the experience of circular building.
The project is a collaboration between 3XN Architects, Lendager Group and Vandkunsten and is expected to be offered in 2018. The construction is due to begin in 2019, and will be completed during 2020.

Framework conditions and business
The transition to circular building implies, among other things, that the components must be produced so that they can be cleanly seperated for reuse. However, it is not just a purely technical challenge. Today, some of the key elements in the building's value chain are also missing, which are necessary to allow the materials to be recycled. In only a few cases will manufacturers offer to take back their own used products to allow them to be sold again. Leasing, which is common practice in the automotive industry, is also not yet developed for building construction.

There is also a need to re-establish the traditional business models and ensure that the legislation supports material recycling. This is key to accelerating circular construction methods within the industry. It is currently unclear for example who is responsible for the used components and the quality of the material.

The Circle House project wants to get closer to answering these challenges. The project aims to analyse value chains, business models, business cases and framework conditions. All results and recognitions are shared through a broad discussion of circular construction throughout the industry. This part of the work has been supported by Realdania.

The Circle House project aims to develop and distribute knowledge of circular construction across the industry and across sectors. In order to achieve this, the project has brought together 30 different companies from across the entire building value chain. The future goal is a scalable circular lighthouse building project that is offered on market terms by 2020.

Circle House in numbers

— Circle House consists of 60 social housing units built according to the principles of circular economy.
— The objective is that 90% of residential materials can be recycled without losing significant value.
— The project runs for over 3 years, starting in spring 2017.
— The building is expected to be offered, on market terms, by the end of 2018
— The building is expected to start in 2019 and be completed by 2020.
— The project involves more than 30 companies from the Danish construction industry across the entire value chain.

Photo (top): Detail of the prefabricated concrete structure provided by Consolis showing the steel connections that allow for clean dissassembly.

Photo (right): Facade build up using MDfacade expanded insulation cork panels mounted on timber battens.

Photos © GXN

Five Circular Business Models
— five models for the circular future

Circular economy is as much about economy as it is about enhancing resource productivity through optimal sustainable use and re-use of resources. Hence, any business model relevant to the circular economy must focus on value capture and creation.

Any business designing a model addressing the circular economy should therefore include the basic elements as described by Alexander Ostenwalder in his book 'Business Model Generation' [d], where he outlines how value is created for customers and how profit is secured.

There are a number of different ways to approach designing and building a business model that exploit the opportunities presented in a world that progresses toward circular principles. In their book 'Waste to Wealth' [e], Accenture's Peter Lacy & Jakob Rutqvist suggest five different general business models for the circular economy which are free of linear constraints.

On the following pages, the basic ideas for Lacy & Rutqvist's five business models are explained and expanded upon with a view to a construction sector perspective.

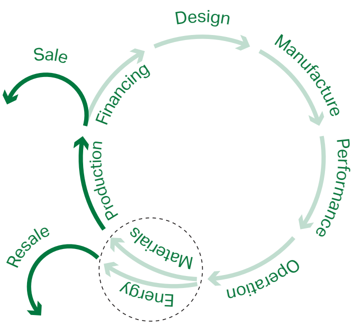
The models are described in a generic, isolated form to allow them to be explained in detail. However, in real life circumstances most companies are expected to use a combination of elements from multiple models when building their own value proposition and business model.

When designing and building these new value propositions and business models, companies can benefit greatly from applying the ideas of Blue Ocean Strategies. The value propositions for a circular future do not necessarily need to match the current propositions offered by traditional companies in the present economy. As an example, the design and construction costs will most likely be less significant than the total cost of ownership for a leased building, road or bridge, unlike the current procurement situation governed by traditional thinking. Likewise, the customer will most likely be more satisfied having an elevator, a lighting or heating system installed that operates without issue, as opposed to owning these facilities and having to service them themselves.

For further descriptions of the models and their use, refer to the Danish publication 'Circular Buildings' [f]

d Business Model Generation
e Waste to Wealth — The Circular Economy Advantage

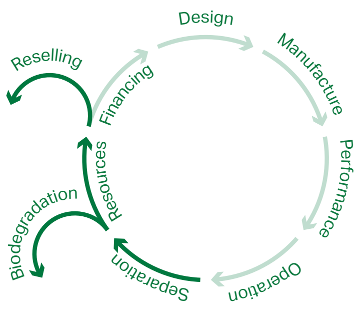
f Det Cirkulære Byggeri — Scenarier – Trends – Forretningmodeller

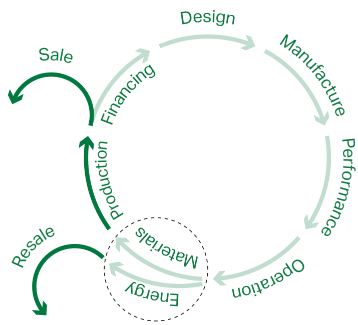


1. Circular supply chain

The general commercial concept behind this model suggests that companies who are currently producing their products using scarce or environmentally destructive resources should find alternative fully renewable, recyclable, or biodegradable materials as a basis for their production.

Products should rely on the development or sourcing of new materials that are less resource intensive or fully recycleable, particularly those that are bio-based. Additionally these resources should be able to be used in consecutive lifecycles, thereby reducing costs and increasing predictability and productivity in the supply chain. New processes could be further developed to increase the reusability of construction and industrial products, by-products, and waste streams.





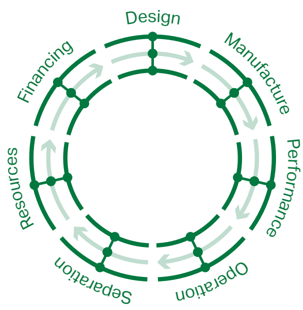
2. Recovery and Recycling
This model emphasises the exploitation of end of life products, either generated by the business itself or other businesses, as a basis for their future production. This model also includes recovery and recycling of energy.

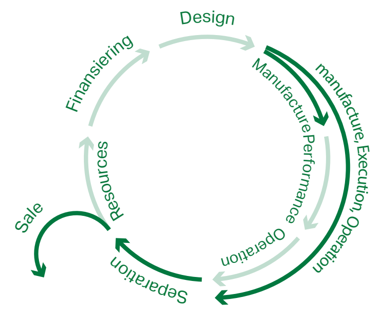
By reusing materials and resources at the end of their current use the amount of waste is reduced significantly and therefore in most instances, so is the cost of resources. The profit from a change in production will increase with streamlined efficiency in usage of the 'new' resources and with the increased cost of traditional resources.

This model is however not an entirely new concept to the construction industry. Brick, stone, and timber for example have been reused for thousands of years in times of scarcity.

3. Product Life Extension
This business model aims to extend the lifespan of the products produced and exploit the value of this extended life time. This covers both resale, upcycling, restoration, and rebranding of the existing product with the purpose of maintaining, increasing or extending their current value. In the construction industry this model could be applied by building higher quality, more flexible, sustainable buildings and rent them to the market instead of selling them.

This model is to some extent already being introduced as a number of clients with a long economic horizon build buildings that are able to maintain their value for longer periods of time. This is also seen when municipalities or the state build their buildings using the PPP and BOT models, where the PPP or BOT company has the obligation not only to design and construct the building but also to operate it for up to 30+ years.





4. Sharing Platform
This model involves extending the use of existing products which are not fully utilized by sharing them. This model is closely related to the sharing economy. The model builds on renting, sharing, and lending of existing products or buildings that are still in operation, the most famous example of this being AirBnB. Societies could also benefit economically and environmentally from making increased use of public buildings.

A school building for example is empty in the evening and could therefore be used for other purposes. In the circular economy, this model ensures better usage of resources and the extension of the lifespan of products by securing re-use, and a second or even third life of products. Sharing platforms financially exploit opportunities to easily and effectively connect owners without a use for their product, with companies or people that have a need.

5. Product as a Service
This model becomes a direct extension of the sharing platform model. The model builds on the fact that it's not always economically viable to own a product or building. In a number of instances it's wiser to rent a product, lease or even buy a service based on a pay per use principle. In the construction industry this model is applied more on a building scale in which offices, schools, bridges, roads and other structures are rented out.
In the circular economy, this becomes applicable also at a component level. We expect to see building components and fixtures bought as a service and not as a product.

The subsequent benefit of this model to the service companies is that they can exploit economics of scale to develop competencies and therefore implement more efficient solutions. The benefits to the end user include the ability to offer a more reliable service at a lower cost.

The Circular Future is Now
— a circular focus across all levels of business

At present, increased focus is on developing a circular future. This is seen at the highest intergovernmental organizations as well as at the level of the national states, globally branded and privately owned companies and within global consulting businesses, as they all focus on securing responsible consumption and production as well as harvesting the benefits and advantages of a circular economy.

Intergovernmental organizations
The UN launched their 17 Global Goals for a more sustainable and better world in 2017. Half of these goals both require and support the creation of a construction industry that on a global scale is sustainable and circular.

In the European Union, where we consume six times as many resources as we produce, more attention is put on the implementation of more circular economic models. We are still early in the process, but are now seeing that public entities are allowed to select suppliers based on total cost of ownership and not only lowest cost. In the near future, we must expect to see guidelines for green public procurement that will support industries and companies that market sustainable and circular solutions.

At the World Economic Forum, creation of a circular future is getting more and more attention from the top business leaders of this world and the heads of states as it becomes increasingly evident that we cannot continue to secure economic growth and well-being for our populations by means of the current economic models. These models need to be updated to include more and more elements which by current standards are regarded only as externalities. These include; generation of waste, pollution of water, land, and air as well as inattentive use of resources.

In his book 'The Fourth Industrial Revolution'[g] Klaus Schwab, Founder and Executive Chairman, World Economic Forum, states 'New ways of using technology to change behavior and our systems of production and consumption offer the potential for supporting the regeneration and preservation of the natural environment, rather than creating hidden costs in the form of externalities'.

g The Fourth Industrial Revolution

Photos: United Nations' 17 sustainable development goals

We believe in this statement and hope that the third edition of this book will continue to inspire leaders, specialists and practitioners in the construction industry to support and accelerate the introduction of a circular economy in the construction industry.

Doing that, we in the construction industry can contradict Dr. Klaus Schwab's concern 'that decision makers are too often caught in traditional, linear (non-disruptive) thinking or too absorbed by immediate concerns to think strategically about the forces of disruption and innovation shaping our future.

National states
At this level it's seen that the governments in Finland, Holland and Denmark etc. are starting to implement strategies for how they can exploit the opportunities and benefits of the circular economy, and become forerunners in this most promising game.

In late 2015 in Denmark, the Danish Government requested McKinsey and Ellen MacArthur Foundation to analyse the potential of a circular economy in Denmark. In 2016 this initiative was followed up by the Danish government by establishing an Advisory Board for circular economics

This Advisory Board presented their suggestions in the summer of 2017.

Some of these initiatives are now being implemented whereas others are still discussed. Furthermore, State of Green was established as a public private partnership to officially brand Denmark.

The reports from McKinsey and the Ellen MacArthur Foundation, the Advisory board as well as from State of Green are shown here.

In Holland, Finland and Denmark, initiatives are taken to promote the establishment of a circular future through changes in the procedures for public procurement. It's still too early to talk about true Green Public Procurement — but the first steps have been taken.

Photos: Publications relating to the future of denmark as a forerunner in the future of the circular economy.

Photo © GXN

Global companies and businesses
A number of globally branded companies are now seeking to develop and transform their business model in order to be able to exploit the opportunities presented by more circular business models that allow these companies to increase the resource productivity significantly.

At the First World Circular Economic Forum in Finland a range of companies including those such as IKEA, DELL and Philips Lighting presented their strategies for going circular.

Additionally, some of the largest and most respected international consulting companies such as McKinsey, Accenture, KPMG, and Deloitte to name a few are putting increased focus on the opportunities of a circular future. They are all researching in the field and they are all working with clients on an everyday basis in order to help those become leaders of a new, significantly more resource effective world.

Final remarks
In the civil and construction industry we see more on more clients request buildings and structures that are optimized with regards to total costs of ownership and buildings that are certified as sustainable buildings using systems like DGNB, LEED, and BREEAM.

Therefore, it's time for the stakeholders of this industry — who want to become leaders of the industry and secure their relevance in the new economy, to start developing, marketing and selling solutions that are more sustainable and designed for a circular future in which resource productivity is the corner stone. This is the case regardless of whether these stakeholders are the owners, investors, material producers, contractors, architects, or consulting engineers of this industry.


Kingo

Foreword

— by William McDonough

It is wonderful to see the concepts and practices from *The Hannover Principles* (1992) and *Cradle to Cradle: Remaking the Way We Make Things* (2002) being celebrated by a fellow architect. In *Cradle to Cradle*, Dr. Michael Braungart and I posted a values-based design which, by generating perpetual value in the making and remaking of things, puts the 're' back into 'resources' and improves the quality of life. This is now being taken up vigorously by people interested in the 'circular economy', an important concept within *Cradle to Cradle*. In fact, the book was published in China as *Cradle to Cradle: The Design of the Circular Economy* (2005). We further expanded on this in *The Upcycle: Beyond Sustainability — Designing for Abundance* (2013) describing how these approaches to design and commerce can actually improve the state of the world, rather than simply recirculating materials, or worse, continuously downcycling them in endless cycles of contamination.

While the circular economy is the critical part of the quantification of material flows, *Cradle to Cradle* calls first for a qualification of materials, processes and practices. Moving from linear to regenerative 'circular' systems of production and logistics. *Cradle to Cradle* designs go beyond simple less-is-more statistical efficiency toward practices that generate vital, healthy and 'effective' growing systems. Considering quality of life calls upon us to ask questions of our creative values — what is good and what is bad, what is right and what is wrong — before we move to the more straightforward question of value creation, of what is less and what is more.

As an architect and colleague of Kasper Guldager Jensen, I know our job in creating buildings is to put wisdom into practice, to render these important concepts visible for all to see, and to actually build them, allowing everyone to experience firsthand their intergenerational benefit — for all humanity and for all time. Our goal is a delightfully diverse, safe, healthy and just world — with clean air, soil, water and energy — equitably, ecologically, economically and elegantly enjoyed.

This new book is inspiring in its ambition to show us what this can look like now.

Cradle to Cradle is a qualification and quantification, with five criteria:

1. Healthy Materials in Biological and Technical Metabolisms.
2. Circular Economy including quality products and buildings as continuous assets
3. Clean Energy and restorative carbon balances.
4. Clean Water in production and use cycles.
5. Social Fairness and shared abundance.

William McDonough, FAIA Int. RIBA
Co-author of Cradle to Cradle; Remaking the Way We Make Things

PRELUDE

Executive summary (UK)
— findings and conclusions

Natural resources are scarce and construction accounts for around 40% of the material and energy consumption in Europe, this is why a switch to a circular future is necessary. 'Building a Circular Future' maps out where we are, where we are going, and what is needed for the conversion of the construction industry from a 'use and waste model' to a 'circular economic model' to take place.

The construction industry is facing a major upheaval and must rethink both its business strategies and construction practice in order to handle the new market mechanisms and reap the rewards of the circular future based on a 'circular economic model'. To facilitate this, new companies with business strategies that do not yet exist will have to be developed, such as material exchanges that can handle heavy elements used in superstructures, digital material managers and deconstruction experts. Last but not least, the circular future vision includes buildings that are designed for disassembly.

A proven positive business case
Based on a specific 3XN project and existing construction practice at MT Højgaard, the project partners have developed and tested a business case for the reuse of the superstructure of larger buildings based on the project's 15 principles for 'Building a Circular Future'.

The financial result is a profit of DKK 35 million, generated by the super structure alone, providing the building can be disassembled and a majority of the materials can be reused as an alternative to the demolition of the buildings superstructure, which is commonplace in the industry today.

The DKK 35 million has to be compared to the total cost of the building, coming to around DKK 860 million. This figure corresponds to approximately 4% of the total cost of the building and approximately 8% of the total cost of the superstructure.

’Building a circular future means redesigning industry logic from building scale to business scale’

— Kasper Guldager Jensen
Architect, Senior Partner 3XN, Director GXN

Circular Economics
— is about circulating value and resources

From the discussion, we have had with different stakeholders in the industry, it has become clear that it's important to emphasize that circular economy is as much about recycling value as it is about recycling resources for two reasons:

1. By focusing on recycling value (i.e. re-use, upscaling, re-manufacturing etc.), we will avoid losing all the labour and energy invested in the making for the product – thereby also reducing the need for new labour and energy needed to build a new product from recycled material.

2. By focusing on recycling value (i.e. ruse, upscaling, remanufacturing etc.), we will be able to capture the value all-ready build into or embedded in the product a hence get a competitive advantage as private companies, public entities, and as societies.

Similar examples exist in other industries. According to Xie Zhenhua, vice chairman of the National Development and Reform Commission (NDRC), the economic value of remanufacturing a 500 kg vehicle engine is 30 times higher than the economic value of recycling the steel from the engine — as the value of the remanufactured engine is approximately 4900 USD, whereas the value of the recycled steel is only 160 USD *.

* Waste to Wealth, 2015

Photo: Demolition site with piles of downcycled materials with low or no value as resources for future buildings.

Photo © GXN

‘We have a proof of concept, if today’s demolition cost can be turned into a positive future business case’

— John Sommer
Sales Director, MT Højgaard

The total potential value of the materials retrieved, calculated when the projected increase in material prices over a 50 year period is taken into account, is estimated to be up to 16% of the total construction cost.

This study demonstrates that by designing for disassembly and by incorporating new circular economic strategies/principles from the early design phase, it is possible to show that there is a business case for converting today's model of demolition and downgrading of materials into a future model of disassembling and reusing of materials without degrading.

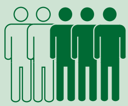
Hence, it is proven that there is an economic viable business case for a circular economic model in the construction industry.

Positive effects here and now
The incentive for the implementation of circular strategies is not only in the future. Increased flexibility, optimized operation and maintenance, as well as healthier buildings, are low-hanging fruit that can be harvested today. The project's principles can already be implemented in industrialized construction on a large scale today.

This has been proven in part by constructing three 1:1 prototypes of building elements in timber, steel, and concrete, which has been designed for disassembly and therefore designed to be reused. Moreover, studies of international projects have shown that there are already a number of built projects based on one or more of the 15 principles recommended in this book. In other words, it shows that commercial components are available and are ready to be used.

This book gathers a number of applicable solutions and provides 15 principles for 'Building a Circular Future'. However, of most value is the positive business case made by the major Danish contractor MT Højgaard along with leading demolition specialist Kingo Karlsen, which documents that a demolition that currently would cost DKK16 million, can be turned into a DKK 35 million business upside in a future circular building industry.

↑ +3BN

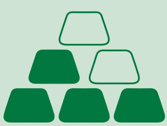


middle class
growth in 2030.

↑ +3TR

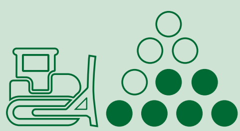
world economic
GDP in 2015 alone.

↑ x1,5



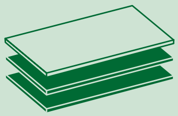
more resources use than the
planet can provide in 2015.

40%



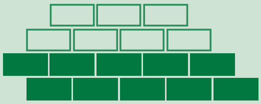
of all waste in Denmark comes
from the building industry.

35%



of the total materials used by the
construction industry in the world.

↑ +70%



growth of demand for global
construction in 10 years.

Resource scarcity
— amplified by global growth

The world's population is accelerating, from approximately 3 billion people in 1950 to a projected 9 billion people in 2050.[01] Additionally, the world's middle class is projected to grow by a staggering 150% over the next 15 years, from 2 billion people in 2010 to 5 billion people in 2030.[02]

Moreover, it took the entirety of human history to build a 3 trillion dollar economy, reached in 1940, this is the figure in which the world economic GDP was expected to grow in just 2015 alone.[03]

Additionally, the global migration from land to cities indicates that by 2050 almost 75% of the world's population will be urbanized. These developments put tremendous pressure on the world's resources, which are already under pressure, as we currently on average use more the 1,5 times the resources that the planet can provide.[04] On a global scale, this means that by 2030 we will have to produce 50% more food and energy and provide access to 30% more fresh water, while we simultaneously fight global warming and climate change.[05]

Looking more specifically at the construction industry, which today consumes about 40% of the energy used in the EU[06] and 35% of the materials used in the world[07] the consequences of the above changes are tremendous. It is estimated that the result will be a demand for urban construction for housing, office spaces and tranportation services that over the next 40 years could roughly equal the entire volume of such construction made in world history.[08] Over the next 10 years, the demand for global construction is expected to increase by 70%.[09]

In the 2014 book 'Resource Revolution — How to capture the biggest business opportunity in a century'[10] by Stefan Heck, a Stanford Professor and former McKinsey director, and Matt Rogers, a McKinsey director, this development is put into perspective by showing that China alone, over the period 2000 to 2020, will build what is equivalent to 100 'New Yorks', or more than 200 cities with more than 1 million inhabitants.

01 Hot, flat and Crowded, p 28 **02** Ph.D Homi Kharas **03** World's Gross Domestic Products Growth **04** World's Footprint 2015
05 Den Store Omstilling **06** Deutsche Bank Research 2013 **07** United Nations Environment Programme
08 US Department of Defence **09** PWC Global Construction 2025 **10** Resource Revolution

A prerequisite for this development is ensuring that we have the necessary resources. Leading economic thinker Jonathan Hook addressed how this lack of resources could be a barrier in a report in PWC Global Construction 2025, when he asked, ‘do we have the resources to deliver?’

One of the reasons for this question is that we have seen a sharp increase in a variety of commodities’ prices since the year 2000, because of increased scarcity. This was effectively addressed by McKinsey in the '2013 Trend Survey', where authors showed that all the gains in ‘resource productivity’ in the 20th century were nullified during the first 10 years of the 21st century. As shown in the graph on the opposite page.[11]

Moreover, we see that a great number of our most needed metals are becoming increasingly scarce. On the periodic system shown on the following page, the elements that will become difficult to obtain in 50 years, 100 years and 500 years from now are categorized into three different colours. From this figure, it is seen that a large number of the materials that will become limited 50 years from now are the metals used in the construction industry.

11 McKinsey Global Institute **12** McKinsey Commodity Price Index 1900-2010 **13** McKinsey Commodity Price Index **14** Resource Revolution

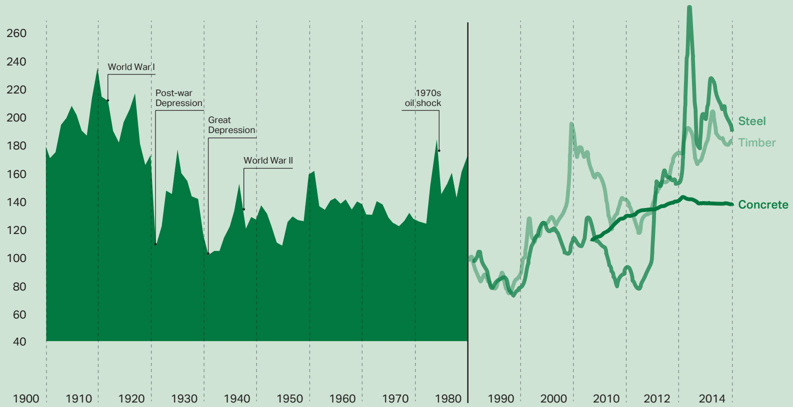


Diagram: McKinsey Commodity Price Index: Concrete, Steel and Timber.[12] The price on concrete, steel and timber in relation to the average commodity prices.[13] In 2013 and 2014 there has been a decline in commodity prices.

This diagram is an reinterpretation of an original owned by Ellen MacArthur Foundation

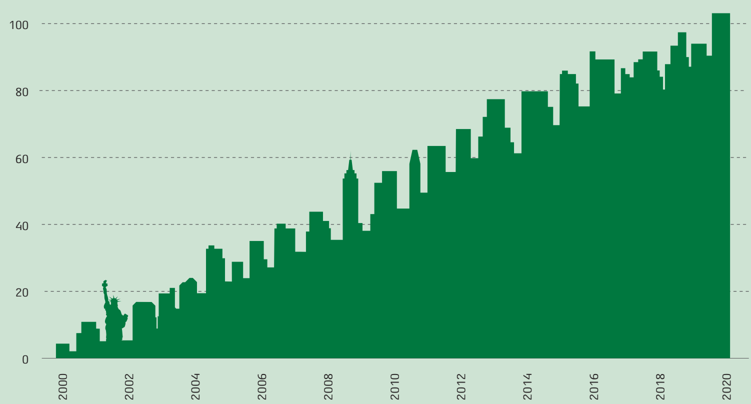


Diagram: China is building the equivalent of 100 New Yorks.[14] 2020 projections: 350 million in additional urban population, 221 total cities with populations of more than 1 million and 170 new mass transit systems.

This diagram is an reinterpretation of an original from the book 'Resource Revolution'

Value to society
— the economical and sustainable perspective

The facts of resource scarcity, combined with discussions on the difference in value of the reuse of precast concrete elements, between 3XN and MT Højgaard in the autumn of 2014 inspired further investigation into the business opportunities of introducing a circular economic paradigm to the construction industry. One of the examples discussed was that the value of a reinforced concrete wall element is some 50 times higher per ton than the value of the gravel into which it is currently broken down when buildings are demolished. Similarly, the value of prefabricated and painted steel beams are some 30 to 40 higher per ton than the pure 'metal value'.

In order to thoroughly investigate this business opportunity, GXN and MT Højgaard invited 3XN, Vugge til Vugge, henrik•innovation, VIA University College and Kingo Karlsen to participate in the project.

Since the partners launched this investigation, commodity prices, including those on metals, have fallen significantly over the last 12 months.[15] The team is aware that this price reduction in the short term could make many business people and politicians think that it's not that urgent to commence introduction of a circular economy model in the construction industry.

That, however, is not the case, as the long-term projections clearly indicate that we will have to increase our 'material productivity' significantly in order to accommodate future needs for construction and civil services at reasonable prices. Moreover, introduction of a 'circular economy' in the construction industry will take one or two decades and should not be evaluated economically based on the current fluctuation in commodity prices, but on long-term projections, like those provided in the previous chapter.

15 imf.org **16** Towards the Circular Economy, p. 20-21

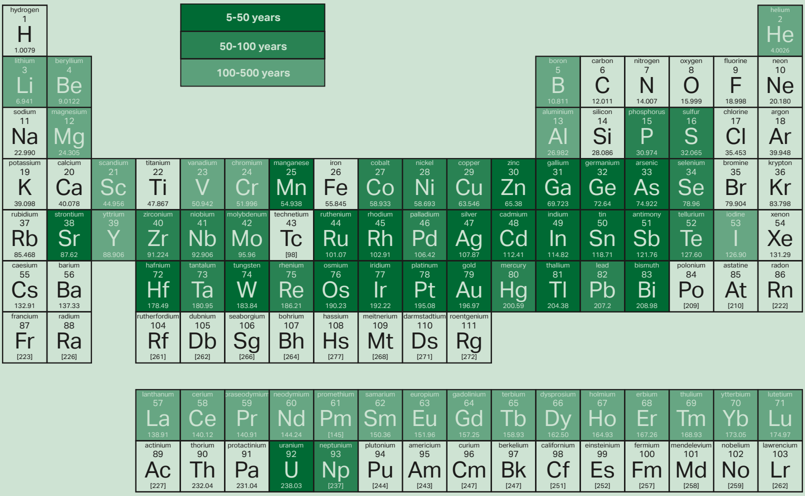


Diagram: Years remaining until depletion of known resources.[16]

This diagram is an reinterpretation of an original owned by Ellen MacArthur Foundation

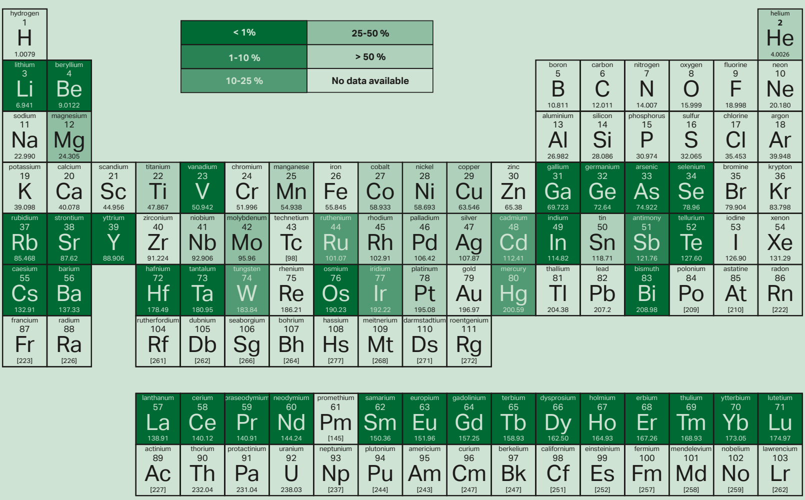


Diagram: Current recycling rates of know ressources.[16]

This diagram is an reinterpretation of an original owned by the Ellen MacArthur Foundation

Area of focus
— where this project has the biggest impact

As stated in the previous section, the construction industry will have to build as much in the coming 40 years as we have done since the beginning of humanity. This could be a challenge in a world where an increased number of resources are becoming scarce and where the construction industry already consumes approximately 35% of all materials produced in the world, measured by weight. Therefore, the parties behind this book have decided to investigate how circular economy can be advanced in the construction industry.

Market and relevant segments
This book chose to focus on large and complex office buildings, specifically their superstructure and load-bearing façades, for a number of reasons. These are among the most technically advanced buildings constructed at present, mainly because of the need for large open spaces, high requirements for the indoor environment, access to daylight, as well as demand for very low energy consumption etc.

These requirements necessitate larger and more advanced ventilation, lighting and electrical systems compared to what is needed for other types of buildings. Moreover, the request for the large open spaces and flexibility necessitate the use of larger and stronger beams, columns and joints, compared to the types of construction elements used for housing or other building types.

As these office buildings are the most complex to design for disassembly, we expect that the methods developed for this building segment can be used directly or in a modified and simpler version in less complicated buildings. In order to limit the scope of the analysis, we decided to focus on the superstructure and the envelope of the building, partly because these usually represent about ¾ of the materials used in buildings, measured by weight, and partly because a number of other solutions have focused on installation, internal walls, etc.

Office buildings are among the most interesting
The buildings most similar to office buildings in terms of structural systems are larger and more complex apartment buildings and educational buildings. We expect that the methods for disassembly developed for complex office buildings can be applied to these other segments with limited alternations.

Why Office Buildings?

— Office buildings are technically amongst the most advanced buildings constructed. Consequently, the idea is that technology developed for this segment can be used for other building segments.

— Office buildings are business wise amongst the most interesting and relevant to 3XN and MT Højgaard, as both are leading companies in Denmark when it comes to design and construction of this typology.

— Office buildings account for ⅒ of the building stock and 10 to 20% of the buildings to build in the years to come.

Office buildings and the Danish building stock
In 2015 the Danish building stock amounted to approximately DKK 665 million m^2. Measured in square meters. The largest segments are 'individual housing' and 'farm production buildings', which account for 26% and 21% of the building stock respectively. Office buildings, administration and trade buildings account for DKK 66 million m^2 or 10% of the building stock. Apartments and educational buildings taken together amount to another 16% or 108 million m^2. It is therefore expected that the methods developed without modifications will be relevant for between 15% and 25% of the buildings to be constructed in the years to come. That is if the buildings to be built in the future continue to be distributed between the different segments, as they have been for the last 50 years. The figures for this analysis are provided by Statistics Denmark.

Based on a forecast from e.g. ByensEjendom, a Danish knowledge center for city development, it is expected that office buildings to the value of DKK 170 billion are to be constructed from 2016 to 2025. This amounts to DKK 10 to 20 billion over the next 10 years, which corresponds to about 10% to 20% of the total value of the Danish market for new build and refurbishment and approximately ¼ of the value of the market for new build.

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BACKGROUND

Case study project
— introducing 'de fire styrelser'

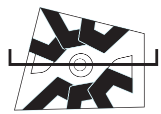
Location: Kalvebod Brygge, Denmark
Year: Competition, 2014
Developer: The Danish Government
Team: 3XN Architects, MT Højgaard, DEAS and Balslev
Size: 37.839 m^2
Type: Office building

There are lots of numbers circulating about the perceived or expected value of the introduction of a model for circular economy in different societies. However, most of these estimates are made for the entire society or for industries that are different to the construction industry. An estimate of the value of the introduction of a circular economy model for the structural part of the superstructure in the Danish construction industry is therefore needed. In order to make such an estimate of the number and values involved in the introduction of a circular economy model, we have decided to make an estimate of the values involved based the 3XN Architects and MT Højgaard turnkey bid project for 'De Fire Styrelser'.

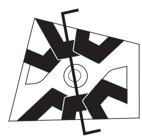
If built, the project will be among the largest and most complex headquarters built in Denmark and therefore perfect for a case study — as the principles developed for such a complicated building will be easy to use for smaller and less complicated buildings.

Image: Visualization of 'De Fire Styrelser' seen from above.

Section AA: 1:1000 View of the facade.



Section BB: 1:1000 View of the facade.



Thus, it is on of the safe side with regards to economic value to base our estimate of the economic value of circular economy model on this project. The project is also interesting because it is a Private Public Partnership (PPP), that requires the contractors and the architects not only to compete on the design and functionality, as well as the price of the project — but also on the operation and maintenance costs of the project over a 30 year period.

The costs of operation and maintenance over a 30 year period for such a project are approximately 50% of the value of the contract with the client. Consequently, this kind of competition forces the competing contractors to focus on the Life Cycle Costs (LCC) of the project and not only on the construction costs. That will always result in a better and more robust building of higher quality — and therefore a more sustainable building.

'De Fire Styrelser' is intended to be an office hub for four Danish government agencies and will house: the Transport Authority, Banedanmark (Danish railways), the Energy Authority and the Danish Road Directorate. The building is located on Kalvebod Brygge in the centre of Copenhagen, Denmark.

The vision for the building is to create a flexible and future-proof office building with an inspiring and healthy environment. The workplace framework provides for movement, social interaction and sharing of knowledge, in a working environment with great visual experiences and where the individual users can work more or less privately, according to their needs, and have influence on the indoor climate.

The main architectural concept for the government office hub is the desire to have single building around the public park in the centre of the site. This creates room for cooperation and synergy through social interaction. A number of divisions of the body of the building give an organic adaptation in the green park area and excellent opportunities for views from the workplace.

Building structure

The building represents a typical new office building in Denmark, but it contains a few twists that make it more complex than a basic rectangular column-beam building. It's main structure is concrete slab elements, with load bearing façades and cores. The elements are spanning widthway across the 'arms' of the building (see diagram on page 18) like traditional office wings.

This case study will focus only on the closed structure of the building, and therefore not installations, interior, etc.

Foundations and ground slab

The lower level covers the entire construction field and is founded on piles. The floor on the ground level is concrete cast on site in level with existing terrain. It is impregnated and polished with wax, which makes it easy to clean and requires minimal maintenance.

Cores, façades and windows

The main structure is stabilized by the few solid cores around, through stairs and elevators. The façades are load carrying and enable office floors without interior columns; the only bearing walls are around the shafts and elevator cores.

This provides optimal flexibility for unimpeded rebuilding and reprogramming of the building. By allowing the wall elements to contribute to the stability of the structure, a building with a minimum number of inner bearings is obtained. From an overall economic perspective, this facade solution is also optimal in terms of construction and operation.

The windows are a combination of wood, which is a renewable material, aluminium, which is maintenance free, and an intermediate composite profile that efficiently insulates and prevents condensation.

Slabs and roof

The floor and roof are rendered as 400 millimeter prestressed hollow core slabs, which range freely between the curtain walls. Where office wings are merging, the slabs are carried by steel composite beams, as SWT or Peikko, which attaches to façades, shaft walls and individual columns. Thus, there are little or no beams protruding down into the office space, ensuring optimal conditions for the horizontal transfer of the installations and possibly later expansion.

Outer walls and windows

The inside of the offices' outer walls of are rough plastered concrete with dust binding. The surface will appear as 'new' in the lifetime of the building, and from an overall economic perspective saving paint for the walls, which would otherwise have to be painted every six to seven years.

The general exterior walls are moulded brick. Tile is a natural material that requires minimal maintenance, which can last more than 100 years if the joints are done correctly, and at the same time age gracefully for many years and contribute to the building's distinctive identity.

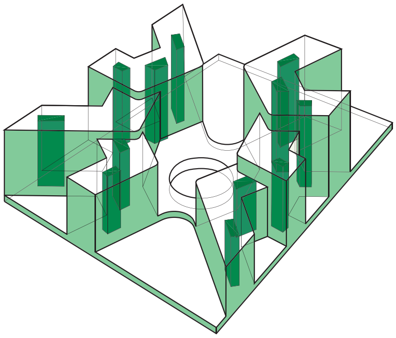


Diagram: View of the loadbearing facades and cores.

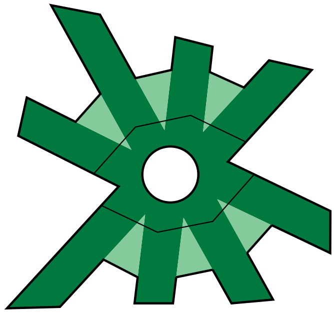
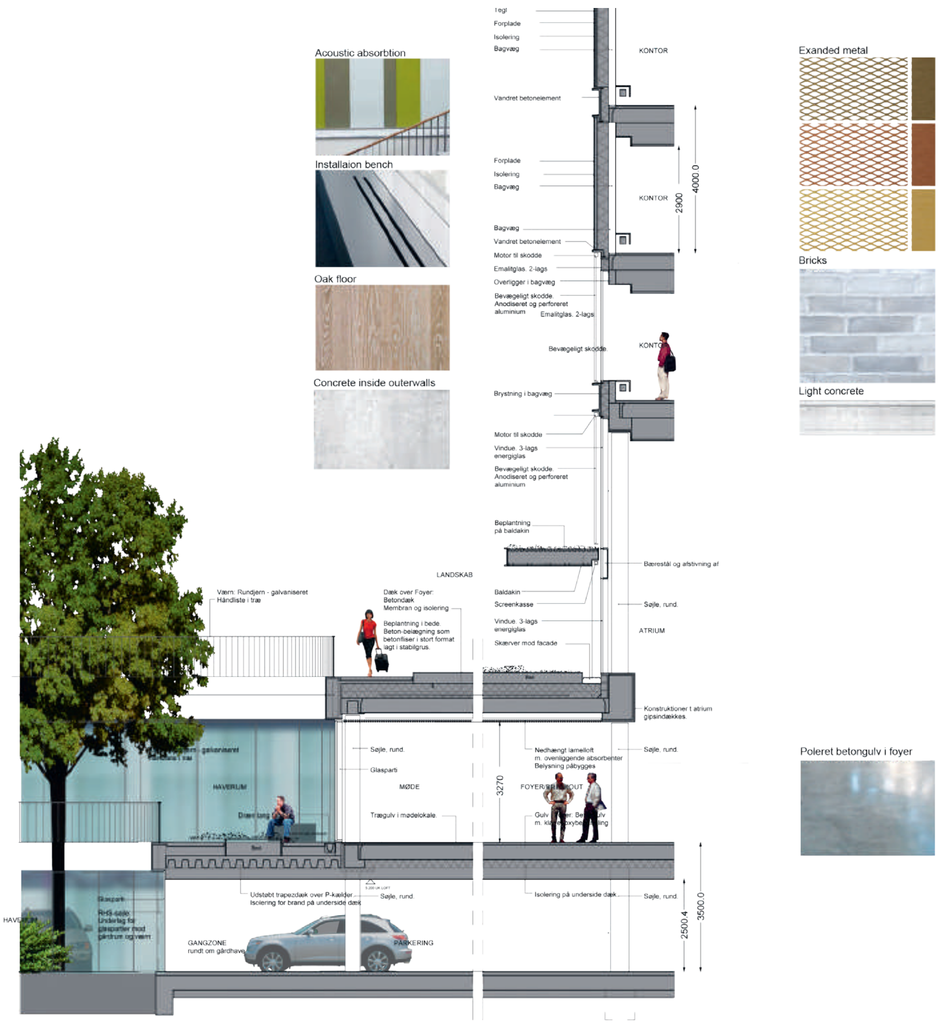


Diagram: Traditional office wings transformed into a coherent and inspiring office hub.



Section: Showing the structure and the materials of the building.


2.7
Møderum
6-8p
7.1
Toiletter
7.3
Kopirum
2.5
Flex-rum
7.2
Gard.
2.8
Møderum
10-15p
2.6
Caféer
7.4
Arkivrum
7.5
Reng.
Terrasse
Udgang fra
café område
6.0
10.5
9.5
8.0
Udgang fra
café område
1.5
Caféer
1.4
Flex-rum
1.7
Møderum
10-15p
1.6
Møderum
6-8p
10.0
8.5
8.75
7.0

Plan: 1:1000 First floor

Digital framework
— introducing BIM and VDC

The development and use of digital tools in the construction industry identifies a new area with increasing focus on efficiency and productivity. These tools were initially designed for optimizing the design and construction phases, but over the years have been developed to be able to support the required data and features that are needed for future recycling and the introduction of a circular economy. Two strong tools are especially relevant when talking about intelligent design and construction in combination with circular economy: Building Information Modelling (BIM) and Virtual Design and Construction (VDC).

BIM and VDC
With BIM, the 3D visualization of a construction can be modelled, making it possible to three-dimensionally visualize the construction to be built.

Photo: Project team visiting MT Højgaards VDC Lab in May 2015, learning about state of the art in digital construction.

Photo © GXN

In addition, every single construction part is identified with exact dimensions and characteristics (i.e., type of concrete, quality of steel). This gives access to detailed information about the entire project with respect to the final design, constructability and provides a model and drawings that are kept fully updated throughout the entire process.

In order to increase the productivity in the construction industry, MT Højgaard has worked intensively to develop the optimal tool for Virtual Design and Construction. Taking the basis in BIM, since this is a tool that has been widely implemented and used in the industry up to now.

MT Højgaard has succeeded in combining all of the detailed information with respect to the project schedule for the design and construction phase with the existing data in BIM, making it possible to simulate the exact and detailed construction process day by day throughout the entire process.

It is hereby possible to identify all potential routes for optimization in order to save time and building materials, predict possible collision conflicts etc.

So far, the companies in the forefront with regard to using VDC experience that tremendous resources are saved by implementing this type of modelling in advance of the actual construction of a structure (building, bridge, or power plant etc.). So far, the experience at MT Højgaard, working with VDC in order to increase the productivity in the construction phase, has been that VDC is an efficient tool when it comes to optimizing a project.

Moreover, VDC facilitates a close collaboration between the client, architects, construction companies, engineers and main suppliers. Allowing all competences to be involved at an early stage of the project and facilitating the optimization of the project with regards to the solutions chosen, the performance of the building, etc. by logging the data for later use.

Photo (top): The project team inspecting the BIM model and discussing the future possibilities of VDC.

Photo (bottom): MT Højgaards Niels W. Falk explaining how they work with BIM and VDC.

This data is used and updated during the construction phase and can be used over the lifetime of the building for operation and maintenance. VDC ensures that 'one model' holds all relevant information with regard to design, construction, operation and maintenance of a certain structure.

Hence, VDC holds all information with respect to full maintenance of the structure throughout the entire lifetime. VDC is basically BIM (the detailed 3D visualization of the design), with the following information added:

— Time schedule during the construction phase.

— Information about the economy related to the exact choice of building materials and amounts of these, as well as the solutions chosen.

— All specific data needed in order to manage full maintenance of the construction during the entire life time of the building.

When adding detailed information about all the construction materials in use, including amount, location and price, it becomes possible to follow and identify each component in the entire structure. It is therefore only a matter of introducing a new element to the information already in the model, if a material passport is to be introduced in order to log the historical data for each construction component.

When using the Virtual Design and Construction tool also with regard to later recirculation of materials, unique data for each component in a structure will be available and can be tracked at any time with respect to information like location, time of exposure and other relevant information for a material passport. Unique data sets and history are available in a new way, making the construction components available for future use in a whole new manner.

BIM, VDC and material passport modelling
As explained by MT Højgaards Niels Wingesø Falk, when the research team visited MT Højgaards VDC Laboratories in Søborg in May 2015, all information regarding the different structural elements can be entered into the model. The top photo on the opposite page, shows on the screen where all information on a certain element is displayed.

However, it is recommended that only information identifying the unique element be entered into the model, as that would allow the model to operate faster. As long as all elements of the structure are uniquely identifiable in the model, all other information on the unique characteristics of the structural elements can be kept in a separate database, as long as there is access to this information.

There are no limits to the amount of information that can be attached to the unique structural elements. It is therefore recommended that all data relevant for a material passport are incorporated into the digial model that is also is going to be used for operation and maintenance.

The seventh dimension
— optimizing the design

6+1 Dimensions
The 1st, 2nd and 3rd dimension of the VDC model are the traditional geometric dimensions i.e. length, width and height.

The 4th dimension is the time schedule of the construction work.

The 5th dimension the integration of the costs and quantities with the three dimensional figure.

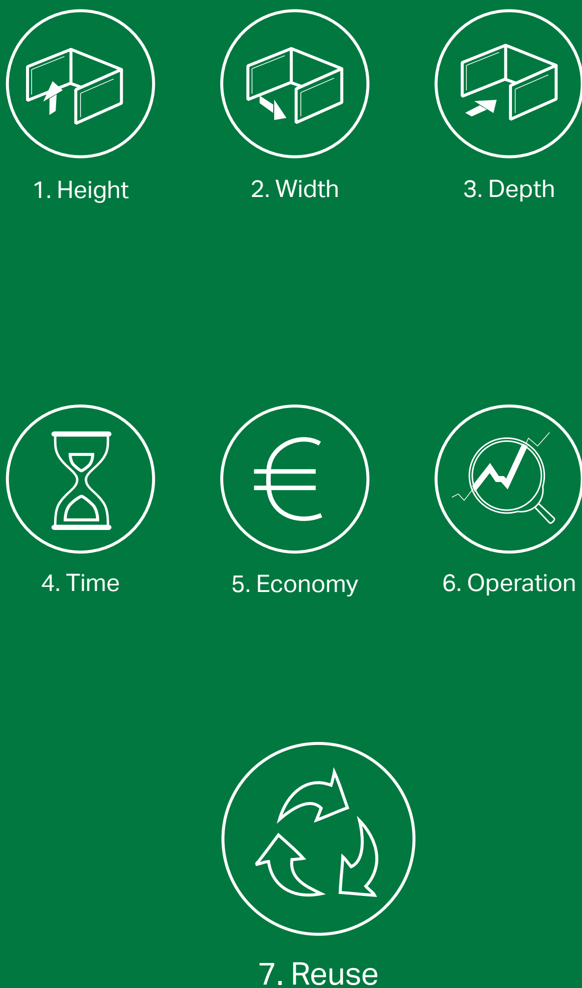
The 6th Dimension is the integration of data for maintenance and operation into the VDC model. This information not only enables the client and the facility manager to maintain and operate a building, it is also part of the design parameters used in the design phase to optimize the design of a building in order to ensure the lowest Life Cycle Costs (LCC) of the building and the optimal operation.

The 7th dimension is therefore the integration of data that enables disassembling and reuse of the structural elements into the VDC model.

That would not only enable the client to sell off the structural elements of his building when it reaches the end of its life or has to be refurbished for other purposes.

It would also allow the client and his consultant (i.e. architects, contractors and engineers) to take this information into consideration at the time the building and the structure is designed, and thereby not only to design and construct the building with the lowest Life Cycle Cost (LCC), best design and performance, but also the building with the highest value when it comes to future recycling.

6+1 Dimensions



1, 2, 3D
The traditional geometric dimensions

4, 5, 6D
Todays advanced BIM operation and modelling

7D
The future introduction of reuse of building elements

Reinventing the past
— looking backwards to go forward

Timber constructions
Historically in Denmark, half-timber construction is the most widespread system for building with timber. The method allowed for easy disassembly, due to the use of timber pegs that connect the different members of the construction. The design was flexible and the different members could be prefabricated and composed a highly modular structural system.

This provided the possibility for easy extensions or removable building parts without changing the overall character of the building. This also resulted in many buildings being disassembled and reassembled in other places. The system was spread all over Europe, resulting in different countries and regions having different styles and patterns caused by the adaptation to the local resources.

Image: Traditional Danish half-timber construction is, as a result of material scarcity, made as design for disassembly.

Image © GXN

However, the main construction systems are mostly alike.[01] The reuse of timber components from old construction has been a common practice in many parts of the world for centuries. In medieval Europe, a scarcity of suitable construction timber led to the dismantling of old buildings to recover parts, such as beams and columns, that could be reused in new buildings. The construction methods started to adapt to this movement and a design for disassembly approach was introduced.

In the sixteenth century, in the Swiss region of Appanzell, an attempt to avoid taxes sprouted another movement of design for disassembly. The church, which owned the forests, taxed all building timber. However, they granted free access of the resource if it was for the purpose of private building on private land. A small group of entrepreneurs exploited this opportunity and started to design and build houses on their own private ground that could easily be disassembled, moved and reassembled on another piece of land and thereby avoid the tax. [01]

01 denstoredanske.dk

Steel constructions

The mass production of steel and iron are closely related to the industrial revolution (1760 to 1840). Their use became more widespread during World War II and significantly expanded after the war, when steel became more available and steel buildings gained popularity in the mid 20th century.

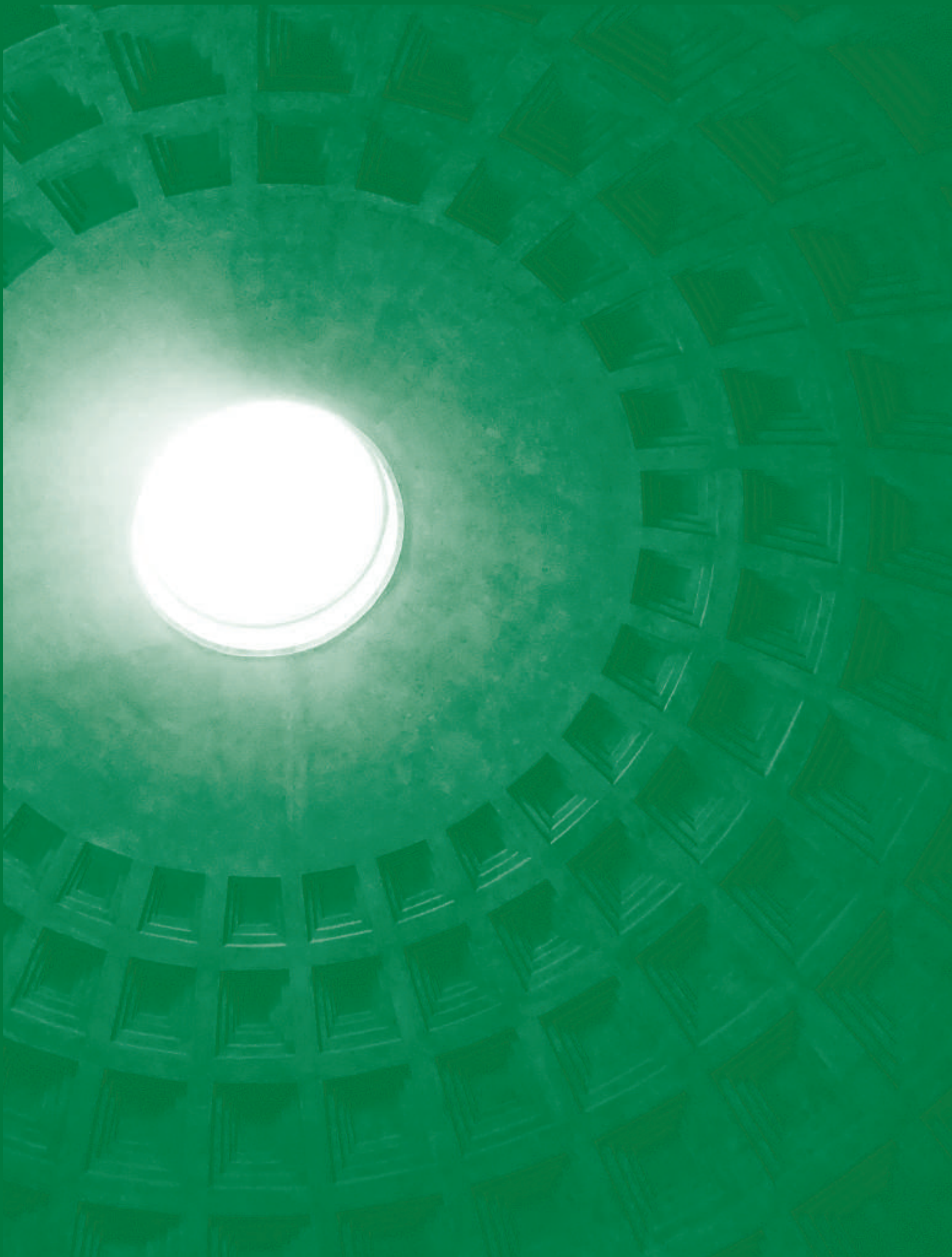
In the beginning, steel structures were assembled by riveted connections. The technique of hot riveting was quickly introduced to the building industry after being invented for the shipping and boilermaking industries. The cheapness of the rivet joints was highly praised, but the inflexibility of the joint lead to the introduction of high strength bolts during the 1950s. At that time, rivets became less common, since the installation of rivets required more equipment and manpower. Besides the installation of rivets having its disadvantages, high strength bolts also offered more strength. Bolted connections were privileged when dismantling was required, but also in applications for which rivets were inappropriate, that is, when the grip length was too long or in connections between wrought and cast iron.

In 1851, Britain hosted an international trade and technology fair that took place in London's Hyde Park. A building, which came to be known as the 'Crystal Palace', designed by Joseph Paxton, was built for the fair under the constraints that it was to be temporary. Paxton designed the building on a simple system of prefabricated structural and cladding units that could be quickly assembled, disassembled and relocated.

The 560 meter long building was based on a structural grid of columns linked with standard trusses, made of cast iron. These trusses were fitted into flanges on the columns and locked into place with wedges of cast iron or timber. This skeletal frame of columns and trusses was then clad and roofed using panels of timber, iron and glass. These factory produced panels allowed for the quick assembly and disassembly of the building.[02]

Image: Crystal Palace, designed by Joseph Paxton, was built for the Great Exhibition of 1851 and could quickly be assembled, disassembled and relocated.

Image © GXN



Concrete constructions
Because of its durability and versatility, concrete is one of the materials used most in the construction industry today. Already during the Roman Empire (300 BC to 476 AD), concrete was widely used. The Pantheon is one of the best known concrete buildings from that period. The Roman concrete (or opus caementicium) was made from quicklime, pozzolana and an aggregate of pumice. Recent studies show that Roman concrete had as much compressive strength as modern concrete.

'Portland cement' is the predominant concrete used today. One of the major differences between Roman concrete and Portland cement is the latter's ability to set in wet conditions or underwater.

The development of Portland cement began in 1756, when John Smeaton needed a cement that would set in wet conditions for a lighthouse. Later, Portland cement was used to make a mortar stronger than the traditional lime mortar, allowing for a faster pace of construction. By 1950, Portland mortar became more popular than lime mortar.

Unfortunately, the widespread use of Portland cement has its disadvantages. The concrete is so strong that it has become impossible to 'disassemble' two materials that it holds together, so it doesn't allow the reuse of bricks, for example. Mechanical connections for concrete were widely used in the 1970s and allowed for disassembly. But because of efficiency improvements in the construction industry and increased requirements in fire regulations, the Danish building sector has completely stopped using this technique.

A clear example of a concrete structure designed for disassembly is Kisho Kurokawas Nakagin Capsule Tower, from 1972. It consists of 140 prefabricated concrete modules that are connected to a central structure and are designed to be interchangeable. [03]

Image: Already during the Roman Empire concrete was widely used. It was made from quicklime, pozzolana and an aggregate of pumice. The Pantheon is one of the best known concrete buildings from that period.

03 wikipedia.org

‘The circular future represents an optimized building practice with integrated closed loop economy, resource strategies and life cycle design’

— Casper Østergaard Christensen
Architect, 3XN Architects and GXN Innovation

Image: A ‘high reach machine’ crushing a concrete structure into material fractions; rebar and concrete gravel. Compared to a complete building element, materials in this state has a very low value.

Image © GXN


MIS
Recycling
bare bedre...

DESIGN FOR DISASSEMBLY

What is design for disassembly

— Page 32 to 41

Explanation of design for disassembly and some of the general concepts behind it.

‘Today buildings are statically welded, glued and cast together. By designing for disassembly future buildings will be flexible and function as material banks’

— Kasper Guldager Jensen
Architect, Senior Partner 3XN and Director GXN

Introduction
— to design for disassembly

'Design for disassembly' is a holistic design approach where the intention is to make any given product easy to disassemble into all its individual components.

The approach is a cornerstone of the circular economy because it allows the different components to fit into a closed material cycle, where they can be reused, reassembled and recycled to new products of similar or higher quality.

Because of the holistic nature of the philosophy, it can be applied to any type of product in every scale with any level of complexity. Examples range from all the way from materials used in electronic devices, furniture and to buildings.

Overall approach
There are a lot of different ways to make a product able to be disassembled. The main thing to remember is that when two or more components are put together, the connection must be reversible without damaging the components. This means that screws, splits, and nuts and bolts are favoured over nails, as wells binders, like glue, are to be avoided.

To allow for easier deconstruction, connections must be easy to access nad preferably visible. It is also key to ensure that the quality of the material can withstand the use and reuse over time and doesn't get worn out.[04, 05]

On page 46 in this book, we offer five principles of how work with design for disassembly in the built environment.

In the building industry
Design for disassembly has been present in the building industry for decades, but more out of necessity than by conscious choice. Examples includes smaller houses, pavilions and temporary structures that are built to be moved around or in times where resources were scarce, buildings were made so that the building materials would be available again.

This book investigates how to integrate design for disassembly in larger scale buildings and prepare them for a circular future.

Multiple gains
— when designing for disassembly

Design for disassembly requires a different way of thinking yet carries many positive side effects that are activated by the extra thought put into the product. Many of them will effect the use on a daily basis from the beginning, some will be harvested in the future and some will affect the planet as a whole.

Immediate gains
Because the product is easier to assemble, it is simpler and cheaper to produce.

Because the product can be easily disassembled, it is easier to remove things that are broken and repair them, change or upgrade outdated technology, making it easier and cheaper to maintain and operate.

When a broken part is removed, it can be disassembled into all its smaller components, enabling all of the parts to be upcycled to new products in the best possible way.

Environmental footprint
Because products are easier to produce, repair, maintain and upcycle, less waste is produced. This waste reduction helps ease the demand for new raw materials and the resource scarcity the industries are facing.

Future
When it is possible to disassemble something without damaging the materials from which it is made and access them years later without any loss of quality or value, you can start to see everything as a material bank where you save up for the future.

Positive side effects
The possible positive side effects from designing the building for disassembly can be summed up to:

- Quicker and simpler construction process.
- Optimized operation and maintenance.
- Less waste.
- Optimized upcycling, recycling and reuse.
- Released pressure on resource scarcity.
- Buildings as material banks.

Image: Designing for dissambly means rethinking the way we construct our buildings — but as a result lot of positive side effects is gained.

Conclusions from design for dissasembly

The research and case study in this section show that the concept of design for disassembly is not far from being able to be integrated in the building industry and that it to some extent already has found a place in smaller products and been used on small scale building projects.

Positive side effects here and now
When designing a building for disassembly, it is important to see design for disassembly as a new way of thinking. The underlying new idea is that the building is not a permanent structure, but should be thought of as a temporary compilation of building materials. Hence, it is important to plan how the building can be taken apart and reconstructed again using the same materials to the largest extent. The positive side effects from using the 'design for disassembly' method are that it improves flexibility and optimizes operation and maintenance of the building over its lifetime.

Small-scale products in the lead
Industries with smaller scale products, like electronics and furniture, have already adopted the design principles in some of products. It attracts that industry because it offers the possibility for the customer to personalize the product, make it easier to upgrade, repair and of course recycle. This is important because the industry relies on many of the rare metals that are already scarce. The electronics industry is quicker to revolutionize because the replacement rate is much faster than with buildings.

Industry adaptation
Compared to the electronics industry, the building industry is still in the starting phase. Buildings designed for disassembly now are smaller niche projects built in timber with steel joints. The most significant challenge which the sector faces, is how to disassemble large and complex concrete structures, which represent a lot of value and leave a huge environmental footprint. Currently, there is no reasonable means of reusing or recycling concrete structures.

However, the industry might catch up quickly. Commercial products already exist that, with a few changes, will make it possible to construct buildings that can be disassembled when their end of life is reached. The prototypes developed as part of this project show that it is possible to use mechanical connections to build even larger scale buildings with a superstructures made predominantly of concrete. In order to increase recirculation of materials from one building to the construction of the next building without degrading the materials, the industry can also choose to build more in timber and steel, which already are considerably easier to construct for disassembly.

5 Principles

— to consider when designing for disassembly

Materials

Choose materials with properties that ensure they can be reused.

Quality
Use materials of a high quality that can handle several life cycles.

Healthy
Use non-toxic materials to provide a healthy environment — now and in the future.

Pure
Use as pure materials as possible, which can recycled with ease.

Service Life

Design the building with the whole lifetime of the building in mind.

Layers
Make the long lasting building elements allow for flexibility, so other elements are easily changed.

Flexibility
Make a flexible building design that allows the functions to adapt and change in the future.

Interim
Think of the building as a temporary composition of materials and design with the preservation of material value in mind.

Standards

Design a simple building that fits into a 'larger context' system.

Modularity
Use modular systems where elements easily can be replaced.

Prefabrication
Use prefabricated elements for a quicker and more secure assembly and disassembly.

Components
Create a component when the composition of elements becomes too complex to handle.

Connections

Choose reversible connections that tolerate repeated assembly and disassembly.

Accessible
Make the connection accessible in order to minimize assembly and disassembly time.

Mechanical
Use mechanical joints for easy assembly and disassembly without damaging the materials.

Dissolvable
Avoid binders, but if necessary, use binders that are dissolvable.

Deconstruction

As well as creating a plan for construction, design the building for deconstruction.

Strategy
Create a simple plan for deconstruction, to ensure a quick and easy disassembly process.

Stability
Make sure that stability in the building is maintained during deconstruction.

Environment
Ensure the deconstruction plan is respectful to the nearby buildings, people and nature.

Existing examples

— Page 42 to 65

Explore examples of design for disassembly already implemented in architecture and other industries.

ICEhouse
— existing architecture

Location Davos, Switzerland
Year 2016
Owner SABIC
Architect William McDonough + Partners
Size 100 m^2

William McDonough + Partners showcased a new structure in Davos in conjunction with the 2016 World Economic Forum's Annual Meeting: the ICEhouse™, a place to discuss the future of Innovation for the Circular Economy (ICE). Wiiliam McDonough is the Chairman of the World Economic Forum's Meta-Council on the Circular Economy.

The ICEhouse™ is designed to demonstrate the positive design framework described in '*Cradle to Cradle©: Remaking the Way We Make Things'*, [06] the sustainable development goals of the United Nations, and the reuse of resources implicit in the circular economy.

As an experimental prototype, the ICEhouse™ illustrates the use of technical nutrients and is primarily made from three materials from the technical metabolism: aluminum for the structural frame, aerogel as insulation and polymers for cladding and furniture. The concept originates in work William McDonough is pursuing in using recycled polymers as safe, super affordable building materials.

Photo: There are just four materials that make up the ICEhouse™ and two types of materials make up the construction aspect. The facade panels are modular and are designed to be able to reconfigure to optimize daylighting.

Photo © Bertram Radelow and McDonough + Partners

06 Cradle to Cradle® is a registered trademark of MBDC, LLC

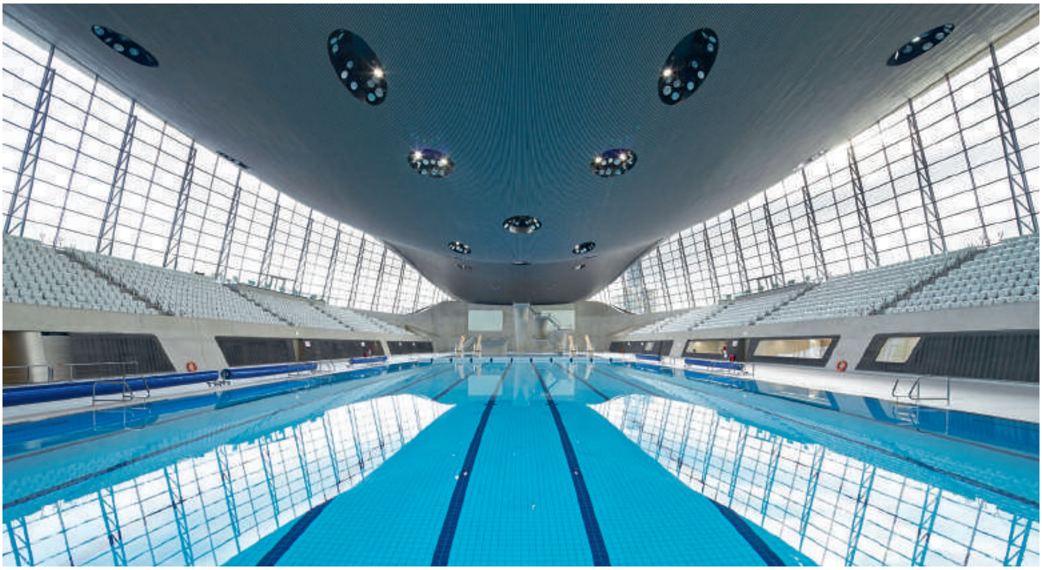
The patent pending structural system consists of two simple elements that together create a three-dimensional structural frame integrating the floor, walls and roof. The facade is made from polymer skins filled with aerogel.

The structure concept, designed to be used by people in need around the world, can be assembled and disassembled with simple tools and can be easily and compactly transported to different locations. It can be used for housing, community structures, shelters or even small bridge structures around the world.

The name ICEhouse™ is a poetic reflection of the building: like ice, it is ephemeral — only to be in a place for a short period of time. It will melt away and reappear somewhere else.

Photo: The frame elements are light and easily disassembled and thus can be convenient to adapt to different structures around the world.

Image © McDonough + Partners



London 2012 Olympics
— existing architecture

Location London, United Kingdom
Year 2012
Owner Olympic Delivery Authority
Architect Zaha Hadid Architects
Size 21,897 m^2 and 15,950 m^2

The London Aquatics Centre, is designed by Zaha Hadid Architects before London won the bid for 2012 Summer Olympics, where it was one of the main venues.[07]

Because the centre was designed before the Olympic bid was completed, the spectator wings were not part of the original design. They were later added as a temporary structure to fit the larger audience and accommodate the London Games whilst also providing the optimum capacity for use in legacy mode beyond the event.

The temporary add-ons was only possible because of a very flexible design of the permanent structure. The roof is only supported in two places, which provides for a completely open space with no columns.

The temporary structure was designed and constructed with disassembly in mind. This provides for an easy and light construction that quickly could be erected and dismantled after the games. The 'Olympic mode' was 21,897 m^2 and allowed for 17,500 seats and the 'legacy mode' of the building reduces the size from to 15,950 m^2 and a capacity of 2,500 seats.[08]

Photos: The London Aquatics Centre during the Olympics and in Legacy mode.

After the Games, the frame wings on either side of the central space were removed, unbolted, and sold. The PVC wrap that temporarily enclosed the space was also sold, while the seats and toilets were reused elsewhere. As certain parts of the building were no longer needed, they were recycled.

07 zaha-hadid.com **08** londonaquaticscentre.org

3XN Architects Offices
— existing architecture

Location Copenhagen, Denmark
Year 1860 and 2014
Owner 3XN Architects
Interior 3XN Architects
Size 2,000m^2

3XN Architectss transformational renovation of a historic and listed canon boat sheds on Holmen in Copenhagen has resulted in a spectacular new environment for the Copenhagen branch. The waterfront offices dates from 1826 and was originally used by the Royal Danish Navy for the repair and storage of military gunboats in Holmen

From 1690 to 1993, Holmen had served as the navy's base, but after its departure, the area, not far from the Copenhagen Opera House, began to turn into a cultural enclave. The Royal Danish Academy of Fine Arts schools and educational facilities for theatre and music are now located there, and the black stained wooden gunboat sheds are being renovated and leased to assorted businesses in fields such as media, advertising, and architecture.

In 2006, five of the sheds where ravaged by fire, leaving only a few structural elements and some of the brackets. The sheds were then rebuild using the traditional joints and brackets — all visible and following many of the principles of design for disassembly.

Photos: The connections in the timber structure are made as traditional joints with bolts and carvings that easily can be disassembled.

The studio is designed as a large open space, with meeting facilities located between the cantina and the rest of the office.

Also the office is designed so all of the employees has a waterfront view. The meeting rooms are designed like rooms within the room and together with the model workshop, they are the only partitioned areas within the office but have an open feel to them through use of glass walls.

The open environment contributes to a creative and interactive space, where sharing of knowledge and interconnectivity amongst the studio's architect's comes naturally. [09, 10]

09 3xn.com **10** architecturalrecord.com

Photo: The modern open office displays the visible traditional timber connections and adds to experience of the space.

Photo © Adam Mørk

Bullitt Center
— existing architecture

Location Seattle, USA
Year 2012
Owner Bullitt Foundation
Architect Miller Hull Partnership
Size 800 m^2

The Bullitt Centre was designed to be the greenest commercial building in the world when completed in 2012. It was built by a nonprofit organisation that occupies half of the building, while another tenant takes up the rest of the building. In that way the use reflects a traditional commercial office building.[11]

The structural backbone of the Bullitt Centre comprises three principal materials: timber, concrete, and steel. These materials are carefully used an separated in the structure according to their specific load-bearing characteristics, while reduction of carbon emissions during construction of the Bullitt Centre has been top priority.

Concrete is one of the most notorious carbon emitters in the construction industry. There is an incredible amount of energy embedded in the manufacturing of concrete, but it is also valued for its durabilitty, flexibility, affordability, and capacity to handle enormous amounts of compression. So the design team limited the use of concrete to the bottom of the building, where it is most needed to carry the loads of the building — the two bottom floors.

Photo: The Bullit Centre clearly expresses the separation of different systems. The skin is a high performance building envelope that is estimated to last 50 years. On the roof is active solar control photovoltaic that lasts about 25 years.

Photo © Nic Lehoux

11 bullittcentre.org

Above the second floor, the Bullitt Centre is constructed with heavy timber framing. 100% of the timber used in the building is Forest Stewardship Council (FSC) certified, ensuring it comes from a responsibly managed forest. Glued laminated timber (glulam) beams and columns are used for structural timber, which is a more efficient method of using wood, since they are engineered and cut off site.[12]

By some the Bullitt Center has been called the greenest office building in the world, due to its high tech, self-sustainable and eco-friendly features.

The building provides itself with energy through a huge sun panel system on the rooftop, which produces enough electricity for the whole building plus a large residual that is sent to the power grid. It uses a geothermal cooling and heating system, that together with automatic operable windows for natural ventilation, provides the building with its own temperature regulation.

In addition, the building harvests rainwater that, together with the grey water, is pumped through a system that filters and disinfects it, so the water is drinkable.

12 wbdg.org

13 corporatetechdecisions.com

Photo: Inside the building the separation of the different systems is clear. The structure is estimated to last 250 years and made from glue laminated timber, concrete, and steel.

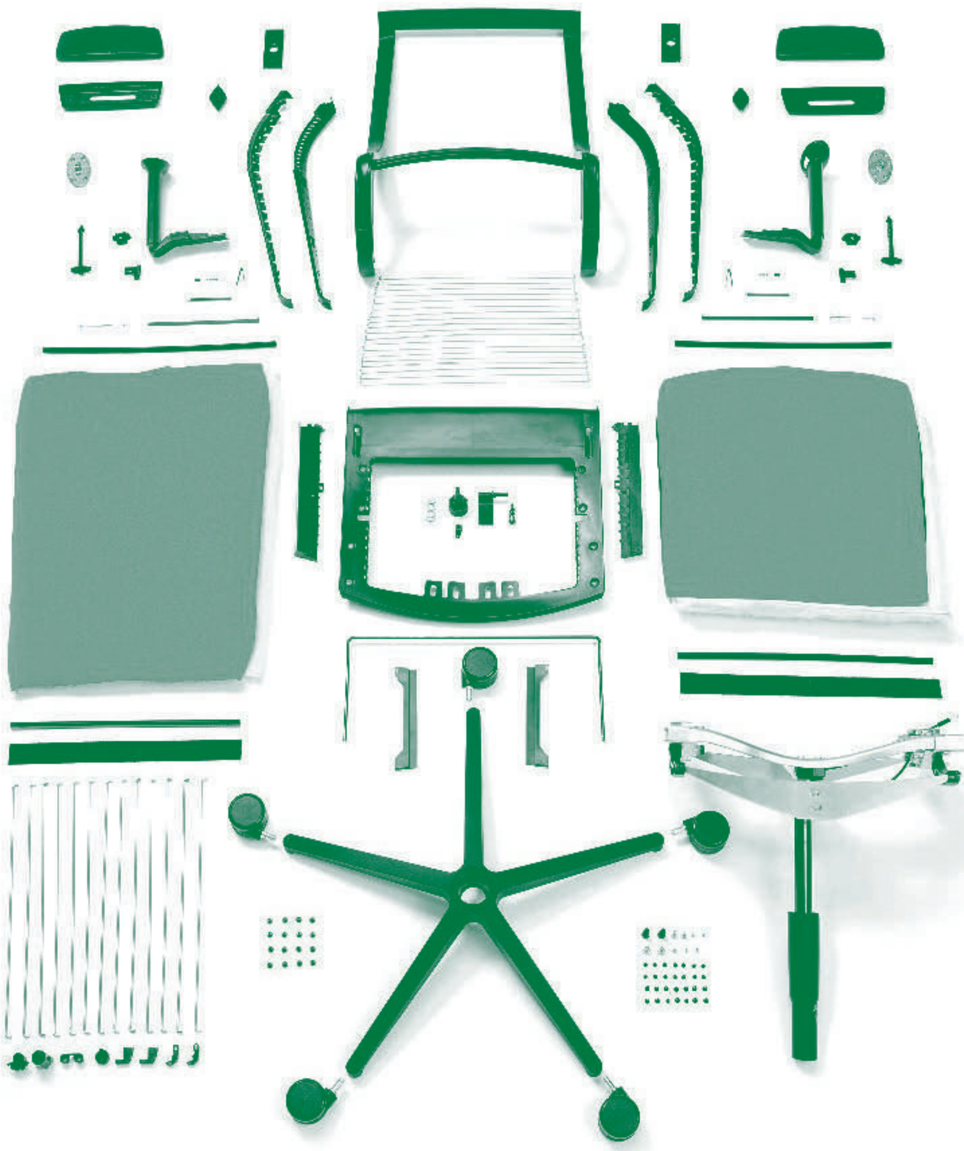
Photo © Nic Lehoux

All the waste composite of the toilets is collected and treated on site to be used as fertilizer.[13]

To manage these features, the Bullitt Centre contains an extensive performance surveillance system that continuously monitors and analyses the building. The many types of information, ranging from energy and water consumption to indoor air quality and occupant satisfaction, are frequently analysed and evaluated.

The performance statistics and operation information, together with other information about the building, such as building design and construction details, are then available for review via an online dashboard.[14]

14 wbdg.org



Think Chair
— the interior industry

What Office chair
Purpose 99% recyclable and made from up to 28% recycled materials and is already available on commercial scale.

Image: A Think Chair disassembled in all its individual pieces and material fractions.

Image © Steelcase

Steelcase has applied a circular business case around its Think Chair, which they claim to be 99% recyclable by weight and is made from up to 28% recycled materials. The Think Chair weighs 14,5 kg and contains up to 44% of recycled materials. The chair contains no PVCs, CFCs, solvents, benzene, chrome, lead or mercury and every part is assembled without the use of glue.

The chair is easy to repair and old parts can easily be exchanged with new ones. When the life time of the chair has ended, Steelcase retrieves the chair and reuses the parts and materials in its production chain.

Steelcase has also established an 'end of use' program where it helps businesses to dispose of surplus furniture in socially, economically and environmentally responsible ways. First, Steelcase works with the business to understand its situation. It then meets with their partners to find and present options that meet their goals, whether it is income, landfill diversion or charitable donation.

Steelcase shows that it is already possible to make positive business cases with products available on a large commercial scale.[15]

15 steelcase.com

Bloom Laptop
— the electronics industry

What Laptop
Purpose Can be completely disassembled by hand in ten steps and in under 30 seconds

Photo: By designing for disassembly the laptop of the future will be easy to repair, upgrade and extract the material to reuse in other electronics.

Photo collage © GXN

Moore's Law states that the amount of transistors that can be built on to the same chip doubles every second year. This means that the pace at which we evolve new technology is accelerating and the technology that is new today will be obsolete in a few years. Huge amounts of resources are being used to produce both new gadgets and electronic waste.

The Bloom Laptop, which can be completely disassembled by hand, in under 30 seconds, and in ten steps. By contrast, a traditional laptop requires three tools, up to 120 steps, and takes about 45 minutes.

A by-product of making the computer modular was the development of a detachable wireless keyboard and trackpad — a feature that allows users to type from wherever they wish, without having the screen right there in their face.

Upgrading is also much easier, as users can just pop out the obsolete piece, buy a new one, then pop it in. A traditional modern laptop already consist of recyclable materials, but they are all mixed and glued together in a way that makes them very difficult and expenisive to recycle.[16]

16 materialconnexion.com

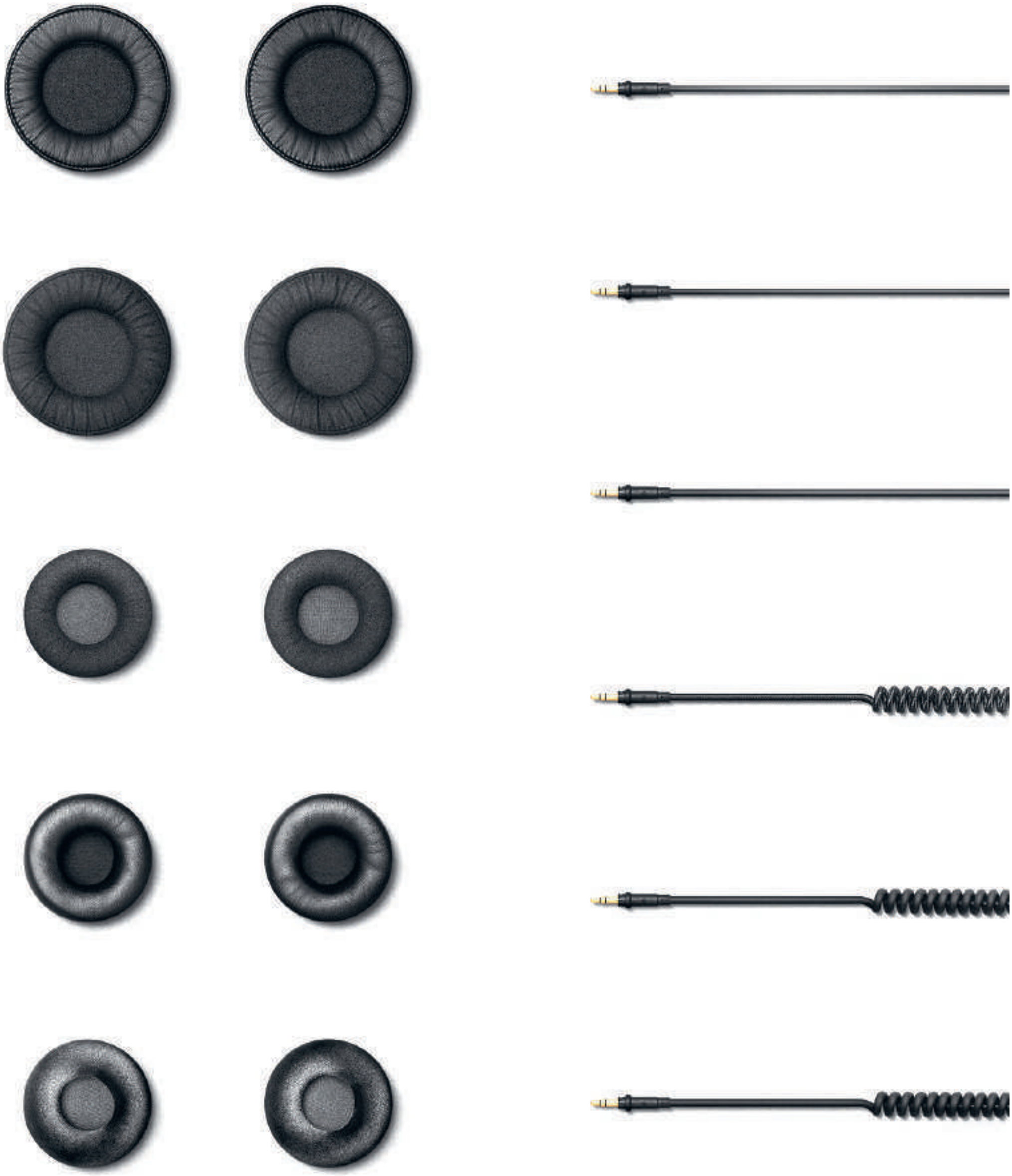


Photo: The TMA-2 Modular Headphone from the Danish headphone manufacturer AIAIAI is designed as a framework of elements, including the speaker unit, headband, ear pads and cable, which can be connected or combined in different ways.[17] The parts are bought and assembled according the specific requests of the user, which allows for mass customization. The design also allows for disassembly of the headphones if the customer are to upgrade certain parts or change them if something breaks.[18]

Photo © Kilo Design **17** kilodesign.dk **18** aiaiai.dk


vodafone
vodafone
MARTINI
FIAT
POTENZA
vodafone
vodafone

Formula One
— the car industry

What Formula One cars
Purpose High tech machines that are optimized for easiest and fastest possible disassembly process

Image: This fascinating sport and machine reveals how extreme you can make a design for disassembly strategy if every element counts. E.g. the ability to detach a wheel with only one bolt, compared to at least four on private cars.

Image © GXN

Formula One cars are the fastest road course racing cars in the world, with speeds up to 360 km / hour on the track. The cars are designed for one thing only — speed. The chassis is where everything is bolted and attached. In Formula One cars, the chassis is made out of a single piece of material, largely a carbon fibre composite, rendering it light but extremely stiff and strong.[19]

The whole car, including engine, fluids and driver, weighs only 691 kg — the minimum weight set by the regulations. If the construction of the car is lighter than the minimum, it can be ballasted up to add the necessary weight.

A pit stop takes about seven to ten seconds. The pit crew consists of up to 20 persons that during pit stops have to complete following tasks:

— Remove debris from air intakes.
— Refuel the car.
— Change tires.
— Check suspension settings.
— Check tire pressure.
— Clean the windshield. [20]

The design of the car is optimized to have all these workflows done in just a matter of seconds.

19 formula1.com **20** f1technical.net

How to design

— Page 66 to 99

Discover tools and strategies for how you can implement a design for disassembly in the construction industry.

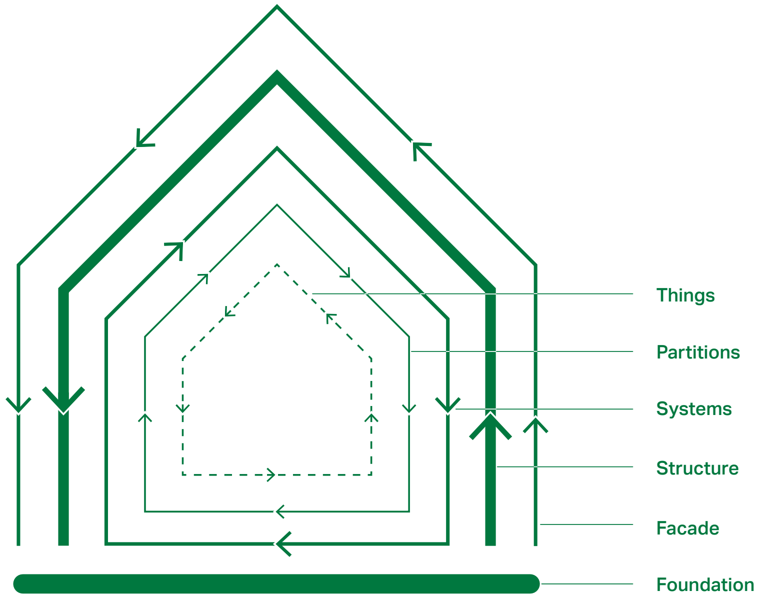


Diagram: Showing the division of the elements involved in building in relation to lifetime.[21]

This diagram is an reinterpretation of an original owned by Steward Brand

Lifecycles
— a buildings life

When a building undergoes renovation, is rebuilt or has to be torn down, a lot of building materials often end up in landfills. This requires a lot of energy and the loss of scarce and valuable raw materials, which have been used to create the building.

Rebuilding often happens when the use of the building is changed. A building's use can change over time due to new trends, expansion or reduction in users, or a new owner.

Foundation (100+ years)
The foundation is buried in the ground and is difficult to access, which is acceptable because the element has a long life that can endure several buildings.

Structure (50+ years)
The structure is the spine of the building, so it is acceptable that connections are the least accessible. The lifetime of this element is longer than most buildings, so it is important it can be taken out and reused in another building.

Facade (30+ years)
Due to the facade claddings exposure to the weather, it is expected that during a building's life the facade will be either changed or at least undergo major renovation, so it is key that these actions can easily be made.

Partitions and systems (10+ years)
A building must be able to adapt to the changing needs of its occupants, and flexibility in the partition walls and technical system is the keystone to achieve this.

Things (1+ years)
The things we put inside our buildings, furniture, decorations, etc., in genera has a very short lifecycle. These things should be thought of in regard to the overall use of the building so they don't interfere with the flexibility and reuse of the resources. [21, 22]

21 How Buildings Learn **22** Cradle to Cradle® in the Built Environment, p. 72

Strategies
— for which connections to choose

The general rule for designing for dissambly is to use connections that are reversible. Mechanical connections, e.g. can be assembled and disassempled multiple times without damaging the material or the connector itself.

The following are some strategy suggestions to implement when considering design for disassembly.

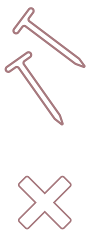
Nails and screws
Piercing nails through structures and materials to make connections is very common find in the construction industry. Unfortunately, the downside to this is that nails damage the material and cannot be retrofitted to other uses. Instead, it is better to practise using screws, nuts and bolts because of easier design for disassembly allow for reuse of materials.

Fasteners
Fasteners come in all shapes and sizes to allow maximum freedom when assembling things together. This, however, becomes problematic when considering for second use of the same material. By using common and similar fasteners, there will be less trouble identifying different types of fasteners used and fewer tools needed for deconstruction.

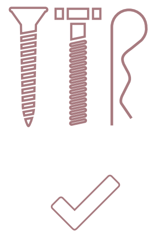
Adhesives
It is better to use dissolvable binders rather than glue and sealants when considering the disassembly. Glue and sealants do not consider the next life of the material and thus leave residues and sometimes tear the material when separating material elements. By using dissolvable binder, the strength of the adhesive is lost when exposed to water, temperature, etc. without agitation.

Cement in masonry
It is better to use lime mortar instead of Portland cement because the latter is impossible to disassemble, it will only leave rubble when it is destroyed, as well the brick will break before the cement. Lime mortar is much more flexible and permeable, and it can be removed by hydroblasting or beat it away with a hammer.

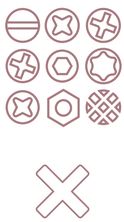
Diagram: Showing some strategies to follow when considering design for disassembly.



Nails damage the material.



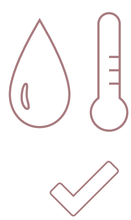
Use screws, pins,
nut and bolts.



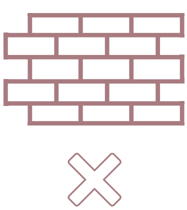
Fasteners can be found in
all shapes and size.

Use common and
similar fasteners.

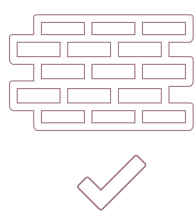
Avoid glue and sealants.



Use easy dissolvable binders.



Portland cement is
impossible disassemble.



Use lime mortar instead.

Overview of volume, value and time of structural elements

TABLE 1

Timber structure	Foundation	Column	Beam	Wall	Slab	Facade
Volume (% of total)	0%	10%	30%	20%	10%	20%
Value (dkk / ton)	—	5,000	5,000	5,000	5,000	5,000
Time (durability)	—	100 years	100 years	30 years	100 years	30 years

TABLE 2

Steel structure	Foundation	Column	Beam	Wall	Slab	Facade
Volume (% of total)	0%	30%	50%	0%	0%	20%
Value (dkk / ton)	—	32,000	32,000	—	—	32,000
Time (durability)	—	100 years	100 years	—	—	50 years

TABLE 3

Concrete structure	Foundation	Column	Beam	Wall	Slab	Facade
Volume (% of total)	10%	10%	20%	40%	20%	0%
Value (dkk / ton)	1,000	4,500	3,000	900	450	—
Time (durability)	150 years	100 years	100 years	100 years	100 years	—

Table: Showing an overview of the approximate average values and amounts of the different structural elements to know which joints to focus on in a design for disassembly strategy.

Where to focus
— quantities, qualities and values

In order to know which joints to focus on i a design for disassembly strategy, MT Højgaard has made an assesment of the structural elements that most often are built together in contemporary static structures made from timber, steel and concrete.

To ease and optimize implementation of a circular economic model in the construction industry, focus must be on designing for disassembly the joints and connection between the static structures that most often are built together in contemporary construction, and between the structures with the highest value.

Columns and beams are often integrated parts of the static systems, whereas e.g. columns rarely are integrated statically with slab elements. Hence, focus should be on developing effective joints that are easy to disassemble for the connections between columns and beam and not on developing ditto for columns and slab elements.

The tables on the left page provide an overview of the approximate average values and amounts of the different structural elements.

Timber
Wall — Foundation | Wall — Column | Beam — Column

Steel
Column — Facade | Slab — Column | Beam — Slab

Concrete
Wall — Foundation | Wall — Column | Beam — Column

Peikko
— existing products

Peikko, founded 1965 Finland in, is a large mechanical connections for concrete elements and composite structures.

The solutions were initially invented out of necessity. Since the cold Finnish weather doesn't allow for traditional casted connections. The resulting mechanical joints not only avoids the long drying times but as a side effects also makes the building easier and faster to construct — and because of this also cheaper in labor.

Their system for mechanical assembling is in theory actually reversible, which makes it possible to disassemble the structure and reuse the components.

Furthermore is the system a basic mechanical connection that is already seen in many buildings today. But the challenge is that these connections are cast in cement in order to prevent sound from escaping and screws loosening. This problem however, could be solved by using a dissolvable binder instead of the traditional Portland cement typically used today.[23]

23 peikko.dk

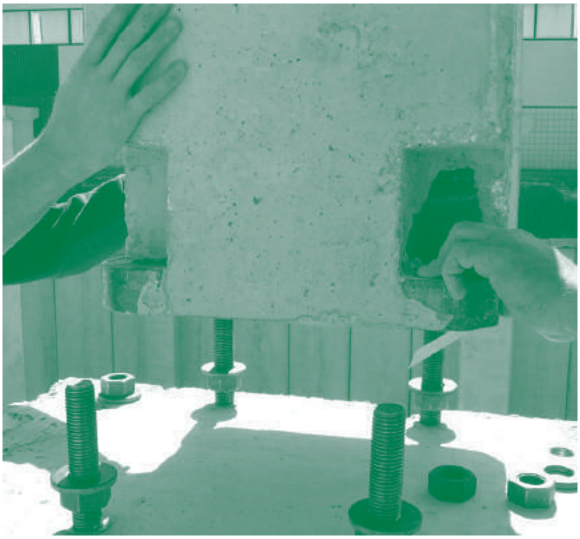
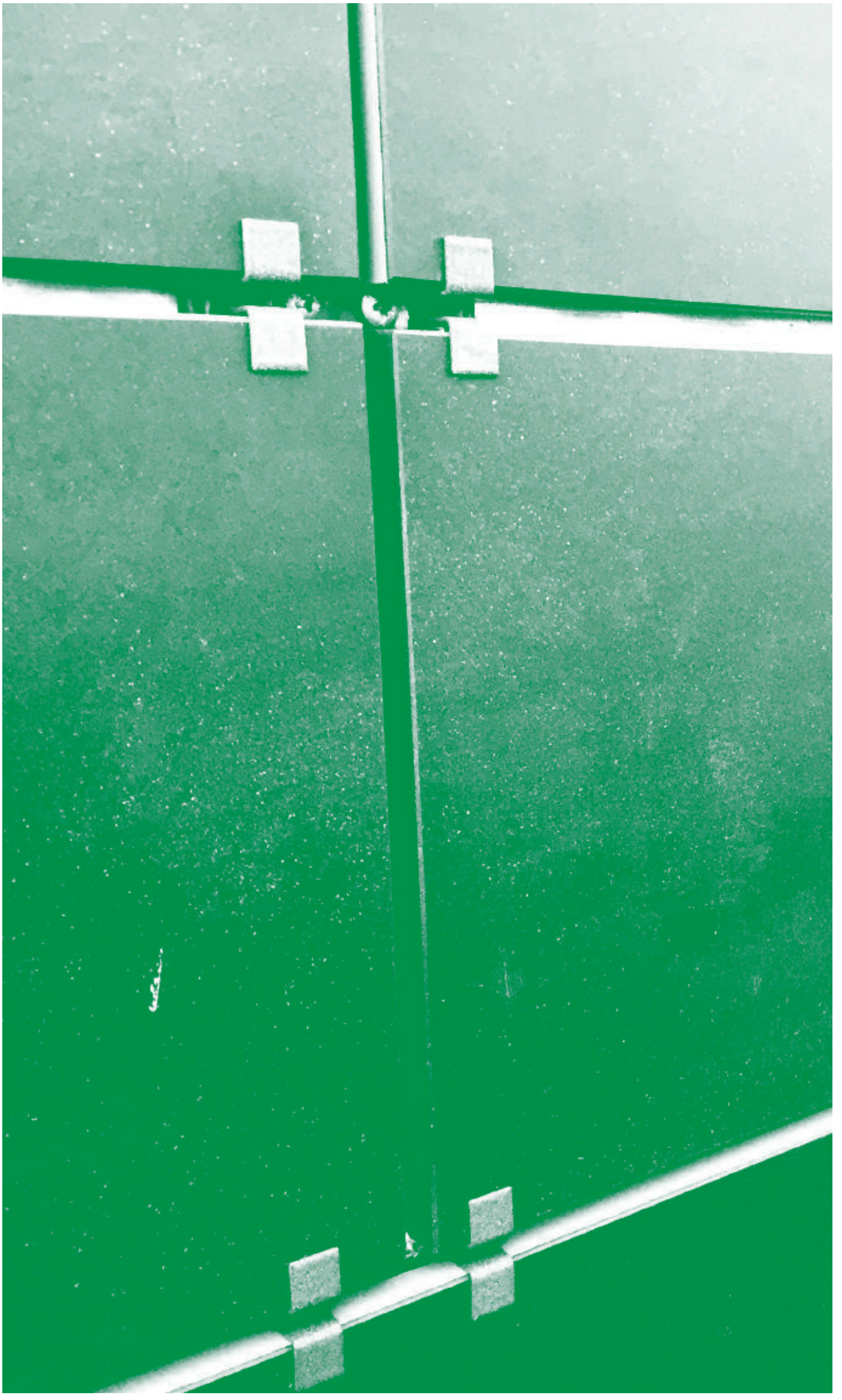


Photo (opposite page): The 'Tenloc Panel Connector' is an example of a commercial available mechanical connection for large concrete structures.

Image (this page): The four bolts on the column shoe stabilizes the element without the need of any additional support. This means fewer work processes and shorter drying times, resulting in a faster construction.



Mosa Facade Systems
— existing products

The Dutch ceramic company Mosa already offers a façade solution designed for disassembly. It is a lightweight ventilated façade system with ceramic tiles mounted with mechanical fasteners, that comes either with visible or concealed fixations.

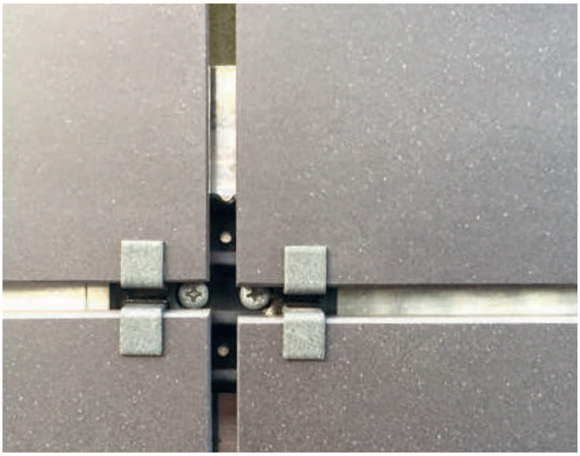
The tiles in the first solution are attached to a vertical aluminium profile on the underlying frame using a double clamp system. The clamps remain visible and are integrated into the facade as a part the architectural design.

In the second solution, the tiles are mounted on horizontally and vertically fitted aluminium profiles. Using an undercut drill in the rear of the tile and the anchor is fixed in this using a steel plug.

The mechanical fasteners secures the tiles can easily be attached and later detached to optimize renovation, deconstruction and reuse. All the tiles from Mosa is Cradle to Cradle[24] Certified™ which guarantees the material can be reused to high degree and fits into a circular building ecosystem.[25]

The detail shown is from the facade on Green Solution House (see more about the project on page 194 to 197).

24 Cradle to Cradle® is a registered trademark of MBDC, LLC **25** mosa.nl



The tiles from Mosa are easy to reuse and renovate due to its double clamp system and mechanical fasteners.

All photos © GXN

‘Rethinking and reusing resources is not only good business, but also a very important perspective, considering the massive scale in future use of building materials and climate change’

— Heidi Sørensen Merrild
Associate Professor, Aarhus School of Architecture

Adaption of the current
— commercialization of products

Commercial building products that support the new of way designing are needed for 'design for disassembly' to break through and become the new standard in the building industry.

Commercialization
For the methodology to be a completely to be an integrated part of the building industry a critical mass is a necessity. The large-scale manufacturers of building materials will need to adapt their products to support this change. It will never be a new standard if the solutions and products remain a niche that never gets widely spread.

As the research shows, the change for the manufacturers doesn't have to be that big. Some of them are already producing building components that are almost ready for this shift. A good example is the concrete element manufacturer Peikko's 'Tenlock'-system and column shoe. They are designed with the intention to be easy to assemble by using mechanical connectors to join the elements. However, the mechanism they use is, in theory at least, reversible, so it should be possible disassemble them again without changing a lot on the current product.

In every product evolution, some companies have a longer way to travel. They now have the opportunity to take the lead and drive innovation or take the risk and stay with staus quo. Inevitably, the industry will be distrupted by completely new companies that will arise and become the leaders of the future.

One way for companies to start out could be by changing their business models, e.g. by leasing out the building elements and establish take back agreements. More about this is described in the circular economy section of this book.

Timber prototype
— a new building element

Developed by Tinus Bengt Petersen and Ingri Bollingmo Løvskogen
School: VIA University College
Year: 2015

Photo: The timber element is protected by a layer of envelope and inner wall so that in the future, the virgin element can be reused and allows for design for disassembly. It is important to create a system that allows for multiple use and configurations.

Photo © GXN

Goals and intentions
The prototype of a new timber building element has three primary objectives to achieve:

— Standard timber element protected behind a removable envelope and inner wall, including a separate wall for technical installation.

— Connections between the elements allow for disassembly and reuse of the virgin element several times.

— The element is made of timber and 99% will be reusable 'as is' and afterwards for controlled downcycling in the biological cycle.

Context
The timber element created consist of 99% wooden material, designed to be a part of a controlled biological cycle. By using wood fibre insulation material with a natural capacity for moisture regulations, it also ensure a natural regulation of the indoor air climate, without relying too much on technology.

The timber element is a part of a modular system, that is designed for disassembly, making sure that the element can be mounted and demounted in a safe way.

The aim has been to make a system that will save the load-bearing timber element for a second and maybe third use in other configurations until the wood will be reused for other purposes.

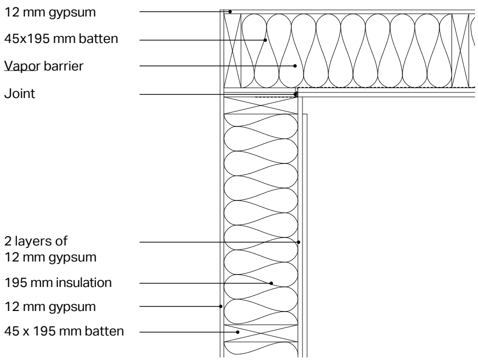
Construction

The chosen solutions and connections secure flexibility, tolerances, robustness and is of high quality. The connections are fastened by using bolts through laminated timber.

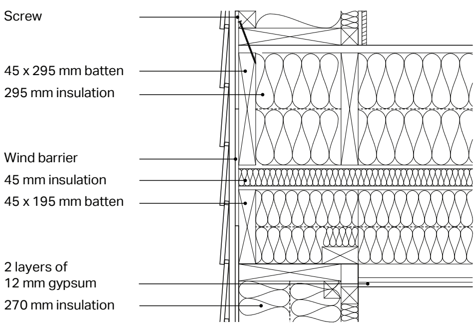
Photo: The connections are fastened by using bolts and steel washers with nuts through laminated timber.

Challenges

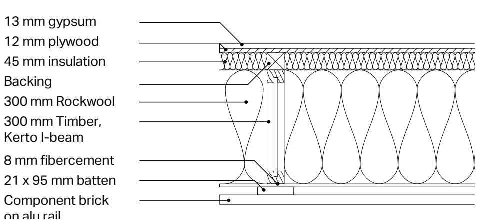
Detail 1: Horizontal view of a traditional corner construction.



Detail 2: Vertical view of a traditional wall — slab construction.

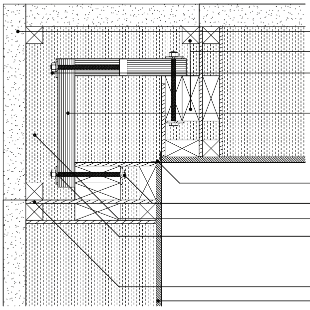


Detail 3: Horizontal view of a traditional wall construction.

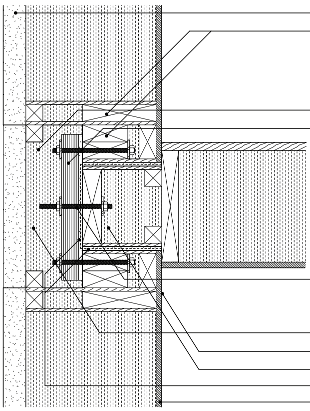


Solutions

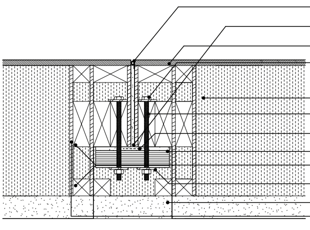
Detail 1: Horizontal view of a corner construction designed for disassembly.

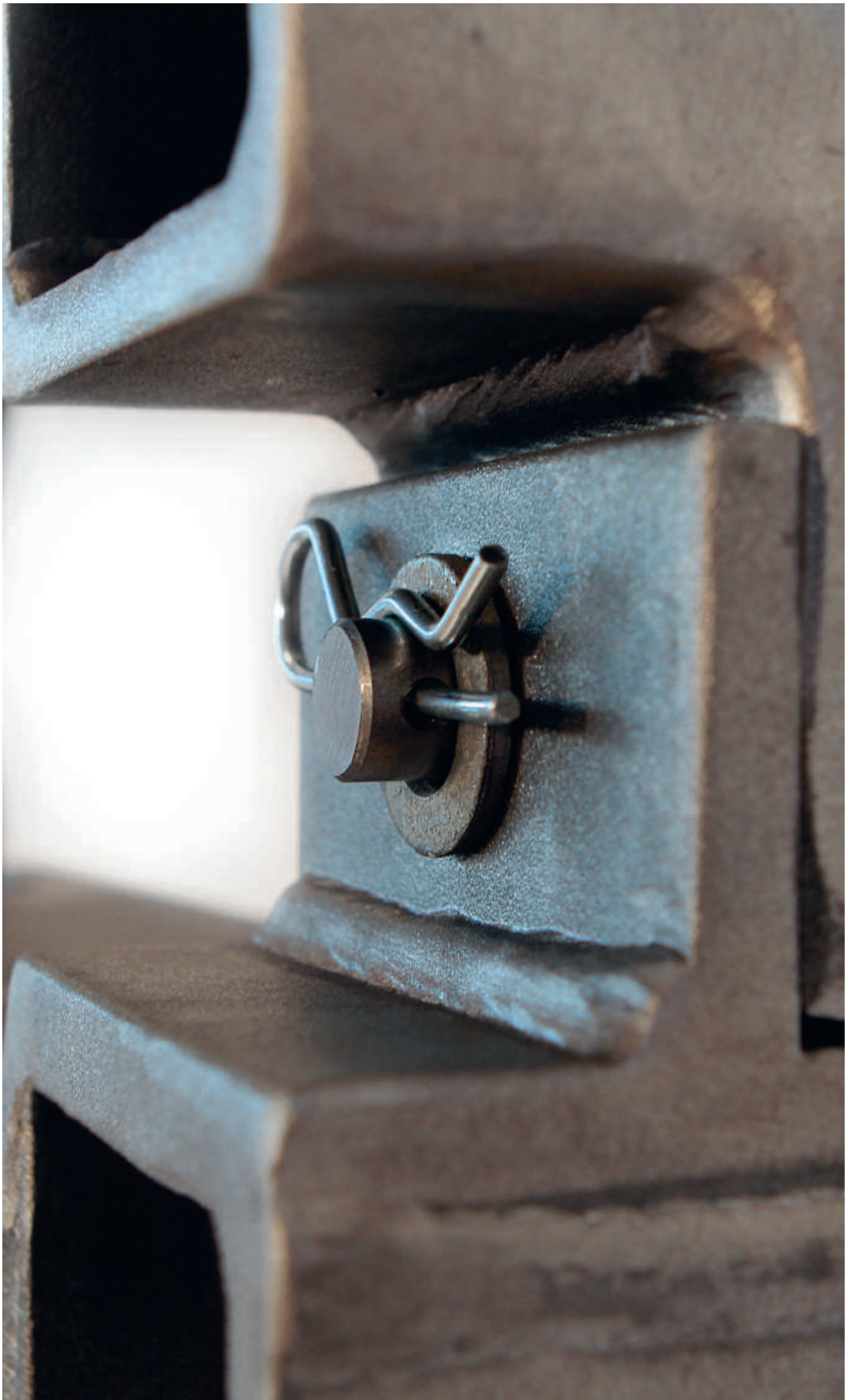


Detail 2: Vertical view of a wall — slab construction designed for disassembly.



Detail 3: Horizontal view of a wall construction designed for disassembly.





Steel prototype
— a new building element

Developed by Jimmi Jensen and Milad Ahmad Tokhi
School: VIA University College
Year: 2015

Goals and intentions
The prototype of a new steel building element has three primary objectives to achieve:

— High quality steel solutions that focus on design for disassembly and greater direct reuse solutions.

— A modular building system of high flexibility including standard columns and beams.

— Optimizing the construction and dismantling process by focusing on safety, ease of assembly and disassembly and thereby saving time.

Context
Buildings will be our future material banks and by using high quality steel structures that is flexible and highly reusable, this system will provide substantial economic advantages for stakeholders of the future.

Most use of steel today results in a constant downcycling of steel quality, therefore our aim is to make sure that continuous and repeated use of quality steel is maintained or even improved.

Photo: The steel protoype aims to focus on flexibility, ease of disassembly, as well as safety.

The modular steel building system provides short assembly times both in terms of mounting and in terms of dismantling. Dismantling and reuse 'as is' are the keywords instead of demolishing and remelting.

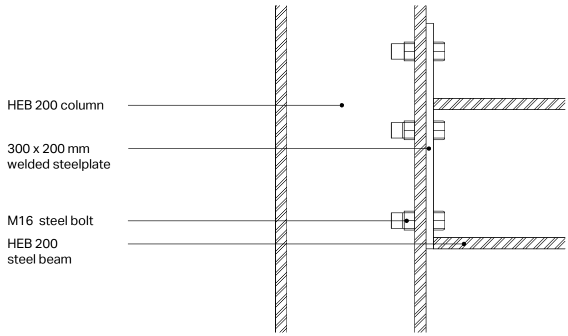
Construction

The connection is simple. The nut and bolt connection is replaced a mandrel with two splits and stabilizing washers. This makes for a quick and easy assembly and disassembly process — and very noteworthy — with no tools necessary.

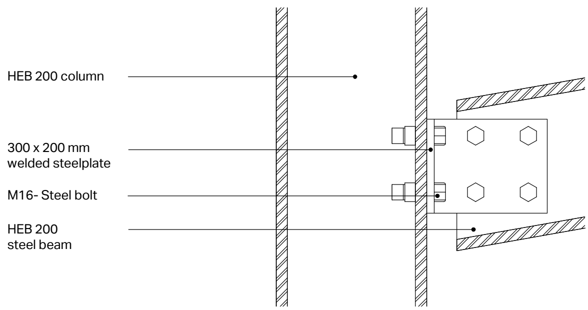
Photo: The disassembly method is optimized for a very quick and simple action. The connections are joined by a mandrel with two splits and stabilizing washers, which can be undone to take apart the pieces.

Challenges

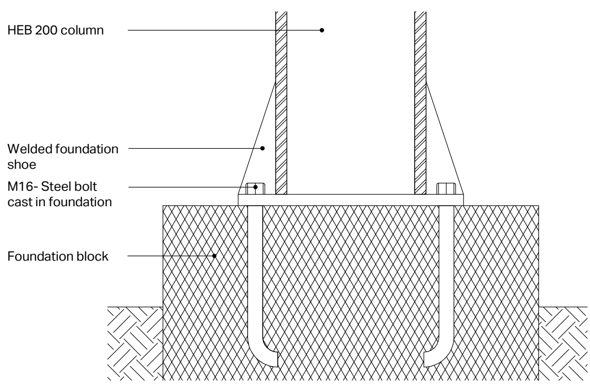
Detail 1: Vertical view of traditional column — beam assembly.



Detail 2: Vertical view of traditional angular column — beam assembly.

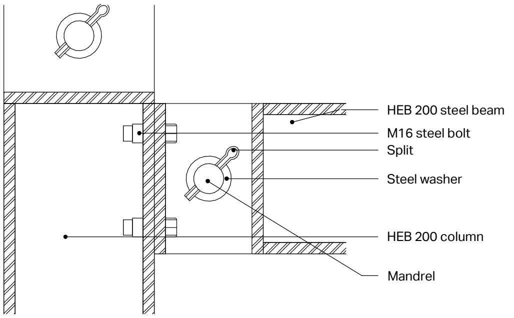


Detail 3: Vertical view of traditional column — foundation assembly.

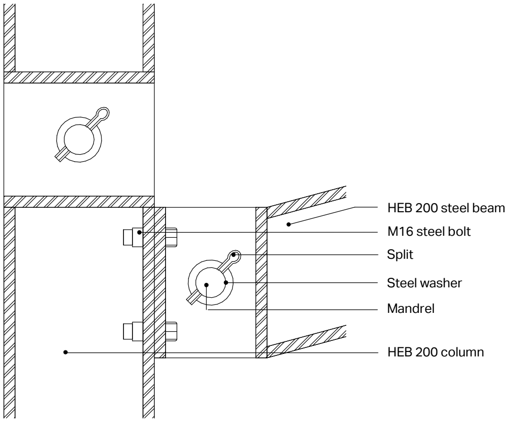


Solutions

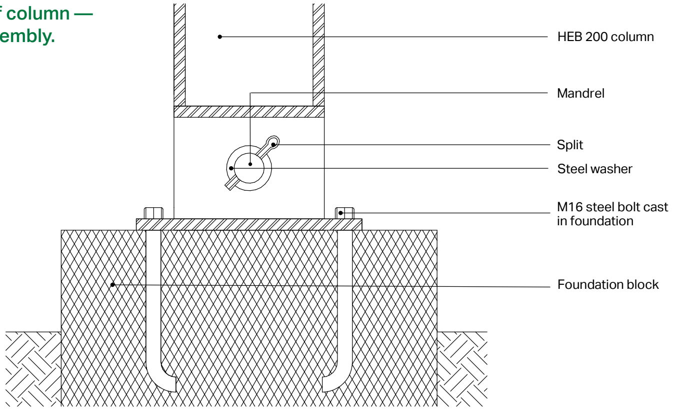
Detail 1: Vertical view of column — beam mandrel assembly.



Detail 2: Vertical view of angular beam — column mandrel assembly.



Detail 3: Vertical view of column — foundation mandrel assembly.



Concrete prototype
— a new building element

Developed by Martin Ravnsvbæk and Hans Nicolai Søndergaard
School: VIA University College
Year: 2015

Photo: Using mechanical connections instead of casting everything together allows for disassembly and reuse.

Photo © GXN

Goals and intentions
The prototype of a new steel building element has three primary objectives to achieve:

— Flexible concrete wall and column solutions that focus on design for disassembly and direct reuse.

— The system makes it possible not to cast out between elements and instead using mechanical connection.

— Optimizing the construction and dismantling process by focusing on safety, ease of assembly and disassembly and thereby saving time.

Context
The excessive use of energy in the production of concrete elements calls on ingenuity and creative solutions when it comes to secondary reuse of the elements in other configurations.

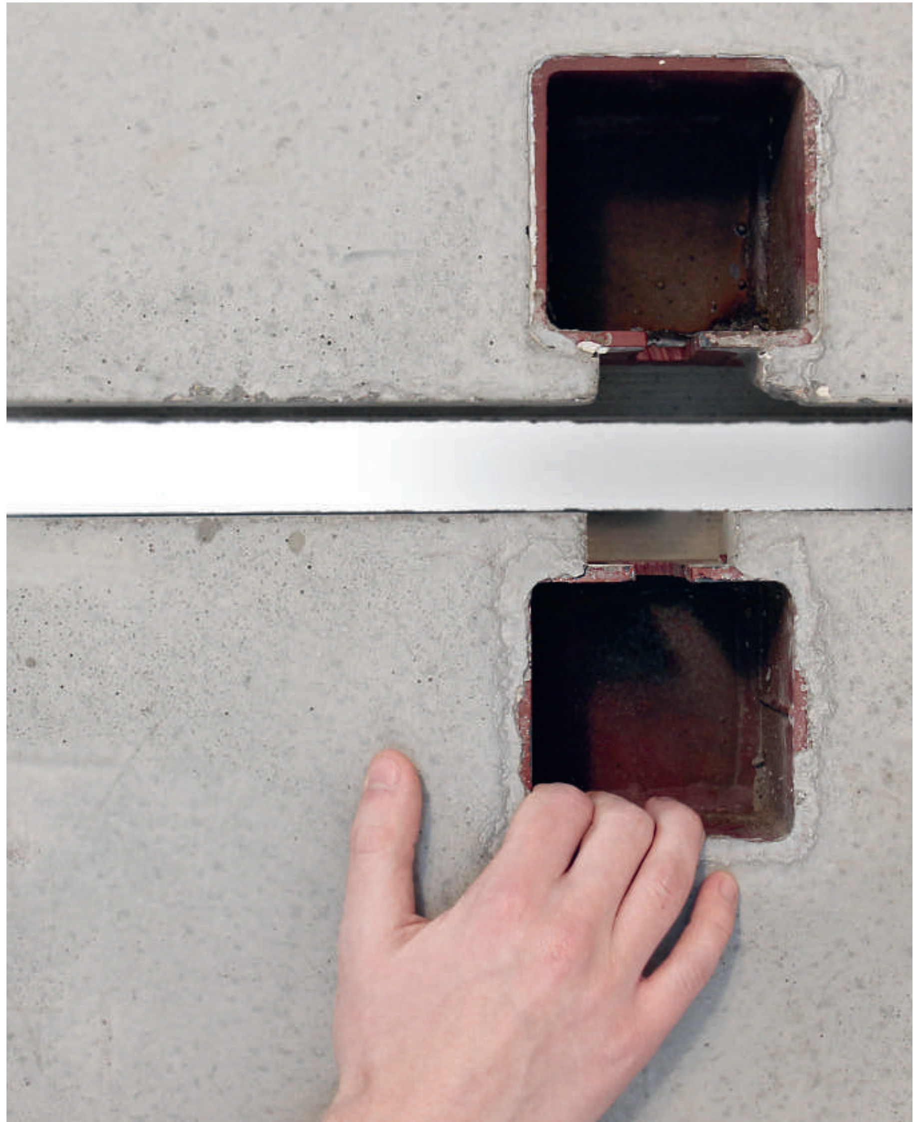
The aim is to show that a circular economy is possible also within the concrete building elements sphere, that in turn will create a new secondhand marked for stakeholders in the industry.

The prototype shows a typical connection between two precast concrete corner elements, as well as two wall elements side by side using the same connection technology. These connections between elements are based on accessible load transferring bolts placed in embedded anchor boxes in precast recesses. Easy to fasten and easy to dismantle.

Construction

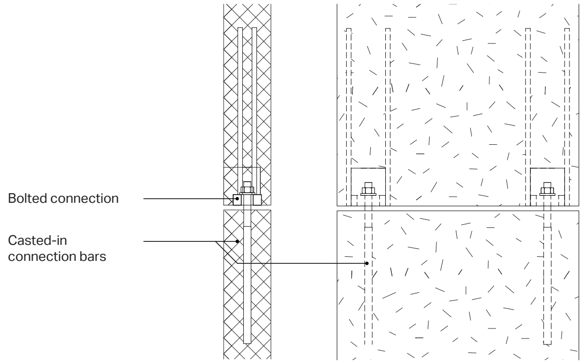
The bolted joints are accessible from the external side of the element, protected against fire due to insulation and external cladding. This concept is primarily targeting buildings of up to four storys.

Photo: The connections between elements are based on accessible load transferring bolts placed in embedded anchor boxes in precast recesses. Easy to fasten and easy to dismantle.

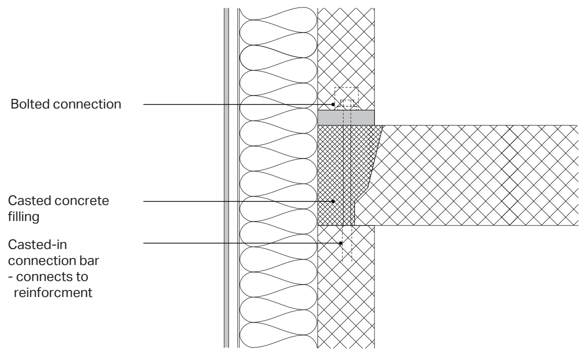


Challenges

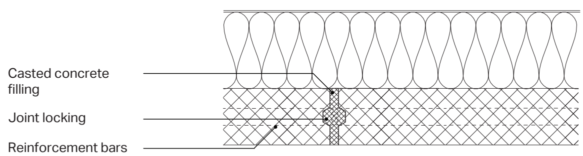
Detail 1: Traditional casted bolt assembly.



Detail 2: Vertical view of a traditional wall — deck construction.

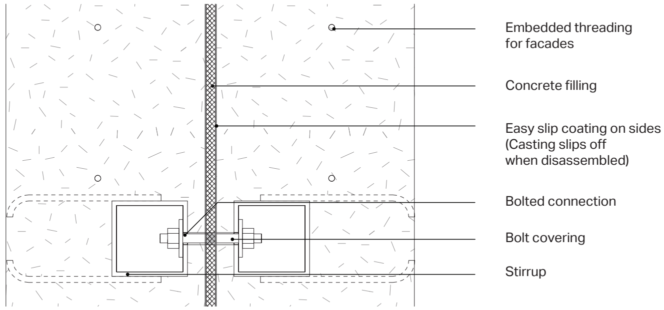


Detail 3: Horizontal view of an traditional assembly of wall elements.

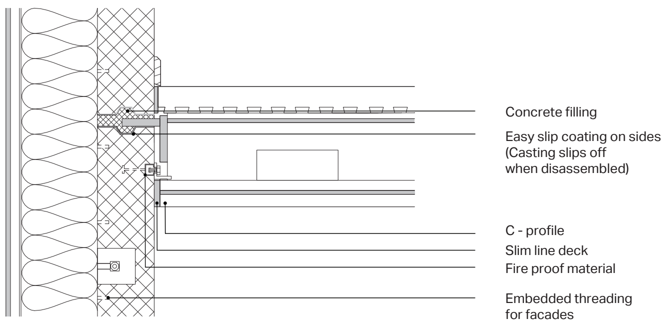


Solutions

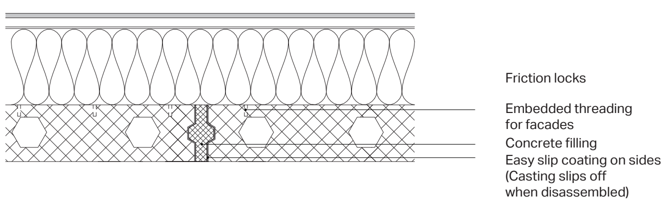
Detail 1: Front view of wall — wall assembly



Detail 2: Vertical view of wall — deck construction designed for disassembly.



Detail 3: Horizontal view of wall elements designed for disassembly.



Criteria for reuse
— information and volume

In order to secure the safety of the building, a certain level of information is needed by third parties to in order to accept building with reused components instead of completely new ones.

The information will be stored in the material passport that follows each individual building element. This concept is described further in the Material Passport section, page 125 to 177.

In order for 'design for disassembly' and the circular future of buildings to have any impact on society, it is critical that the availability of reused building materials reaches a certain mass. Contractors must be sure that they can always get the materials they require and in a timely manner, or else they will continue to work with the traditional suppliers they already now.

Structural integrity
The structural integrity of the individual element is also key. The ability of the reused building elements must be maintained, tested and documented by educated personnel that can provide a certification of the quality. This will result in the development of a new certification system and business opportunities.

Mounting manual
In order integrate the reused building material properly in a new building, it is necessary to provide a 'building manual' of how the component is mounted and connected to other parts of the building.

The joints must also be certified for reuse by authorized personnel in order to guarantee their safety.

Contents
This system also requires a thorough collection of data about materials and substances that documents the content and potential effects it may have on the building, indoor climate and ability to reuse.

Achieving critical mass
The critical mass will not be present in the beginning. It is something that

must be built up over time. To achieve it, clients, contractors, developers and manufacturers must make investments to enable this shift in supply. The payback time can vary depending on where in the world it's made and what business model is used. Business models are elaborated on in the Circular Economy section page 179 to 249.

The critical mass can be achieved by taking down buildings that are designed for disassembly. In this case, the building needs to stand for one lifetime, which is several decades (unless you look to Asia, where some buildings have a lifespan of only one to two decades.)

This is a long term and unsure investment, since it is not guaranteed that the materials will be retrieved again unless the owner of the building or the stakeholders are very aware of it.

The manufacturers can also choose to lease out their building components and let the users of the building lease the service on building component. This is a quick way to get the technology spread and for manufacturers to keep control. When the mass is achieved, a completely new business of the handling and storing the reused components will emerge. These companies are from ere on referred to as the 'material stock'.

Photo: To ensure structural integrity, the building elements must be tested and the personnel well-educated to successfully deliver material quality. This could open doors for new businesses and certifications in the industry.

Photo © GXN

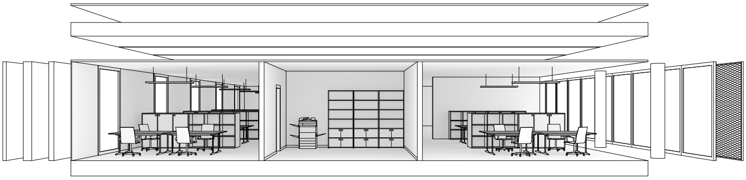
Case study redesign

— Page 100 to 117

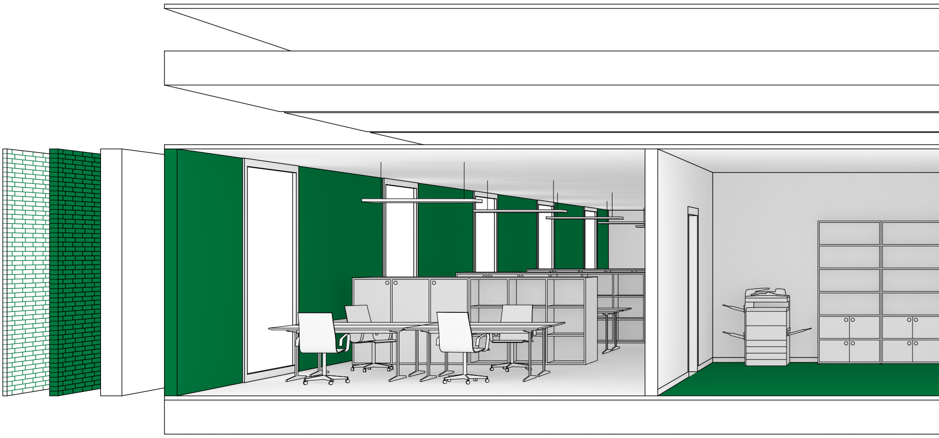
Redesign of the case study using the five principles, to make an optimized building with realistic alterations in todays industry.

Image: Visualization of 'De Fire Styrelser'.

Image © 3XN Architects



The current design of the building.



Bricks: The bricks in the facade is collected into a single component for a quick and easy construction and dismantling process. The bricks are held together by lime mortar so the bricks are separable and can be reused.

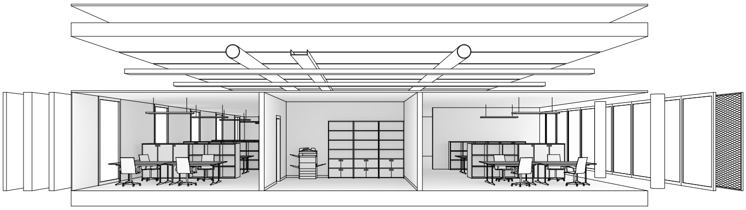
Walls: The walls are made from a pure and durable concrete so no paint is necessary. This gives a quicker construction, low maintenance and better conditions for reuse and recycling.

Floors: The floors the service cores of the building are made from a pure and durable polished concrete. This gives a quicker construction, low maintenance and better conditions for reuse and recycling.

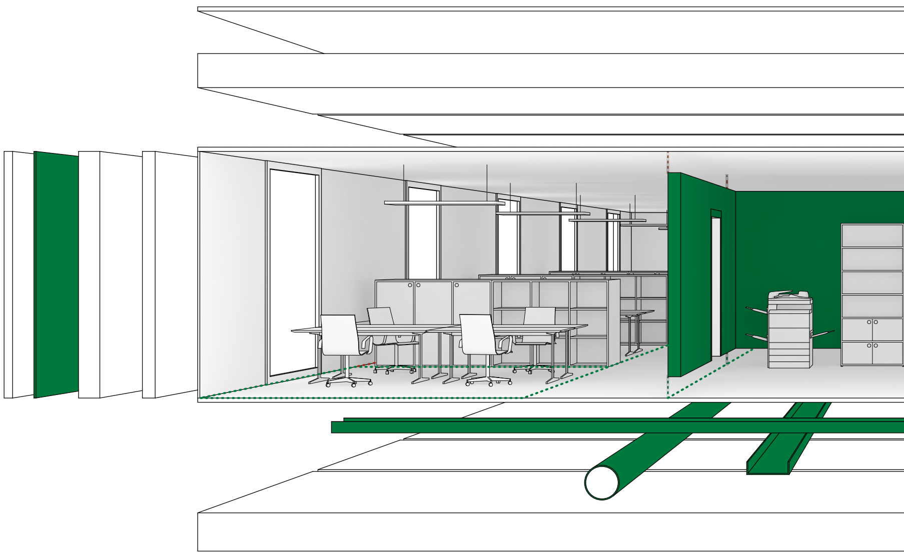
Materials
— optimizing for reuse

Windows: Windows are exposed and will have to be changed during the buildings lifetime. So the frame and glass of the window is made for disassembly so the materials can fit into technical cycle and be recycled into new windows.

Shading: The solar shading is made from expanded metal on frames is assembled using mechanical connections rather than welding. In this way the metal can be reused and sorted by grades allowing for higher recycling prices.



The current design of the building.

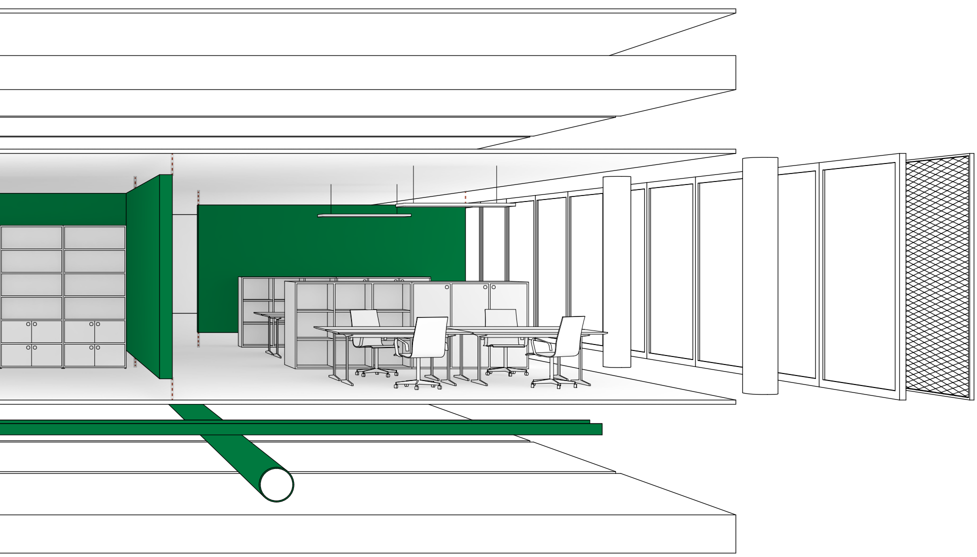


Facade: The facade cladding is attached to the building so it easily can be renovated or changed during the buildings life.

Zoning: The wearing surfaces of the floor is divided in zones. This allows for only changing the areas that are very exposed for wear for example walking areas, without having to change the entire floor.

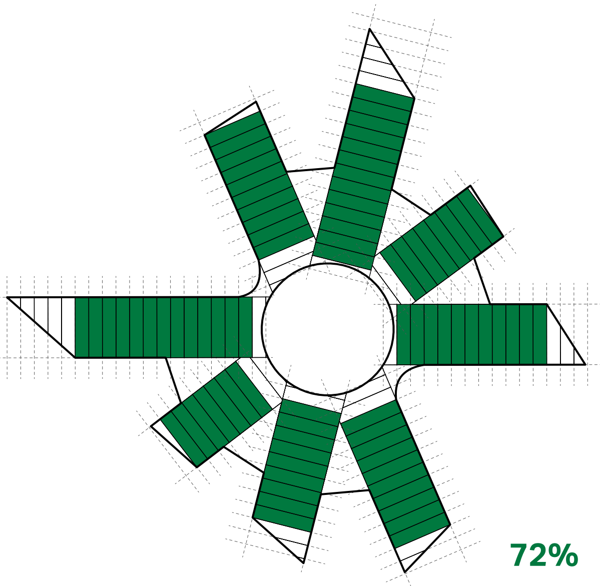
Partitions: The partition walls are are made to be easily moved. This allows maximum flexibility of the interior decor of the building.

Service life
— lifetime design



Ventilation: The ventilation is put in floor this allows maximum flexibility of the interior decor of the building.

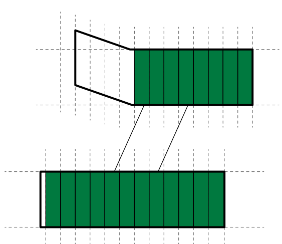
Cables: The the power cables, etc. are put in floor this allows maximum flexibility of the interior decor of the building.



72%

Standardized elements

De Fire Styrelser
3XN Architects,
Kalvebod Brygge, Denmark 2014,
Offices, 42,000 m^2

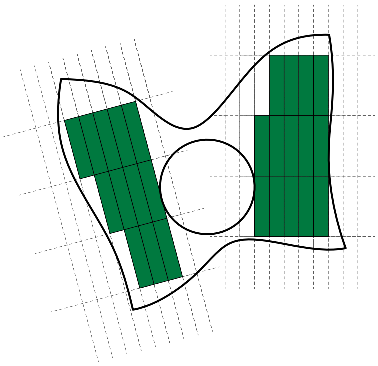


82%

Standardized elements

Bella Sky
3XN Architects,
Copenhagen, Denmark 2011,
Hotel, 42,000 m^2

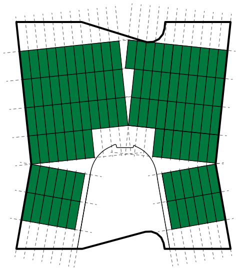
Standards
— analyzing projects



60%

Standardized elements

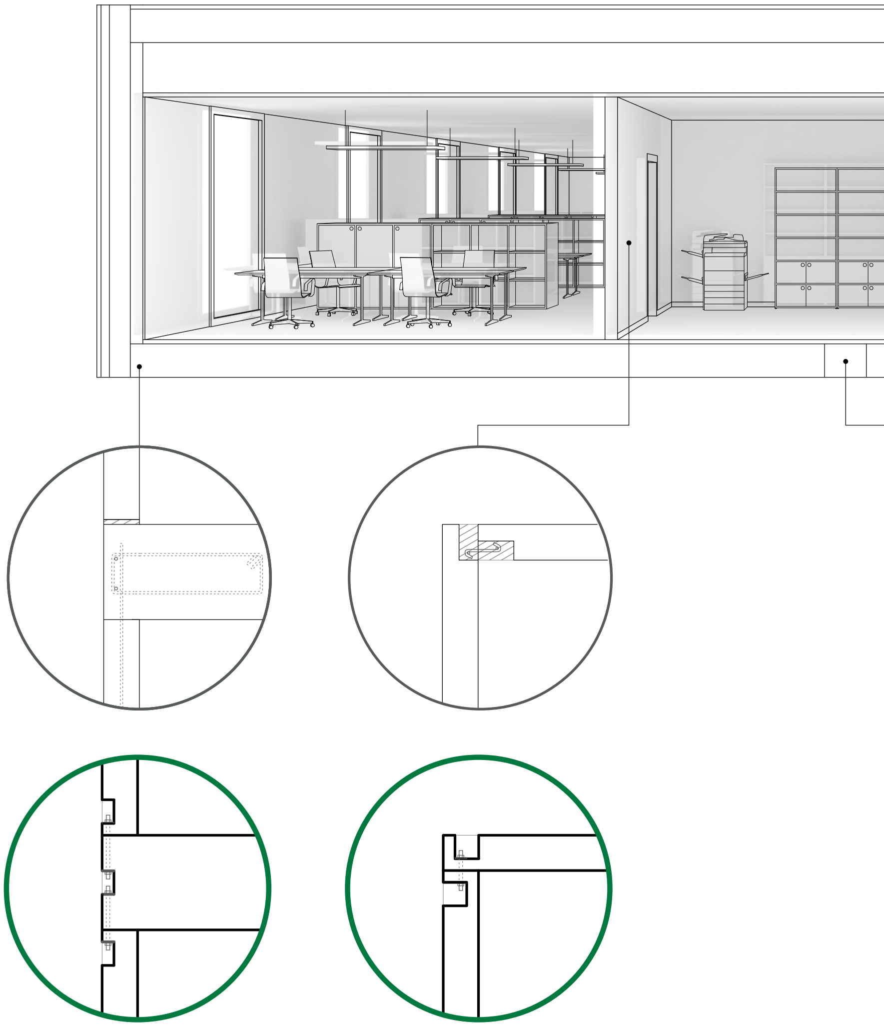
IOC Headquarters
3XN Architects,
Lausanne, Switzerland 2014
Offices, 15,000 m²



72%

Standardized elements

Saxo Bank
3XN Architects,
Hellerup, Denmark 2008,
Offices, 16,000 m²



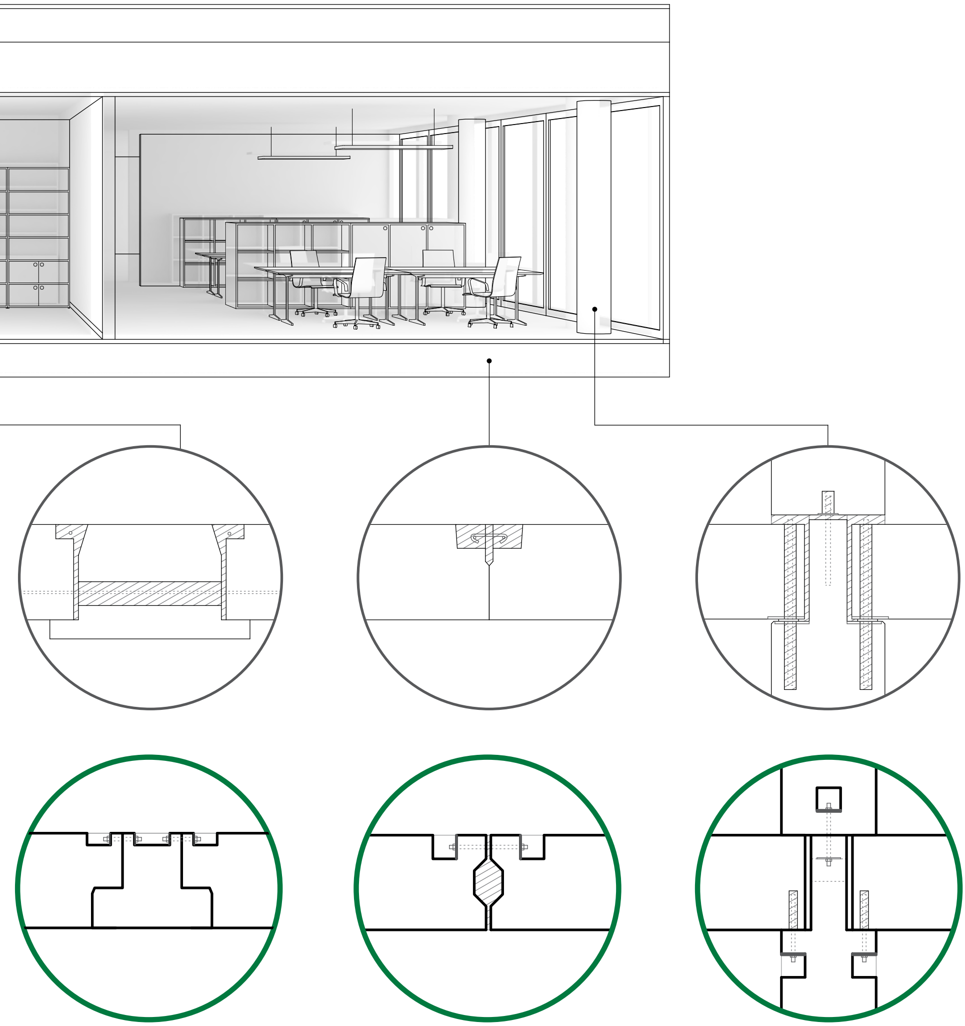
Current joints

Optimized joints

Slab — Wall: New separable joints using mechanical connections with nuts and bolts.

Wall — Wall: New separable joints using mechanical connections with nuts and bolts.

Connections
— separable and mechanical



Slab — Beam: New separable joints using mechanical connections with nuts and bolts.

Slab — Slab: New separable joints using mechanical connections with nuts and bolts and lime mortar.

Column — Slab: New separable joints using mechanical connections with nuts and bolts and lime mortar.

‘The optimal deconstruction scenario would be if it simply was the building process in reverse’

— Richard Kristensen
Quality- and Environmental Manager, Kingo Karlsen

Deconstruction
— defining a strategy

A future deconstruction of 'De Fire Styrelser' will look much like demolition work typically does today. Like with selective demolition, buildings will be systematically dismantled, removing all equipment, installations, façades, windows and doors and other building materials.

During disassembly, these materials will be sorted and disposed of in recyclable fractions. Before this, the extent of hazardous substances is located and decontaminated. Typically there will be up to approximately 5% of the total construction that cannot be recycled and will end up in landfills or as hazardous waste for disposal.

Where the future process really stands out compared to today's demolitions will be when the structure must be broken down.

Today, the structure is typically demolished by destruction of the supporting concrete structures. It will typically be perfo med with excavators mounted with concrete cutters. After cutting, the concrete will be smashed so the rebar can be separated for scrap recycling, see page 35 for a photo of the process.

The concrete is now free from rebar and will then either be transported to a central concrete crushing plant or be crushed on site with a mobile crushing plant. After crushing, the concrete gravel can be used as a substitute for virgin raw materials in new building materials (upcycling) or as substrates in roads and parking lots, etc. (downcycling).

The plan for 'De Fire Styrelser' is that load bearing structures will be made with the principles for disassembly, so that all the load bearing components can be separated and reused in the construction of a similar building.
The dismantling will follow the same principles as when the building is erected, where the individual components are attached and hoisted down with cranes. The components are packed and transported to temporary storage or directly to a new construction site where they will be reused (recycling).

It is expected that up to 70% of the concrete in the building can be recycled directly as structural elements in new buildings. The remaining concrete will be crushed and recycled as a bearing layer of roads and squares onsite, or used as aggregate in new concrete structures.

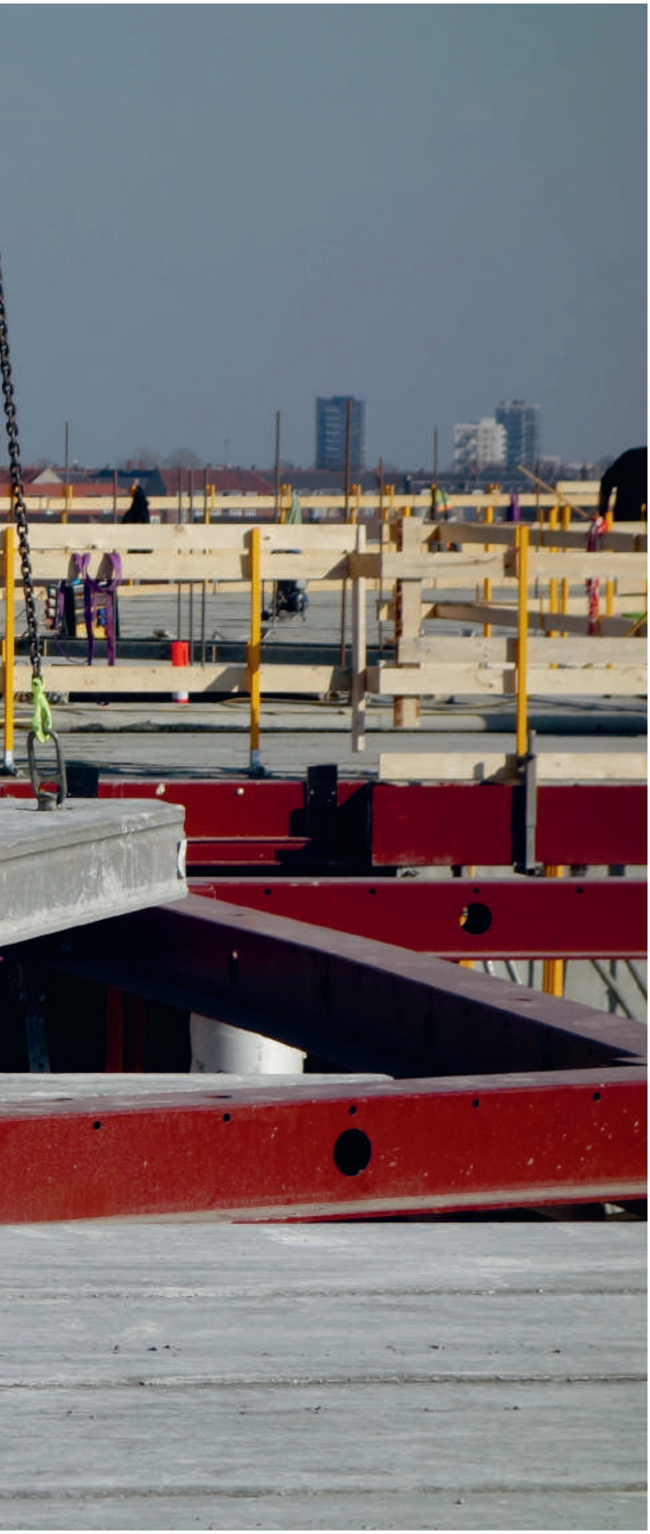


Photo: The process of dismantling and lowering elements is like a reversed construction process.

Photo © GXN

During dismantling of the load bearing components, the demolitioner's knowledge of the building's static structure is of great importance.

Incorrect disassembly can cause unintended collapse, with risk of damage to people and building elements, whose recycling potential is then lost. Future 'dismantlers' must therefore have a thorough knowledge of the assembly methods in the structural parts of the buildings and, at the same time, they must have a thorough knowledge of a building's static principles.

The external façades at 'De Fire Styrelser' are self-supporting, with concrete cores inside the building, which ensures its stability. By contrast, the interior façades are stability-dependent on the external façades and building cores. This knowledge is of great importance for the demolition expert, who should dismantle the interior façades before they remove the facade, which ensures stability.

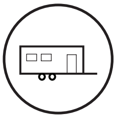
It is estimated that the dismantling and lowering of the elements of the structure will not take longer than with the methods used today. The demolition itself is faster, but subsequently a lot of time is spent on processing prior to and crushing of the concrete. The overall assessment is that the future dismantling method is not more time consuming than todays demolition.

Current demolition plan

Kingo Karlsen, the demolition experts of today, has made a step by step plan of how they would demolish 'De Fire Styrelser' using today's state of the art techniques.

Step 1

Workplace
Establishment and maintenance of workplace.



Step 2

Environmental decontamination
Removing of PCB, PVC and asbestos.

Step 3

Emptying
Emtying and stripping all elements except the shell.

Step 4

Selective demolition
Selective demolition step by step.

Step 5

Blasting
Demolition of the structure by blasting.

Step 6

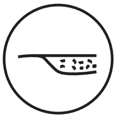
Downcycling
Crushing and downcycling of the concrete.

Step 7

Removal
Removal of construction waste.

Step 8

Reestablishment
Reestablishment of the site for original terrain.

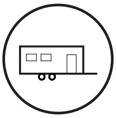


Future deconstruction plan

Kingo Karlsen, the demolition experts of today, has made a step by step plan of how they imagine the deconstruction process of 'De Fire Styrelser' would look like in the future.

Step 1

Workplace
Establishment and maintenance of workplace.



Step 2

Environmental decontamination
Removing of decontaminators, if any.

Step 3

Emptying
Emtying and stripping all elements except the shell.

Step 4

Dismantling
Dismantling of reusable building elements.

Step 5

Relocation
Relocation of elements at new building or storage.

Step 6

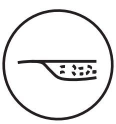
Recycling
Crushing and recycling of materials to new elements.

Step 7

Removal
Removal of construction waste.

Step 8

Reestablishment
Reestablishment of the site for original terrain.



MATERIAL PASSPORT

What is a material passport

— Page 120 to 129

Explaining what a material passport is and some of the general concepts behind it.

A material passport
— for the construction industry

The concept of a material passport ensures the ability to gain access to all relevant information describing the characteristics and quality of a component or material in a product. The material passport is not necessarily a collected database integrated in the VDC or BIM model.

The important issue is that the information is available in a database that it is easily accessible and identifiable when the ID of any given element from the digital building model is entered into the database. It is therefore, the mechanism that makes the connection between the physical element and the digital model possible, that is the critical factor for success. With the relevant data available, the quality and reliability for reuse is documented and can thus form the basis for the best possible exposure to the market and thereby ensure the highest possible market value.

The passport is the documentation of the component's history and is thus rather important when you want reuse an element as this material passport contains lots of information relevant for reuse (such as the size, the number and the steel quality of reinforcement bars in a beam).

The relevant information must be collected for each component in the construction and described according to the following categories:

— The initial, characteristics of the component as delivered from the supplier or manufacturer).

— The actual, characteristics and conditions of the component after use (historical exposure to weather, transport, disassembly, and contact with chemicals etc.).

Other relevant examples of information represented in a material passport are:

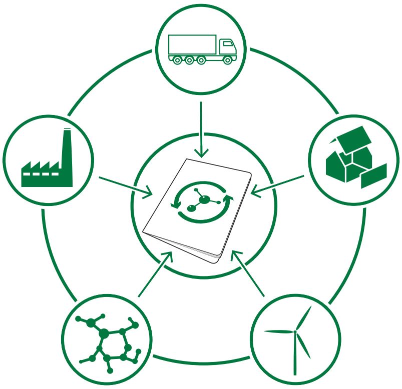
— Chemical and technical specifications.
— Environmental impact during production and lifetime.
— Description of quality assurance and relevant certificates.
— Instructions for assembly, disassembly, maintenance, reconstruction and reuse.
— Unique code to identify exact location in the construction.

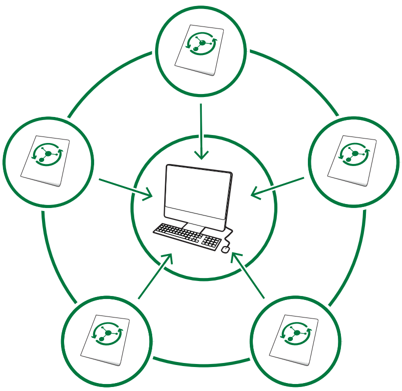
The first part is relatively straightforward to map, since this information will be available from the supplier. But when it comes to identify and measure the condition of the component after use and disassembly, it becomes more complicated.

How does it work

The passport must always represent the current state of the building and the materials. Therefore, it must be regularly updated, which makes it dynamic and ever changing.

When looking into the scenario after the disassembly of a construction, several types of fractions are identified. The fractions are typically wood, glass, insulation, steel, concrete, etc. Each fraction must be mapped according to its further use: combustion, recycling, upcycling ,reuse, etc. All components intended for reuse must be tested or examined properly, in order to deliver the assessment required for the digital material passport and provide security for the next life. Some parameters can be described by a simple visual inspection (cracks in concrete elements, fracture in steel, etc.) or by simple physical tests, like a test of humidity (and the absence of mould) in facade elements.





Diagrams: A material passport provides the ability to access all relevant information about any product or component that are intended for reuse and it connects the information from all the materials and building elements.

But in order to identify the exposure during the entire lifetime of the component, it will be required to introduce monitoring kits, like electronic chips for logging of historical exposure with respect to temperature, humidity etc., for components such as facade elements, which are sensitive to humidity. Other elements, such as concrete used for internal walls, beams, columns etc. does however have a lifetime of up to several hundred years if they aren't damaged physically or polluted by paint or other chemicals. These elements are not sensitive to humidity, unless it's to an extent that damages the reinforcement.

Digitalization
The digital revolution in the construction industry is here to stay, and the vast majority of buildings in the future will be designed and planned with BIM or BIM-like tools, where the many complex factors surrounding a construction project are assembled in a single digital model.

MT Højgaard develops their buildings based on BIM and is applying Virtual Digital Construction (VDC) on larger and more complex projects. This represents the perfect platform for mapping, storing and connecting the information in the material passport.

What are the prerequisites
Some prerequisites is made in order to work with the material passport in this book. In today's market, some technologies for tagging and measuring critical parameters, like exposure to temperature, are available. However, the limitations in the lifetime of this technology i.e. the lifetime of a RFID (Radio Frequency Identification) tag is limited to the capacity of the battery, which usually is up to seven years. Compared to the lifetime of the structural components for example facade elements with an expected lifetime of approximately 50 years, the usefulness of this technology is still limited In order to make them useful, further improvements of the technology is are necessary.

Unfortunately, it is also relatively complicated to measure or identify if the components have been exposed to shock, extreme storage or transport conditions or other critical circumstances that might have reduced the quality or characteristics of the component.

It is therefore important that qualified personnel (engineers or other trained people) verify the qualities of such element and document their qualities using the digital material passport prior to the reuse of such elements

It can be concluded that we have methods in place that will allow us to map the qualities of elements for reuse on a digital material passport and reuse most of the material used for the superstructure and façades of modern office building. It would, however, be most beneficial if technologies like RFID are developed further in order to measure reliable data describing the condition of a construction component after long term use and storage. Hence, existing technologies must be improved and new technologies must be developed.

Once relevant detailed information is available in the digital material passport describing the construction component, it becomes much easier to decide if the component is suitable for the intended reuse and the component can be included in a circular building.

Moreover, such technologies will make it much easier to use IT-based systems to facilitate the introduction into the construction industry of a circular economic model as such.

Conclusions
from material passport

A material passport provides all relevant information about any product or component that is intended for reuse. The research and casestudy in this book show that a material passport is connection between information and element, rather than a collection of information about an element.

Certification and caretaking
All the information in the passport must represent the current state of the building and materials. This leads to the need for testing the state of the materials using different types of measuring equipment. To ensure safety for the construction of the building, all the information must be certified and kept up to date by an authority that can guarantee the correctness of the data.

Handling of data
The main challenge in the material passport is how to handle and structure the huge amounts of data that are accumulated when mapping out the elements and materials in a building. The main point is to collect all the information about the different elements in a database where each individual element can be identified and traced back. In the beginning, BIM could provide the framework for handling the data. However, this is not the optimal solution.

The extensive amount of data causes the models to become extremely big and heavy, which results in the fragmentation into smaller models that are easier to handle. In the future, new digital frameworks, whose shape we cannot predict, will take over, However, as long as the above is cared for the material passport is future proof.

The interim phase
When the building materials are ready for their next life, they become part of a material stock, which can either be passive — where the contractors find the materials — or active — where the materials are offered to contractors.

5 Principles

— to consider in a material passport

Documentation

To ensure the quality and value of the materials and resources, documentation during all phases is crucial.

All inclusive
The documentation includes all relevant building information from material level to the entire construction system

Accessibility
All information must be accessible for the relevant partners during the whole process.

Responsibility
The ownership, accessibility and responsibility of the information should clear.

Identification

Physical identification on the individual elements are important for finding the correct information.

ID code
Each material should have a unique label for easy identification.

Database
A database containing all relevant information about the material must be created.

Link
A link between the ID code and the database has to be established and maintained.

Maintenance

To secure the value of the materials, correct maintenance is crucial.

Physical
Guidelines for the physical maintenance of the individual building materials needs to be accessible.

Digital
The digital passport has to be updated if modifications or renovations on the building are made.

Restoration
Guidelines for how the materials can be restored back to their full value after disassembly needs to be accessible.

Safety

Provide safety procedures to handle all phases of the building's life.

Construction
Document specific safety procedures for the construction process.

Operation
Document specific safety procedures for operating and maintaining the building.

Deconstruction
Document specific safety procedures for the deconstruction process.

Interim

Provide the necessary information on how to handle materials in the interim state.

Ownership
Document who is responsible for the materials and components in the transition phase.

Transition
Direct transition of materials between buildings are preferred in order to minimize storage.

Storage
Document how materials should be handled and stored, if needed, in the interim phase.

Existing examples

— Page 130 to 149

Explore examples of material strategies and documentation methods found in existing architecture and other industries.

Alliander HQ
— existing architecture

Location Duiven, The Netherlands
Year 2015
Owner Alliander
Architect RAU Architects
Size 21,852 m^2

Photo: The idea of circularity has been embedded into the design process for the Alliander HQ since the early stages and is now the first circular building in the Netherlands

The energy grid company Liander has transformed its headquarters into a remarkably sustainable building and energy positive complex, becoming the first renovation project in The Netherlands to obtain the BREEAM-NL outstanding sustainability certificate. RAU architects have been responsible for the renovation of the existing buildings and the extension, which houses 1,550 workers.

Circularity has been an integral part of the design, transforming the building into a material depot where materials are temporarily stored rather than just being a conglomeration of materials with a limited life cycle.

A circular building is a temporary aggregation of components, elements, and materials with a documented identity, recording their origin and possible future repurposing, assembled in a certain form, which accommodates a function for an established period of time.

Liander is the first circular building in the Netherlands, and its material passport is the document that specifies the types and amounts of all the materials present in the building, both preexisting and new.

By providing materials with an identity and adequate information, waste is prevented. The document includes information about who has handled the materials, where they were temporarily stored and ways in which they can be reused.

The existing complex was composed of six different constructions, which are almost entirely maintained (over 80% of the original surfaces remain).

A large atrium covered by an iconic roof connects the six different volumes visually, programmatically as well as logistically, creating a continuous urban-like space which facilitates encounters and communication among employees.

The shape of the roof is derived from studies for the optimization of natural ventilation, which reinforce the air circulation. The large glass façades and the circular skylights provide the adequate amount of daylight, and strengthen the relation with the landscape, contributing to a healthy and inspiring workspace.

Maintaining the façades of the existing buildings was important from a reutilization point; therefore, a second skin is placed in order to avoid heat losses, reducing the energy demand. The existing windows are kept in all the façades except the inner ones, where larger operable windows are placed, creating a close visual relation with the atrium and allowing natural ventilation.

Sustainability is understood as an optimization of the system, therefore, three principles were established as design strategies:

— Conservation and reuse of the existing materials.
— Minimization of material use.
— Employment of materials that can later on continue their biological or technical life cycle.

The design of the roof is an example of how these strategies were implemented. A roller coaster company helped with the design of the metal structure, achieving a lighter construction, reducing the unnecessary use of raw materials and allowing disassembly for later reuse. The new façades attached to the existing volumes are built using waste wood that comes from the old cable coils and utility poles found in the terrain. This not only gives a characteristic and fresh appearance to the building but also establishes a bond between the building and the company.

The building is both effective and efficient, providing an energy surplus which can be redistributed into the local grid. This has started a Green Alliance in the community and stimulates other companies in the area to take a more sustainable approach. The solar panels, covering the parking spaces deliver 1.5 million kWh annually, and the ground heat and cold storage accumulates the excess. Since the solar panels were placed first, it was possible to achieve an energy positive building site for the first time in the Netherlands

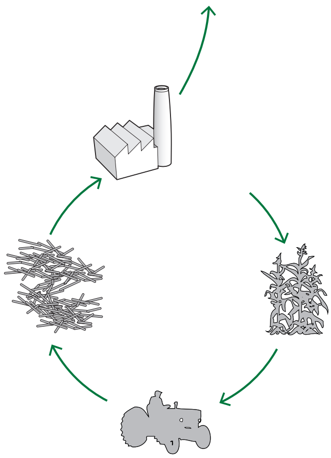
The consortium for the Design & Build of Liander in Duiven consists of VolkerWessels Vastgoed, Rau Architects, Fokkema & Partners, Innax, Kuiper Compagnons, Van Rossum, Boele & van Eesteren, Homij and Turntoo.

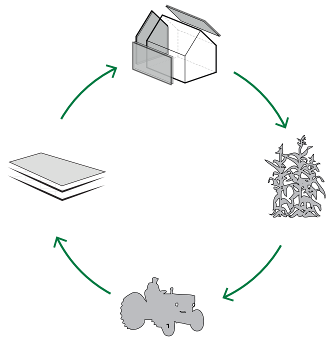
Photo (top): The new façades attached to the existing volumes are built using waste wood that comes from the old cable coils and utility poles found in the terrain. This not only gives a characteristic and fresh appearance to the building but also establishes a bond between the building and the company.

Photo (bottom): The form of the iconic roof structure derives from studies based on achieving the most optimal natural ventilation and daylighting.

Photo © Marcel van der Burg

The biological house
— existing architecture

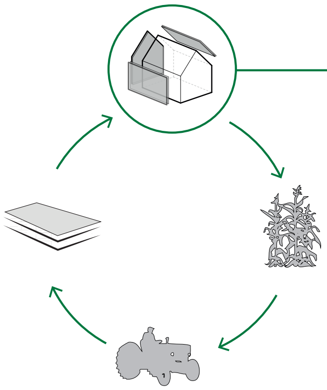


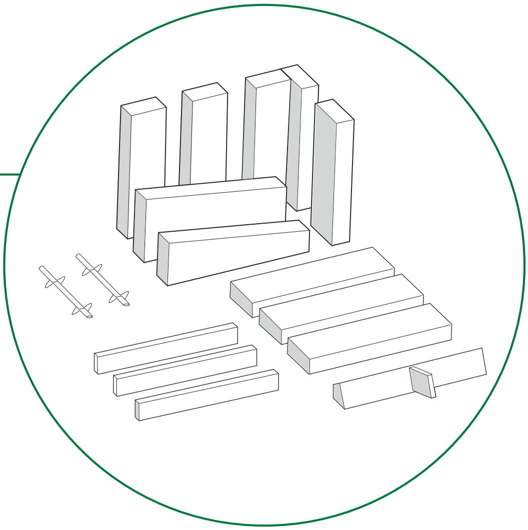


Location Middelfart, Denmark
Year 2016
Client Danish Environmental Protection Agency
Architect EEN TIL EEN, GXN
Size 125 m^2

The Biological House is built using EEN TIL EEN's innovative building concept — a digital production technology that ensures an effective as well as flexible system minimizing waste.

The house is also designed to be disassembled in order to guarantee both a fast construction and dismantling. The simplified production and its modular design makes future adaptation and change of the construction less complicated and less costly.





Diagrams: The diagrams are illustrating how to go from incineration of residue products to closed loop of resources and how the house is designed for disassembly, so it can be incorporated in closed material circuit

Photo: Visit in 'Katrine og Alfreds' tomato greenery, where tomato stems collected as a waste material. A tomato plant can grow up to 12 to15 metres in one season and they pay DKK 500 per ton to get rid of it, which makes for a huge expense for a small company

Closed biological cycle

The concept behind the Biological House is to build with upcycled residual products from the agricultural industry. Materials that today are considered 'waste' and burned for energy — grass, straw, tomato stems, seaweed, etc. — will be processed into valuable building materials. The project is inspired by Cradle to Cradle® [25] principles and digital production technologies in the development of a modern ecological house with a focus on circular economy and healthy materials.

The Biological House is designed with circular economy in mind and is developed with a set of principles that

secure the building's separability, and the possibility to preserve materials, elements and components in a closed loop over time. In this way, valuable raw materials that are used to construct the building don't end up as waste, but can be fed into new closed loops.[26]

25 Cradle to Cradle® is a registered trademark of MBDC, LLC
26 gxn.3xn.com

Photo: The fibres from the tomato stems is mixed with a bioresin to make a new type of board material made from upcycled agricultural waste. This innovation opens up for new business opportunities where an expense — getting rid of waste — can be turned into a income — selling resources.

Photo © GXN

Photo: The exterior of the pavilion looks like traditional office, but is a pioneer in design for disassembly and by following the principles og Cradle to Cradle ®[27] with clear a material strategy for this life and the next.

Photo © Sander Van der Torren Fotografie

Technical Nutrient Pavilion
— existing architecture

Location Hoofddorp, The Netherlands
Year 2012
Owner Delta Development Group
Architect William McDonough + Partners
Size 413 m^2

The Technical Nutrient Pavilion was designed by William McDonough + Partners and located at Park 20|20, where it serves as an experience center for both the Cradle to Cradle® [27] design framework and specific Cradle to Cradle [27] Certified™ products, together with its main function as the international headquarters for The Delta Development Group and Maatschap Zachariasse Consulting.

The Technical Nutrient Pavilion is a showcase of materials that can be upcycled back into the technical loop at the end of their initial use periods. Half of the interior space is dedicated to educational exhibits where the public can engage, get inspired and strengthen networks while showcasing the latest in Cradle to Cradle® [27] and sustainable innovation.

The Pavilion incorporates sustainable features, such as roof-mounted photovoltaic panels and adjustable folding perforated aluminium panels, that provide dynamic daylighting and shading throughout the day. The sunscreen panels are continually adjusting to the sun: They perform like a solar timepiece that 'awakens' in the morning and 'sleeps' at night.

27 Cradle to Cradle® is a registered trademark of MBDC, LLC

Alcoa
Aluminium panels

AGC Glass
Facade glass

Interward Intersmart®
Wall system

Desso Airmaster®
Carpet tiles

Saint Gobain
Gypsum boards

Derbigum® Derbipure
Roofing membrane

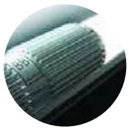
The building was designed in collaboration with 41 manufacturers who produce Cradle to Cradle[28] Certified™ products, making the Pavilion a showcase for innovative Cradle to Cradle® [28] designs and material use. Besides using healthy materials to build the Technical Nutrient Pavilion, the building also acts as a pioneer of 'design for disassembly' solutions and strategies.

One aspect of the construction that contributes to ease of disassembly is that mechanical joints are predominantly used. Also, where possible, materials are kept 'clean,' meaning that paints or adhesives were avoided in the assembly. Layers corresponding to the use periods of elements and easy identification was thought into the design of the building. For example, with respect to steel piping, the different grades of steel are in different hues, so they are easy to tell apart, which is important for sorting and reuse after disassembly.

28 Cradle to Cradle® is a registered trademark of MBDC, LLC

Dow Building Solutions
Foam insulation

Rheinzink®
Facade cladding



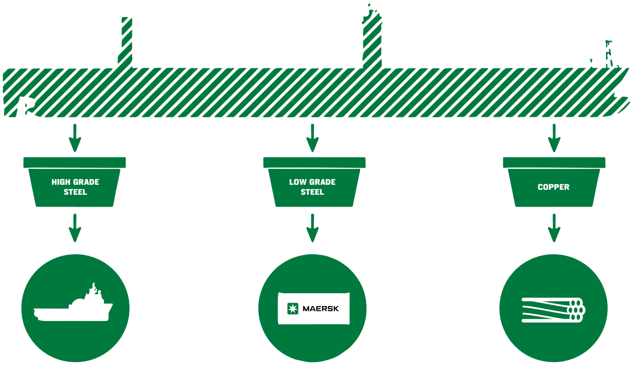
BB-Ligtconcept
Lighting system

Mechosystems
Sun screens

Shaw
Hardwood floor

The building is easily accessible for deconstruction upon its end of use period and the different materials can be correctly sorted and processed into the technical cycles available in that location at that time. With this vision in mind, both the building process and the different materials were documented to ease the demolition process.

Photos: A selection of the Cradle to Cradle[28] Certified™ products used and showcased in the Technical Nutrient Pavilion.


HIGH GRADE STEEL
LOW GRADE STEEL
COPPER
MAERSK

C2C material passport
— the ship industry

What Cradle to Cradle® Material Passport
Purpose Integrated sustainability strategy focusing on material qualities to improve the recycling rate

In 2010 Maersk Line, a Danish multinational shipping company, took on the challenge creating a Cradle to Cradle®[29] material passport for their new 20 Triple-E container ships.

Maersk Line has an integrated sustainability strategy and their rationale for making a material passport for the Triple-E ships was:

'When we know what quality of material we have where on the ship, then it is possible to separate each quality of material from each other and benefit not only environmentally by improving the recycling rate of the materials, but also economically' [30]

Maersk Line estimated that they might be able to command a 10% higher recycling price for ships with a material passport because they would be able to negotiate a higher price for the high value materials in the ship.[31]

Photo and diagram: The material passport helps sorting the different types of metals from the new 20 Triple-E container ships and thereby increase the level of reuse and the value of the materials.

Photo © Maersk

29 Cradle to Cradle® is a registered trademark of MBDC, LLC
30 youtu.be/PRgp9tcOwaw **31** maersk.com

Inventory of hazardous materials
— the ship industry

1C. Materials Containing PCBs (Polychlorinated Biphenyls) at levels of 50mg/kg or more.

Supporting documents should be included in Appendix C.

	Item*	Location*	Manufacturer trade name/designation	Relevant standard/ certificate	Approximate Quantity*	Hazard Type	Remarks	Equipment/System
	Electric cable	Throughout ship	Not marked		Unknown: See Appendix C and Visual/sampling Check Plan (Appendix E) for details	Not known	Vessel does not have PCB free certificate from build	
	Fluorescent lighting ballasts	Throughout ship	KOC		Six pieces: See Appendix C for details		Vessel does not have PCB free certificate from build	
	Transformers	Engine room, Switchboard rooms, Transformer rooms	KOC		See Appendix C for details		Vessel does not have PCB free certificate from build	

1D. Paint on Vessel's Structure – Organotin Compounds (TBT, TPT, TBTO)

Supporting documents should be included in Appendix D

	Item*	Location*	Manufacturer trade name/designation	Relevant standard/ certificate	Approximate Quantity*	Hazard Type	Remarks	Equipment/System
	Epoxy finish	Deckhouse outside (deck)	INT		100kg		595 m2 (125 mic)	
	Epoxy anti abrasive KNA	Fore peak tank	INT		12740kg		589 m2 (50 mic)	
	Alkyd finish	Engine room & sterring gear room (deck)	INT		40kg		598 m2 (50 mic)	
	Ceramic zinc primer	Deckhouse (insu)	INT		90kg		2341 m2 (25 mic)	
	SPC A/F (tin free)	Flat bottom	INT		780kg		4211 m2 (125 mic)	
	SPC A/F (tin free)	Side bottom	INT		775kg		4385 m2 (125 mic)	
	Polyurethene finish	Topsides	INT		220kg		4211 m2 (50 mic)	
	Epoxy primer	Flat bottom	INT		880kg		2779 m2 (150 mic)	
	Epoxy primer	Side bottom	INT		920kg		4385 m2 (125 mic)	

What Inventory of hazardous materials
Purpose Identifies, locates and lists out all the hazardous and potentially hazardous materials on the ship

From the mid 1980s, the centre of the ship scrapping industry shifted towards Asia, in particular to India, Bangladesh and Pakistan. This industry was, and still is, virtually unregulated and has one of the worst safety records of any industry. It also causes massive environmental pollution.

Initially, there was little awareness or acknowledgement of the appalling working conditions and environmental pollution. However, a campaign by environmental groups has brought about widespread awareness of ship scrapping practices.[32]

32 A Guide to the Inventory of Hazardous Materials

1F. Chemicals in Ship's Equipment or Machinery: (Cont.)								
	Item*	Location*	Manufacturer trade name/designation	Relevant standard/ certificate	Approximate Quantity*	Hazard Type	Remarks	Equipment/System
	Antifreeze fluids	Engine room & machinery spaces			See Inventory List 1			
	Anti-seize compounds	Engine room & machinery spaces			137kg			
	Hydraulic oil	Mooring, control and lifting systems, hydraulic rooms, valves and control systems			See Inventory List 1			
	Engine additives	Engine room & machinery spaces			See Inventory List 1			
	Boiler/water treatment	Engine room & machinery spaces			See Inventory List 1			
	Light oils	Engine room & machinery spaces			2149L			
	Lube oils	Engine room (ME, GE and Aux)			42234L			

1G. Electrical and Electronic Equipment								
	Item*	Location*	Manufacturer trade name/designation	Relevant standard/ certificate	Approximate Quantity*	Hazard Type	Remarks	Equipment/System
	Communication equipment	Bridge and other navigation stations	El Co.		4000kg			
	Switchboards / distribution boards	Throughout ship and cargo spaces	El Co.		2000kg			
	Generating equipment / alternators	Engine room, Emergency generator room	El Co.		11000kg			
	Transformers / converters / rectifiers	Transformer room	El Co.		3500kg			
	Printed circuit boards	Throughout electrical & electronic equipment	El Co.		Unknown		Approximate quantity to be confirmed at later date	
	Control equipment	Bridge and other navigation stations, Throughout ship	El Co.		11000kg			

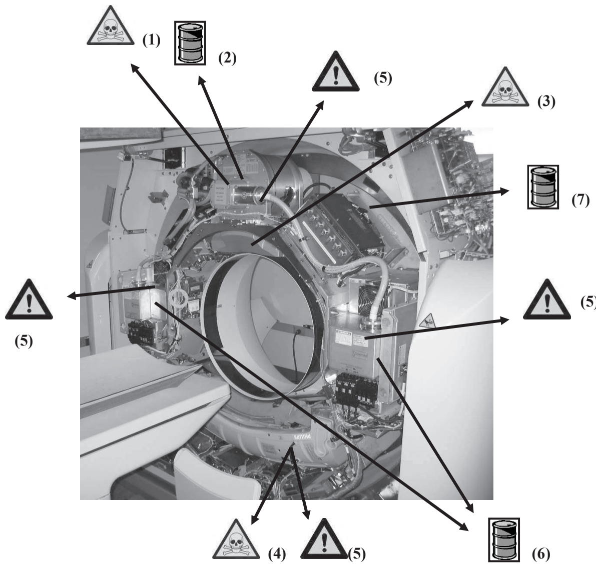
The industry has now started to make a kind of material passport of the dangerous substances each ship contains, called an 'Inventory of Hazardous Materials' (IHM). This inventory identifies, locates and lists all the hazardous and potentially hazardous materials on board a vessel. The inventory makes it easy to identify and locate hazardous materials and remove them from the when it is scrapped.

Soon a ship recycling convention will be in place that requires any ship that is greater than 500 tonnes to maintain an Inventory of Hazardous Materials. [33]

Image: Example of an Inventory of Hazardous Materials, which lists out items, quantities, locations potential hazard type of different elements on the ship.

Image © wilhelmsen.com

33 wilhelmsen.com



PHILIPS Healthcare	Recycling Passport	Page 1 of 6

Product name:	**Ingenuity CT Gantry**		
Identification code(s)	**459800029801**		
Total weight (in Kg)	**1941**		
Producer/ Manufacturer	Name company:	Philips Medical Systems	
	Address:	595 Miner Road Highland Heights, Ohio	
	Zip code:	44143	
	Country:	United States of America	

Recycle Info	**Items:**	**Location**
Special attention	Spring loaded cover	Figure 1 (1)
	Actuators: Unstable when removed, possible rotation of frame	Figure 4 (2), Figure 5 (2)
	System Unbalanced when rotor components are removed causing rotation	Figure 3 (5)
Fluids / Gases	**Items:**	**Location**
	X-Ray Tube Hydrocarbon Oil	Figure 3 (2)
	Generators Hydrocarbon Oil	Figure 3 (6)
	Overflow Tank Hydrocarbon Oil	Figure 3 (7)
Batteries	**Type:**	**Location**
To be Removed		
Hazardous	**Substances:**	**Location**
	Printed Circuit Boards	Figure 1 (2), Figure 2 (1), Figure 4 (1), Figure 5 (1)
	Lead	Figure 3 (1),(3),(4)
To be Removed		

Recycling passport
— the healthcare industry

What Recycling Passport
Purpose Easy overview of location and information about dangerous materials

Philips Healthcare produces a wide range of equipment for the healthcare industry and specializes in X-ray, Computed Tomography (CT) and Magnetic Resonance (MR) Imaging equipment.

To adapt to requirements in the EU, Phillips Healthcare has applied a sustainable strategy for their line of products.

Besides making the products easy to disassemble, they have made a 'Recycling Passport' where important information regarding the materials is available.

In their 'Recycling Passports', Phillips Healthcare displays the information about the equipment and arranges it so the information that is needed by a specific business is easy to locate. The information is typically shown in pictures and on sheets where individual parts are tagged with a product name and number and categorized in different classifications.[34]

This very pedagogical way of displaying the information makes it very easy to locate dangerous materials when a machine is broken and needs to be fixed or scrapped.

Image: Example of a 'Recycling Passport' from a MR-scanner. It shows in a very pedagogical way where the dangerous materials are placed inside the machine. It also shows tells how to deal with the materials once they are located.

Image © Philips

34 philips.dk

How to implement

— Page 150 to165

Tools and strategies for how you can implement a material passport in the construction industry.

Materials
— healthy and pure

The use of the right materials is not only good for the environment, it also helps the process of documenting what a component contains and makes it is easier to reuse in the future.

Certified
Choosing materials that are Life Cycle Assessed (LCA), has EPD- and Cradle to Cradle[35] Certified™ can ease the documentation process. For example, to get a product certified by Cradle to Cradle®[35], its contents must be documented and accounted for down to parts per million

Hence, the use of well documented materials provide a wealth of useful information for the material passport.

Healthy
Using healthy and nontoxic materials contributes to a clean environment, now and in the future, for both people in the building and workers handling the material. Healthy materials don't require special safety equipment to work with, so it is not necessary to provide special guidelines for handling.

Hence, the use of healthy and nontoxic materials saves documentation work in the material passport.

Pure
It is easier to reuse and recycle pure materials, which also have a higher value than mixed or treated materials. The value of concrete elements, e.g. is increased if the element is finished by polishing it instead of by painting. That avoids the risk of contamination by use the wrong type of paint.

Environmental friendly paint can of course be used — but in the material passport it should be noted exactly which kind of paint that has been used.

Another example is that mixing of different types of metal, paint or other material should be avoided as it can be difficult to identify the materials correctly at a later stage, when the materials are to be reused.

Hence, the use of pure and nontreated materials saves documentation work in the material passport.

35 Cradle to Cradle® is a registered trademark of MBDC, LLC

Monitors and sensors
— manual, passive and active

This chapter maps and describes the possibilities of the testing and monitoring of building elements, which generally can be put into three categories: Manual, passive and active. Manual testing is the only technique used in the building industry today. About the three techniques it can be noted that the better feedback from the sensons — the farther out in the future before is technology ready for use in the industry.

Monitoring manually
Today, most inspections are manually executed. It is the most basic way to test a material and is done by visual inspection and using different instruments.

The visual test can be applied to damages that are obvious or on the surface, like mould in timber and cracks in steel or concrete.

Building components can be damaged even if is not noticeable on the outside. For example, if it has been dropped or exposed to moisture, which can effect the structural integrity of the building component. Reinforced concrete can be subjected to a corrosion process that ultimately leads to a total failure of the structure. This can be detected by using different measuring devices.

Load bearing concrete structures in Denmark have to be inspected every one to three years depending on the vulnerability of the building part. Water is the most common cause of damage on concrete elements.[36]

Manual testing is time consuming and cannot be done automatically to constantly monitor your building. Therefore a more automated process would be favourable when a large scale reuse of elements is anticipated.

Photo: Using tensile testing to manually test the strength of the concrete.

Photo © MT Højgaard

36 reboundhammer.com

Passive monitoring

Passive monitoring is a quicker and more favourable way of monitoring a material or a product as the information is obtained through low tech measures. By attaching a sensor to the element, its status is constantly measured and, when effected, the sensor gives of a simple visual clue, like changing colour. This makes it quicker to determine the status of the element, because it only requires a visual inspection. In the delivery industry, passive monitoring is used to ensure that the goods or packaging hasn't been tilted, dropped or similarly mishandled. They often affix applications that can indicate improper care taking upon delivery. These indicators are typically simple, cost-efficient and highly effective.[37]

In iPhone and most iPod devices, Apple has built in passive monitors called Liquid Contact Indicators (LCIs) that can tell if the phone has been exposed to liquids. The LCI's colour is normally white or silver, but when it contacts water or other liquids, it will turn fully red. An LCI won't activate because of humidity and temperature changes that are within the product's environmental requirements. In this way, during a repair the technicians can easily identify if the problem was due to water exposure.[38]
In the construction industry, passive monitors have been adapted for structural health monitoring. Concrete elements especially are surveyed through passive monitoring. Strain measurements, foil strain gauges and fibre optic gauges are the most widely used sensors. The foil strain gauge consists of a thin film where a difference in resistance within a strain sensitive pattern indicates if the concrete has been stressed. [39]

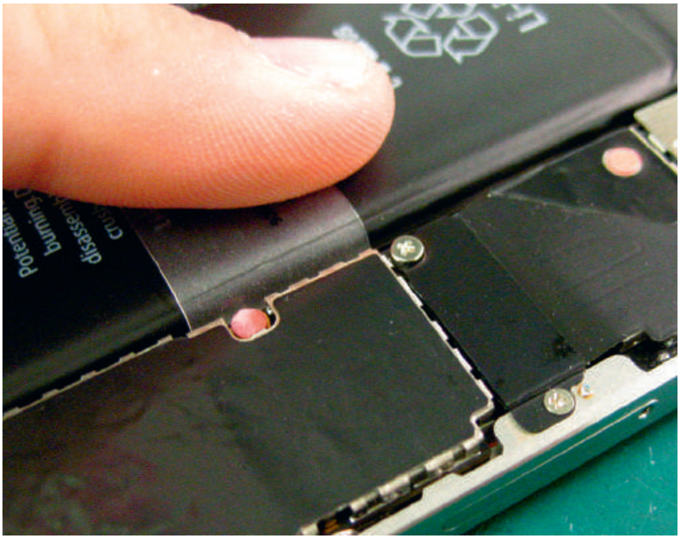


Photo: Activated LCIs inside an iPhone shows i has been in contact with water.

Image © iosmac.es

Active monitoring
The material passport is only valid if it represents the current state of the material. The optimal situation would be if it was possible to constantly measure the status of the building. By constantly being updated with new information that can determine how the materials in the building are suited are doing.

The best way to achieve this is by having active sensors that are constantly monitoring and sending information about the building to it's owner or caretaker. For this automation to be implemented in the construction industry, the building components need to be embedded with sensors that can sense and communicate the state to the material passport. Through this active monitoring, information about the individual material's temperature, tension, moisture etc. will be accessible in real time. When the building is to be disassembled for reuse, the material passport will contain a report with the status and history of the building materials properties and where repairs might be needed to secure the it's quality when being reused in a new construction.

One of the major constraints of this is the power requirement of most of these sensors, which must be supplied from either to wires or batteries. This issue represents a barrier for implementation of active monitoring, since batteries do not last for the entire life of the building and wires are too impractical. However, researchers from the University of Washington has developed an experimental wireless communication system that lets sensors transmit and receive data, without using power of their own. The devices operate using ambient backscatter, which lets two or more sensors communicate using already present broadcast transmissions instead of generating their own radio waves. The researchers assert that this method is orders of magnitude more power-efficient than traditional radio communication.[40]

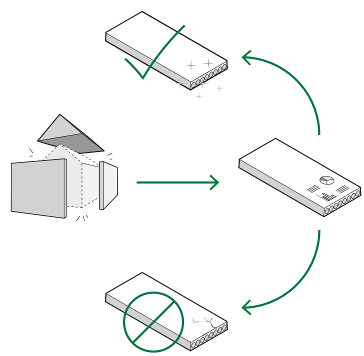


Diagram: In the future sensors embedded in the building elements provides real time feedback about the status of the building.

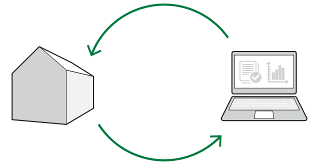


Diagram: Sensors in the building elements can tell if what they have been exposed to and if they are approved or rejected for reuse.

37 shockwatch.com **38** apple.com **39** thesensorsguide.com
40 washington.edu

Identification
— radio frequency identification

RFID means Radio Frequency IDentification, and is used for individual identification of objects. The RFID-technology is already well developed and widely applied. Examples of use can be found both commercially and in everyday life. A RFID device serves the same purpose as a bar code or a magnetic strip on the back of a credit card, and also normally requires scanning to read.

In everyday life RFID is the technology inside the small key tag that, by swiping it across a panel, identifies you and gives you access to your apartment or office. Commercially, RFIC is used for tracking and identifying specific objects in a large mass, such as packages and livestock.[41]

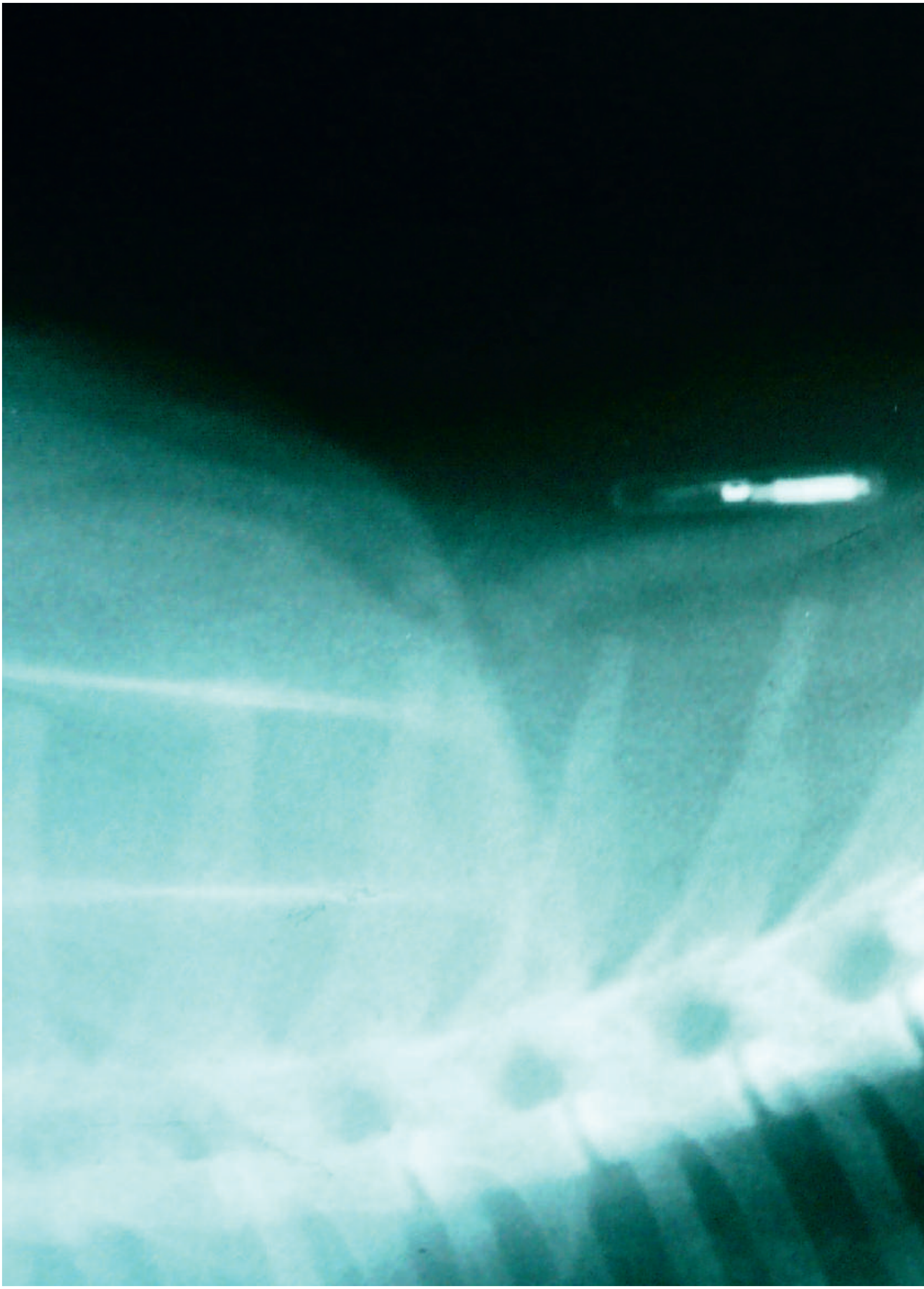
In the cattle industry, RFID ear tags are put on the cattle to more easily identify each animal. In addition to tracking an animal's history and performance, it helps to determine which ones are performing well. The small 'button-like' tags are placed in the ear. Each tag has a unique 15 digit number printed on it, and the number can also be read by scanning the tag. The technique is practically a 'cattle passport' and it is easy to see the resemblance between tracking, identifying and monitoring individual cows in a large herd and doing the same thing with a specific concrete element in a building or on a construction site.[42]

However, the technology requires a battery, that currently only last seven years, which is fine for cattle, but in order to be adapted by the building industry, the technology needs to be developed further, so the batteries last the entire life the of building component — which is several decades.

41 rfidsolutions.in **42** cattlemax.com

Photo: An RFiD-chip cast in a concrete element for the Circle House Demonstrator. The chip links to a material passport containing information about the element, e.g.: the recipe for concrete, the structural integrity of the element and drawings of the building. See more about the project on pages XVI to XIX.

Photo © Spæncom



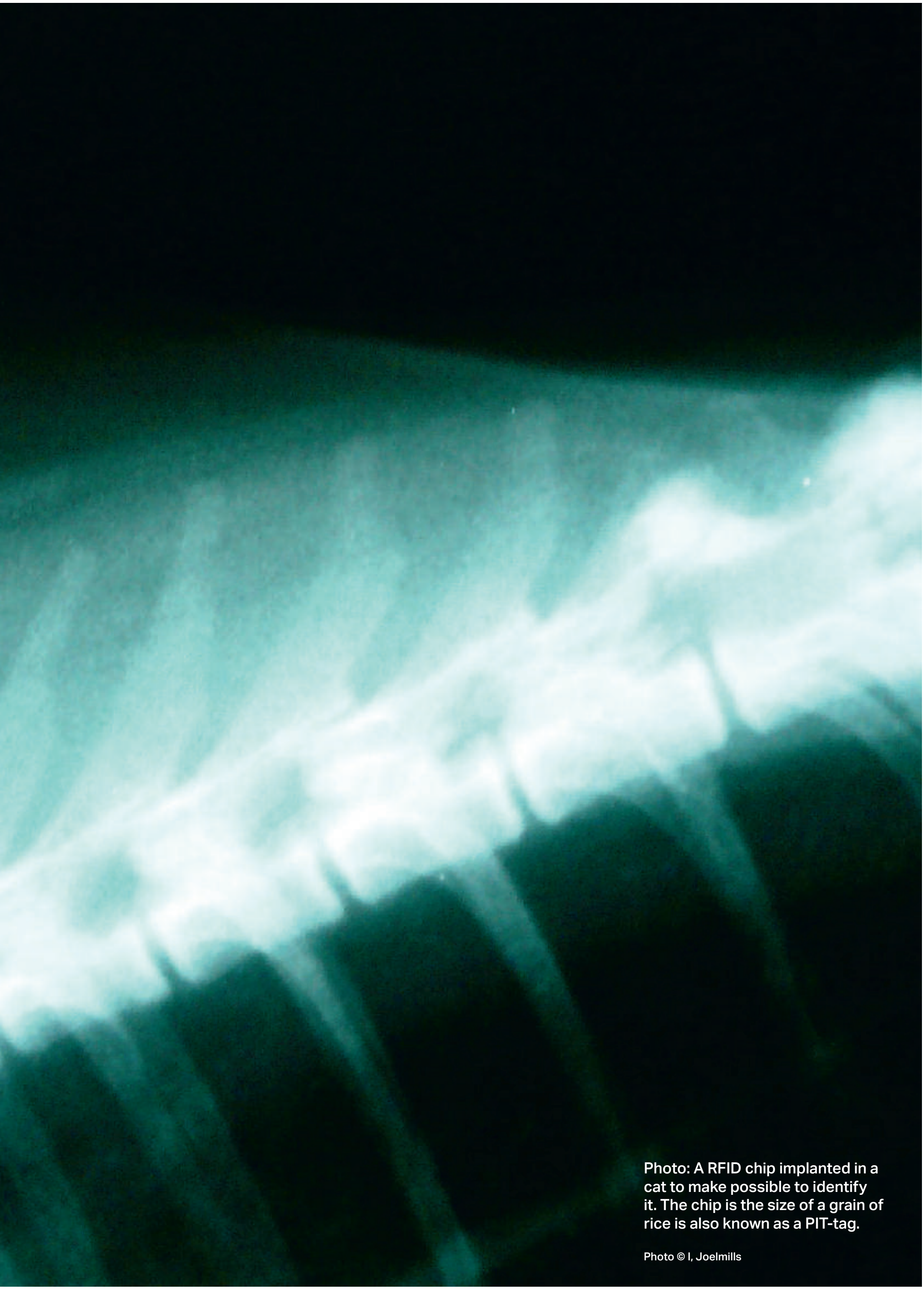


Photo: A RFID chip implanted in a cat to make possible to identify it. The chip is the size of a grain of rice is also known as a PIT-tag.

Photo © I, Joelmills

Handling of information
— navigation, certification and caretaking

Material

However, they are not present in the building on a daily basis and do not have a full overview. However, as the building owner ultimately is the one that either has to pay for demolition of the building and the handling of the waste or benefit from the values retrieved, they are the ones who has the incitement to take action – either by doing it herself or by securing that the facility manager and 'material passport manager' takes action.

'Material passport manager' could be a future job description for the people having the responsibility of the caretaking and to be the anchor point between, craftsmen, staff, user and owner.

Certification of the information
As well as maintaining and updating the information, it is equally important to get the information from all the different links in the process and be able to guarantee the correctness of the data. To provide this safety, some kind of certification system must be implemented.

Certification in all links is one method to guarantee a thorough documentation. If a system were set up so that all the different links in producing a building component had a certification, each link the production chain could check the certification of the contens they use. That would ensure that products only enter the final component if their contents are known. For example, the manufacturer of cement will make sure he only uses certified chalk and clay in his product. He will then get his product certified before he sells it to the concrete manufacturer, and so on. This method divides the task of certification among many authorities and makes a dense system with certifications that is targeted directly to the specific industry.

But the many small authorities can also be difficult to check up on and greater authorities might be needed to ensure the quality of these sub-certifications.

Having only one general certification of building elements ready for reuse would be convenient, but has it's flaws as well. For all markets where there is only one player, there is the risk of monopoly. One dominant power that rules can be targeted by lobbyist to favour different products. which could twist the market.

Smaller manufacturers will also have the risk of being forgotten among the bigger players. If the certification system is not accessible to all sizes of companies, it can be excluding. If you, e.g., have to pay a lot of money to get your product certified, it will favour the big and established companies.

‘Material passports have the potential to revolutionize the construction industry and for the first time match the real value of materials with the prize we pay’

— Henrik Sørensen
Founding Director, henrik•innovation

The interim
— example of a material stock

Since 1998, the Danish company Genbyg has specialized in the purchase and resale of used and recycled building materials. Used doors, windows and other materials are given a new life when they are carefully taken down and shipped to the warehouse and shop on Amager, Copenhagen.

The materials are recorded and put their website, so that both private customers and professionals can find the used building materials that are old, inspiring, funny and beautiful. The materials are available whether sitting at home in front of your computer or visiting the store in person. Genbyg's concept goes beyond regular recycling: doors, floorboards and other from their stock will be upcycled and converted into modern tables, shelving and other furniture.[43]

Genbyg's concept of purchasing and reselling building materials can be seen as a small-scale version of the proposed 'material stock' that handles building in the interim phase.

The prices for the reused building materials at Genbyg is actually higher than new ones from the manufacturer. There's several reasons for this; the materials are of a higher quality and they have a unique attracive patina that the customers want to pay for.

On top of that, are some of the materials connected to a special history, which is explained on the website — like a material passport. Examples are hospitals, ships, schools and factories that have special place in Danish history and culture, which customers wants to own a part of.

Photos: Genbyg's store on Amager is a like an archive of reused building materials. They sell all types of non-structural reused building components like doors, floor boards, tiles, lamps, etc. The elements comes as both individual unique objects and larger bulks of identical pieces are sold to both private and professional customers.

43 genbyg.dk

Case study implementation

— Page 166 to 171

How a material passport could look if implemented in the case study project.

Passport implementation
— using bim and vdc

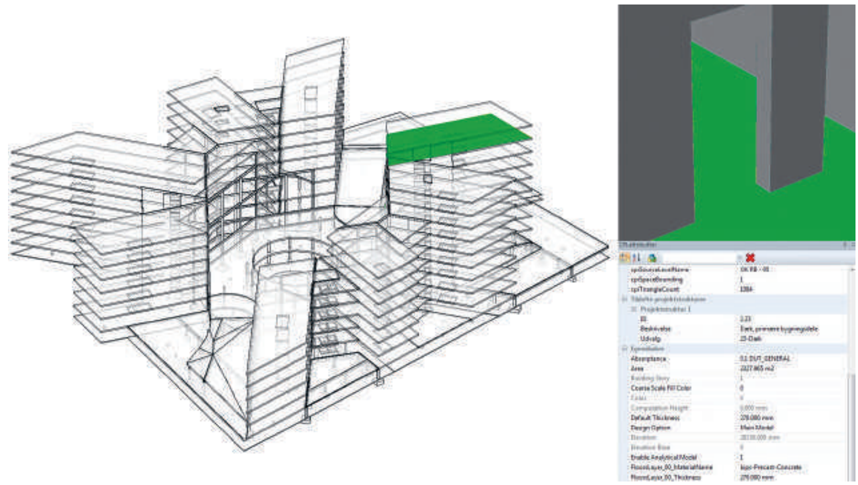
In order to successfully introduce a model for circular economy in the construction industry in Denmark or abroad, it would be very beneficial if a digital model (i.e. a BIM and VDC model) could be developed and maintained that allows the building owners — present and future — access to all vital information with regard to the potential for reuse of all of the structural elements that constitute their buildings.

Consequently, as part of the case study, it is investigated how such a model could be developed and exploited in the design phase, and used as well as maintained over the lifetime of the building. The first step is naturally to build the BIM model. In the design phase, these models are used to optimize a number of different elements and aspects critical for the building.

Some of these aspects are: the design of the building with regard to optimal use of daylight, the indoor environment, the structural system, the buildability of the building, the gross vs. net areas of the building, as well as optimization of the life cycle cost of the building.

If information on costs for procurement, installation, and maintenance etc., as well as information with regard to time is added to the model, the BIM is transformed into being a VDC (Virtual Design and Construction) model. In the design phase, such a VDC model allows the clients, contractors, suppliers, and consultants to simulate not only the construction phase but also the future use of the building – and use this information to optimize the design of the building.

Information access
With regards to procurement of materials, it has since 2012 been recommended that the BIM model also is used for optimization of the procurement processes, as it has all the specifications and quantities of the materials that have to be built in the future building. In his 2012 book, 'BIM for Building Owners and Developers', K. Reddy states the following:



‘Using BIM to determine the gross quantity of commodity materials (steel, copper, etc.) will continue to be important. With natural resources and commodities being subject to global demands and market volatility, the ability to develop commodity hedging practices is becoming important’

We need to develop this idea further in order to give present and future clients the opportunity to use the buildings they are going to build or own as ‘warehouses’ for materials for use in future buildings, and thereby transform the liability of having to pay for the future demolition of a building into an opportunity to sell off the materials used in the present building to use in future buildings.

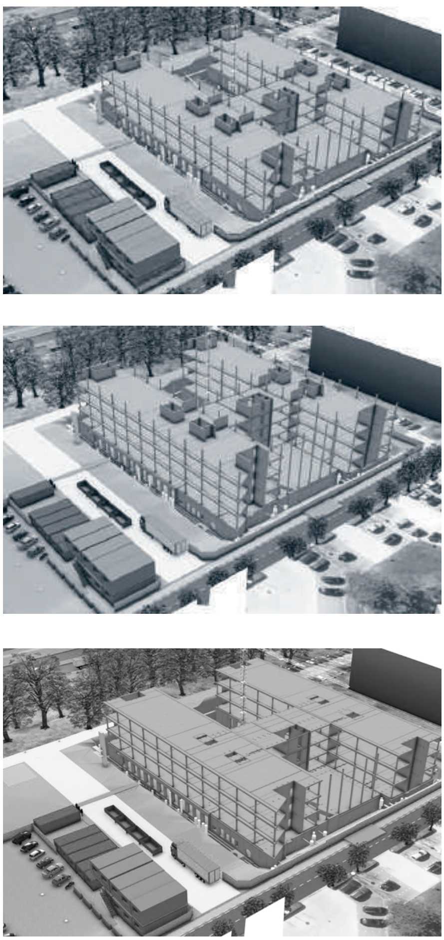


Image (top): A digital mockup of how information about supplier, size, geometry, steel qualities,painting, etc. on each element is integrated in a BIM model.

Images (right): Screen shot of the VDC simulation of week 10, 12 and 14 of the construction process.

44 BIM for Building Owners and Developers, p. 19

‘As long as all elements of the structure are clearly and unambiguously identified, all other information can be stored in a separate database’

— Niels Wingesø Falk
Vice President VDC, MT Højgaard

In order to do so, we need to ensure that each and every structural element is clearly and unambiguously identified in the VDC model. How that is done is shown in the pictures on page 175. Here it is clear how information of supplier, size, geometry, steel qualities,painting, etc. on each element can be entered into the VDC model.

Consequently, all information relevant for the reuse of structural elements after end of first lifetime can be entered into the model. If this information is integrated into the VDC model, this model basically becomes the material passport for all structural elements used in the building, as long as each element as also described above is unambiguously physically branded.

Practical use
However, as explained by Niels Wingesø Falk, MT Højgaards division director with responsibility for VDC implementation and laboratories, it is not necessary and not recommend that all sorts of information is entered into the VDC model, as that could make the model difficult to operate because the IT processors will have too much information to handle during a number of simulations, where this information is not needed.

Niels Wingesø Falk recommends that only information on geometry and information that unambiguously identifies the unique elements is entered into the VDC model, allowing the model to operate faster. As long as all elements of the structure are clearly identified, all other information, besides that contemporaneously used for an ongoing analysis (e.g. on the optimization of the schedule for the erection of the superstructure), can be stored in a separate database.
It is, however, extremely important that both the database and the VDC model are maintained and updated over the lifetime of the building in order that all information on the individual elements reflects the contemporaneous status of the elements and includes information about maintenance, modification and amendments made to the individual elements as consequence of renovations, refurbishment, etc.

The VDC model is a tool for communication, discussing how different elements of the superstructure are to be optimized with regard to time for construction and costs of construction. In the same way, the VDC model can be used for discussion on energy consumption, functionality, detailed design, scheduling, choice of solutions, future maintenance, as well as discussion on which design is optimal for the structures and joints, when it is required that the superstructure is designed for disassembly.

Moreover, the VDC model will be the optimal tool for accessing all information on all the structural elements in the superstructure, even if some of this information is stored in separate databases. The VDC model will be the key to structure and locate this information over time.

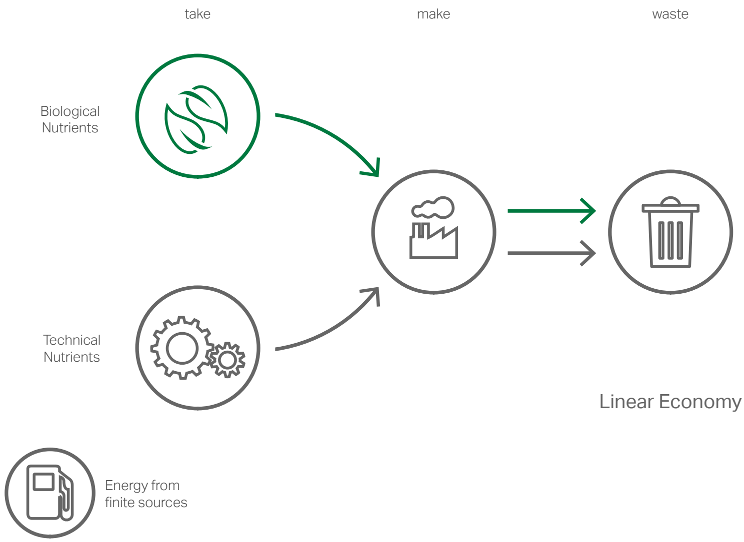
CIRCULAR ECONOMY

What is circular economy

— Page 174 to 185

Explaining circular economy and some of the general concepts behind it.

Circular business models
— as driver for ‘the seventh dimension’



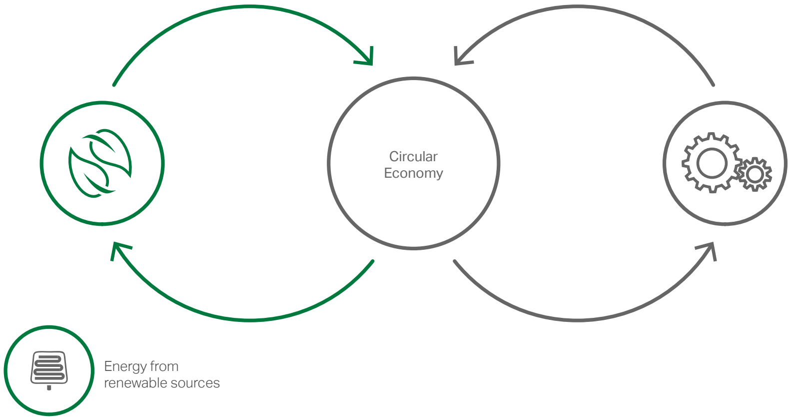
The most advanced parts of the building industry today operates with six dimensions. The three traditional dimensions i.e. height, length, and depth as well as three additional dimension .i.e. time, economy and operation. If the industry is to meet the challenges related to sustainable growth, these dimensions need to be supplemented with a seventh dimension. This dimension is the recycling and reuse of building material without degrading and thus maintaining or improving the value of the material.

From linear to a circular economy
The building industry is responsible for the use of up to 40% of the materials produced globally and about 35% of the world’s waste. That’s a tremendous challenge as most of the building materials that are used today require large amounts of resources to manufacture and are rarely recycled neither in biological nor in technical circles. As an example, the production of cement alone consumes approximately 2% of the global energy consumption.[45] The life cycle of a typical building material follows the linear model of cradle to grave. After the material is extracted, it is then manufactured into a building component.

Once the full lifetime of the component has been reached, it is then either downcycled or ends up as building waste. This means that the value of the material generated during extraction and production is lost. The circular economy, based on Cradle to Cradle®[46] principles, developed by William McDonough and Michael Braungart, is a new model for sustainable growth that challenges the current form of production and consumption, and which

45 IEA Greenhouse Gas R&D Programme

46 Cradle to Cradle® is a registered trademark of MBDC, LLC



Diagrams: Illustrating the flow of bioloical and technical nutrients in the linear vs. the circular economy.

The diagrams are reinterpretations of originals owned by the Ellen MacArthur Foundation

introduces a model where the value of the material is preserved during its lifetime. Material cycles close, leading to less building waste, the generation of less CO_2 and subsequent minimization of resource use.

Generating economic value through increased recycling

In today constructions industry, the main focus when designing a building, are the construction costs. In more advanced models, the design of a given building is optimized not only based on the construction cost, but the construction cost plus the cost of operating the facility over its physical lifetime or its economic lifetime.

These more advanced models are named either Total Cost of Ownership (TCO) or Life Cycle Cost (LCC) and if ownership of the structures rest with the contractor or operators for a number of years (typically 20 to 30 years), the model is named Public Private Ownership (PPP).

Thus, the basic idea in these concepts are that both the construction cost and the cost of operating the building over its life time should be taken into consideration and be optimized, when the design of a building is made. Such models are becoming more and more used as EU legislations now allow public clients to ask the contractors and vendors to compete on Total Cost of Ownership as opposed to direct ‘day one cost’ only.

Moreover, such models are an essential part of the international renowned sustainability concept

DGNB and on it ways into other systems such as LEED. These models operate with two dimensions of the economics of a building — construction cost and operation cost.

There is however a third dimension, the cost of demolishing and deposition of the building on to a land field. When it comes to the superstructure of buildings, these costs are not taken into consideration in today's construction industry — most likely because the industry is 'unaware' of alternatives.

However, if the principles of the circular economy are applied to the superstructure of a buildings, the third dimension of a buildings cost (the cost of demolishing and deposition) can be taken into consideration, when a building is designed. Not only can these costs be taken into consideration as the third economic cost dimension, when the cost of a building is evaluated. This third economic dimension does not necessarily need to be a cost — It can actually become a source of income if the principles explained in this book are applied. That is application of a circular economic model transforms costs into revenue. This is the incentive for applying the principles of circular economy to the superstructure of buildings.

The biological and technical cycles
The biological and technical cycles together represent the core elements of the circular economy.

The biological cycle consists of materials that after end use can be biodegradable without polluting nature. Timber is an example of a material that belongs to the biological cycle.

The technical cycle consists of materials that after end use can be separated and reused in new generations of industrial products without loss of quality. Steel and concrete are examples of materials that belong to this cycle.

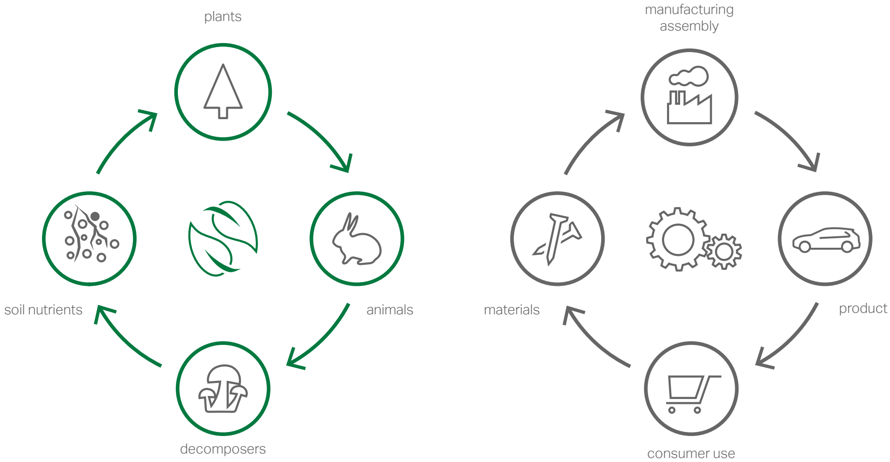
Healthy materials
An integral part of the Cradle to Cradle®[42] framework is that materials are not just considered as components with a certain lifetime and function, but also as potential nutrients for new generations of products.

A prerequisite for this is that only healthy materials are used. This requires a better knowledge of where the materials come from, their impact during use and their potential for reuse.

Designing for the biological and technical cycles
Whilst timber is a biodegradable material, its further use within the biological cycle is not necessarily thought about. This is because wood is often surface treated, glued or in other ways mixed with non-biodegradable materials. The focus for biological materials should therefore be on optimizing their performance by increasing the length of time they can be used, see diagram of cascades on the opposite page, before they for example need to be incinerated and the ashes and the nutrients are returned to the earth.

In relation to technical materials, it is essential that individual, pure materials are not mixed with other materials in a way that impairs their quality. This means that it becomes more important to design in a way that materials can be separated when a product can no longer be used.

47 Cradle to Cradle® is a registered trademark of MBDC, LLC



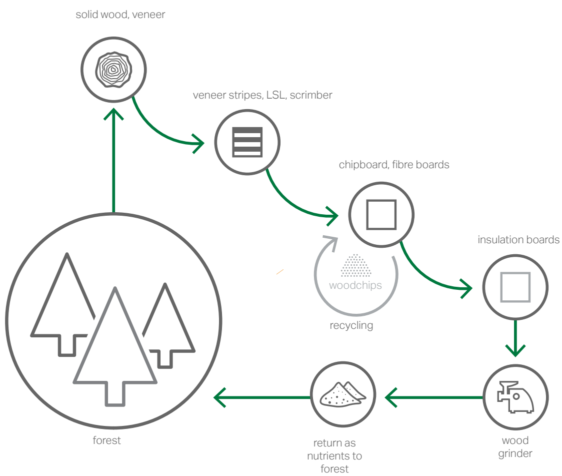


Diagram (top): Cradle to Cradle®[47] cycles; materials are designed to be resources over multiple use cycles.

Diagram (bottom): Cascades; in Cradle to Cradle® [47] biological materials are remade to new products to keep the value as long as possible before eventually returning as nutrients to the forest.

The diagrams are reinterpretations of originals owned by MBDC, LLC

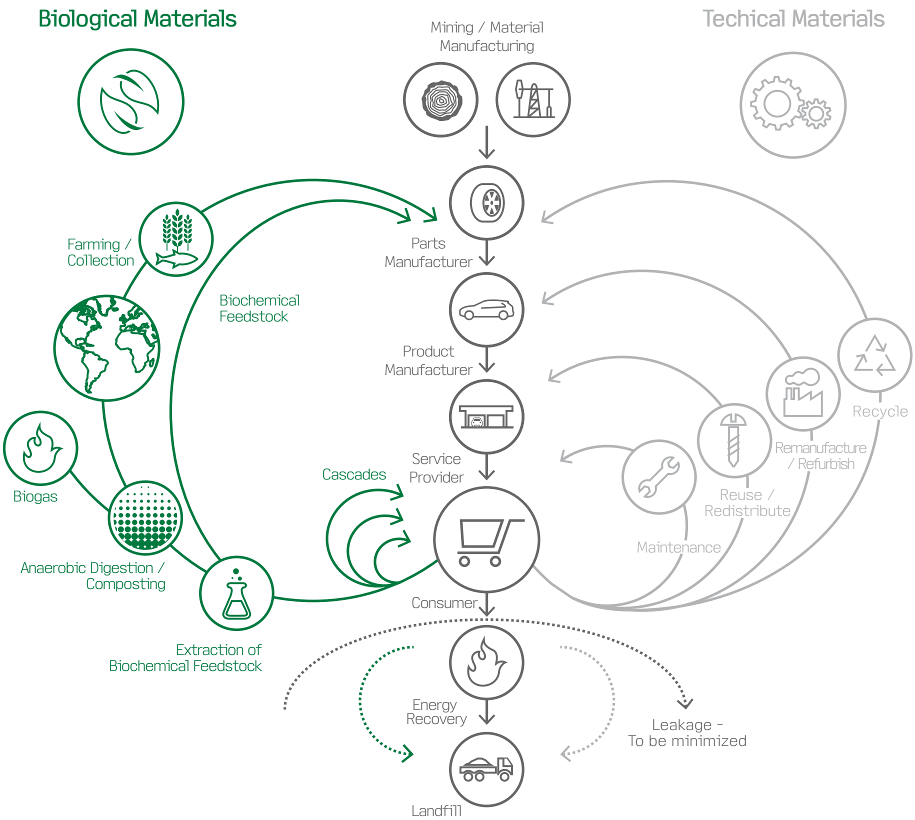


Diagram: The system diagram illustrates the continuous flow of technical and biological materials in the value circle. There are four circles of value creation. The diagram comprises a plethora of different terms that are integral to understand the different activities that contribute to a circular economy.

This diagram is an reinterpretation of an original owned by the Ellen MacArthur Foundation

Concepts and models
— in the circular economy

The power of the inner circle
The inner circle refers to a minimization of material usage compared to a conventional linear system. The tighter the circle, the better the reuse of the materials and the energy etc. used to produce the materials. A longer circling refers to increasing the number of consecutive circles i.e., whether the materials are reused, recycled etc.

Cascades
Cascaded use refers to diversifying reuse across the value chain. Steel from the building industry is, for example, often cascaded in the metal industry because of its economic value. Wood meanwhile is commonly used as a biofuel in combustion power plants. Finally, there are pure circles, which refer to uncontaminated material streams. These streams lead to more efficient collection and redistribution efficiency.

Recycling, downcycling and upcycling
Recycling is the process of recovering materials for the original or alternative purposes. The materials recovered feed back into the process as crude feedstock. If this results in a reduction in quality then this is referred to as downcycling. The process of improving the quality of the material or product is upcycling.

Refurbishment and remanufacturing
Refurbishment and remanufacturing is the processes of returning a product to good working condition by replacing or repairing major components that are faulty or close to failure and making cosmetic changes to update the appearance of the product. Remanufacture refers to the process of disassembly and recovery at the subassembly or component level.

Reuse and redistribute
Reuse and redistribute is to reintroduce a product for the same purpose and in its original form.

Maintenance
The maintenance of a product is the process of keeping the product in good condition without changing use. The use of a product means having the service or performance it provides without degradation while consuming involves degrading it. The use of a product can be extended through take back systems such as deposit schemes.

Access over ownership
Access over ownership is where businesses retain ownership of products and more items are shared through business models, such as functional sales, leasing and rental.

Conclusions
from circular economy

The research and case study in this section show that integration of the circular economy has already started and that the implementation of the new models is good business.

A game changer
The introduction of a circular economic model in the construction industry will be a game changer, which could mean that the industry will move from being an 'ownership system' to a structure focusing on 'access over ownership'. The transition, however, faces barriers because it represents a huge paradigm shift in the industry. In the building sector, this could turn into a game changer for the contractors, where the main business model potentially could move from the current 'construction only' and 'design-construction' of buildings to a much longer 'design-build-operate' business model. The new financial models would prioritize the total cost of ownership, including operations and the optimization of the 'scrap value' of buildings when they no longer meet contemporary requirements for functionality, energy efficiency and operations etc. — and hence are qualified for demolition or as advised in this book: for disassembly.

Even if the introduction of a circular economic model in the construction industry doesn't change the ownership of buildings or materials. It can make substantial disruption as the architects, contractors and consulting engineers, can then provide the client with solutions that transforms the 'end of life cost' to 'end of life revenue', gives a competitive advantage compared to other contractors, who provides traditional solutions only.

Big circular business

The most significant result of this section, and the entire book, is that it presents a case study that thoroughly calculates the effect of the implementation of all the strategies for a circular economy in on the superstructure of a specific representative building of 42,000 m^2 with a value of DKK 860 million (€112.5 million.) The result shows that instead of having an expense of DKK 16 million (€2 million) for the demolition of the building, there is a potential net profit of approximately DKK 19 million (€4.6 million) if the building can be disassemble and the materials can be resold. The business case is even better if the two alternatives are compared. Using today's model, the owner of the building will have to pay an equivalent DKK 16 million for the demolition of the building whereas she would have an opportunity to sell of material in the value of DKK 19 million. This gives a positive business case of DKK 35 million (€4.7 million) using today's material prices or about 4% of the total value of the building and looking only at the superstructure.

In 2065, when the building is 50 years old, the material prices will most likely have doubled (estimated projection) and the retrieved value will therefore also have doubled, to more than DKK 70 million (€9.4 million) or 8% of the total building value. On top of that are all the additional building components such as technical installation, façades, partitions, interior etc.. Even though they don't represent the same initial value as the superstructure, they have a faster replacement rate and therefore it can be argued that their total value, equals that of the superstructure. This equals a positive business case of 16% of the total building value. However, it is outside of the scope of this book to deal with the design, handling and recycling of these materials.

The investment to prepare the superstructure of the buildings for the use of a circular economy model is estimated to be only 0.35% of the total value of the building.

5 Principles

— to consider in a circular economy

New businesses

To complete the circle in the circular economy model, new businesses need to emerge.

Incentive

All partners in the supply chain will have to benefit economically.

Physical
New facilities are necessary to manage, handle and certify building materials and elements.

Business
It must be visible that the implementation of a circular economy is beneficial for the business.

Financing
New opportunities for business investors will kickstart the circular economy.

Society
It must be visible that the implementation of a circular economy is beneficial for the society.

Consultants
Intermediary consultants can bring the different parties together.

Environment
Implementation of the circular economy model creates a positive impact on our environment.

New models

Rather than creating products, businesses need to provide the user with a service.

Access over ownership
Get the service of the product rather than the product it self.

Leasing
Make a performance based contract where the user hands back the product after a defined period of use.

Take back
Companies that facilitates take back of products at the their end-of-life.

Partnerships

Partnerships and collaboration agreements are necessary, thus nobody can run the circular economy alone.

Interdisciplinary
Collaboration between different professions are important to cover all aspects of the circulation.

Knowledge sharing
Communication and knowledge sharing across industries is important to get high quality and integrated solutions.

Benefit
All partners involved has to benefit from the collaboration for the circular economy to work.

Circulation

The value of the products in the technical and biological cycle as needs to be maintained as long as possible.

Redistribute
Products that are in good shape can be used several times.

Repair
Replace parts that need replacing and keep the product working for as long as possible

Recycle
Materials recovered after a products end-of-life will replace the use of virgin materials.

Existing examples

— Page 186 to 207

Explore examples of circular economy already implemented in architecture and other industries.

Green Solution House
— existing architecture

Location Rønne, Denmark
Year 2015
Client Green Solution House
Architect 3XN Architects (design), Steenberg (execution)
Size 4,500 m^2

Photo: Inspired by the Cradle to Cradle® [48] principles, the Green Solution House comprise of sustainable building materials and reuses the energy consumed in the building and natural sources, such as rainwater, to facilitate the building.

Photo © Stamers Kontor

The Green Solution House conference centre and hotel in the Danish island of Bornholm is designed to be a platform for the highest level of sustainable development achievable.

Circular sustainability
In accordance with the principles of Cradle to Cradle® [48] all materials used in the fan shaped building are either fully recyclable or biodegradable. Hence, it is a building design that takes on the ambition to eliminate the concept of waste.

Eliminating waste means that everything must be part of a closed loop. Thus, the building is designed for disassembly and constructed of defined recyclable materials.

Moreover, in order to ensure that the building is truly sustainable, solar cells produces the energy consumed in the building, rain water is collected and water used is biologically cleaned and reused. Integrated green houses produce organic fruits and vegetables for the hotel restaurant. Further, the daily material flows from running the centre is either recycled or composted. [49, 50]

48 Cradle to Cradle® is a registered trademark of MBDC, LLC
49 gxn.3xn.com **50** greensolutionhouse.dk

Circular foundation
Behind the project is a foundation that reinvest all earnings back into the centre, which makes it a project under continuous development. Hence, the building will always introduce the newest sustainable solutions on biodiversity, materials, energy, water, and waste.

Photo: The landscape around the Green Solution House collects the water and clean it in a 'living machine', before it is used in the building. Here it is reused over and over in a closed cycle e.g. for watering of green walls.

Photo © Adam Mørk, from D-A #25 by VELUX.

Photos: B / S / H features a full height four-story atrium with an living green wall.

B / S / H
— existing architecture

Location Hoofddorp, The Netherlands
Year 2011
Client Bosch Siemens Home
Architect William McDonough + Partners
Size 8,670 m^2

The new headquarters for the Bosch Siemens Group (B / S / H) Netherlands is the first building to be completed at Park 20|20, a Cradle to Cradle® [51] inspired development. The building consolidates multiple home appliance brands and workgroups, providing a unified workspace and promoting collaboration and intersection between departments while maintaining multiple identities.

Additionally, showrooms allow public and user groups to view and test home appliance products within simulated home environments. The design optimizes these various programmatic demands by providing multiple areas of exchange, where both research and development groups overlap with users to create a Living Laboratory. Showrooms are transformed into active observation and social space with multiple programmatic uses that promote the interaction between user, developer, worker, visitor, and machine or appliance.

A green vegetated 'biological' surface folds into and up the building to organize work areas and showrooms. A unifying central open gathering space provides an area for demonstrations under a photovoltaic integrated glass roof. Like the appliances it contains, the building is designed for disassembly,

51 Cradle to Cradle® is a registered trademark of MBDC, LLC

utilizing modular systems to allow for future flexibility and demountability while reducing volume, waste, and construction time. All materials are assessed according to Cradle to Cradle® [52] requirements to ensure safe and healthy. [53]

Closed technical loop

The slabs in the B / S / H are made from a hybrid product called 'Slimline'. It is made from steel beams and a thin layer of concrete. This hollow construction offers space to accommodate cables and pipes, so the building doesn't need a false ceiling to hide them. This means that the gross floor height can be reduced, resulting in material savings of up to 20%. With the lighter construction, the foundation can also be lighter. In addition, the life of the building can be greatly extended because the functionality can be adjusted easily.

It is possible to dismount Slimline from the building and reuse the materials for new buildings. Due to this technology, a takeback system has been made with Slimline Buildings, which has delivered the structural element out of steel to take the resources back at the end of the building's lifetime.[54]

52 Cradle to Cradle® is a registered trademark of MBDC, LLC
53 park2020.com **54** slimlinebuildings.com

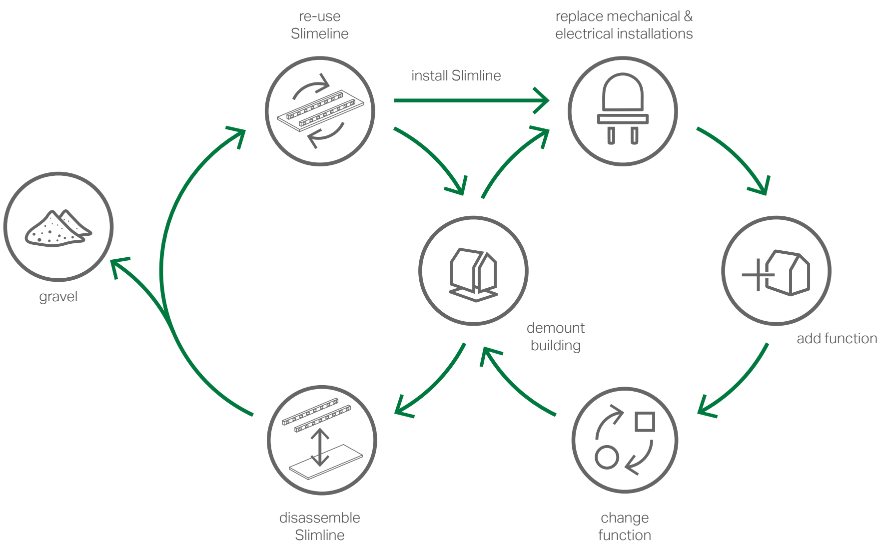


Diagram: Shows how Slimline can be reused in a closed technical loop. [54]

This diagram is an reinterpretation of an original owned by Slimline Buildings

Photo: Slimline can be dismounted from buildings for reuse in new buildings, as well as allow for disassembly.

Photo © Slimline

Brummen Town Hall
— existing architecture

Location Brummen, Netherlands
Year 2013
Owner Brummen Municipality
Architect RAU Architects
Size 3,000 m^2

Photo: The Brumen Town Hall is designed to stand a period of 20 years and with a design made for disassembly. As well, future plan for theconstruction materials and details for their second life have been considered.

Image © Petra Appelhof

The Brummen Town Hall has its starting point in the request for proposals for a temporary housing facility for a period of 20 years. Background for this request is the increased aggregation of Dutch municipalities into larger administrative units and the uncertainty if a town hall would be needed beyond the 20 year time horizon.

The answer by RAU Architects and Turntoo to this proposal was a design made for disassembly, consistent use of reusable and renewable, high quality construction materials and a contract that guarantees circularity at the end of the intended user period.

The architects call it the first building in the world conceptualized as a raw materials depot.[55] The building is a temporal organization of construction materials, of which all details are known, including their destination in a second life.

The building is made as a light extension to an existing building. The supporting structure, facade and floors are made from timber in prefab components and use of concrete has been minimized. The prefab timber components can be easily dismantled and reused in a new building.

55 turntoo.com

Interestingly, manufacturers asked for several minimal, yet very intentional, design changes so that the components would have an easier case for their second life application.

For example the timber supplier wanted to provide timber of larger dimensions because it will be easier to reuse in 20 years when he gets the materials back.

What will remain after 20 years is the original land and house that was already there before the project started.

RAU
The RAU architectural team, based in Amsterdam, designs buildings with a strong emphasis on sustainability and through its building designs aims to accelerate the transition to a sustainable circular economy.

As one of the first architect studios it focuses on circularity by designing buildings as 'raw material depots' — materials are placed temporarily and can be relocated and reused in future cycles without loss of quality.

According to RAU a truly sustainable building is not just one that incorporates energy efficient technology and fulfils the standards of given sustainable certificates, but also takes into account the effects on the social and physical wellbeing of its users. [56, 57]

Turntoo
Turntoo focuses on developing business models, which close the loops for reuse, repair, refurbish, reinvent or recycle. This way components and materials remain available for future products, and automatically incentive manufacturers to opt for better design and material choices.

Turntoo has developed an economic model that regards products as raw a materials depot; therefore products are provided as a service — on performance basis — and remain in ownership with the manufacturer.

The user buys the service the product provides, but does not own the materials the manufacturer uses in the product. The manufacturers retain ownership of the product and the materials used and bears the cost of installation, operation and maintenance.

For example Turntoo developed Circular Lighting with Phillips. A model where the client pays for light quality (lux) rather than light fittings. This performance agreement put the responsibility (for the efficiency and maintenance of the lamp units) back on the manufacturer.

This also incentives Phillips to opt for repairability and upgradability of their equipment as well as working with architects to ensure that the design maximizes natural light to reduce energy consumption. [58, 59]

56 rau.eu **57** construction-manager.co.uk

58 Cradle to Cradle® — In the Built Environment **59** turntoo.com

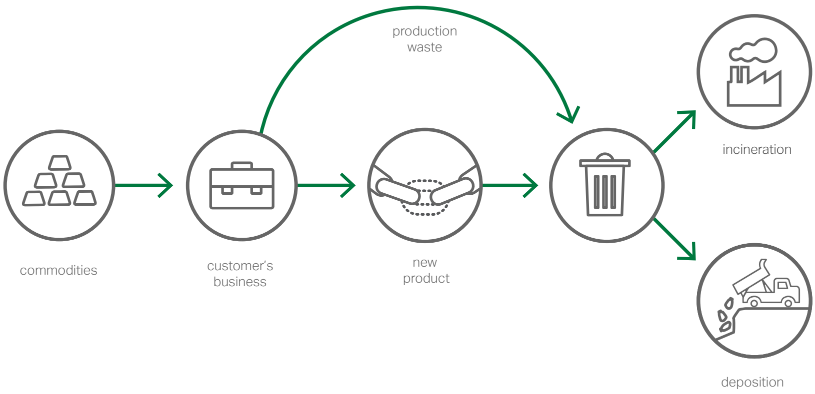
Photo: Visible connections designed for disassembly is part of the architecture.

Image © Woodteq

Photo: Overview of the existing building and the new timber structure designed for disassembly by RAU Architects and Turntoo.

Image © Petra Appelhof

Advance Nonwoven
— other industries



What Nonwoven fibres
Purpose Upcycle reused fibres and granulates to new products of high quality

The company Advance Nonwoven has developed a plant that, with the help of a patented Carding Airlaid Fusion Technology (CAFT), can produce a series of products based on recycled fibres or granulate materials. The products consist of thin tissue-like textures to lofty structures and from low to high-density compositions and can be used in insulation, mattresses, for upholstery and in growth mats for the horticultural industry.

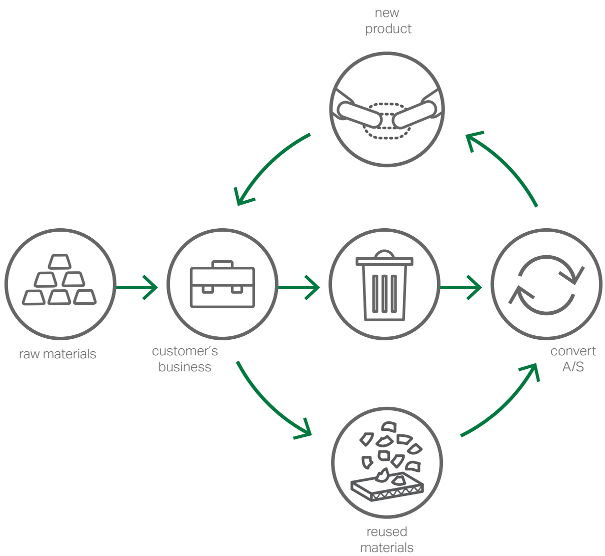


Diagram: Ilustrating how production waste and unused products in a traditional business model are either disposed of to incineration or landfill, and how Convert with the new green business model becomes the pivotal point for companies that convert to the circular economy.

With a starting point in this technology, Advance Nonwoven is establishing a completely new company, Convert. This company can service production companies on an hourly basis that wish to convert their waste and spill materials to tailored products that they can use or sell.

The products will typically be able to be recycled again and again, so that waste, in line with Cradle to Cradle® [60] principles, becomes a resource that generates added value in a circular economy model.

Convert offers customers a complete package of services covering warehouse space for the storage of customers' waste material, a pretreatment plant for shredding of material together with an aftertreatment plant, for example, for compression and packaging of fibre and granulate, compression moulding, etc.

Convert customers will typically be companies that, based on a Cradle to Cradle® [60] philosophy, wish to have full control of their own materials and ensure traceability in the products for which the materials will be reused.

60 Cradle to Cradle® is a registered trademark of MBDC, LLC

Ege Carpets
— other industries

What Carpets
Purpose Business model with integrated take back system and reuse of used carpet tiles

Founded in 1938 and based in Herning, Jutland in Denmark, Ege Carpets is a leading European designer and manufacturer of high quality carpets. Ege's carpets contain both biological and technical nutrient materials.

Ege's long-term goal is to develop carpet designs for disassembly, enabling 100% recovery and recycling of materials for new carpet production.

Ege has recognized it needs to embark on a journey of transition to achieve this long-term goal, moving progressively to a fulfilment of Cradle to Cradle® [61] principles.

The company has therefore developed a three-legged strategy:

Take back system and reuse
Ege offers to take back used carpets from 'business to business' customers, regardless of brand, when buying new Ege offers a service agreement for regular service of the new carpet and eventual take back whenever the customer wishes to change the carpet.

Ege provides the business to business customers equipment for easy collection of used carpets, as well as transportation of used carpets.

61 Cradle to Cradle® is a registered trademark of MBDC, LLC

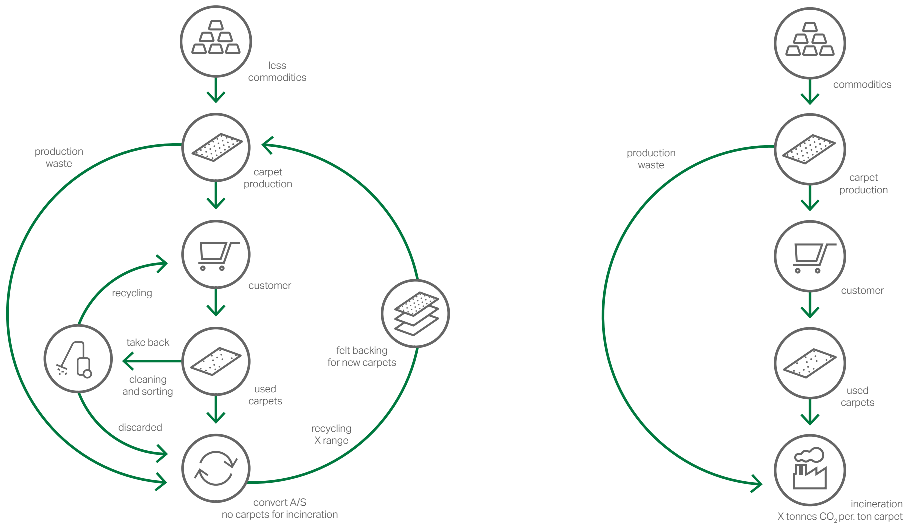
Photo: Used carpets are bought by Ege from 'business to business' customers and sold as fuel to the cement industry. This results in saving new raw materials and reduced carbon emission.

Used tiles that are not suitable for sale, as well as other used carpets and residues, are sold as secondary fuel to the cement industry, replacing fossil fuel like petroleum coke and heavy fuel.

Recycling of carpet and backing

Ege Carpets wishes to manufacture felt backing or underlay for carpet tiles at Convert, described on page 209. Felt backing and underlay is purchased today from external suppliers and is manufactured using the same type of materials as carpet pile. In addition to used carpets received through the take back system, Ege Carpets will also reuse production waste at Convert. By converting carpet waste at Convert, a number of positive environmental effects are achieved by Ege Carpets, as illustrated in the figure on page 212 and described below:

Saving of new felt backing underlay, i.e. new raw materials, with reused carpet waste reduced CO_2 emissions from incineration of carpet waste in the cement industry Felt backing substrates manufactured at Convert can be recycled several times.



Design for disassembly

The long-term strategy is design for disassembly, ensuring that the materials in their pure components can be recycled. Ege plans to investigate possibilities for designing carpets for easier post-use disassembly and recycling.

As part of this strategy, Ege recently had the majority of their carpet products Cradle to Cradle [62] Certified ™.

A certification means that everything in the product has been assessed in relation to material health and its ability to be incorporated into a recycling or reuse scenario.

This will ensure a high level of traceability and optimized materials.

Diagrams: Illustrating a general current business model before the circular economy and Ege Carpets new model with integrated take back agreements, reuse and recycling.

This diagram is an reinterpretation of an original owned by Ege Carpets

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Refurb

— other industries

Diagram: Refurb's business model is circular since IT is refurbished and procurement and sales are targeted towards the same customer groups.

This diagram is an reinterpretation of an original owned by Refurb

Refurb is a retail business that buys used, refurbished and overstock IT and telecommunication equipment from businesses and public institutions in Denmark, Scandinavia and Europe. The company then strives to sell the equipment on to private consumers, companies and organizations in Denmark and Norway. Refurb's mission comprises four elements:

— Value recovery.
— Competitive sale of used electronics to private and public sectors.
— Reduced environmental impact by reducing the need for production.
— Reuse by donation of products that cannot be reused through sale.

Refurb offers reused IT at second hand prices, but products are as-new retail goods in nice packaging. They come with extended guarantee, primarily through its own web shop and via direct sales to the public and businesses. Many of the products offered are from quality brands such as Lenovo, Dell, HP and Apple. The company procures, deletes data, cleans and substitutes worn parts and installs new software, so the computer in practice becomes new again, but at a significantly lower price. The focus on reuse is an integral part of the circular economy. Access to new customers is obtained through both procurement and sales — from the final customer to the final customer — and at the same time removes the 'middle man'.

How to make circular business

— Page 208 to 219

Discover how you can transform a traditional linear business model to circular business model.

Transition
— going from linear to circular

The process from raw material to finished and installed building product includes a large number of processes, stakeholders and specialized manufacturers.

For each process in the value chain, many manufacturers compete, focusing on lowest price as the primary competitive advantage. In this business environment, it is difficult to create a new business model, merging more levels in the value chain or initializing take back, upcycling or other circular economy instruments and at the same time maintaining the position in the market.

While the flow from raw material to finished building product is characterized by many processes, only a few processes characterize the flow from demolition to firewood (wood), melting and casting for new profiles of same type (steel) or road fill (concrete). Therefore, also the drop in specific value per process is larger per process and represents a potential for upcycling, remanufacturing and recycling at a higher level than currently seen in the market.

Analysis of current linear value chains
The ownership structure in the traditional linear value chain is dominated by a direct ownership structure. This means that each link in the value chain purchases the materials and products from subsuppliers, adds value through processing and sells the material to the next link in the chain. Exceptions are surface treatment companies and other processes where a limited amount of material is added, but where the value of the material is increased dramatically, such as painting or galvanization.

This ownership structure also means that the business model for each step in the processing is very dependent on financial control, cash flow, order based production and other mechanisms to reduce risk and financial burden for each manufacturer involved.

One of the key challenges to overcome when moving from a linear to a circular economy is the design of ownership structures to match the circular economy business model — how to share the burden of premium costs for products suited for this, compared to the traditional products.

‘The circular economy focus on recycling without downcycling, makes investments in quality attractive’

— Annette Hastrup
CEO & Owner, Vugge til Vugge Danmark

Concrete
The use of precast concrete elements in the building industry is a good example of this. The current linear value forces the industry to optimize per step and not from a holistic approach. If precast concrete elements were designed with the option to be disassembled, the end user would be able to reuse, upcycle or regain a higher part of the value, compared to current dramatic loss in value when demolishing concrete buildings.

The key barrier for the market in order to realize this potential, is the financial risk involved where capitalization of the value of recycled precast concrete elements will happen maybe 50 years or more from the time of investment. Who can finance the cost for this added feature?

If a single manufacturer starts introducing this in the market, the specific costs up front will be higher. Due to the ownership structure, the costs will be need to be covered up front by the contractor or the client — but the value from improved possibilities will not be gained until demolition of the building, when the elements will be available on the market — maybe 50 years or more from now.

All stakeholders in the industry will perceive this as a huge risk — no one knows what the value of the improved elements will be, compared to the traditional elements and a price in the market will be speculative until the elements are actually available. Only clients with the specific demand to erect buildings designed for disassembly or legal requirements, e.g. in the building code, are realistic drivers in the current market.

A paradigm shift has started in some industries, such as the, fashion industry and the IT-industry, where software as a service is taking over from individual ownerships of hardware and software. Introduction of a similar model in the building industry would mean that the manufacturer of the concrete elements would keep the ownership of the precast concrete elements, and clients would gain only a right to use the elements when erecting a building — access over ownership. The manufacturer would then be able to gain a profit, when realizing a profit on the sales price (or new leasing period based new use of the element).

From the client's point of view, this could be attractive, since the costs up front would be lower. However, the absolute risk is not reduced but merely moved to the contractor, who will take the full risk on the value of the element and the uncertainty of the future market remains unchanged. The key parameter that makes the situation in the building industry different from other industries is lifetime — where the very long 'turnover' time for materials in the building industry, e.g. minimum 50 years for precast concrete elements, is very difficult to cover with traditional financial instruments.

Potential instruments, which could support and stimulate the transition to a circular economy based business structure for concrete, could be: increased focus on access over ownership, based on deposit systems or including design for disassembly in building codes. For concrete, in contrast to steel and timber, the circular economy structure will need to be more regional because of the relatively high cost for transporting

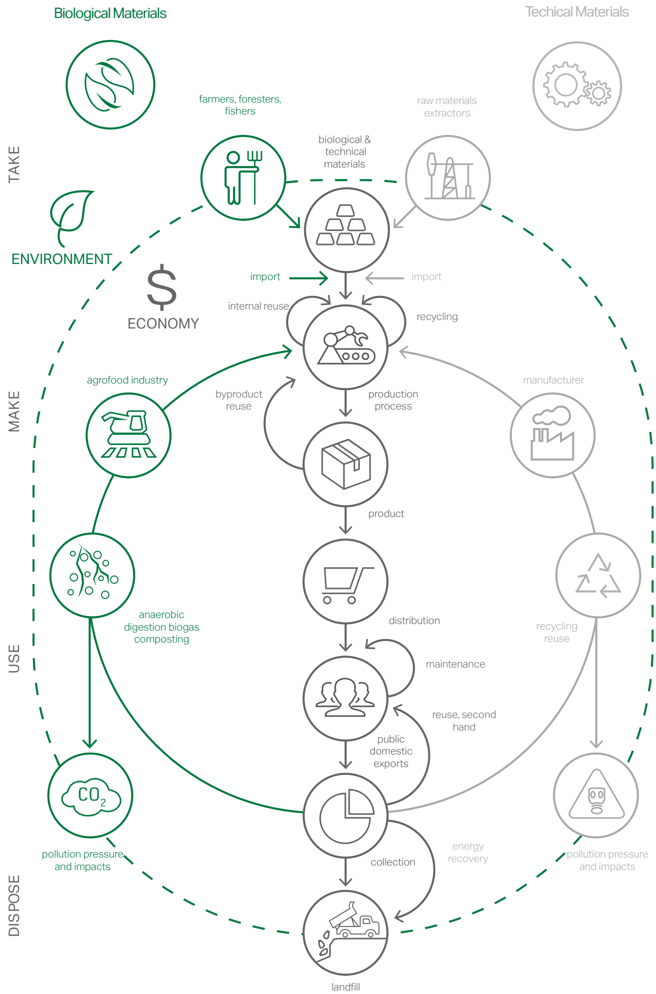

Diagram: Illustrates the principal linear value chain, where only very few circular flows can be identified for concrete, steel and timber.

This diagram is an reinterpretation of an original from the report 'Scoping Study to Identify Potential Circular Economy Actions' heavy precast concrete elements. This could potentially be easier to regulate, however this also increases the need for many circular economy based structures nationally to achieve a high concentration of 'circular economy'-based concrete products in the market.

Steel and timber

The situation is slightly different for steel and timber. These materials are widely used in all industrial industries, compared to concrete, which is more limited to the building industry. This means that the potential reuse of timber and steel is much higher than of concrete.

However, when volume and values are compared, there is a bigger potential in the reuse of concrete than of steel and timber from the construction industry.

Comparing steel to timber, steel is a more global commodity than timber. Steel qualities are internationally standardized and a global market for steel exists. The recycled content of structural steel produced using the EAF-process averages near 90%. For production of steel plates or rolled sheet steel, the recycled content is typically 25%.

Seen solely from a materials point of view, the recycled content of construction steel is positive, but in the processing of recycled steel a substantial amount of energy per ton, approx. 10 MJ / kg, is lost, although it is still better than virgin steel, which will hold 40 MJ / kg in embodied energy.[63]

The markets for timber and steel are much more volatile, with a high turnover in materials and the value of timber and steel can be directly linked to the many different qualities. When considering the circular value chains of timber and steel, many other industries may potentially be customers of timber from the building industry, besides the industry itself.

The challenge in the creation of new circular value chains is not the identification of technical potential, the availability of materials at any given quality or identification of the potential revenue, it is that the circular value chain has to be developed to a certain level for all of the materials considered.

As illustrated in other chapters in this book, numerous examples on the design for disassembly and the principal requirements for a materials passport can be developed.[64]

63 tufts.edu **64** Going on a metal diet

Stakeholder and partnerships
— the change of roles

In the introduction of this chapter, the ownership structure of the materials processed in the industry represents a major barrier to introduction of more circular value chains. A paradigm shift in the construction industry would be the widespread implementation of a ownership structure focusing on 'access over ownership'. Despite the fact that the house owners and investors in real estate have a major driver for their investment in the expected return of investment, the primary need is not to own a house — it is to have rooms to host the user.

Currently in Copenhagen, the rental market is growing much faster than housing for private ownership – and projects are converted from traditional build and sell to flats for rent. Many drivers in society and markets can explain this, but seen from the perspective of circular economy, this provides a unique potential for more holistic building design.

Here the overall financial rationale for the creation of buildings based on design for disassembly and materials, which do not lose their value when demolished, can be prioritized since the main income and return on investment is providing the facilities and all services associated with operating housing for rent. In the building sector, this could also turn into a game changer for the contractors, where the main business model potentially could move from erecting buildings to a much longer design, build and operate business model.

This would also catalyse a revision of the usual optimization strategies of the contractors, where the focus in achieving the lowest possible costs and building as fast as possible to reach the point of handover to the client. The new financial models would prioritize the total cost of ownership, including operations and the increased scrap value of buildings for demolition.

As with all disruptive changes in the markets, the first-movers will be the ones who benefit the most – which is contradictory to all historic experience in the building sector, with only very few radical innovations to date.

Pestel analysis
— perspectives for business models

The discussion of the circular economy chapter is organized in a so called 'PESTEL analysis', focusing on Political, Economic, Social, Technical, Environmental and Legal aspects of circular economy models for the built environment focusing on steel, timber and concrete. This structure addresses the externalities more than the internal issues of the markets and competitive situations of the current businesses.

This approach is chosen to reflect the fact that the evolving circular economy in the sector is driven as much by external factors to the building sector than a drive in the sector to differentiate or pursue new business opportunities by the dominant parties of the building sector worldwide.

Political
Drivers in favor of circular economy include European initiatives on recycling, product declarations and the large potential identified for whole EU if circular economy would be stimulated in a wider sense, such as described in the 2014 report 'Growth Within', by the Ellen MacArthur Foundation, McKinsey and Sun. Barriers include competition in Europe, where political measures to stimulate certain market mechanisms can be considered in disfavour of traditional industries.

Economic
From an EU perspective, the financial benefit for the EU to move towards a 'circular economy'-driven business sector is proven by being more attractive than continuing the current linear value chains. However, there is still a substantial lack of financial incentive for private businesses and households in Europe to shift into value chains based on circular economy.

Key issue is the structure of the current value chain as well as the structure of environmental taxation, fiscal structures and the perceived risk on investments which tend to be based on a shorter time frame than the technical lifetime and capitalization of the increased value of future buildings.

In order for the circular economy model to work, a new value chain has to be established containing companies that designs for disassembly, companies that disassemble building, storage facilities, a market for reused material. The establishing of such a system will most likely require political support such as a supportive legal system, a supportive tax system etc. However, this is not a new phenomenon. When the first coal fired power plants in Denmark were built, they were built with subsidies from the government. The same is the case for the installation of windmills.

Social
Several studies show the positive effect of job creation, stimulation of SME businesses (small and medium-sized enterprises), and growth potential in rural districts if a green and circular economy is stimulated in the EU. When considering the global competition, a risk might be that jobs are moved outside of the EU to lower cost regions, with industries continuing manufacturing traditional products in other areas. This aspect needs to be carefully considered for any industry or clusters of industries that have plans for changing to a circular economy model

Technical
Compared to the other aspects in the PESTEL analysis, the technical challenges are the smallest ones. The technical barriers identified are often not technical barriers as such — many design changes to create designs based on design for disassembly principles can be realized with known technology, but due to the structure of ownership described in this chapter, the related investment in new ways of designing buildings can be difficult to argue.

Environmental
The environmental drivers are potentially the strongest driver for circular economy. Scarcity of materials, global changes in power, the increased direct environmental destruction of biological habitats and global warming all call for changes in the direction of circular economy. However, a key challenge is still the lack of pricing of materials in general that reflect the real environmental costs and hence economic optimization of building design often leads to results that do not reflect and take the real costs into account.

Legal
There are few legal barriers to circular economy. Anybody can make the change and create businesses based on circular economy, but for many industries, the consequences of the legal framework can be a barrier. Examples are standards and tests based on only virgin materials and not on recycled or upcycled materials and components.

Reuse with respect
— treating old as new

When selling a reused product, it is very important that the product appear as new as possible for the customer. There are both a psychological- and a practical barrier to address. Even though the product is used, it still cost a lot of money for the customer. Therefore, they want to have the feeling they buy a product that is treated with respect and that has a value.

For example, when you buy a second hand shirt, you want it to be washed, without traces of the previous owner and to buy it from clean store with a good service.

Another example is the previously mentioned company 'Refurb' that sells remanufactures used products with a extended guarantee from a professional looking webpage that could just as well sell new products.

The Danish company 'Gamle Mursten' ('Old Bricks') is a good demonstration of a company in the building industry that has built their business on the principles for design for disassembly and circular economy. They purchase old bricks held together with lime mortar. The bricks are cleaned, repacked on pallets and just like new bricks wrapped in foil. This strategy gives the customers a product they feel have the same quality as a new one and the bricklayers doesn't charge extra for working with it.[65]

Furthermore, 'Gamle Mursten' hires socially disadvantaged people like mentally vulnerable and refugees, adding a layer of social sustainability to the company.[66]

Photo: The bricks are cleaned, repacked on pallets and just like new bricks wrapped in foil. This strategy gives the customers a product they feel have the same quality as a new one.

65 gamlemursten.dk **66** socialvirksomhed.dk


Kawasaki

Business case on case study

— Page 220 to 246

Calculated effects of a fully implemented circular economy model on the case study project.

The demolition
— calculating the cost

The demoltion experts at Kingo Karlsen has calculated an offer for the tearing down of the case study project 'De Fire Styrrelser'. They can do this quite exactly since the project material contains all they need to know about the building, e.g. material contents, structural layout, site location, etc.

Regulatory requirements
Like when constructing buildings, in order to tear buildings down, a municipal building authority has to grant a permit. After application, the authorities will investigate whether the buildings are worth preserving and whether there are other administrative matters that prohibits demolition.

When the demolition permission is granted, it will include a number of conditions that must be respected. These are typically geotechnical relations to the neighbouring buildings, environmental conditions and requirements for waste management as well an obligation to report the demolition site to the Working Environment Authority (WEA).

The client must also declare the volume of waste and ensure that the building is free of PCBs and carry out a mapping thereof. The demolition contractor must notify the environmental authorities of the work and account for how environmental issues will be handled in relation to the demolition and crushing on site.

Prior to the demolition, information about wiring and installations onsite must be obtained and, if necessary, restructuring of cables, wires, etc. must be carried out

The client must appoint a 'work coordinator' who carries out a 'risk assessment' and ensures the prevention of any dangerous work, which is done with a 'plan for safety and health'. During the execution, the workers must ensure that the responsible person continuously monitors the project and updates the plan. The demolition contractor must likewise prepare an workplace assessment for the chosen working methods.

Photo: The demolition experts from Kingo Karlsen inspecting what they can reuse from recently torn down building.

Photo © GXN

Calculation of a traditional demolition of 'De Fire Styrelser'

Traditional demolition	Amounts	Price dkk / unit	Reduction dkk / addition	Potential value dkk
Built area	40,000 m^2	—	—	397,88
Floor	40,000 m^2	—	—	397,88
Ton / m^2 (concrete)	1.1 tons	—	—	—
Concrete	42,000 tons	60	2,520,000	178,50
Dump	1,000 tons	1,250	1,250,000	31,25
Combustible	400 tons	700	280,000	7,00
Metals	900 tons	—	—	—
Excavator	3,000 hours	1,000	3,200,000	71,25
Hand man for excavator	3,000 hours	275	825,000	20,63
Building site	10 months	25,000	275,000	6,25
High reach excavator	3 months	450,000	1,350,000	33,75
Front loader	10 months	19,000	209,000	4,75
Crane	1 months	300,000	300,000	7,50
Tools, container etc.	1 sum	400,000	400,000	10,00
Supervision	10 months	30,000	300,000	7,50
Environmental, quality and safety documentation	1 sum	106,090	106,090	2,97
Building site office, operation	10 months	4,500	49,500	1,13
Combined costs			15,298,680	
Contribution margin			976,511	
Common cost Kingo Karlsen			764,934	
Total turnover			17,040,125	
Sales of metal			2,187,500	1,250
Sales of materials				
Offer			**15,915,215**	

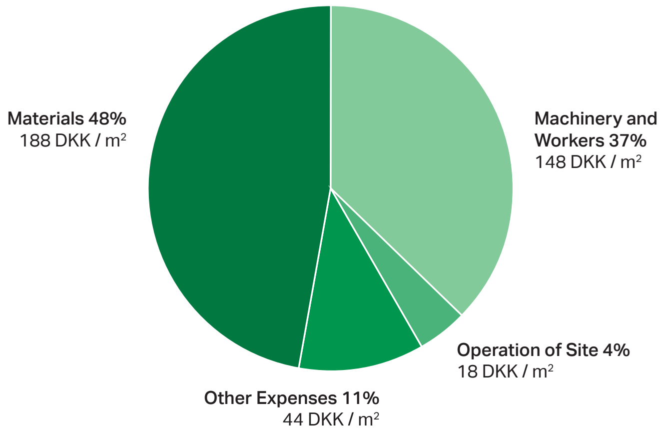

Diagram: Distribution of the demolition costs in percent.

Calculations
Two calculations are made:

- Demolition of the structure and crushing of materials as a substitute for natural resources at the same place.
- Demolition and removal of concrete for environmentally approved crushing area.

In both calculations, it is assumed that building materials are clean and free of hazardous substances, so that either the buildings have been decontaminated before demolition or decontamination is not necessary. The calculations include a prior clearance of the buildings of light carpentry, flooring, etc. It includes disposal to landfill and incineration.

The difference in demolition rates is primarily in that the crushing and recycling at the site liberates steel from the concrete reinforcement for recycling. Furthermore, transporting materials for environmentally approved crushing incurs significant transportation costs. Additionally, there will be a corresponding savings of transport of the raw materials for the subsequent construction, which is not shown by our calculations. There are different solutions demolition of concrete structures. The somewhat outdated method with a wrecking ball or a 'high reach machine' (see photo of the process on page 35) where concrete is cut with hydraulic scissors. The last method is typically used where there are special requirements for noise and dust nuisance. The prices for the two calculations are at the same level.

Analysis
— synopsis

The next logical step when speaking about how to increase the sustainability of such a project is to try to enhance this PPP (private public partnership) model even further by adding the element of a circular economy scheme it.

As shown in the practical example on the following pages, the introduction of a circular economy model could add economic value for superstructure parts alone in the amount of approximately DKK 35 million (€4.6 million) to the project at present price levels for construction, resources and landfill. The underlying assumption and the details of the estimate are provided below. The turnkey value alone of the project is approximately DKK 860 million (€114 million).

The extra value added by the introduction of a circular economy model only to the superstructure parts therefore corresponds to a little more than 4% of the total turnkey price of the building as such.

However, as we are only looking at the economic value of a circular economy model for the superstructure of the building, the added value should be compared only to the costs of the superstructure of the buildings and not to the cost of the entire building.

The additional economic value of a circular economy model for the interiors as well as for the electrical and mechanical systems should be compared to ‘new build’ value of these. It is outside the scope of this study to look into such models. It should be mentioned that systems are in place that allow the building industry to retrieve substantial value from the reuse of the resources used for the electrical and mechanical installations (e.g. copper, zinc and aluminium).

For the actual project, the turnkey value of the superstructure and the envelope is 46% of the total value of DKK 860 million (€115.2 million).

The extra value added by the introduction of a circular economy model only to the superstructure parts corresponds to about 8.5% of the 'new build' value of the superstructure and the envelope. As price levels for resources are expected to increase more than average price levels, the economic value of a circular economy model will increase over time. Estimates show the economic value will increase further and be doubled in 2065.

Macro level analysis shows that the potential of the introduction of a circular economy model in Denmark could be as much as 1.5 billion DKK (€201 million) per year when the model is fully introduced. Looking at all of EU, the year by year potential could be approximately DKK 100 billion (€13,4 billion).

The costs of being ready for a future circular economy model are 0.35% of the total costs of the project. The first step in estimating the economic value of the introduction of a circular economy model to the superstructure parts is to determine the value the retrieved elements have for reuse at the present price level for the structural parts that are to be retrieved.

Introducing a circular economy
These estimates are based on a number of assumptions. This section is therefore concluded by a sensitivity analysis of the assumptions made.

Additionally, the costs of resources and landfill are expected to increase more than average price levels. Consequently, this section also includes analyses of different developments in the relative price of resources and landfill compared to the increase in the average price level.

Calculating the cost
— concrete elements

Marked value of the concrete
The first parts considered are the concrete elements. The values of these are estimated in the table below. From this table it is seen that the 'net' value of the retrieved elements is approximately DKK 14.5 million (see table 01).

This estimate is based on the amounts of, as well as the current unit prices for, reinforced precast concrete 'slab elements', columns, beams, internal wall elements and SWT-Peikko Beams, as well as the percentages of each of the elements that are expected to be retrieved and the values the retrieved elements are expected to have at the time a circular economy business system is in place in Denmark.

In order to determine the 'market value' or the 'sales price' of the elements installed on a new project and compare the result to MT Højgaards turnkey price of approximately DKK 860 million for the entire building, overhead costs must be added.

The relevant overhead costs are cost for administration, site installations, site management, quality assurance, health and safety has to be added both at the subcontractor and main contractor level. Moreover, the fees for architects and engineers as well as the cost of clients own staff has to be added. Finally, all parties' allowances for risk have to be added. Based on experience, these costs correspond to an add-on of approximately 50% of the net price of the elements. When the costs are added, the 'sales price' or 'market value' of the elements installed on a new project is approximately DKK 21.6 million.

Demolishing savings
The next element that is taken into consideration is the amount of demolition that is saved because it will be substituted by the disassembling of the elements that are to be retrieved. The 'net value' has been determined based on the calculations on the costs of a traditional demolition of the project, made by Kingo Karlsen on page 230, as well as stating that on average 70% of

Value of concrete elements

TABLE 01

Elements	Amounts	Price dkk / unit	Retrieve pct.	Retrieve value pct.	Potential value dkk
Slab elements	44,823 m^2	450	60%	50%	6,051,105
Columns	751 tons	4,500	90%	50%	1,520,775
Beams	363 tons	3,000	90%	50%	490,050
Internal wall elements	12,702 m^2	900	80%	50%	4,572,720
Composite beams	2,391 pm	1,850	80%	50%	1,769,340
Subtotal (rounded net value)					14,400,000
Subtotal (rounded market value)					**21,600,000**

Source: Demolition unit prices from Kingo Karlsen

Demolition cost

TABLE 02

Demolition	Amounts	Price dkk / unit	Reduction / addition	Potential value dkk
Excavator	3,200 hours	1,000	70%	2,240,000
Workman	3,000 hours	275	70%	577,500
Demolition machinery	3 months	450,000	70%	945,000
Earth mover	11 months	19,000	70%	146,300
Savings on demolition (rounded net value)				3,900,000
Subtotal (rounded market value)				**5,900,000**

Source: Demolition unit prices from Kingo Karlsen the demolition does not need to take place when the circular economy model is used.

This percentage is set to cover the different ‘retrieve’ percentage for the different parts i.e. 60% for slab elements, 90% for columns etc. The ‘market value’ of this ‘saving’ due to the reduced amounts of building that has to be demolished traditionally has been determined by adding the same overhead costs as above. Based on these prerequisites, the ‘market value’ of these savings is about DKK 5.8 million (see table 02).

The disassembly
The third step is to estimate the costs of disassembling the parts that are to be retrieved. This amount has to be deducted from the savings, as these are additional costs compared to traditional demolition This is marked by the minus in front the costs figures. The ‘market value’ or ‘sales price’ of these dismantling costs is DKK 7.3 million (see table 03).

The logistics
The fourth element to estimate is the costs of transport, temporary storage and management of the elements before their second use.

Disassembly

TABLE 03

Elements	Amounts	Price dkk / unit	Retrieve pct.	Potential value dkk
Slab elements	44,823 m²	110	60%	-2,958,318
Columns	751 tons	250	90%	-168,975
Beams	363 tons	200	90%	-65,340
Internal wall elements	12,702 m²	75	80%	-762,120
Composite beams	2,391 pm	200	80%	-382,560
Add man hours	2,000 hrs	275	—	-550,000
Subtotal (rounded net value)				-4,900,000
Subtotal (rounded market value)				**7,300,000**

Source: Unit prices from ‘De Fire Styrelser’

Transportation and storage

TABLE 04

Elements)	Amounts	Price dkk / unit	Reduction / addition	Potential value dkk
Slab elements	44,823 m²	50	60%	-1,344,690
Columns	751 tons	150	90%	-101,385
Beams	363 tons	150	90%	-49,005
Internal wall elements	12,702 m²	60	80%	-609,696
Composite beams	2,391 m	150	80%	-286,920
Additional cost on disassembly	—	—	—	-2,400,00
Subtotal (market value)				**-3,600,000**

Source: Unit prices from 'De Fire Styrelser'

These costs are based on the assumption that the average time for transport from the place of dismantling to the storage is 60 minutes and that the average time for transport to the 'second site' is 60 minutes. This prerequisite seems reasonable, as a storage facility placed in or around either Taastrup or Roskilde could cover most of Copenhagen and Zealand, whereas a similar facility located in or around Horsens could cover the busiest areas of Jutland.

This is also an additional cost that reduces the retrieved value of the 'circular economy model' in use. Hence, the figures are marked with a minus (see table 04). The additional 'market value' or 'sales price' of the additional storage, transport and management of the elements is DKK 3.5 million.

The fifth element that needs to be estimated are the costs saved because the elements retrieved do not need to be ground to gravel (see table 05). The additional 'market value' or 'sales price' of the savings of not having to grind the concrete element to concrete gravel on site is approximately DKK 7.5 million.

Designing the building
The sixth and final element that needs to be estimated is the additional cost of designing a superstructure that actually can be disassembled. These costs do also reduce the economic value of the 'circular economy model' in use and is therefore marked by a minus (see table 06).

The additional 'market value' or 'sales price' of the additional design costs is approximately DKK 2.2 million. In total, the saving that can be obtained by the introduction of a 'circular economy model' on the concrete part of the superstructure is approximately DKK 21.8 million (see table 07).

Total value of concrete structure

TABLE 07

Elements	**Value in dkk**
Retrieve value (market value)	21,600,000
Saved demolition (market value)	5,900,000
Disassembly costs	7,300,000
Transportation and storage costs	3,600,000
70% savings on the dispensed grinding of concrete	7,500,000
Design and construction for disassembly costs	2,200,000
Sub total (market value)	**21,800,000**

Source: Unit prices from 'De Fire Styrelser'

Grinding of concrete

TABLE 05

Elements	Amounts	Price dkk / unit	Reduction / addition	Potential value dkk
Grinding og concrete to gravel	42,000 tons	170	70%	5,000,000
Additional savings (rounded net value)	—	—	—	5,000,000
Subtotal (rounded market value)				**7,500,000**

Source: Unit prices from 'De Fire Styrelser'

Design and production

TABLE 06

Design and production (Estimated unit prices)	Amounts	Price dkk / unit	Retrieve pct.	Retrieve value pct.	Potential value dkk
Slab elements	44,823 m^2	50	60%	50%	-672,34
Columns	751 tons	200	90%	50%	-67,590
Beams	363 tons	200	90%	50%	-32,670
Internal wall elements	12,702 m^2	100	80%	50%	-508,080
Composite beams	2,391 pm	200	80%	50%	-191,280
Subtotal					-1,800,000
Subtotal (market value)					**-2,200,000**

Source: Unit prices from 'De Fire Styrelser'

Calculating the cost
— steel and facades

The next part of the superstructure that contributes to the value of the introduction of a 'circular economy model' is the structural steel.

The structural steel
The structural steel is somewhat easier to estimate. The main figures are summarized in the table on the opposite page. The prerequisite for the estimate is that 80% of the structural steel can be retrieved and that the value of this will be 50% of the value of new steel.

The façades
Based on the experience of Kingo Karlsen and their discussions with MT Højgaard, it has been concluded that there isn't much to gain from the introduction of a 'circular economy model' on the façades.

This is because:

— The façades usually are worn out after 50 years, if not earlier, and that the resources, such as aluminium and glass, must be fully recycled before reuse.

— There already is a system in use that ensures that the façades are dismantled and broken down into the different factions i.e. glass, insulation, aluminium, steel and timber etc. and that, with the exception of the wooden parts, these are already now recycled the way these part needs to be handled.

— The value of the resources retrieved by these traditional processes has not been taken into consideration, as there is no additional gain from the introduction of a circular economy model.

Structural steel elements

TABLE 08

Elements	Amounts	Price dkk / unit	Retrieve pct.	Retrieve value pct.	Potential value dkk
Steel structure	900 tons	32,000	80%	50%	11,520,000
Disassembly	900 tons	1,200	80%	—	-864,000
Design for disassembly	900 tons	1,000	80%	—	-720,000
Transportation and storage	900 tons	150	80%	—	-108,000
Normal scrap value	900 tons	1,250	80%	—	-900,000
Total difference (rounded net value)					8,900,000
Subtotal (rounded market value)					**13,400,000**

Source: Unit prices from 'De Fire Styrelser'

Calculating the cost
— findings

The total economic value of the introduction of a 'circular economy model' for the superstructure of a building like 'De Fire Styrelser' is therefore approximately DKK 35 million. The main figures are listed in table 09.

The turnkey value alone of the project is approximately DKK 860 million. The extra value added by the introduction of a circular economy model only to the superstructure parts does therefore correspond to a little more than 4% of the total turnkey price of the project as such and to about 8.5% of the 'new build' value of the superstructure and the envelope alone as these parts account for 46% of the total value of DKK 860 million.

The investment a client needs to take on, if they want to make sure that she has the opportunity to take advantage of a future circular economy model in the construction industry, is the additional cost of designing the superstructure for disassembly.

These costs are the additional design costs for concrete elements of DKK 2.2 million that is listed in table 7, as well as the additional design costs for structural steel elements of DKK 0.7 million that is listed in table 8.

The additional investment that has to be made today in order to be able to take advantage of a future circular economy model in the construction industry is thus approximately DKK 3 million.

The costs of being ready for a future circular economy model are 0.35% of the total costs of the project.

Total value of the superstructure

TABLE 09

Total value of the superstructure	Value in dkk
Concrete elements	21,900,000
Structural steel elements	13,400,000
Total value of 'Building a Circular Future' on the superstructure	**35,200,000**

Source: Unit prices from 'De Fire Styrelser'

‘Circular economy is not about recycling of volume, but about recycling of value’

— John Sommer
Sales Director, MT Højgaard

Critical reflection
— sensitivity analysis and perspectives

Retrieval percentages
As there could be some uncertainty as to what retrieval percentages can be achieved, as well as the retrieved value of the retrieved elements, we have made a sensitivity analysis for both of the parameters.

As seen from the first sensitivity analysis (table 10), the estimated value of the introduction of a 'circular economy model' of approximately DKK 35 million will fall to about DKK 31 million if the retrieval percentage is reduced by 10%, whereas the retrieved value will fall to about DKK 25 million if the retrieval percentage is reduced by 25%.

In all three cases, the value of the introduction of the 'circular economy model' is significant and worth pursuing.

Retrieval value
A similar analysis is set out in the second sensitivity analysis (table 11), showing that the estimated value of the introduction of a 'circular economy model' of approximately DKK 35 million will fall to about DKK 27 million if the retrieved value is reduced by 10%, whereas the retrieved value will fall to about DKK 17 million if the retrieved value of the individual elements is reduced by 25% to 25%. However, this model also shows that the value will increase to about DKK 42 million if the retrieved value is increased by 10% compared to the example.

Based on this sensitivity analysis, it can be concluded that based on current prices, the retrieved value of the individual elements should be at about 40%. If the retrieved price is much lower than that, the incentive to introduce a circular economy model is probably too low.

At a micro level
As stated above, prices on landfill, concrete, and steel are expected to increase by a higher percent than the prices of average good and services, which increase by inflation.

First sensitivity analysis (retrieval percentage)

TABLE 10

Elements	**Calculated example**	**1. Analysis -10%**	**2. Analysis -25%**
Slab elements	60%	50%	35%
Columns	90%	80%	65%
Beams	90%	80%	65%
Internal wall elements	80%	70%	55%
Composite beams	80%	70%	55%
Structural steel	80%	70%	55%
Value of the circular economy model.	**35,000,000**	**31,700,000**	**25,500,000**

Source: Unit prices from 'De Fire Styrelser'

Second sensitivity analysis (retrieve value)

TABLE 11

Elements	**Calculated example**	**1.Analysis -10%**	**2.Analysis -25%**	**3.Analysis +10%**
Slab elements	50%	40%	25%	60%
Columns	50%	40%	25%	60%
Beams	50%	40%	25%	60%
Internal wall elements	50%	40%	25%	60%
Composite beams	50%	40%	25%	60%
Structural steel	50%	40%	25%	60%
Value of the circular economy model.	**35,200,000**	**31,700,000**	**25,500,000**	**25,500,000**

Source: Unit prices from 'De Fire Styrelser'

Rates of prices

TABLE 12

Elements	Low	Most likely	High	Weighted average	Inflation	Weighted average (net value)
Retrieve value in pct of new value	—	50%	—	50%	—	—
Material price (concrete)	1.5%	3%	7%	3.4%	2%	1.4%
Material price (steel)	2%	4%	10%	4.7%	2%	2.7%

Rates of prices in million dkk

TABLE 13

Elements	Net value	Sales value (2015)	Sales value (2030)	Sales value (2040)	Sales value (2050)	Sales value (2065)
Total difference (Concrete elements)	DKK 14,6	DKK 21,8	DKK 27,0	DKK 31,0	DKK 23,8	DKK 29,4
Total difference (steel)	DKK 8,9	DKK 13,4	DKK 13,2	DKK 17,2	DKK 22,2	DKK 33,3
Total market value (in million)		**DKK 35,2**	**DKK 40,2**	**DKK 48,3**	**DKK 46,2**	**DKK 62,7**

We have therefore made an analysis of the perspectives of such differences. This has been done first by estimation of a low value for the price increase year by year for concrete, steel and landfill. Then by estimating the most likely year by year increase as well as the highest likely year by year increase in prices for concrete, steel and landfill.

Based on these estimates, the weighted average has been calculated by using the formula:

$$\text{weighted average} = \frac{\text{low} + 4 * \text{most likely} + \text{high}}{6}$$

Finally, the average inflation for the coming years is set to be 2%, which corresponds with the 'inflation ceiling' set by the countries in the Eurozone. By deducting the expected inflation from the weighted average for price increases on concrete, steel and landfill, the net weighted average is determined. This net value for the weighted average can then be used to determine the development of the value of the implementation of a 'circular economy model' in the years to come. These values are shown in the table 12 and 13 on the left page.

From table 13, it is seen the present value of approximately 35 million will increase to about DKK 49 million already in 2030 and to more than DKK 50 million in 2050 — only 35 years from now. In 2065, when the building is 50 years old, the retrieved value will most likely have doubled to more than DKK 70 million.

At a macro level
In Denmark, the total market for new build in 2015 is expected to be approximately DKK 38 billion annually. If values corresponding to just 4% this DKK 38 billion could be retrieved by introducing a circular economy model for the superstructure alone, the potential is DKK 1.5 billion p.a. or €200 million p.a. using current price levels for resources.

The order and magnitude of this potential is the same as the one that Ellen MacArthur Foundation identifies for reuse and high value recycling of components and materials, enabled by, e.g. design for disassembly and new business models, in their publication 'Potential for Denmark as a Circular Economy' [67].

In this report Ellen MacArthur Foundation identifies a potential of 100 to 150 million annually if building materials such as wall and floor segments and bricks are reused and recycled without being degraded.

Most interesting is, however, that the Ellen MacArthur Foundation report mainly focuses on building components that forms part of finishing works such as flooring, walls etc. and only to a limited extend on parts of the superstructure. The only part of the superstructure taken into consideration in the Ellen MacArthur Foundation estimate is bricks.

Moreover, the Ellen MacArthur Foundation report also includes a higher degree of reuse of asphalt from the civil industry in their estimate.

67 Potential for Denmark as a Circular Economy, p. 14-23

The potential identified by the Ellen MacArthur Foundation can thus to some extend be added to the potential identified in this report for the reuse of the superstructure from buildings designed for disassembly.

According to the forecasts of the 79th EUROCONSTRUCT conference, the construction activities in the EU (new build, refurbishment and civil works) will amount to €1,360 billion in 2015. That corresponds to DKK 10,000 billion. Using the numbers from Denmark, where new builds correspond to about 25% of the entire market, the market value for new builds in EU corresponds to approximately DKK 2,500 billion.

Using these figures, the potential on the EU level is about DKK 100 billion annually or €13 billion annually. This rather substantial potential is, however, only a part of the total resource savings potential in the European construction industry identified in the McKinsey, Sun and Ellen MacArthur report 'Growth Within: A circular economy vision for a competitive Europe' [68] from June 2015. In this report, McKinsey, Sun and Ellen MacArthur identifies a total resource potential of €360 billion.

The reason for the substantial difference in these figures are that the potential estimated in this book only covers the potential of reusing the superstructures of buildings, whereas the potential in the report takes into consideration increased energy efficiency, distributed production and water recirculation over the life time of buildings.

Even though the potential identified in this report[68] is substantial, it should be regarded only as a part of the total resource saving potential in Europe in case a circular economic model is implemented throughout the European construction industry.

Based on these our findings and the findings of McKinsey, Sun and Ellen MacArthur it is safe to say that, there are huge economic incentives for implementation of a Circular Economic model in the construction and real estate industry in Europe.

Now the only question is — who will lead the way and set the standards — and reap the 'first-mover' opportunities?

68 Growth Within, p. 91

‘This book seeks to provide inspiration with solutions, innovations and ingenuity that leave one not only with hope, but also with anticipation of a circular future’

— Kasper Guldager Jensen
Architect, Senior Partner 3XN and Director GXN

Environmental Impact
— Case study

The environmental impact of Design for Disassemble, reuse of the superstructure elements, and Circular Economics Leonora Charlotte Malabi Eberhardt, has in collaboration with The Technical University of Denmark and the Danish Building Research Institute through a life cycle assessment (LCA) estimated the potential environmental benefits of designing the project 'De Fire Styrelser' for disassembly as part of her master's thesis project in 2016.

Why focus on building materials?
A recently published study by the Danish Building Research Institute shows that over the last 50 years Danish buildings are have become increasingly energy efficient and the energy demand for heating, ventilation and cooling in new buildings in Denmark have significantly reduced from approximately 350 kWh / m^2 pr. year to 40 kWh / m^2 pr. year.

Along with the expectation of the development of more sustainable energy production methods in the future the environmental impacts from energy consumption during operation of buildings will gradually decrease. This means that the embedded environmental impacts of our buildings and their building components and materials will have an increasing importance for buildings sustainability profile in the future.

Why focus on concrete?
As mentioned earlier in this book, concrete has a very long lifespan and is a very durable and flexible material that can take almost any imaginable form and is thus widely used in the construction industry.

In fact most buildings are made up predominantly of concrete as is also the case for 'De Fire Styrelser' which contains more than 80% concrete measured by weight, see Diagram 1. Concrete is the second most consumed substance next to water. To put it into perspective it corresponds to three tonnes of concrete being consumed by every person on the planet annually.

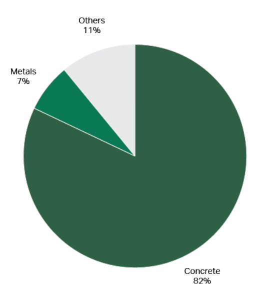

Diagram: Building material distribution

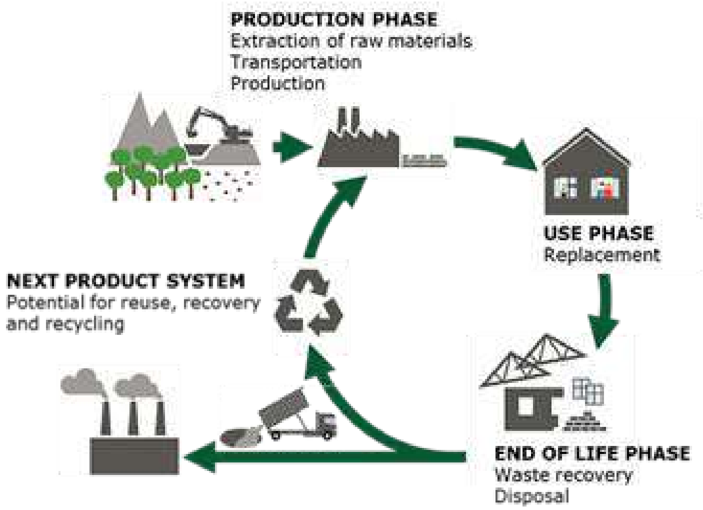

Diagram: Distribution of the demolition costs in percent.

Concrete poses a big challenge for the natural environment since production of the primary ingredient in concrete, cement, is responsible for 5-8% of the global CO_2-emissions. And instead of reusing concrete elements the elements are down-cycled and the construction industry thereby only manages to use a small percentage of the concretes durability potential.

Calculations
The calculations are performed in the open source software openLCA 1.4 using the Ecoinvent 3.2 database assuming a lifespan of 80 years for 'De Fire Styrelser'. For comparison purposes two calculations are made on the project'

— The environmental impact of the conventional case study project

— The environmental savings when the case study project is designed for disassembly and the components can be reused

Life cycle phases of the building
The life cycle phases evaluated in the LCA are shown in the figure above. As mentioned the environmental impacts related to buildings energy consumption is decreasing.

Therefore environmental impacts related to the buildings energy consumption during operation have been excluded from the study. Thus, this study only focuses on the embedded environmental impacts related to the building materials.

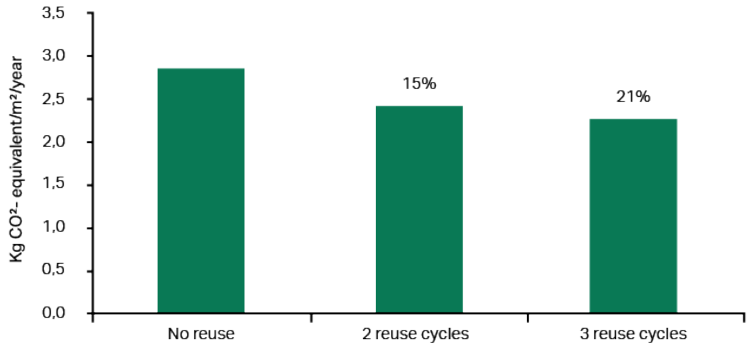

Diagram: Total CO_2 emissions of 'De Fire Styrelser' when the components are not reused, compared to when the components can be reused two or three times. Percentage CO_2 savings are stated above the bars.

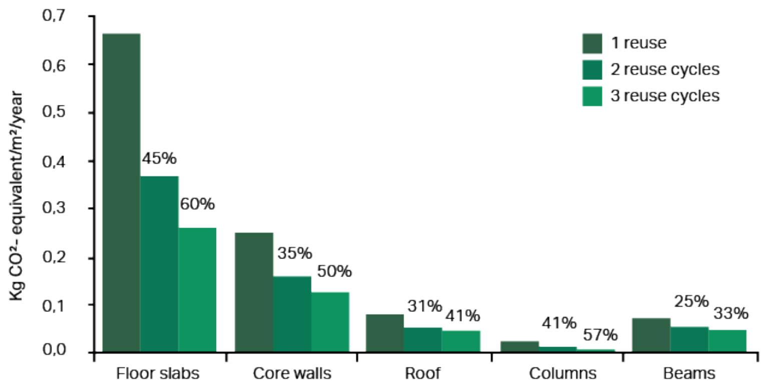

Diagram: Total CO_2 emissions of 'De Fire Styrelser' building components when the component are not reused, compared to when the components can be reused two or three times. Percentage CO_2 savings are stated above the bars.

Conventional building design
The environmental impact of the conventional building design are calculated based on the assumption that the building is constructed using traditional building design methods as well as disposing of the materials at the buildings end of life using traditional waste management (incineration, landfill or downcycling of the building materials).

Design for disassembly
The potential environmental impact savings when the building is designed for disassembly are calculated based on the same assumptions made for the business case. This means that:

— 90% of the concrete columns
— 90% of the composite beams
— 80% of the concrete beams
— 60% of the concrete roof slabs
— 90% of the concrete floor slabs
— 80% of the concrete core walls

are assumed to be suitable for reuse. Due to the long life span of concrete it is assumed that the components are suitable for at least three reuse cycles in three different buildings including 'De Fire Styrelser'.

Findings
From the diagram above, it is seen that a great deal of the building's embodied CO_2-emissions are related to many of the structurally important components with a long lifespan containing a lot of concrete such as the floor slabs and internal walls.

From the diagrams on the next page, it's seen that reuse of the components two times will save up to 45% of the superstructures total CO_2-emissions, whereas reusing the component three times will save up to 60%. A lot of the buildings embodied CO_2-emissions are related to some of the more structurally important components, and therefore also where the largest CO_2 savings can be obtained in relation to reuse of the components.

Conclusion
The case study has shown that there is potential for significant environmental impact savings when designing for disassembly. The longer the building materials and components can be kept in use (the more reuse cycles) the higher the savings. 'De Fire Styrelser' was not intentionally designed for disassembly from the onset.

Thus the environment and economic gains described in the case or hypothetical. Had the building from the onset been designed for dissemble and were the infrastructure in place — then these gains could have been accomplished.


KLAUS ALLER

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GXN innovation was established in 2007 as an internal division of Danish architectural practice 3XN Architects, and has since day one been working with applied architectural research in green materials and building technologies. The 'G' stands for Green, highlighting GXN's dedication to ecological design research through digital processes and innovative material solutions.

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MT Højgaard is a leading construction company in the Nordic countries. We collaborate with customers throughout Denmark and abroad. We solve all needs from the smallest construction and civil engineering projects to large and complex construction works, infrastructure projects and offshore wind turbine foundations.

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The VDC division is responsible for development, implementation and operation of MT Højgaard's use of BIM and VDC on the groups building and construction projects. The goal is to radically increase productivity by building virtually before constructing in real life, and to become and stay best in class. That is why VDC is in the center of the MT Højgård strategy framework.

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Kalk og Tegl is is the industry association for Danish manufaturers of bricks and tiles. One of the most important tasks of the association is to ensure the continuous knowledge and awareness of the Danish bricks and tiles products. The association enables and ensures cooperation with other parts of the Danish as well as international bricks and tiles clusters.

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Vugge til Vugge is Denmark's most experienced advisor in Cradle to Cradle© and circular economy. We help companies to create sustainable and profitable solutions that bring us all closer to a clean world without waste. Vugge til Vugge is a Cradle to Cradle Certified™ Assessment Body accredited by the Cradle to Cradle© Products Innovation Institute to help companies achieve certification of their products.

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The Aarhus School of Architecture is an independent institution under the Danish Ministry of Higher Education and Science. Our aim is to educate architects who can develop the physical environment of the future by engaging with society. We offer teaching at Bachelor, Master and PhD level within architecture and areas related to the architectural profession.

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At MT Højgaards sustainability department we focus on putting the individual at the center and develop, build and take responsibility for the spaces we live, work and move in as human beings. We focus on creating buildings that meets the user's needs but also have a positive impact on human health and well-being.

Richard Kristensen
Quality- and Environmental Manager, Kingo Karlsen

Kingo Karlsen provides all kinds of demolition services. With over 50 years of experience, we have solutions to small as well as large, complex cases. It is our goal that building materials is recycled. Our 'crush area' receives materials for recycling, e.g. asphalt paving and concrete and brick rubble, which are reprocessed for resale.

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Key principles

The 15 principles are developed as a result of the project and are seen as guidelines and strategies for working with reuse and circular economy in the building industry.

Design for Disassembly

See page 46

Materials
Choose materials with properties that ensure they can be reused.

Service Life
Design the building with the whole lifetime of the building in mind.

Standards
Design a simple building that fits into a 'larger context' system.

Connections
Choose reversible connections that can tolerate repeated assembly and disassembly.

Deconstruction
As well as creating a plan for construction, design the building for deconstruction.

Material Passport

See page 134

Document
To ensure q
materials an
during all ph

Identificat
Physical ide
individual el
for finding t

Maintenan
To secure th
materials, c
is crucial.

Safety
Provide safe
to handle al
building's lif

Interim
Provide the
information
materials in

Circular Economy

See page 190

tation
uality and value of the
d resources, documentation
hases is crucial.

ion
entification on the
ements are important
he correct information.

nce
he value of the
orrect maintenance

ety procedures
l phases of the
fe.

necessary
on how to handle
the interim state.

New Businesses
To complete circle in the circular economy, new businesses need to emerge.

Incentive
All partners in the supply chain will have to benefit economically.

New Models
Rather than creating products, businesses need to provide the user with a service.

Partnerships
Partnerships and collaboration agreements are necessity, thus nobody can run the circular economy alone.

Circulation
The value of the products in the technical and biological cycle as needs to be maintained as long as possible.

← Key principles

Building a Circular Future — 3rd Edition

This book presents all findings, case studies, background and context for the project 'Building a Circular Future', and consist of three main chapters: Design for Disassembly, Material Passport and Circular Economy. All content comes from extensive research or through workshops with partners across industries.

The book furthermore provides 15 principles for 'Building a Circular Future' and a thoroughly calculated business case, which documents that a demolition, which today would cost DKK 16 million, can be turned into a DKK 35 million business upside in a future circular building industry.

This third edition, published 2018, contains new state of the art examples of circular building projects, along with a case study calculating the positive environmental impact of a future circular building practice.

'This book underlines the cross-disciplinary nature of the circular economy, as well as the utmost importance of design. The authors make a strong case for an innovative and collaborative approach across the architecture and building industry'

— The Ellen MacArthur Foundation
Circular Economy Leaders

'It is wonderful to see Cradle to Cradle taken up vigorously by people interested in the circular economy. As an architect, I know our job in creating buildings is to put wisdom into practice, and to render these important concepts visible for all to see. This book is inspiring in its ambition to show us what this can look like now'

— William McDonough
Co-author of Cradle to Cradle