Zero-waste Industrial Building System
R.S. van Houten & N.A. de Lange
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Demolition jaws
Controlled demolition
Construction and demolition waste
- Heterogeneous mixture
- Uneconomical to separate
- Non-recyclable materials

Loss of resources
Construction and demolition waste amounts to:
- 125 million tonnes in the USA annually (390 kg per person) (Guy, 2001)
- 180-240 million tonnes in the EU annually (480 kg per person) (te Dorsthorst, & Kowalczyk, 2003)

Almost 1/3rd of all solid waste going to landfills comes from the building construction and demolition industries. (Crowther, 2002)
Introduction - Background

- Climate change and environmental issues are important in today's society
- Energy efficiency is increased (te Dorsthorst & Kowalczyk, 2003, p. 3).
  - Optimized for use phase - not optimized for end of life (Crowther, 2002, p. 6)
- Demolition waste materials are not reused but dumped on a landfill (Laefer & Marke, 2008, p. 7)
- Current way of unsustainable designing should not be accepted (Durmisevic & Brouwer, 2002, p. 84)
Introduction - Problem statement

- Large amounts of waste and debris are currently produced by the building industry worldwide
- Lack of reuse and recycling in the building industry
  - Resource depletion
  - Waste of energy
- Expected growth in population and prosperity
  - Land-filling or incineration will be unsustainable

Depletion of iron ore (Earth Policy Institute, 2005)

Depletion of bauxite (Roper, 2014)
Introduction - Goal of this study

The goal of this study is to assess a zero-waste approach on practical application on a design and its process.

- Defining demands and requirements for zero-waste building
- Assessing a zero-waste design process
- To create an exemplary zero-waste building design
Organisation

- Two authors for more depth and value of the study
- Same main focus, different research aspects:
  - N.A. de Lange - Focus on facade aspects
  - R.S. van Houten - Focus on structural aspects
How can a building be designed to generate no waste in all phases of its construction and demolition?

- What are the principles and functional requirements of a zero-waste building design?
- What is a possible design solution for an industrial building according to zero-waste principles and requirements?
- What are important factors in realising a zero-waste building design?
Methods

- Literature research
  - Relevant information in articles etc.
  - Reference projects, methods and systems
- Research by design: Iterative design process
  - Variants studies
  - Sketching, computer modelling
  - Extensive 3D computer model
  - Physical scale models
Content

- Introduction
  - Background
  - Problem statement
  - Goal of study
  - Organisation
  - Research question
  - Methods

Part I - Zero-waste in theory
- Definition and demands
  - Primary demands
  - Secondary demands
- Assessment methods

Part II - Zero-waste in practice
- A. Requirements
  - Design: outline and requirements
- B. Design process
  - Conceptual design
  - Facade design
  - Superstructure design
  - Foundation design
- C. Design review and analysis
  - Summary of the design
  - Assessment of the design

Part III - Conclusion and reflection
- Final conclusion
- Reflection

- Questions
- References
Part I

Literature and requirements of ‘zero-waste’

Zero-waste in theory
Definition of waste and zero-waste

- **Waste**
  - A heterogeneous mix of materials resulting from construction or demolition activities
  - No longer useful: landfilled
  - Virgin materials are more economical

- **Zero-waste**
  - No waste is produced
  - Concept requires clear definition for use and application
  - ...?
Definition of waste and zero-waste

Zero-waste process

- Closed cycle
- No waste

Common process

- Linear process
- Waste generation
Primary demands and secondary demands

- 0 kg of waste is produced during all (de-)construction phases of the building
- Every material should remain in its respective material cycle
- Reuse of materials should be made possible in such a way that invested/embodied energy is maintained as much as possible, or can be easily increased

Diagram of the Delft Ladder as explained by van Dijk, te Dorsthorst & Kowalzyk (2000)
Primary demands and secondary demands

- In addition to primary demands:
  - Materials
  - Connections
  - Components
  - Assembly and disassembly

- Efficient disassembly at the end of life

- Increasing likelihood of zero-waste
### Zero-waste assessment method

Complete assessment using hierarchic structure

- Existing methods are inadequate
- Based on relevant aspects and existing certification methods:
  - LEEDv4, BREEAM, Living Building Challenge, Cradle to Cradle
- Split in the levels material, component, assembly and the complete building

<table>
<thead>
<tr>
<th>Material 1</th>
<th>Material 2</th>
<th>Material 3</th>
<th>Material 4</th>
<th>Material 5</th>
<th>Material 6</th>
<th>Material 7</th>
<th>Material ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recyclability</td>
<td>Recyclability</td>
<td>Recyclability</td>
<td>Recyclability</td>
<td>Recyclability</td>
<td>Recyclability</td>
<td>Recyclability</td>
<td>Recyclability</td>
</tr>
</tbody>
</table>

**Assembly 1**
- Demountability
- Components:
  - Material 1: Recyclability
  - Material 2: Recyclability

**Component 1**
- Separability of materials
- Reusability
- Materials:
  - Material 1: Recyclability
  - Material 2: Recyclability

**Assembly 2**
- Demountability
- Components:
  - Material 3: Recyclability
  - Material 4: Recyclability

**Component 2**
- Separability of materials
- Reusability
- Materials:
  - Material 3: Recyclability
  - Material 4: Recyclability

**Assembly 3**
- Demountability
- Components:
  - Material 5: Recyclability
  - Material 6: Recyclability

**Component 3**
- Separability of materials
- Reusability
- Materials:
  - Material 5: Recyclability
  - Material 6: Recyclability

**Assembly ...**
- Demountability
- Components:
  - Material 7: Recyclability
  - Material ...: Recyclability
- Assessment sheet per level - based on zero-waste requirements
- Assessments used for final conclusion about zero-waste
- Example: component assessment form

<table>
<thead>
<tr>
<th>Component assessment form</th>
<th>1: Descriptions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of component:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Times used:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight of component:</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Producer:</td>
<td></td>
<td></td>
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<tr>
<td>Percentage of component from recycled source:</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Intended method of recycling of component:</td>
<td></td>
<td></td>
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<tr>
<td>Intended component use post use in assembly:</td>
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<td></td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th></th>
<th>2: Evaluation objectives</th>
<th>Notes</th>
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<tbody>
<tr>
<td></td>
<td>Evaluation</td>
<td></td>
</tr>
<tr>
<td>All component materials used in component are assessed positively (give percentage)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Component materials can easily be separated into its materials</td>
<td></td>
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<tr>
<td>Component can easily be reused in its current shape and form after use in the building</td>
<td></td>
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<tr>
<td>Component uses a minimum amount of materials</td>
<td></td>
<td></td>
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<tr>
<td>Component is identifiable and validatable after use in the building</td>
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<td></td>
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<tr>
<td>Component recycling respects and maintains embodied energy according to the Delft ladder</td>
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<tr>
<td>Component does not result in landfilling (0kg)</td>
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<tr>
<td>Component finishing is easily separable from base material (if used)</td>
<td></td>
<td></td>
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<tr>
<td>Inseparable parts of the component are made from te same material</td>
<td></td>
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<tr>
<td>Chemical bonds between materials are weaker than the materials bonded (if used)</td>
<td></td>
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<tr>
<td>Materials use non destructive bonds to form component</td>
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</tbody>
</table>

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<thead>
<tr>
<th></th>
<th>3: Conclusion</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall, is the component regarded suitable for zero waste purposes?</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Part II - a

Design according to ‘zero-waste’

Zero-waste in practice
• Design goals
  ▫ Optimised for zero-waste
  ▫ Exemplary building design for zero-waste
  ▫ Explorative research into zero-waste design process

• Building type
  ▫ Short life time: most relevant
  ▫ Industrial building

• Research by design
• Theoretical design

Survival probabilities of German building stock (Kohler, Holger, Kreissig, & Lützkendorf, 2010)
• Generic industrial building ~4000m² floor space
  ▫ Assembly hall for demountable zero-waste building methods
• Harnaschpoort between Delft and the Hague
Part II - b

Design according to ‘zero-waste’

Zero-waste in practice
Overall design
Simple geometric shape
Minimal number and types of connections and components by using a box shape for the building

Facade design

Superstructure design

Foundation design

Design: concept

Introduction
Zero-waste in theory
Zero-waste in practice
Facade design
Superstructure design
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Design review and analysis
Conclusion
Reflection
Questions
Design: concept

Building shape
- Complex versus simple
- Geometrical shapes
  - Type and number of elements and connections
  - Programmatic requirements
  - Boundary conditions (plot size)

Chosen option for this situation: Simple box
Facade design
Facade design

**Minimal types of materials**
For the whole facade system only 3 materials are used.

**Flexibility**
Without adding additional components, the integrated utility rail allow for non permanent alterations to the element without damage.

**Minimal types of internal connections**
The simple construction of the element, optimised for zero-waste requires only one type of connection to (de)construct the element into/from its materials.

**Unitised system**
By making the system modular and unitised, removal and replacement is simplified.

**Minimal types of external connections**
The modular and unitised system simplifies removal and replacement. Only one type of efficient connection type is required between facade elements.

**Integrated system connections**
Connections to other parts of the building, such as to the foundation, are integrated in the shape of the element. In this way no additional components or installation steps are required.
Minimal types of materials

For the whole facade system only 3 materials are used.

- Galvanised steel
- Cork
- Glass

Based on extensive material analysis
Facade design - Materials

Material analysis

- Based on zero-waste demands
- Per category; insulation, sealants, waterproofing, cladding and finishing
- 22 of the 52 analysed materials (42%) are suitable for zero-waste (before application)
  - Examples: Plastic, glass
Facade design - Materials

Material analysis

- Sealants proved to be troublesome
- Rubber-like materials are unsuitable:
  - Harmful materials: polycyclic aromatic hydrocarbons
  - Not fully recyclable
- Cork can be an alternative option - meets zero-waste demands

<table>
<thead>
<tr>
<th>Name of material</th>
<th>Material is not listed on the cradle to cradle list of banned materials</th>
<th>Material is not listed on the living building red list</th>
<th>Material is recyclable and verifiable after use in the component</th>
<th>Material can be 100% recycled or biodegraded without waste generation</th>
<th>Material recycling is not harmful to environment or humans</th>
<th>Material recycling respects and maintains embodied energy according to Delft ladder</th>
<th>Overall, is the material regarded suitable for zero waste purposes?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubbers (EPDM)</td>
<td>-</td>
<td>0</td>
<td>N/A</td>
<td>-</td>
<td>N/A</td>
<td>No</td>
<td>Remarks: Not recyclable, harmful materials</td>
</tr>
<tr>
<td>Sillicone based</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>No</td>
<td>Remarks: Not recyclable</td>
</tr>
<tr>
<td>Cork</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>Yes</td>
<td>Remarks: Materials might be suitable, application may not</td>
</tr>
<tr>
<td>'Old' options</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>Yes</td>
<td>Remarks: Could be used when material properties are taken into account</td>
</tr>
</tbody>
</table>

Comparison of sealing materials regarding zero-waste.
Cork analysis

- Cork is currently used as insulation and facade cladding (externally without additional protection)
Cork analysis

- May provide options for sealants - Currently used as gaskets and as wine bottle sealants
- Properties are comparable to other rubber like materials
Cork analysis

- Production and capabilities are different - natural material
- First harvest after 25 years
- Then every 9 years
- Trees live up to 300 years
Facade design - Materials

Cork analysis

- Direct from bark - Limited size
- Granulated
  - Glued - may inhibit zero-waste aspects
  - Expanded in autoclave - no glue required
Cork analysis

- Cork may be used as sealant if applied correctly
  - Correct quality
  - Grain size
  - Pressure
Facade design - System

Unitised system
By making the system modular and unitised, removal and replacement is simplified

- Sandwich elements
- Integration of all required components
- Minimal effort for installation and removal

Based on comparison of building/facade systems
Zero-waste in theory

Facade design

Superstructure design

Reflection

Foundation design

Design review and analysis

Conclusion

Zero-waste in practice

Questions

Introduction

Brickwork
General building/facade system assessment

- Overall assessment of systems - generalised on basic aspects
- Some directly unsuitable:
  - (Prefabricated) concrete
  - Masonry
  - Autoclaved aerated concrete brickwork
Facade design - System analysis

General building/facade system assessment

- Others looked at in more detail:
  - Structural liner trays
  - Sandwich panels
  - Curtain walls
  - Structural glazing
  - Wood skeleton
**Facade design - System analysis**

General building/facade system assessment

- All systems in general not zero-waste: sealants
- Some have inherent advantages towards zero-waste:
  - Sandwich panels
  - Structural glazing
  - Curtain walls
- Sandwich system is chosen to be further developed/improved towards zero-waste:
  - All functions integrated in elements
  - Simple installation
  - Mechanical strength

<table>
<thead>
<tr>
<th>1: Structural liner trays</th>
<th>2: Sandwich panels</th>
<th>3: Curtain walls</th>
<th>4: Structural glazing</th>
<th>5: Wood framing</th>
</tr>
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1. Ease of (de-)construction
2. Number of different connections
3. Number of connections
4. Number of different components
5. Number of components
6. Usage of suitable materials
Facade design - System design

- Analysis of element shape and size

1. Small square elements

2. Large square elements

3. Horizontal rectangle elements

4. Vertical rectangle elements
- Vertical, as large as possible is the most suitable for this situation
- Combination of large square and vertical rectangular options
- Transportation limitations
- Element size of 3,0m x 9,0m
Facade design - System design

- Analysis of roof types and shapes

1. Single sloped roof
2. Roof with two slopes
3. Roof with multiple slopes
4. ‘Bathtub’
5. ‘Umbrella’ roof
- Two sloped roof is chosen
- Symmetry allows for fewer element types
- No internal rainpipes
- Modularisation: large elements - 3,0m x 9,0m
- Integration of all required components
  - Integrated method for attachments
Facade design - Design of the element

Minimal types of internal connections
The simple construction of the element, optimised for zero-waste requires only one type of connection to (de)construct the element into/from its materials.

- Few different materials
- Only bolts need to be loosened

Design of the element
Design is split into:

- Outer layer
- Inside layer
- Connection between layers
Facade design - Design of the element

Outer layer: Material

- Previously assessed: all metals as suitable
- Most of the analysed coatings are unsuitable, except galvanisation
- Galvanised steel is the most economical for its strength per weight, and therefore chosen
Facade design - Design of the element

Outer layer: Shape

- Various shapes are considered and their properties related to zero-waste analysed

1. Flat  
2. Corrugated (rolled)  
3. Combined (flat + corrugated)  
4. Shaped (deep drawn)  
5. U-shaped (rolled)
Outer layer: Shape

- Technically all are possible
- Options only slightly vary in zero-waste properties
- Most optimal: flat with small reinforcement by shape (integrated rail)
Facade design - Design of the element

Inner layer: Material

- Needs to function in a sandwich element
- Material analysis: only relevant suitable zero-waste materials are expanded cork and cellular glass.
- Cork is deemed more suitable:
  - Less brittle
  - Less size limitations

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<tbody>
<tr>
<td>Cellular glass</td>
<td>++</td>
<td>++</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cork</td>
<td>++</td>
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</tbody>
</table>
Connection between layers

- Glue can not be used: demountability
- Combination of options to reduce number of required bolts

Shear studs
Prevents lateral movement

Shaped element layers
Prevents horizontal movement

Bolt
Prevents separation
Facade design - Design of the element

Connection between layers

- Combination between shear-studs, shaped element and bolts
  - Shear studs prevent lateral motion
  - Shape of the element prevents horizontal motion
  - Bolts prevent separation
- Minimal number of bolts are needed because of other measures
Facade design - Design of the element

Detailing of the shear studs

- Allows for a pattern
- Simple separation
Facade design - Utility rail

Flexibility

Without adding additional components, the integrated utility rail allow for non permanent alterations to the element without damage.

- Point of attachment
- Minimal effort for installation and removal
Utility rail allows for flexible and non-permanent attachments to the facade.
Facade design - Openings and connections

Minimal types of external connections
The modular and unitised system simplifies removal and replacement. Only one type of efficient connection type is required between facade elements.

- Only bolts need to be loosened
- Openings in elements are integrated
Integrated openings in elements.

Concept:
- Use of cork: no need for additional framing
- Only bolts used for connections
- Appropriate detailing for materials
Facade design - Openings and connections

- Integration of all required components
- Other attachments using utility rail

Window elements
Door element
Truck access door elements (Two elements)
Facade design - Openings and connections

Integrated connections in elements

Concept after analysis:

- Use of cork as a sealant, embedded in edge
- Only bolts used for connections - simple (dis)assembly
- Appropriate detailing for materials
Facade design - Openings and connections

Integrated connections in elements

- Adjustments with special element
- Separate cork block
Integrated connections in elements.

Roof extra attention
- Continuous seal by overlap
- Only bolts used for connections
- Overlap influences (de)construction order
Integrated connections in elements.

Roof extra attention
- Continuous seal by overlap
- Only bolts used for connections
- Overlap influences (de)construction order
Integrated connections in elements.

Roof extra attention
- Continuous seal by overlap
- Only bolts used for connections
- Overlap influences
  (de)construction order
Facade design - Openings and connections

Integrated connections in elements.

Edge connections integrated in roof elements

- No additional connections
- Designed for wind-loads
Facade design - Openings and connections

Integrated connections in elements.

Edge connections integrated in roof elements
- No additional connections
- Designed for wind-loads
Facade design - Openings and connections

Integrated connections in elements.

Edge connections integrated in roof elements

- No additional connections
- Designed for wind-loads
Integrated connections in elements.

Edge connections integrated in roof elements
- No additional connections
- Designed for wind-loads
Integrated system connections

Connections to other parts of the building, such as the foundation, are integrated as much as possible. This way additional components or installation/removal steps are kept limited.

- Shape fit (foundation)
- Utility rail connection (structure)
Foundation connection

- Shape fit
- No fasteners
- In combination with foundation elements
Foundation connection

- Shape fit
- No fasteners
- In combination with foundation elements
Facade design - System connections

Structure connection

- Feet
- Use of utility rail
- Minimal additional elements for function
Facade design - System connections

Structure connection

- Adjustable feet
- Use of utility rail
- Minimal additional elements for function
Facade design

Overall optimised for zero-waste

Minimal types of materials
For the whole facade system only 3 materials are used.

Flexibility
Without adding additional components, the integrated utility rail allow for non permanent alterations to the element without damage.

Unitised system
By making the system modular and unitised, removal and replacement is simplified.

Integrated system connections
Connections to other parts of the building, such as to the foundation, are integrated in the shape of the element. In this way no additional components or installation steps are required.

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The simple construction of the element, optimised for zero-waste requires only one type of connection to (de)construct the element into/from its materials.

Minimal types of external connections
The modular and unitised system simplifies removal and replacement. Only one type of efficient connection type is required between facade elements.

Introduction
Zero-waste in theory
Zero-waste in practice
Facade design
Superstructure design
Foundation design
Design review and analysis
Conclusion
Reflection
Questions
Superstructure design
Superstructure design

- **Smart material usage**
  Timber is used as the main structural material because it can be engineered for fire safety and does not require additional coatings or encasement.

- **Large prefabricated elements**
  The components are made as large as possible in the factory to reduce elements and connections on the building site.

- **Demountable connections**
  The prefabricated elements are connected on the building site using the same method as the connections in the element itself. The connections are made using steel nodes and bolts.

- **Stable portal structure**
  The structure is designed to be stable during (dis)assembly to improve the attractiveness of the disassembly at the end of life.

- **Truss design**
  The superstructure is made out of trusses to increase the strength of the structure and to make efficient connections possible.

- **Introduction**
  - Zero-waste in theory
  - Zero-waste in practice
  - Facade design
  - Superstructure design
  - Foundation design
  - Design review and analysis
  - Conclusion
  - Reflection
  - Questions
Smart material usage
Timber is used as the main structural material because it can be engineered for fire safety and does not require additional coatings or encasement.

- Renewable
- Fire safety
Superstructure design - Materials

- Analysis of common structural materials
- Zero-waste requirements
  - Recyclable or renewable
  - Reusable
  - Demountable connections
- Technical requirements
  - Structurally safe
  - Safe in fire
- Suitable materials for zero-waste and technical requirements:
  - Metals
  - Timber

<table>
<thead>
<tr>
<th></th>
<th>Masonry</th>
<th>Concrete</th>
<th>Steel</th>
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<tbody>
<tr>
<td>1. Structural safe</td>
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<tr>
<td>2. Safe in fire</td>
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<tr>
<td>3. Recyclable or renewable</td>
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<tr>
<td>4. Reusable</td>
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<td>-</td>
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<tr>
<td>5. Demountable connections</td>
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<table>
<thead>
<tr>
<th>Plastics</th>
<th>Aluminium</th>
<th>Timber</th>
<th>Glass</th>
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Superstructure design - Materials

Fire safety
- Conventional methods
  - Spray
  - Coating
  - Encapsulation
- Timber
  - Charring rate

Timber is chosen over metals
Superstructure design - Materials

- Mass timber
- Engineering for fire safety
  - Not influenced by temperature
  - Predictable charring rate
  - Time safe in fire

<table>
<thead>
<tr>
<th>Minimum nominal solid sawn size</th>
<th>Minimum glued-laminated net size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width [mm]</td>
<td>Depth [mm]</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>150</td>
<td>250</td>
</tr>
<tr>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Timber</th>
<th>Characteristic</th>
<th>$\beta_0$</th>
<th>$\beta_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood and beech</td>
<td>Glulam, density $\geq 290$ kg/m$^3$</td>
<td>0.65</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Solid timber, density $\geq 290$ kg/m$^3$</td>
<td>0.65</td>
<td>0.8</td>
</tr>
<tr>
<td>Hardwood</td>
<td>Solid or glulam, density $\geq 290$ kg/m$^3$</td>
<td>0.65</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Solid or glulam, density $\geq 450$ kg/m$^3$</td>
<td>0.5</td>
<td>0.55</td>
</tr>
<tr>
<td>Laminated veneer lumber</td>
<td>LVL, density $\geq 480$ kg/m$^3$</td>
<td>0.65</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Load bearing wood
Char layer
Large prefabricated elements
The components are made as large as possible in the factory to reduce elements and connections on the building site.

- Minimal components
- Minimal connections
- Efficient disassembly
Superstructure design - System

- Structural systems
  - Slab
  - Cellular
  - Skeletal
  - Frame
Superstructure design - System

- Functional requirements
  - Open floor plan
  - Expansion and downsizing
- Zero-waste requirements
  - Amount of components and connections
  - Efficient to disassemble
  - Open building system

<table>
<thead>
<tr>
<th>Construction method</th>
<th>Function</th>
<th>Zero waste demands</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open floor plan</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Expansion and downsizing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low amount of components</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low amount of connections</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Easy to disassemble</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Usable as an open building system</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Able to be prefabricated</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overall, is the method regarded suitable?</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Remarks</td>
<td>Can be used to combine with facade functions</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not suitable for a large building</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible in function and performs well in zero waste</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Requires many elements and connections</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

- Slab structure
- Cellular structure
- Skeletal structure
- Frame structure
Building method

- Skeletal structure optimised for:
  - Zero-waste
  - Stability
  - Open floor plan
- Large elements
- Trusses

1. Stable during (dis)assembly
2. Large footprint columns
3. Efficient to disassemble
4. Amount of elements
5. Amount of connections
6. Open floor plan
7. Future proof demands
Superstructure design - Trusses

Truss design

Trusses are used in the superstructure to increase the strength of the structure and to make efficient connections possible.

- Sawn timber
- Pinned connections
- Efficient disassembly
- Truss types
- Zero-waste requirements
  - Repetition
  - Amount of connections and components
- Technical requirements
  - Stresses
  - Deformation
Superstructure design - Trusses

Roof bearing truss
- Roof connections
- Transportation size
  ▫ Divided into two parts
- Dimensioning
  ▫ Buckling due to weight
  ▫ Buckling due to wind force
Stable portal structure
The structure is designed to be stable during (dis)assembly to improve the attractiveness of the disassembly at the end of life.

- No additional bracing
- Efficient disassembly
- Stability of structure
Superstructure design - Stability

- Rigid connection to roof elements
  - Steel socket
  - Welded node
- Horizontal force in trusses
Superstructure design - Stability

Space-truss

- Transportation and lifting
  - Divided into three parts
  - Modified Warren-truss
  - No temporary bracing
Superstructure design - Stability

- Stability for entire building
- Individual stable portals
- Stable individual elements
- No additional bracing
Superstructure design - Stability

Column

- Directs forces to foundation
- Placement inwards on foundation slab
  - Cantilever
- Transportation
- Dimensioning
  - Vertical loads - no tension
  - Wind loads small
Demountable connections
The prefabricated elements are connected together on the building site using the same method as the connections in the element itself. The connections are made using steel nodes and bolts.

- Steel nodes
- Bolt connections
- Efficient disassembly
Superstructure - Connections

Internal connections

- Connects timber members
  - Reusable after use
  - Reprocessable
- Steel nodes
  - Welded steel plates
  - Pre-drilled holes
  - Slots in timber
- Bolt connections
Superstructure - Connections

Connections between elements

- Single system
- Bolt connection
  - Pinned

Truss to space-truss
- Shear forces
Space-truss sections

- Shear forces
Superstructure - Connections

Space-truss to column
- Connection of space-truss
- Wind loads
Foundation design
**Foundation design**

- **Integration facade**
  Specially designed edge elements make a shape connection with the facade elements and divert horizontal and vertical forces to the foundation slab.

- **Lightweight floor with integrated gutters**
  The floor elements provide insulation and have gutters which can be used for wiring/ducting/piping.

- **Integration superstructure**
  The foundation slab has an integrated solution to connect to the columns. The columns are placed to reduce stress in the foundation slab, which is also locally thickened to increase load bearing capacity.

- **Demountable aluminium foam elements**
  The foundation is made out of separate elements made out of lightweight aluminium foam. Due to the design of connections the elements form a rigid sandwich slab.

- **Floating foundation**
  The foundation slab is lighter than the soil. The weight of the excavated soil is equalled to weight of the building. This results in a net load of zero on the soil.
Floating foundation

The foundation slab is lighter than the soil. The weight of the excavated soil is equalled to weight of the building. This results in a net load of zero on the soil.
Foundation design - Methods

Analysis of methods
- Location

- Shallow foundations
  - Spread footings
  - Mat foundation

- Piling
  - Suitable for weak soils
  - Support on bedrock

- Floating foundation
  - Slab
  - Based on removed soil
Foundation design - Methods

- Shallow foundations
  - Unsuitable for weak soils
  - Suitable for zero-waste

- Piling
  - Suitable for weak soils
  - Not suitable for zero-waste

- Floating foundation
  - Suitable for weak soils
  - Suitable for zero-waste
Foundation design - Methods

- Floating foundation
  - Lighter than soil
  - Weight of removed soil equal to building
  - Distribute forces as evenly as possible
Foundation design - Methods

- Rigid slab
  - Spread loads over larger area
  - Demountable elements
- Compressive forces
- Bending forces; tensile forces
- Spreading of point loads
  - Columns
**Foundation design - Slab design**

Demountable aluminium foam elements
The foundation is made out of separate elements made out of lightweight aluminium foam. Due to the design of connections the elements form a rigid sandwich slab

- Demountable elements
- Sandwich structure
- Rigid slab
Pouring concrete
Foundation design - Slab design

- Recyclable materials
  - Foamed glass
  - Foamed aluminium
- Lightweight
- Compressive strength
Foundation design - Slab design

- Foamed glass design
  - Restricted size
  - Pre-stressed beams
  - Beams assembled into slab on site
Foundation design - Slab design

- Foamed aluminium design
  - Large elements
  - Overlapping
  - Bolt connections
### Foundation design - Slab design

**Foamed glass**
- Brittle
- Many connections
- Many elements

**Aluminium foam**
- Ductile
- Sandwich structure
- Large elements
- Minimum connections
- Minimum elements

<table>
<thead>
<tr>
<th>Feature</th>
<th>Foamed glass</th>
<th>Foamed aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Structural integrity</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>2. Structural rigidity</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>3. Efficiency to disassemble</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>4. Amount of connections</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5. Amount of elements</td>
<td>-</td>
<td>++</td>
</tr>
</tbody>
</table>
Foundation design - Slab design

- Foamed aluminium sandwich
  - Horizontal shear forces
  - Tensile forces
- Compression
- Bending

Overlap

Sandwich connection

Aluminium sheet
Bolt connection
Shear studs
Cork sealant strip
Foundation design - Slab design

Top element

Bolt with cork sealant

Aluminium sheet

Negative stud shape

Gutter for sealant

Cork sealant strip
### Sandwich connection

- Tensile forces
  - Bending
  - Increases strength
- Hook connection
- Folded aluminium sheet
Integration superstructure
The foundation slab has an integrated solution to connect to the columns. The columns are placed to reduce stress in the foundation slab, which is also locally thickened to increase load bearing capacity.

- Spreading of loads
- Demountable
- Adjustable
Foundation design - Integration superstructure

- Columns
  - High point loads
- Reduce stress in slab
  - Increase footprint
  - Increase load bearing capacity
  - Increase thickness slab
Foundation design - Integration superstructure

Columns placed inward

Column footprint topside

Column footprint underside

Thickening of slab
Foundation design - Integration superstructure

Connection with column

Secondary plate with welded threaded ends

Top steel plate

Bolt connection of column footprint

Bolt connection aluminium elements

Bottom steel plate
Foundation design - Integration superstructure

Column

Connection node with welded plate

Bolt connection

Secondary plate with welded threaded ends

Steel plate

Cork sheet
Connection to facade
Specially designed edge elements make a shape connection with the facade elements and divert horizontal and vertical forces to the foundation slab.

- Vertical loads
- Horizontal loads
- Demountable
Foundation design - Integration facade

- Facade element
- Bolt
- Integrated aluminium strip
- Hook connection
- Cork sealant strip
- Shaped aluminium foam
Lightweight floor with integrated gutters

The floor elements provide insulation and have gutters which can be used for wiring/ducting/piping.

- Insulation
- Integration with utilities
- Demountable
Foundation design - Floor element

- Disperse point loads
- Lightweight
- Insulation

Steel tread plate with welded steel grate

Holes for lifting hooks

Gap for separation steel from cork

Gutter for wiring/piping/ducting

Cork layer
Foundation design - Floor element

Steel is pressed into cork in autoclave
Friction and shape based connection
• Zero-waste materials
• Fully demountable
• Efficient in disassembly
Part II - Design result and assessment
Design result

Zero-waste in theory

Facade design

Superstructure design

Foundation design

Design review and analysis

Conclusion

Reflection

Questions
Design result
1 Starting situation
(Dis)assembly order

2. Excavation of foundation footprint
(Dis)assembly order

3. Placement of bottom part of column connection
Placement of first layer of aluminium foam for column support
5. Placement of second layer of aluminium foam under column
6. Placement of bottom layer of foundation slab
7 Placement of top layer of foundation slab and foundation edge
(Dis)assembly order

8. Placement of top part of column connection
(Dis)assembly order

Placement of floor components
(Dis)assembly order

10 Placement of column components
(Dis)assembly order

Placement of end components of space-truss assembly
12 Placement of mid section component of space-truss assembly
Placement of truss assemblies between space-trusses
(Dis)assembly order

14 Placement of roof components
(Dis)assembly order

Placement of wall components
Completion of building by additions to facade elements (doors, sun shading, installations)
Design assessment

- Assessment design
  - Based on established zero-waste requirements
  - Using the assessment method as developed

- Total building
  - Facade assemblies
  - Foundation assemblies
  - Superstructure assemblies

---

<table>
<thead>
<tr>
<th>Total building assessment sheet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1: Descriptions</strong></td>
</tr>
<tr>
<td>Intended method of building construction:</td>
</tr>
<tr>
<td>Intended method of building deconstruction:</td>
</tr>
<tr>
<td>Intended tools needed for (dis-)assembly of building:</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>2: Evaluation objectives</strong></th>
<th><strong>Evaluation</strong></th>
<th><strong>Notes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>All building assemblies are assessed as positive (give percentage)</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building is made using a minimal amount of different connections</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building assemblies are not inseparable and avoids inseparable components</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Chemical bonds are non-destructive</td>
<td>...</td>
<td>N/A</td>
</tr>
<tr>
<td>Chemical bonds are weaker than the assemblies, components or materials bonded</td>
<td>...</td>
<td>N/A</td>
</tr>
<tr>
<td>Inseparable components are made from the same material</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building construction requires no specialised tools</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building can be demounted into its assemblies in a non-destructive manner</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building uses a modular and open building system</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building provides access to all assemblies</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building uses a hierarchic structure related to the lifespan of its assemblies where also the most reusable assemblies are the most accessible</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>Building is flexible and provides means for expanding or reducing its size and function</td>
<td>...</td>
<td>+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>3: Conclusion</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall, is the total building regarded suitable for zero waste purposes?</td>
</tr>
</tbody>
</table>

---

- Introduction
- Zero-waste in theory
- Zero-waste in practice
- Facade design
- Superstructure design
- Foundation design
- Design review and analysis
- Conclusion
- Reflection
- Questions
## Design assessment - Roof component

### Component assessment form - Roof elements

<table>
<thead>
<tr>
<th>1: Descriptions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of component:</td>
<td>Roof elements</td>
</tr>
<tr>
<td>Function:</td>
<td>Inside/outside separation</td>
</tr>
<tr>
<td>Times used:</td>
<td>165</td>
</tr>
<tr>
<td>Total weight of component:</td>
<td>~1140 kg</td>
</tr>
<tr>
<td>Percentage of component from recycled source:</td>
<td>Varies per material</td>
</tr>
<tr>
<td>Intended method of recycling of component:</td>
<td>Direct reuse</td>
</tr>
<tr>
<td>Intended component use post use in assembly:</td>
<td>Material reuse</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2: Evaluation objectives</th>
<th>Evaluation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>All materials used in component are assessed positively (give percentage)</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>100% - All materials assessed positive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component materials can easily be separated into its materials</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No permanent fixtures are used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component can easily be reused in its current shape and form after use in the building</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Elements do not get damaged during removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component uses a minimum amount of materials</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Only two different materials are used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component is identifiable and validatable after use in the building</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Direct reuse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component recycling respects and maintains embodied energy according to the Delft ladder</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>All materials are highly reused materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component does not result in landfilling (0kg)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Galvanisation is separated during recycling without negative impact on the process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component finishing is easily separable from base material (if used)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No chemical bonds are used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inseparable parts of the component are made from the same material</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Only bolts and connections by shape are used</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical bonds between materials are weaker than the materials bonded (if used)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Materials use non-destructive bonds to form component</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3: Conclusion

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall, is the component regarded suitable for zero waste purposes?</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

---

**Introduction** | **Zero-waste in theory** | **Zero-waste in practice** | **Facade design** | **Superstructure design** | **Foundation design** | **Design review and analysis** | **Conclusion** | **Reflection** | **Questions**
### Component assessment form - Foundation elements

<table>
<thead>
<tr>
<th>1: Descriptions</th>
<th></th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of component:</td>
<td>Foundation elements</td>
<td>Including:</td>
</tr>
<tr>
<td>Function:</td>
<td>365</td>
<td>- Top elements male/female</td>
</tr>
<tr>
<td>Times used:</td>
<td>~6500 kg</td>
<td>- Bottom elements male/female</td>
</tr>
<tr>
<td>Total weight of component:</td>
<td>See materials</td>
<td>Varies per material</td>
</tr>
<tr>
<td>Percentage of component from recycled source:</td>
<td>Disassembly and reuse material</td>
<td></td>
</tr>
<tr>
<td>Intended method of recycling of component:</td>
<td>Direct reuse, disassembly and reuse material</td>
<td></td>
</tr>
<tr>
<td>Intended component use post use in assembly:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2: Evaluation objectives</th>
<th>Evaluation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>All materials used in component are assessed positively (give percentage)</td>
<td>... ... +</td>
<td>100% - All materials assessed positive</td>
</tr>
<tr>
<td>Component materials can easily be separated into its materials</td>
<td>... ... +</td>
<td>Single material</td>
</tr>
<tr>
<td>Component can easily be reused in its current shape and form after use in the building</td>
<td>... ... +</td>
<td>Reusable as foundation</td>
</tr>
<tr>
<td>Component uses a minimum amount of materials</td>
<td>... ... +</td>
<td>Cork &amp; aluminium</td>
</tr>
<tr>
<td>Component is identifiable and validatable after use in the building</td>
<td>... ... +</td>
<td>Easily visible</td>
</tr>
<tr>
<td>Component recycling respects and maintains embodied energy according to the Delft ladder</td>
<td>... ... +</td>
<td>Direct reuse</td>
</tr>
<tr>
<td>Component does not result in landfilling (kg)</td>
<td>... ... +</td>
<td>All materials can be recycled</td>
</tr>
<tr>
<td>Component finishing is easily separable from base material (if used)</td>
<td>... ... +</td>
<td>No finishing used</td>
</tr>
<tr>
<td>Inseparable parts of the component are made from te same materia</td>
<td>... ... +</td>
<td></td>
</tr>
<tr>
<td>Chemical bonds between materials are weaker than the materials bonded (if used)</td>
<td>... ... +</td>
<td>Only one material used</td>
</tr>
<tr>
<td>Materials use non destructive bonds to form component</td>
<td>... ... +</td>
<td>Only connections with bolts are used</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3: Conclusion</th>
<th>Yes</th>
<th>No</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall, is the component regarded suitable for zero waste purposes?</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Design assessment - Foundation component

In this section, the assessment of the Foundation component is presented, focusing on its design, materials, and potential for zero-waste practices. The table outlines the component's characteristics, including its name, function, and intended use, along with evaluation objectives related to material separation, reusability, and embodied energy. The conclusion section highlights whether the component is deemed suitable for zero-waste purposes.
Conclusion & reflection
What are the principles and functional requirements of a zero-waste building design?
- No waste
- Recyclable/renewable materials
- Reuse

What is a possible design solution for an industrial building according to zero-waste principles and requirements?
- The produced design

What are important factors in realising a zero-waste building design?
- Use of materials
- Well considered design of connections
- Appropriate systems
Conclusion - Facade

- Sealant
- Cork is essential

- Connecting different functions

- Reducing elements and connections
Conclusion - Superstructure

- Metals and timber
- Fire safety
  - Encasement
  - Engineering fire safety with timber
- Conventional designs can be sufficient
- Optimisation by pinned connections
- Reducing elements and connections on site
### Conclusion - Foundation

- **System choice**
  - Depends on soil strength
  - Floating foundation

- **Material choice**
  - Concrete can not be used
  - Aluminium foam

- **Design of connections**
  - Form a rigid slab
  - Theoretical

- **Elements**
  - Always made from elements instead of poured
Reflection - Overall

Zero-waste principles and requirements
- Resource depletion
- Technological advancement may help reach zero-waste
- Necessity and awareness: the design may help show the problem
- Requires infrastructure
- Extraction of materials is ignored

Zero-waste design
- Valuable insights
- Many more aspects can be considered for zero-waste
- Zero-waste methods strictly followed
- Unproven and untested
Reflection - Facade

- Untested methods
- Relies heavily on cork
- Necessity of replacement of sealants
- Hierarchical approach
Reflection - Superstructure

- Focus on fire safety
  - May not be required
  - Steel may be required in other designs
- Design is also possible with smaller elements
- Connections are most important
- Timber lifetime and species
Reflection - Foundation

- Theoretical and innovative design
- More research into piling foundations for zero-waste
- Relies on aluminium foam
  - Expensive
  - Untested
  - Other materials
Zero-waste building ‘end’ product
Thank you for your attention
Floor plan and sections
Foundation plan view

Zero-Waste Industrial building Graduation Project

Design part: Structural
Detail number: 00
Location/name: Plan & Sections
Author: R.S. van Houten
Scale: 1:300
Functional floor plan

Zero-Waste Industrial building Graduation Project

Design part: Functional
Detail number: 00
Location/name: Plan
Author: R.S. van Houten & N.A. de Lange
Scale: 1:300
Enlarged sections

Zero-Waste Industrial building Graduation Project

<table>
<thead>
<tr>
<th>Design part</th>
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<tr>
<td>Detail number</td>
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<td>R.S. van Houten</td>
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</tbody>
</table>
Overview of facade elements - roof elements

Zero-Waste Industrial building Graduation Project

Design part: Facade
Detail number: 02
Location/name: Overview of roof façade elements
Author: N. A. de Lange
Scale: 1:100
Truss overview
Space-truss overview
Foundation element top (female)
Foundation edge element (male, long)
Foundation edge element (female, long)
Foundation edge element (male, short)
Foundation edge element (female, short)
Floor element middle

Floor elements overview
Steel-cork-steel sandwich element (roof corner element)
- 1.5mm galvanised steel
- 250mm expanded cork
- 1.5mm galvanised steel

Utility rail (embedded in element, folded from outer layer of element)

Height adjustable feet attached to utility rail and socket (galvanised steel)

Internal element connection, spaced 1000mm
- M10 Bolt with lifting eye
- Galvanised steel washer
- Cork washer (high quality)
- Steel-cork-steel sandwich element
- Cork washer (high quality)
- Galvanised steel washer
- M10 Nut (recessed in utility rail)

Facade element to facade element connection, spaced 1000mm
- Welded on M10 Bolt
- [Two overlapping element edges with 4mm steel reinforcement strip]
- Cork washer (high quality)
- Galvanised steel washer
- M10 Nut or toggle-latch

Steel-cork-steel sandwich element (wall element)
- 1.5mm galvanised steel
- 250mm expanded cork
- 1.5mm galvanised steel

Utility rail (embedded in element, folded from outer layers of element)

Cork protrusion (exposed through triangular holes, preventing water accumulation between sandwich layers)

Socket for adjustable feet (pre) attached to structural frame (galvanised steel)

Main structural frame (see structure design for more detail)
Steel-cork-steel sandwich element (door element):
- 1.5mm galvanized steel
- 250mm expanded cork with cut out door framing
- 1.5mm galvanized steel

Drainpipe connected to utility rail:
- Diameter 100mm
- Zinc, standard product
- Spaced at 600mm

Sliding door:
- 1.5mm galvanized steel
- 150mm expanded cork
- 1.5mm galvanized steel

Aluminium foam foundation edge element (special element for door opening, see structure design for more details)

Floor elements:
- Galvanized steel
- Cork
(see structure design for more details)

Aluminium foam foundation edge element (special element for door opening, see structure design for more details)

Aluminium foam foundation edge element (see structure design for more details)
Steel-cork-steel sandwich element (wall element)
- 1.5mm galvanised steel
- 250mm expanded cork
- 1.5mm galvanised steel

Internal element connection, spaced 1000mm
- M10 Bolt (recessed in utility rail)
- Galvanised steel washer
- Cork washer (high quality)
- Steel-cork-steel sandwich element
- Cork washer (high quality)
- Galvanised steel washer
- M10 Nut (recessed in utility rail)

Utility rail (embedded in element, folded from external layer of element)

Cork protrusion
Folded through triangular holes, preventing water accumulation between sandwich layers

Shear studs
Folded from partial cut-outs in the galvanised steel, spaced at ~200mm (external side), or (internal side) galvanised steel welded to outer layer, spaced at 500mm

Floor elements
- Galvanised steel
- Cork

Aluminium foam foundation edge element
Special element for door opening, see structure design for more details

Aluminium foam foundation element
See structure design for more details
Window frame detailing

- Constructed dual layered glass
- High quality cork washers
- Overlaps to prevent water ingress
- Only bolts used for connections
Wall connection detailing (horizontal)

- Zigzag shape connection
- Only bolts used for connections
Adjustable wall connection detailing (horizontal)

- Separate adjustable cork block in edge of element
- Only bolts used for connections
Internal element connection, spaced 1000mm
- M10 Bolt with lifting eye
- Galvanised steel washer
- Cork washer (high quality)
- Steel-cork-steel sandwich element
- Cork washer (high quality)
- Galvanised steel washer
- M10 Nut (recessed in utility rail)

Facade element to façade element connection, spaced 1000mm
- Welded on M10 Bolt
- [Two overlapping element edges with 4mm steel reinforcement strip]
- Cork washer (high quality)
- Galvanised steel washer
- M10 Nut or toggle-latch

Steel-cork-steel sandwich element (roof element)
- 1.5mm galvanised steel
- 250mm expanded cork
- 1.5mm galvanised steel

Shear studs, spaced 500mm (galvanised steel, welded to outer layer)

Height adjustable feet attached to utility rail and socket (galvanised steel)

Socket for adjustable feet (pre) attached to structural frame (galvanised steel)

Main structural frame (see structure design for more detail)

Utility rail (embedded in element, folded from internal layer of element)

Steel-cork-steel sandwich element (roof element)
- 1.5mm galvanised steel
- 250mm expanded cork
- 1.5mm galvanised steel

Shear studs, spaced 500mm (galvanised steel, welded to outer layer)

Main structural frame (see structure design for more detail)

Socket for adjustable feet (pre) attached to structural frame (galvanised steel)

Height adjustable feet attached to utility rail and socket (galvanised steel)
Roof connection detailing

- Zigzag shape connection
- Only bolts used for connections
**Space-truss to truss connection node**
- 10mm galvanised steel
- Welded internal connections
- Pre-drilled holes Ø20mm

**Truss connection node**
- 10mm galvanised steel
- Welded internal connections
- Pre-drilled holes Ø20mm

**Timber element to node connection**
- M20 steel bolt (galvanised)
- Steel washer (galvanised)

**C24 timber class 300x340mm vertical chord**
- Pre-drilled holes Ø50mm
- Pre-sawn node space 11m

**C24 timber class 130x130mm horizontal strut**
- Pre-drilled holes Ø50mm
- Pre-sawn node space 11m

**C24 timber class 130x130mm diagonal strut**
- Pre-drilled holes Ø50mm
- Pre-sawn node space 11m

**C24 timber class 240x240mm diagonal chord**
- Pre-drilled holes Ø50mm
- Pre-sawn node space 11m

**Socket for adjustable feet (galvanised steel)**
- M10 steel bolt (galvanised)
- Pre-drilled slotted hole in timber element

**Height adjustable feet attached to utility rail and socket (galvanised steel)**

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**Zero-Waste Industrial building Graduation Project**

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<td>Location/name</td>
<td>Space-truss to truss connection</td>
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<td>Author</td>
<td>R.S. van Houten</td>
</tr>
<tr>
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</table>
Space-truss to column connection detail
- 10mm galvanised steel
- Welded internal connections
- Pre-drilled holes Ø20mm

C24 timber class 300x300mm connection piece column-truss
- pre-drilled holes Ø50mm
- pre-sawn node space 11m

Column connection node
- 10mm galvanised steel
- Welded internal connections
- pre-drilled holes Ø20mm

Timber element to node connection
- M20 steel bolt (galvanised)
- Steel washer (galvanised)

C24 timber class 300x300mm vertical chord
- pre-drilled holes Ø50mm
- pre-sawn node space 11m

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Zero-Waste Industrial building Graduation Project
Design part: Structural
Detail number: S4
Location/name: Column to space-truss connection
Author: R.S. van Houten
Scale: 1:10
Column to foundation connection detail

Design part: Structural
Detail number: 3.3
Location/name: Column to foundation connection
Author: R.S. van Houten
Scale: 1:10

Steel connection node (10mm, galvanised)
- 30mm steel plate (welded, galvanised)
- Steel washer (galvanised)
- M42 steel nut (galvanised)

Timber element to node connection
- M20 steel bolt (galvanised)
- Steel washer (galvanised)

Steel-cork floor element

Adjustable column connection
- Aluminium washer
  - Two M42 aluminium nuts
  - M42 aluminium stud bolt (wedged)
- 19mm aluminium plate

50mm aluminium plate
10 mm cork sheet

Connection with foundation slab
- M27 aluminium bolt
- Aluminium washer
- Cork washer (high quality)

Connection column with foundation
- M27 aluminium bolt
-isting cork washer

Integrated threaded aluminium insert
- External Ø 47 mm
- Internal Ø 27 mm

Additional foundation element
- Closed cell aluminium foam

50mm Aluminium plate

C24 timber class 300x300 mm
- pre-drilled holes 950mm
- pre-seen node space 11m
Foundation edge detail

- Foundation edge detail (male edge)
  - Closed collar aluminum (male)
  - Integrated aluminum sheet (0.7mm)

Connection with foundation slab
- M27 aluminum bolt
- Aluminum washer
- Steel washer (high quality 10.9)

Foundation element top (female)
- Integrated aluminum sheet (10mm)
- Closed collar aluminum (female)

Concrete plug (flat quality, 12x12mm)

Foundation element bottom (male, and female)
- Closed collar aluminum (female)
- Intgrated aluminum sheet (0.7mm)

Integrated threaded aluminum insert
- External 18.5mm
- Internal 17.5mm

Additional foundation element
- Closed collar aluminum (male)