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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 m³, including 0.17 m³ of fir/spruce timber per m². 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 m². 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 m²).

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).

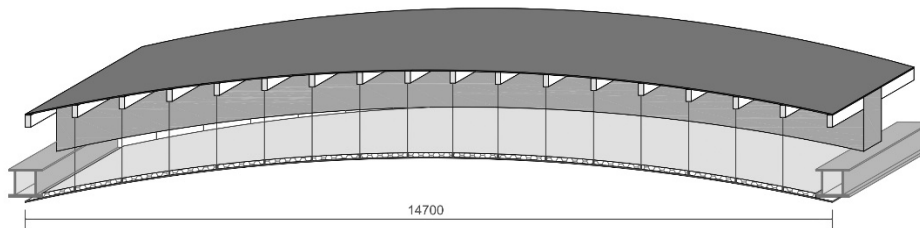


Figure 1. Section of the structural prototype of conventional roof.

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 m². Following in Tables 4 and 5, a section of 420 m² is analysed to extract the material composition of 1 m² 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 m²).

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 m²).

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 m³ of sand-binder formwork and 0.06 m³ of UHPFRC. The composite formwork includes 22.633 kg of sand and 0.559 m³ 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 m²).

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 m³ 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 m³/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).

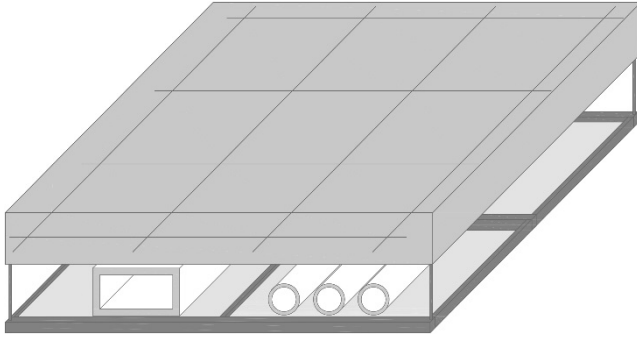


Figure 2. Section of the structural prototype of conventional floor slab.

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^3 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 m²).

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 (kgCO₂ 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 m² of CSC Slab.

UBP (eco-points)	Landfill	Recycling
Silica sand	1434.93	1434.93
Phenolic binder	3.08	3.08
UHPRC	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 m² 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 m² 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 m² 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 m² 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.)
UHPRC	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 CO₂ 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 CO₂ eq.).

3.3. Environmental impacts including end of life.

3.3.1. Case 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 m² 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 m² of CSC Slab considering different end-of-life scenarios.