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# Environmental assessment of multi-functional building elements constructed with digital fabrication techniques

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## Supplementary information

### 1. Case study 1: The Sequential Roof

### 1.1. Definition of product systems

#### 1.1.1. Production

**THE SEQUENTIAL ROOF**

MATERIALS

The Sequential Roof has a total wood volume of 384 $m^3$, including 0.17 $m^3$ of fir/spruce timber per $m^2$. The wood sticks were robotically assembled with steel nails with 90 mm length and ø3.4 mm, employing approximately 2.27 kg of steel per $m^2$. The material composition is shown in Table 1.

| **Wood** | |
|---|---|
| Material type | C24 fir /spruce |
| Total volume ($m^3$) | 384 |
| Total mass (kg) | 161280 |
| Volume ($m^3$) / $m^2$ roof | 0.17 |
| **Nails** | |
| Material | Steel |
| Number units | 815984 |
| Volume ($m^3$)/unit | 8.17E-07 |
| Total volume ($m^3$) | 0.667 |
| Total mass (kg) | 5234.11 |
| Mass (kg) / $m^2$ roof | 2.27 |

Table 1. Material composition of The Sequential Roof (1 $m^2$).

CONSTRUCTION

The digital manufacturing process of the 168 trusses was performed by a custom six-axis overhead gantry robot in the manufacturer’s factory. Each lattice girder with a regular span of 14.70 m was constructed during 12 hours of production.

| Roof construction | 1 m$^2$ |
|---|---|
| Number beams (units) | 168 |
| Construction time / beam (h) | 12 |
| Total time (h) | 2016 |
| Production time (h) / m$^2$ roof | 0.87 |

Table 2. Construction time of The Sequential Roof (hours).

The energy consumption of both technologies during the production time is shown in Table 3.

| Roof construction | 1 m$^2$ |
|---|---|
| Energy demand robot (kWh) | 4.37 |
| Energy demand computer (kWh) | 0.012 |
| Total energy demand (kWh) | 4.38 |

Table 3. Energy consumption of digital technologies during The Sequential Roof construction (kWh).

## CONVENTIONAL WOODEN ROOF

A conventional roof was defined for the comparison with The Sequential Roof. The basic composition of the conventional roof are glulam beams structure and an acoustic suspended ceiling with steel profiles and wooden finishing (see Figure 1).

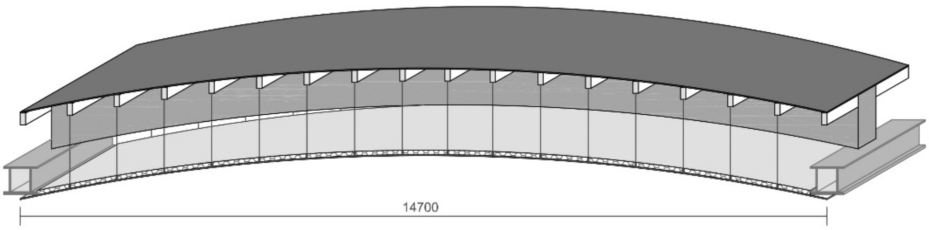


Figure 1. Section of the structural prototype of conventional roof.

### MATERIALS

The conventional roof system is formed by a Glulam spruce structure of 0.3x1x15 m beams and 0.1x0.22x4 m joists. The beams are distributed every 4 meters and the joists every 0.8 meters. The joists are connected to the beams with galvanized steel hangers with dimensions 0.1x0.16x0.16 m. The wood structure is covered by 19 mm of waterproof particleboard. This panel is attached to the structure with steel nails. Finally, a suspended ceiling finishes and improves the acoustic performance of the structure. The ceiling is composed of 0.6x1.2 m laminated wood boards with 5 cm of rockwool insulation and a structure of galvanized steel profiles hanging from ø8 mm steel bars. In total, the roof includes approximately 0.11 m3 of wood, 3.42 kg of steel and 5 kg of insulation per m$^2$. Following in Tables 4 and 5, a section of 420 m$^2$ is analysed to extract the material composition of 1 m$^2$ of roof.

**Structure**

| Wood beams/joists |
|---|

| | |
|---|---|
| Material type | Glulam spruce |
| Beam volume ($m^3$) / unit | 4.5 |
| Number beams (units) | 7 |
| Joist volume ($m^3$) /unit | 0.088 |
| Number joists (units) | 20 |
| Total volume ($m^3$) | 33.26 |
| Volume ($m^3$) / $m^2$ roof | 0.079 |
| **Hangers (joists)** | |
| Material type | Steel |
| Number hangers (units) | 40 |
| Volume ($m^3$) / unit | 0.000067 |
| Total volume ($m^3$) | 0.002688 |
| Total mass (kg) | 21.1 |
| Mass steel (kg) / $m^2$ roof | 0.050 |
| **Wooden cover panel** | |
| Material type | Particleboard |
| Volume ($m^3$) / $m^2$ roof | 0.019 |
| **Nails** | |
| Material type | Steel |
| Volume ($m^3$) / unit | 8.17E-07 |
| Units / $m^2$ roof | 8 |
| Volume ($m^3$) / $m^2$ roof | 0.0000065 |
| Mass (kg) / $m^2$ roof | 0.051 |

Table 4. Material composition of the conventional wooden roof structure (1 $m^2$).

## Suspended ceiling

| | |
|---|---|
| **Insulation** | |
| Material type | Rockwool |
| Volume ($m^3$) / $m^2$ roof | 0.05 |
| Mass (kg) / $m^2$ roof | 5 |
| **Finishing panel** | |
| Material type | Laminated wood |
| Volume ($m^3$) / $m^2$ roof | 0.016 |
| **Ceiling profiles** | |
| Material type | Galvanized steel |
| Volume primary profile ($m^3$) / unit | 0.0072 |
| Number of primary profiles (units) | 16 |
| Volume primary profiles ($m^3$) | 0.1156 |
| Volume secondary profile ($m^3$) / unit | 0.0028 |
| Number of secondary profiles (units) | 14 |
| Volume secondary profiles ($m^3$) | 0.03906 |
| Volume hanging bar ($m^3$) / unit | 0.00006 |
| Number of hanging bars (units) | 384 |
| Volume hanging bars ($m^3$) | 0.023 |
| Total volume ($m^3$) | 0.178 |

| | |
|---|---|
| Total mass (kg) | 1395.78 |
| Steel mass (kg) / $m^2$ roof | 3.323 |

Table 5. Material composition of the hanging ceiling of the conventional wooden roof (1 $m^2$).

#### 1.1.2. Service life

Table 6 presents the summary of data collected regarding service life of the building elements.

| | Conventional roof | | The Sequential Roof |
|---|---|---|---|
| | Structure | Suspended ceiling | Structure |
| **Service life (years)** | 60 | 30 | 60/30 |

Table 6. Service life (years) of each component of The Sequential Roof and conventional roof.

## 2. Case study 2: Concrete-Sandstone Composite Slab

### 2.1. Definition of product system

#### 2.1.1. Production

**CSC SLAB**

MATERIALS

The CSC Slab is composed of 0.03 $m^3$ of sand-binder formwork and 0.06 $m^3$ of UHPFRC. The composite formwork includes 22.633 kg of sand and 0.559 $m^3$ of binder per m2 of structure. The type of binder used for the fabrication is a phenolic urethane binder with a composition of 55% phenolic resin and 45% polyisocyanate resin. Subsequently, the formwork was filled with UHPFRC. Finally, the integration of electrical installations, heat distribution, ventilation system and sanitary facilities in the structure was included in the functional unit. The material composition is shown in Table 7.

**Structure**

| **Formwork** | |
|---|---|
| Material type | Silica sand + Phenolic urethane binder |
| Total volume ($m^3$) | 0.03 |
| Sand volume ($m^3$) | 0.0291 |
| Sand mass (kg) | 40.74 |
| Sand mass (kg) / $m^2$ slab | 22.633 |
| Binder volume ($m^3$) | 0.0009 |
| Binder mass (kg) / $m^2$ slab | 0.559 |
| **Reinforced concrete** | |
| Material type | UHPFRC |
| Concrete volume ($m^3$) | 0.06 |
| Concrete volume ($m^3$) / $m^2$ slab | 0.033 |
| **Installations** | |
| Electrical installation (kg/$m^2$) | 1.9 |
| Heat distribution (kg/$m^2$) | 1.9 |

| | |
|---|---|
| Ventilation system (kg/m$^2$) | 3.3 |
| Sanitary facilities (kg/m$^2$) | 3.1 |

Table 7. Material composition of the CSC Slab (1 m$^2$).

The material composition of the phenolic urethane binder and UHPFRC is shown in Tables 8 and 9.

| Binder component | Composition (%) | Ecoinvent process |
|---|---|---|
| Phenolic resin | 55% | Phenolic resin (RER) \| production \| Alloc Def, U |
| Polyisocyanate resin | 45% | Phenyl isocyanate (RER) \| production \| Alloc Def, U |

Table 8. Material composition and Ecoinvent processes used in the production of phenolic urethane binder.

| Material component | Amount | Unit | Ecoinvent process |
|---|---|---|---|
| Steel fiber | 215.9 | kg | Steel low-alloyed (GLO) \| market for \| Alloc Def,U |
| Cement | 650 | kg | Cement, Portland (CH) \| market for \| Alloc Def,U |
| Superplasticizer | 42.5 | kg | Plasticizer for concrete (GLO) \|market for \| Alloc Def, U |
| Limestone | 559 | kg | Limestone, crushed, for mill (CH)\| market for \| Alloc Def, U |
| Silica fume | 137 | kg | Ferrosilicon (GLO) \| market for \| Alloc Def, U (0.03/1) |
| Water | 180 | kg | Tap water, at user (CH)\| market for \| Alloc Def, U |
| Sand | 573.5 | kg | Silica sand (GLO) \| market for \| Alloc Def, U |

Table 9. Material composition and Ecoinvent processes used in the production of 1 m$^3$ of UHPFRC.

CONSTRUCTION

The digital manufacturing process of the formwork was performed by a ExOne S-Max 3D printer with 6,2 kW power and 0.071 m$^3$/h speed (ExOne, 2015). The complete 3D printed formwork was produced in 0.424 hours with a total energy consumption of 2.63 kWh. The energy consumption of the binder-jet 3D printer during the production of the sand-binder formwork is shown in Table 10.

| Formwork construction | |
|---|---|
| Technology type | ExOne 3D printer |
| Speed (m$^3$/h) | 0.071 |
| Time (h) | 0.424 |
| Power (kW) | 6.2 |
| Energy demand (kWh) | 2.63 |
| Energy demand (kWh) / m$^2$ slab | 1.46 |

Table 10. Construction time (hours) and energy consumption (kWh) of the 3D printer during the CSC Slab construction.

**CONVENTIONAL SLAB**

A conventional slab was defined for the comparison with the CSC Slab. A 15 cm reinforced concrete structure and a suspended ceiling containing the different installations are the main components of the conventional slab (see Figure 2).

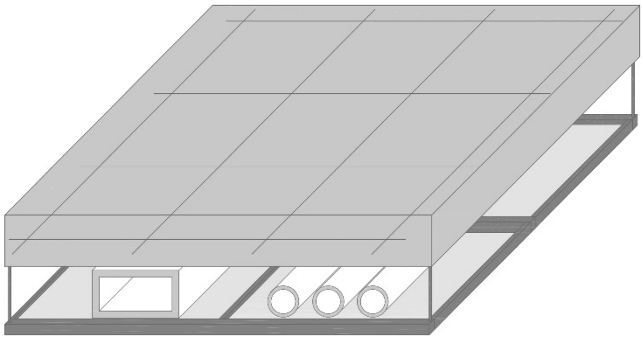

Figure 2. Section of the structural prototype of conventional floor slab.

MATERIALS

During the definition of the conventional slab, a ratio of 85 kg of steel per $m^3$ of concrete was considered in the structure. As a result, 0.148 $m^2$ of conventional C25/30 concrete (EN 1992-1-1 (2004)) and 12.613 kg of steel reinforcement type B500B were included in 1 $m^2$. This structure was constructed traditionally with a wooden formwork 5-times reused, which was also included in the assessment. On the other hand, a suspended ceiling improves the acoustic performance and finishes the structure, hiding the installations. Acoustic plasterboard panels held by a structure of galvanized steel profiles form this building component. In total, the suspended ceiling is made with 9 kg of plasterboard and 6.39 of steel per $m^2$. Finally, the same installations as the CSC Slab were included in the assessment of the conventional slab. Following in Tables 11 and 12, a section of conventional slab with a standard span of 6x6 meters is analysed to extract the material composition of 1 $m^2$.

**Structure**

| | |
|---|---|
| Slab area ($m^2$) | 36 |
| Slab thickness (m) | 0.15 |
| Slab volume ($m^3$) | 5.4 |
| **Concrete** | |
| Material type | C25/30 |
| Concrete volume ($m^3$) | 5.3422 |
| Concrete volume ($m^3$) / $m^2$ slab | 0.148 |
| **Reinforcement** | |
| Material type | B500B steel |
| Steel volume ($m^3$) | 0.0578 |
| Steel mass (kg) | 454.08 |
| Steel mass (kg) / $m^2$ slab | 12.613 |
| **Formwork** | |
| Material type | 3-layer solid wood panel |
| Wood area ($m^2$) | 39.6 |
| Panel thickness (m) | 0.027 |
| Wood volume ($m^3$) | 1.069 |
| Wood volume ($m^3$) – 5 times reuse | 0.2138 |
| Wood volume ($m^3$) / $m^2$ slab | 0.006 |

Table 11. Material composition of the conventional slab structure (1 $m^2$).

**Suspended ceiling**

| **Finishing panels** | |
|---|---|
| Material type | Plasterboard |
| Panels density ($kg/m^2$) | 9 |
| Panels mass (kg) | 324 |
| Panels mass (kg) / $m^2$ slab | 9 |
| **Ceiling profiles** | |
| Material type | Galvanized steel |
| Volume primary profile ($m^3$) / unit | 0.00155 |
| Number of primary profiles (units) | 11 |
| Volume primary profiles ($m^3$) | 0.01703 |
| Volume secondary profile ($m^3$) / unit | 0.00108 |
| Number of secondary profiles (units) | 11 |
| Volume secondary profiles ($m^3$) | 0.01187 |
| Volume hanging bar ($m^3$) / unit | 0.00001 |
| Number of hanging bars (units) | 36 |
| Volume hanging bars ($m^3$) | 0.0004 |
| Total volume ($m^3$) | 0.029 |
| Total mass (kg) | 229.665 |
| Steel mass (kg) / $m^2$ slab | 6.38 |
| **Installations** | |
| Electrical installation ($kg/m^2$) | 1.9 |
| Heat distribution ($kg/m^2$) | 1.9 |
| Ventilation system ($kg/m^2$) | 3.3 |
| Sanitary facilities ($kg/m^2$) | 3.1 |

Table 12. Material composition of the suspended ceiling of the conventional slab (1 $m^2$).

### 2.1.2. Service life

Table 13 shows the summary of service life data from both building elements.

| | Conventional slab | | | CSC Slab | |
|---|---|---|---|---|---|
| | Structure | Suspended ceiling | Installations | Structure | Installations |
| **Service life (years)** | 60 | 30 | 20 | 60/20 | 60/20 |

Table 13. Service life (years) of each component of the CSC Slab and conventional slab.

### 2.1.3. End of life

Table 14-15 show the data collected regarding different end-of-life scenarios for the CSC Slab.

| **GWP ($kgCO_2$ eq.)** | **Landfill** | **Recycling** |
|---|---|---|
| **Silica sand** | 0.65 | 0.65 |
| **Phenolic binder** | 3.08 | 3.08 |
| **UHPFRC** | 31.31 | 31.31 |

| | | |
|---|---|---|
| **3D printing** | 0.14 | 0.14 |
| **Demolition** | 0.43 | 0.43 |
| **Concrete recycling (crushing)** | 0.00 | 0.272 |
| **Sand recycling (thermal)** | 0 | 10.89 |
| **Sorting** | 0 | 0.02 |
| **Landfill (sanitary)** | 1.11 | 0.03 |
| **Avoided silica sand** | 0 | -0.61 |
| **Avoided aggregates production** | 0 | -0.26 |
| **Avoided disposal** | 0 | -0.53 |

Table 14. GWP impacts derived from landfilling and recycling 1 $m^2$ of CSC Slab.

| **UBP (eco-points)** | **Landfill** | **Recycling** |
|---|---|---|
| **Silica sand** | 1434.93 | 1434.93 |
| **Phenolic binder** | 3.08 | 3.08 |
| **UHPFRC** | 31.31 | 31.31 |
| **3D printing** | 0.14 | 0.14 |
| **Demolition** | 1765.06 | 1765.06 |
| **Concrete recycling (crushing)** | 0.00 | 504.900 |
| **Sand recycling (thermal)** | 0 | 30242.00 |
| **Sorting** | 0 | 255.75 |
| **Landfill (sanitary)** | 2208.96 | 70.85 |
| **Avoided silica sand** | 0 | -1363.19 |
| **Avoided aggregates production** | 0 | -479.655 |
| **Avoided disposal** | 0 | -1134.60 |

Table 15. UBP impacts derived from landfilling and recycling 1 $m^2$ of CSC Slab.

Tables 16 and 17 show detailed information related to the recycling process:

| **Process** | **Time (h)** | **Temperature (°C)** | **Power (kW)** | **Energy (MJ)** |
|---|---|---|---|---|
| Thermal recycling | 0.33 | 980 | 114 | 136.8 |

Table 16. Data from recycling process of 1 $m^2$ of CSC Slab.

| **Emissions** | **VOC (kg)** | **HAPs (kg)** | **Methane (kg)** | **PAHs (kg)** |
|---|---|---|---|---|
| | 0.0603 | 0.0179 | 0.0235 | 0.0159 |

Table 17a. Emissions caused by thermal recycling of 1 $m^2$ of CSC Slab.

| **HAPs** | **kg** |
|---|---|
| **benzene** | 0.0035 |
| **toluene** | 0.0015 |
| **m-, o-, p-xylene** | 0.0004 |
| **aniline** | 0.0004 |

| | |
|---|---|
| **phenol** | 0.0067 |
| **o-cresol** | 0.0043 |
| **p-, m-cresol** | 0.0006 |
| **naphthalene** | 0.0005 |

Table 17b. Emissions caused by thermal recycling of 1 $m^2$ of CSC Slab.

# 3. Results

## 3.1. Environmental impacts of production

### 3.1.1. Case study 1: The Sequential Roof

The LCI of The Sequential Roof and the conventional roof were evaluated with the impact method IPCC GWP 100a to obtain data regarding production.

| Ecoinvent process | IPCC GWP 100a (kg $CO_2$ eq.) |
|---|---|
| Sawnwood, softwood, dried (u=10%), planed {RER}\| production \| Alloc Def, U | 19.9264 |
| Steel, low-alloyed {RER}\| steel production, converter, low-alloyed \| Alloc Def, U | 5.18322 |
| Electricity, medium voltage {CH}\| market for \| Alloc Def, U | 0.43205 |

Table 18. LCIA results the production of The Sequential Roof.

| Ecoinvent process | IPCC GWP 100a (kg $CO_2$ eq.) |
|---|---|
| Glued laminated timber, for indoor use {RER}\| production \| Alloc Def, U | 16.7061 |
| Steel, low-alloyed {RER}\| steel production, converter, low-alloyed \| Alloc Def, U | 0.23062 |
| Rock wool {CH}\| production \| Alloc Def, U | 5.71765 |
| Three layered laminated board {RER}\| production \| Alloc Def, U | 4.71496 |
| Steel, low-alloyed {RER}\| steel production, converter, low-alloyed \| Alloc Def, U | 7.58759 |
| Particle board, for indoor use {RER}\| production \| Alloc Def, U | 5.24657 |

Table 19. LCIA results from the production of the conventional roof.

| Building element | Impact category | Unit | Structure | Suspended ceiling |
|---|---|---|---|---|
| Conventional roof | GWP | kg $CO_2$ eq. | 22.18 | 18.02 |
| The Sequential Roof | GWP | kg $CO_2$ eq. | 25.54 | |

Table 20. GWP impacts from the production of The Sequential Roof and conventional roof organized by component.

### 3.1.2. Case study 1: CSC Slab

The LCI of the CSC Slab and the conventional slab were evaluated with the impact method IPCC GWP 100a to obtain data regarding production.

| Ecoinvent process | IPCC GWP 100a (kg $CO_2$ eq.) |
|---|---|
| UHPFRC | 31.6678 |

| | |
|---|---|
| Silica sand {DE}\| production \| Alloc Def, U | 0.64735 |
| Phenolic resin {RER}\| production \| Alloc Def, U | 1.40352 |
| Phenyl isocyanate {RER}\| production \| Alloc Def, U | 1.70968 |
| Electricity, medium voltage {CH}\| market for \| Alloc Def, U | 0.14402 |
| Installations | 31.47 |

Table 21. LCIA results from the production of the CSC Slab.

| Ecoinvent process | IPCC GWP 100a (kg $CO_2$ eq.) |
|---|---|
| Concrete, normal {CH}\| unreinforced concrete production, with cement CEM II/A \| Alloc Def, U | 23.7916 |
| Steel, low-alloyed {RER}\| steel production, converter, low-alloyed \| Alloc Def, U | 28.7999 |
| Gypsum plasterboard {CH}\| production \| Alloc Def, U | 2.20339 |
| Steel, low-alloyed {RER}\| steel production, converter, low-alloyed \| Alloc Def, U | 14.5678 |
| Three layered laminated board {RER}\| production \| Alloc Def, U | 1.76811 |
| Installations | 31.47 |

Table 22. LCIA results the production of the conventional slab.

| Installations | IPCC GWP 100a (kg $CO_2$ eq.) |
|---|---|
| Electrical installation | 6.01 |
| Heat distribution | 5.38 |
| Ventilation system | 12.18 |
| Sanitary facilities | 7.9 |

Table 23. LCIA results the production of the installations for both slabs.

| Building element | Impact category | Unit | Structure | Suspended ceiling | Installations |
|---|---|---|---|---|---|
| Conventional slab | GWP | kg $CO_2$ eq. | 54.36 | 16.77 | 31.47 |
| CSC Slab | GWP | kg $CO_2$ eq. | 35.57 | | 31.47 |

Table 24. GWP impacts from the production of the CSC Slab and the conventional slab organized by component.

### 3.2. Environmental impacts including service life.

Tables 25 and 26 show the results from the application of the evaluation method to the case studies.

#### 3.2.1. Case study 1: The Sequential Roof

| GWP (kg $CO_2$ eq.) | Structure | Hanging ceiling | Total |
|---|---|---|---|
| **The Sequential Roof (60 years)** | 25.54 | | 25.54 |
| **The Sequential Roof (30 years)** | 51.08 | | 51.08 |
| **Conventional roof** | 22.18 | 36.04 | 58.22 |

Table 25. Comparison of environmental impacts between The Sequential Roof and conventional roof during 60 years of service life, expressed in GWP (kg $CO_2$ eq.).

### 3.2.2. Case study 2: CSC Slab

| GWP (kg $CO_2$ eq.) | Structure | Hanging ceiling | Installations | Total |
|---|---|---|---|---|
| **CSC Slab (60 years)** | 35.57 | | 31.47 | 67.04 |
| **CSC Slab (20 years)** | 106.72 | | 94.41 | 201.13 |
| **Conventional slab** | 54.36 | 33.54 | 94.41 | 182.31 |

Table 26. Comparison of environmental impacts between the CSC Slab and conventional slab during 60 years of service life, expressed in GWP (kg $CO_2$ eq.).

## 3.3. Environmental impacts including end of life.

### 3.3.1. Caste study 2: CSC Slab

| GWP (kg $CO_2$ eq.) | Landfill | Recycling (0% recycled content) | | Recycling (100% recycled content) | |
|---|---|---|---|---|---|
| | **Cut-off** | **Cut-off** | **EoL** | **Cut-off** | **EoL** |
| **Production** | 35.2 | 35.2 | 35.2 | 46.0 | 46.0 |
| **Disposal** | 1.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| **Recycling** | 0.0 | 0.0 | 11.2 | 0.0 | 11.2 |
| **Avoided material** | 0.0 | 0.0 | -0.9 | 0.0 | 0.3 |
| **Avoided disposal** | 0.0 | 0.0 | 0.0 | 0.0 | -0.5 |
| **Total** | 36.7 | 35.7 | 45.9 | 46.4 | 57.4 |

Table 27. GWP results from the evaluation of 1 $m^2$ of CSC Slab considering different end-of-life scenarios.

| UBP (eco-points) | Landfill | Recycling (0% recycled content) | | Recycling (100% recycled content) | |
|---|---|---|---|---|---|
| | **Cut-off** | **Cut-off** | **EoL** | **Cut-off** | **EoL** |
| **Production** | 1469.5 | 1469.5 | 1469.5 | 31788.6 | 31788.6 |
| **Disposal** | 3974.0 | 2091.7 | 2091.7 | 2091.7 | 2091.7 |
| **Recycling** | 0.0 | 0.0 | 30746.9 | 0.0 | 30746.9 |
| **Avoided material** | 0.0 | 0.0 | -1842.8 | 0.0 | 1032.4 |
| **Avoided disposal** | 0.0 | 0.0 | 0.0 | 0.0 | -1134.6 |
| **Total** | 5443.5 | 3561.1 | 32465.2 | 33880.3 | 64525.0 |

Table 28. UBP results from the evaluation of 1 $m^2$ of CSC Slab considering different end-of-life scenarios.