A multifunctional Living Wall System
Not just aesthetic, it can filter water!

P5 Graduation, November 11th, 2016

Main Mentor
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Second Mentor
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Maaike Kok  4092724
Motivatie
Greener, healthier cities

Rietveld, Delft (2015)

Rietveld, Delft (2016)

(van der Ven, 2015)
Relevance
Benefits of Green

- Social and psychological benefits\(^1\)
- Reduction of the Heat Island Effect\(^2\)
- Stormwater retention\(^3\)
- Air quality improvements\(^3\)
- Aesthetic value
- Acclimatization (cooling in summer, insulation in winter)\(^4\)

\(^1\) (Chilla, 2004), \(^2\) (Sheweka & Mohamed, 2012), \(^3\) (Peck & Callaghan, 1999), \(^4\) (Perini & Rosasco, 2013)
Lack of Green

Office

UNESCO-IHE - Delft

Hotel

WestCord Hotel - Delft
(District8.net, 2012)

Nursing home

Nursing home NEBO - The Hague
(Boele & van Eesteren, 2016)
Green Solutions

Groene daken

Groene gevels

Living wall systems
Focus on Living Wall Systems

- Living Wall Systems are more effective than Green Facades
- Facade area is larger than roof area
- Vertical green systems can be seen from street level
Problem Statement
Lack of implementation LWS

- **High installation costs**
  - Westfield - London (United Kingdom) (AECOM, 2013)

- **High maintenance costs**
  - Westfield Century City - Los Angeles (USA) (Habitat Horticulture, 2016)

- **Aesthetics only**
  - The Nanjing South Railway Station - Nanjing (China) (Tournesol Siteworks LLC, 2014)
Problem Statement
Unused Potential of Multi-functionality

Urban Farming
Brooklyn Grange - New York (USA) (Rooflife, 2015)

Electricity Generation
Plant-e (Innozaam, 2016)

Water Filtering
Printenbreide - near Lubeck (Germany) (Creative Commons, 2010)
Focus on Constructed Wetlands

**Urban Farming**
- Brooklyn Grange - New York (USA) (Rooflife, 2015)

**Electricity Generation**
- Plant-e (Innozaam, 2016)

**Constructed Wetland**
- Printenbreide - near Lubeck (Germany) (Creative Commons, 2010)
Research aim & question

How to design a Living Wall System that is able to separate, filter and reuse both suitable and valuable wastewater streams exiting a utility building?
Design Location
WestCord Hotel Delft

Southwest facade

© Knevel Architecten BV, 2016
Design Location

Water Demand & Availability

Water demand
20,239 L/day Drinking water

100%

Water availability

Blackwater (4,613 L/day)
Greywater with food particles (3,319 L/day)
Greywater without food particles (12,101 L/day)
Stormwater roof run-off (3,853 L/day)

24%
16%
60%
Design Location
Water flows addressed

3,614 L/day

12,101 L/day
How to create a good filter mechanism?
Total Purification System

<table>
<thead>
<tr>
<th>PRIMARY TREATMENT</th>
<th>SECONDARY TREATMENT</th>
<th>TERTIARY TREATMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretreatment</td>
<td>Biological treatment</td>
<td>Post-treatment (Optional)</td>
</tr>
</tbody>
</table>

- **Pretreatment**
  - Sludge collection pit & grease trap
  - Pump sump

- **Secondary Treatment**
  - Vertical flow constructed wetland

- **Tertiary Treatment**
  - Clean water tank
  - Pond

- Removal of settleable solids & floating substances
- Removal of colloidal & suspended solids (e.g. nitrogen & phosphate)
- Further removal of suspended solids & eventual removal of biomass formed during treatment (e.g. Nitrogen and phosphate)
How to create a good filter mechanism?
Total Purification System

- **3,614 L/day**
- Leaf & Coarse particle filtration
- **12,101 L/day**
- Degreaser
- Constructed Wetland
- Storage

Direct use
Post-treatment
How to create a good filter mechanism?

System Types

- **Vertical subsurface flow constructed wetland (VSSF)**
- **Horizontal subsurface flow constructed wetland (HSSF)**

Horizontal subsurface flow constructed wetland (HSSF)  
Vertical subsurface flow constructed wetland (VSSF)
How to create a good filter mechanism?

HSSF
How to create a good filter mechanism?

VSSF
How to create a good filter mechanism?

HSSF vs. VSSF
How to create a good filter mechanism?

Key Factors

➡️ **High efficiency**

- Long hydraulic retention time  
  (e.g. shallow slope, small grain size, low flow velocity, recirculation)

- Creating an ideal environment for microorganisms  
  (e.g. large area for attachment, both anoxic and oxic conditions)

➡️ **High capacity**

- (e.g. large substrate volume, steep slope, large grain size)

➡️ **Prevention of clogging, organic- and hydraulic overload**
How to create a good filter mechanism?

Design challenge - Shape

90 Degrees

Horizontal

Angled
How to create a good filter mechanism?

Constructed WetRoof
Design
Angle, Possible Configurations
Design
Angle, Possible Configurations
# How to create a good filter mechanism?

## Choice of Substrate

<table>
<thead>
<tr>
<th>Natural materials</th>
<th>Synthetic materials</th>
<th>Industrial by-products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apatite (igneous)</td>
<td>Activated carbon</td>
<td>Blast or steel furnace slag</td>
</tr>
<tr>
<td>Apatite (sedimentary)</td>
<td>Calcite</td>
<td>Burnt oil shale</td>
</tr>
<tr>
<td>Bauxite</td>
<td>Cat litter (burnt diatomaceous earth)</td>
<td>Charcoal</td>
</tr>
<tr>
<td>Bentonite</td>
<td>Filtralite</td>
<td>Coal ash</td>
</tr>
<tr>
<td>Calcined alunite</td>
<td>Filtralite-P</td>
<td>Dewatered alum sludge</td>
</tr>
<tr>
<td>Carbonate gravels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crushed marble</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homblende</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Igneous gravels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laterite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone (sedimentary rocks)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural materials</td>
<td>Synthetic zeolites</td>
<td></td>
</tr>
<tr>
<td>Maerl (marine sediment)</td>
<td>Filtralite</td>
<td>Fly ash</td>
</tr>
<tr>
<td>Marl</td>
<td></td>
<td>Iron ore</td>
</tr>
<tr>
<td>Natural zeolite</td>
<td></td>
<td>Ochre</td>
</tr>
<tr>
<td>Opoka (marine sediment)</td>
<td>LWA (light-weight aggregate)</td>
<td>Quartz sand</td>
</tr>
<tr>
<td>Marl</td>
<td>LECA (light-weight expanded clay aggregate)</td>
<td></td>
</tr>
<tr>
<td>Natural zeolite</td>
<td>LESA (light-weight expanded shale aggregate)</td>
<td></td>
</tr>
<tr>
<td>Oyster shell</td>
<td>Filtralite</td>
<td></td>
</tr>
<tr>
<td>Peat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polonite</td>
<td>LWA (light-weight aggregate)</td>
<td></td>
</tr>
<tr>
<td>Sands</td>
<td>LECA (light-weight expanded clay aggregate)</td>
<td></td>
</tr>
<tr>
<td>Shale</td>
<td>LESA (light-weight expanded shale aggregate)</td>
<td></td>
</tr>
<tr>
<td>Shell sand</td>
<td>Synthetic zeolites</td>
<td></td>
</tr>
<tr>
<td>Soils</td>
<td>Filtralite</td>
<td></td>
</tr>
<tr>
<td>Spodosols</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wollastonite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Grain size 0.1-4mm**
- **Porosity 0.3**
- **Hydraulic conductivity $10^{-4}$ m/s**
How to create a good filter mechanism?

Vermiculite

- Relatively low saturated weight
  \(840 \text{ kg/m}^3\)

- Relatively high HRT
How to Construct?
Research Living Wall Systems
How to Construct?
Types of Living Wall Systems

- Planter Boxes System
- Panel System (Foam)
- Panel System (Mineral wool)
- Felt Layers
How to Construct?
Material Efficiency

![Bar chart showing material efficiency for different systems.](chart.png)
How to Construct?
Panel System
Design
Panel Dimensions

- Panel dimensions
  2100 x 3400 (W x H)

- Width = window width in GF atrium

- Height = Floor height

- Panel dimensions are outer boundaries

Southwest facade
Plant Species
Suitable for southwest facade

**Constructed Wetlands**
- Echte koekoeksbloem
  - Silene-flos-cuculi
- Voorjaarszegge
  - Carex Caryophyllea
- Stijve zegge
  - Carex Elata
- Hangende zegge
  - Carex Pendula

**Living Wall Systems**
- Gele dovenetel
  - Lamium galeobdolon
- Gevlekte dovenetel
  - Lamium maculatum
- Kleine maagdenpalm
  - Vinca minor

- Indigenous
- Evergreen
- Low maintenance
- Fast growth
Plant Species
Suitable for southwest facade

**constructed wetlands**
- Echte koekoeksbluem
  - Silene-flos-cuculi

**living wall systems**
- Gele dovenetel
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- Indigenous
- Evergreen
- Low maintenance
- Fast growth
Final Design
Visualisation
Final Design
Final Design
Materials & Components

- Front plate (PP)
- Partition (PP)
- Anti-root foil (PP)
- Grid (PP)
- Planter box (PP)
- Irrigator (PP & EPDM)
- Anchor & bolts (Stainless steel)
Final Design
Substrates

40mm Glass foam (8-12mm)

60mm Vermiculite (0.1-0.5mm)
Final Design
Water supply

Influent (greywater)

Collected stormwater &
treated effluent from the panel above

Collected stormwater &
treated effluent from this panel
Design Conditions
System Configuration

Legend:
- = (Source)
- = (Source)
- = (Pretreated greywater)
- = (CW treated effluent & Stormwater)
- = (Purpose)
- = (Purpose)

Sludge collection pit & grease trap
Pump sump
Storage tank & pump
RO - System (Activated Carbon Filters & UV Filtration)
Water Savings

Drinking water consumption: 20,239 L/Day

Stormwater discharge (roof-run-off): 3,853 L/Day

Capacity Wetland: 318 L/Day

Drinking water consumption: 16,068 L/Day

Stormwater discharge (roof-run-off): 0 L/Day
Step 1 - Position the supporting beams
Step 2 -
Place the box
Final Design
Assembly

Step 3 -
Mount the anchors
Final Design
Assembly

Step 4 -
Place the anti-root foil, grid and vermiculite place holders
Final Design

Assembly

Step 5 -
Fill the box with
60mm thick vermiculite
Step 6 - Position the rasterized partition with attached rasterized plant pots (Ø 50mm)
Final Design
Assembly

Step 7 -
Place the glass foam place holders
Final Design
Assembly

Step 8 -
Fill the box with
40mm thick glass foam
Final Design
Assembly

Step 9 -
Mount the front panel
Step 10 -
Front panel is mounted,
behold
Step 11 -
Raise the box by 1 degree on the water supply side
Final Design
Assembly

Step 12 -
Add sloped supporting beams
(1 degree)
Step 13 -
Add bare root seedlings, surrounded by two halves of coco fibre (ø 50mm)
Step 14 - Sprinkle with a little bit of love and water. The slope ensures the water gets drained.
Final Design
Assembly

Step 15 -
Wait till fully covered
Step 16 -
The panel is ready for installment
Step 17 -
Remove the vermiculite and glass foam place holders
Final Design
Assembly

Step 18 - Prepare the facade (westfacade WestCord) for the waterfiltering living wall system
Final Design
Assembly

Step 19 -
Remove the wooden cladding
Final Design
Assembly

Step 20 -
Cut the styles for anchor placement
Final Design
Assembly

Step 21 - Remove the vapour permeable & water proving membrane
Step 22 -
Remove the insulation
Final Design
Assembly

Step 23 -
Place the anchors in the gaps
Final Design
Assembly

Step 24 - Anchors in place
Final Design
Assembly

Step 25 -
Reinsulate
Final Design
Assembly

Step 26 - Make the facade water tight again
Final Design
Assembly

Step 27 -
Place horizontal supporting beams on the styles
Step 28 -
Position the elements
Step 29 -
Cover the entire facade
Final Design
Assembly

Step 30 -
Finish by placing the irrigators
Questions?
Final Design
Facades WestCord Hotel Delft

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Final Design
Detailing - Overview
Final Design
Detailing - Detail A, Horizontal Connection between Elements
Final Design
Detailing - Detail A, Horizontal Connection between Elements

- EPDM rubber ring
- PP Threaded ring Ø38mm, 3mm thick
- PP Irrigation tube Ø38mm, 3mm thick
Final Design
Detailing - Detail A, Horizontal Connection between Elements
Final Design
Detailing - Detail A, Horizontal Connection between Elements

- PP Threaded ring
  ø38mm, 3mm thick

- EPDM rubber ring

- PP Irrigation tube
  ø38mm, 3mm thick
Final Design
Detailing - Detail B,
Vertical Connection between Elements
Final Design
Detailing - Detail B,
Vertical Connection between Elements
Final Design
Detailing - Detail C, Horizontal Detail

Planter box
Rasterized partition with attached plant pots

Front panel
Final Design
Detailing - Detail D, Vertical Detail

Planter box
Rasterized partition
with attached plant pots

Front panel
Final Design
Detailing - Wall Connection
Final Design
Detailing - Wall Connection
Final Design
Detailing - Wall detail WestCord Hotel Delft (Original)

Floor construction:
- Anhydrite topfloor
- Sound insulation
- Constructual pressure layer
- Hollowcore floor

- Wooden plinth
- 2 x Plasterboard 12.5mm
- Damp proof foil
- Insulation
- M-s-profiles 75mm
- Plywood 18mm
- Insulation 140mm
- Vapor permeable & waterproofing membrane
- Battens
- Wooden cladding

Deltabeam
Final Design
Detailing - Wall detail WestCord Hotel Delft (Including design)

Floor construction:
- Anhydrite topfloor
- Sound insulation
- Constructural pressure layer
- Hollowcore floor

- Wooden plinth
- 2 x Plasterboard 12.5mm
- Damp proof foil
- Insulation
- M-s-profiles 75mm
- Plywood 18mm
- Insulation 140mm
- Vapor permeable & waterproofing membrane
- Battens
- Wooden cladding

Deltabeam

11.225+ 70 112 18 45 95 63
10.880+ 345
## Final Design

### Elemental Weight

<table>
<thead>
<tr>
<th>Element weight</th>
<th>Dry bulk density [kg/m³]</th>
<th>Wet bulk density [kg/m³]</th>
<th>Material volume [m³]</th>
<th>Total weight [kg]</th>
<th>Weight [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vermiculite</td>
<td>-</td>
<td>840</td>
<td>2.77E-01</td>
<td>232.33</td>
<td>32.54</td>
</tr>
<tr>
<td>Glass foam</td>
<td>515</td>
<td>-</td>
<td>1.48E-01</td>
<td>76.31</td>
<td>10.69</td>
</tr>
<tr>
<td>Planter box (polypropylene)</td>
<td>900</td>
<td>-</td>
<td>1.06E-04</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>Anchors (stainless)</td>
<td>7910</td>
<td>-</td>
<td>5.42E-04</td>
<td>4.29</td>
<td>0.60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>4.25E-01</strong></td>
<td><strong>313.02</strong></td>
<td><strong>43.84</strong></td>
</tr>
</tbody>
</table>
## Research

### Substrate Weight

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Grain size [mm]</th>
<th>Provided bulk density [kg/m³]</th>
<th>Dry bulk density [kg/m³]</th>
<th>Wet bulk density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Traditional substrates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Fine sand</td>
<td>0,1-0,5</td>
<td>1,551</td>
<td>1,535</td>
<td>1,832</td>
</tr>
<tr>
<td></td>
<td>0,6-1</td>
<td>1,594</td>
<td>1,554</td>
<td>1,935</td>
</tr>
<tr>
<td>2 Sand</td>
<td>1-2</td>
<td>1,614</td>
<td>1,572</td>
<td>1,945</td>
</tr>
<tr>
<td>3 Gravel</td>
<td>8-16</td>
<td>1,495</td>
<td>1,494</td>
<td>1,896</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>1,287</td>
<td>1,285</td>
<td>1,776</td>
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<tr>
<td><strong>Lightweight substrates</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Activated carbon</td>
<td>1-2</td>
<td>450</td>
<td>469</td>
<td>1088</td>
</tr>
<tr>
<td>5 Clay aggregate</td>
<td>1-2</td>
<td>521</td>
<td>513</td>
<td>1134</td>
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<tr>
<td></td>
<td>2-4</td>
<td>498</td>
<td>471</td>
<td>1062</td>
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<td></td>
<td>4-8</td>
<td>525</td>
<td>492</td>
<td>984</td>
</tr>
<tr>
<td></td>
<td>8-12,5</td>
<td>433</td>
<td>437</td>
<td>917</td>
</tr>
<tr>
<td></td>
<td>12,5-16</td>
<td>399</td>
<td>401</td>
<td>855</td>
</tr>
<tr>
<td>6 Expanded perlite</td>
<td>1-2</td>
<td>114</td>
<td>117</td>
<td>759</td>
</tr>
<tr>
<td></td>
<td>2-4</td>
<td>90</td>
<td>94</td>
<td>726</td>
</tr>
<tr>
<td>7 Glass foam gravel</td>
<td>4-8</td>
<td>530</td>
<td>529</td>
<td>1096</td>
</tr>
<tr>
<td></td>
<td>8-12,5</td>
<td>508</td>
<td>515</td>
<td>1079</td>
</tr>
<tr>
<td></td>
<td>12,5-16</td>
<td>505</td>
<td>519</td>
<td>995</td>
</tr>
<tr>
<td>8 Vermiculite</td>
<td>1-2</td>
<td>110</td>
<td>113</td>
<td>837</td>
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<tr>
<td></td>
<td>2-4</td>
<td>98</td>
<td>98</td>
<td>793</td>
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</tbody>
</table>
## Research

### Capacity vs. Weight Calculations

<table>
<thead>
<tr>
<th></th>
<th>60mm</th>
<th>90mm</th>
<th>12mm</th>
<th>150mm</th>
<th>180mm</th>
<th>210mm</th>
<th>240mm</th>
<th>270mm</th>
<th>300mm</th>
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</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Influent volume (for one zigzag) [L/day]</td>
<td>1.77</td>
<td>2.67</td>
<td>3.57</td>
<td>4.47</td>
<td>5.37</td>
<td>6.28</td>
<td>7.17</td>
<td>8.07</td>
<td>8.97</td>
</tr>
<tr>
<td>Amount of zigzags per element [n]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Amount of elements on WestCord [n]</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td><strong>Total Capacity [L/day]</strong></td>
<td>318.6</td>
<td>480.6</td>
<td>642.6</td>
<td>804.6</td>
<td>966.6</td>
<td>1130.4</td>
<td>1290.6</td>
<td>1452.6</td>
<td>1614.6</td>
</tr>
<tr>
<td><strong>Total Capacity [%]</strong></td>
<td>2.63</td>
<td>3.97</td>
<td>5.31</td>
<td>6.65</td>
<td>7.99</td>
<td>9.34</td>
<td>10.67</td>
<td>12.00</td>
<td>13.34</td>
</tr>
<tr>
<td><strong>Element Weight</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight per element [kg]</td>
<td>313.02</td>
<td>430.64</td>
<td>548.25</td>
<td>665.87</td>
<td>783.49</td>
<td>901.10</td>
<td>1,018.72</td>
<td>1,136.34</td>
<td>1,253.95</td>
</tr>
<tr>
<td>Weight per m² [kg/m²]</td>
<td>43.84</td>
<td>60.31</td>
<td>76.79</td>
<td>93.26</td>
<td>109.73</td>
<td>126.20</td>
<td>142.68</td>
<td>159.15</td>
<td>175.62</td>
</tr>
</tbody>
</table>
Research

Angle / Substrate Test
Research
Angle / Substrate Test

Stayed dry
Curved edge is desired