Floor slab optimization

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs

4385896 Kees Leemeijer

Building Technology
Master of Science
at the Delft University of Technology,

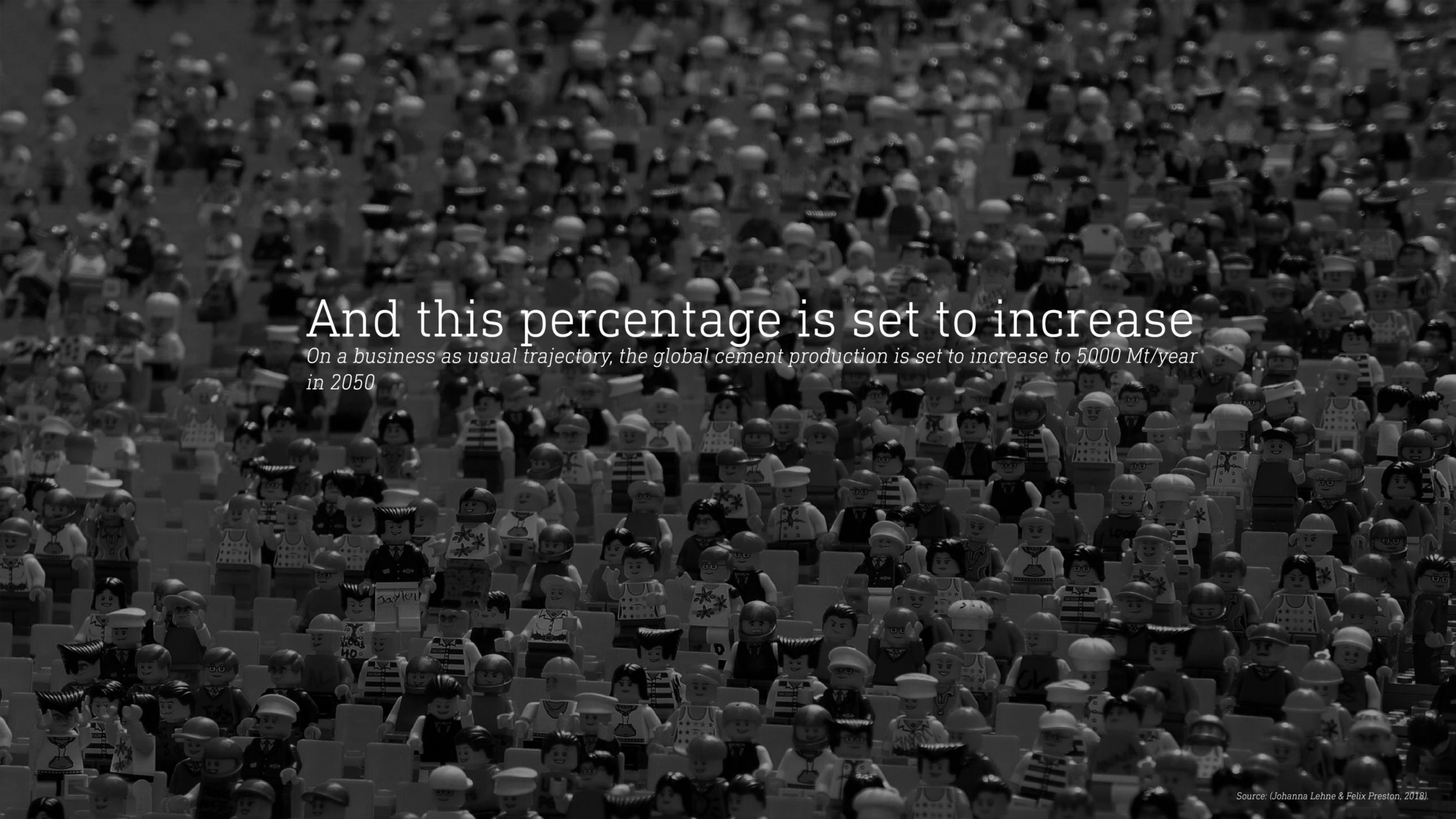
Supervisor: Dr. S. (Serdar) Asut, Dr.ir. H.R. (Roel) Schipper
Graduation committee: G. Coumans

TUDelft
BK Bouwkunde

8% of the worldwide CO_2 emissions

is caused by concrete construction

Source: (Andrew, 2019)



And this percentage is set to increase

On a business as usual trajectory, the global cement production is set to increase to 5000 Mt/year in 2050

Source: (Johanna Lehne & Felix Preston, 2018).

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8% of the worldwide CO_2 Emissions

Is caused by concrete construction

Source: (Andrew, 2019) / (Favier et al., 2018) / (Wight & MacGregor, 2009)

8% of the worldwide CO_2 Emissions

Is caused by concrete construction

50% is used in buildings

4% of the worldwide concrete emissions is caused by the buildings sector

Source: (Andrew, 2019) / (Favier et al., 2018) / (Wight & MacGregor, 2009)

8% of the worldwide CO_2 Emissions

Is caused by concrete construction

50% is used in buildings

4% of the worldwide concrete emissions is caused by the buildings sector

56% of the concrete is used in flooring

2.39% of the worldwide concrete emissions is caused by concrete floors

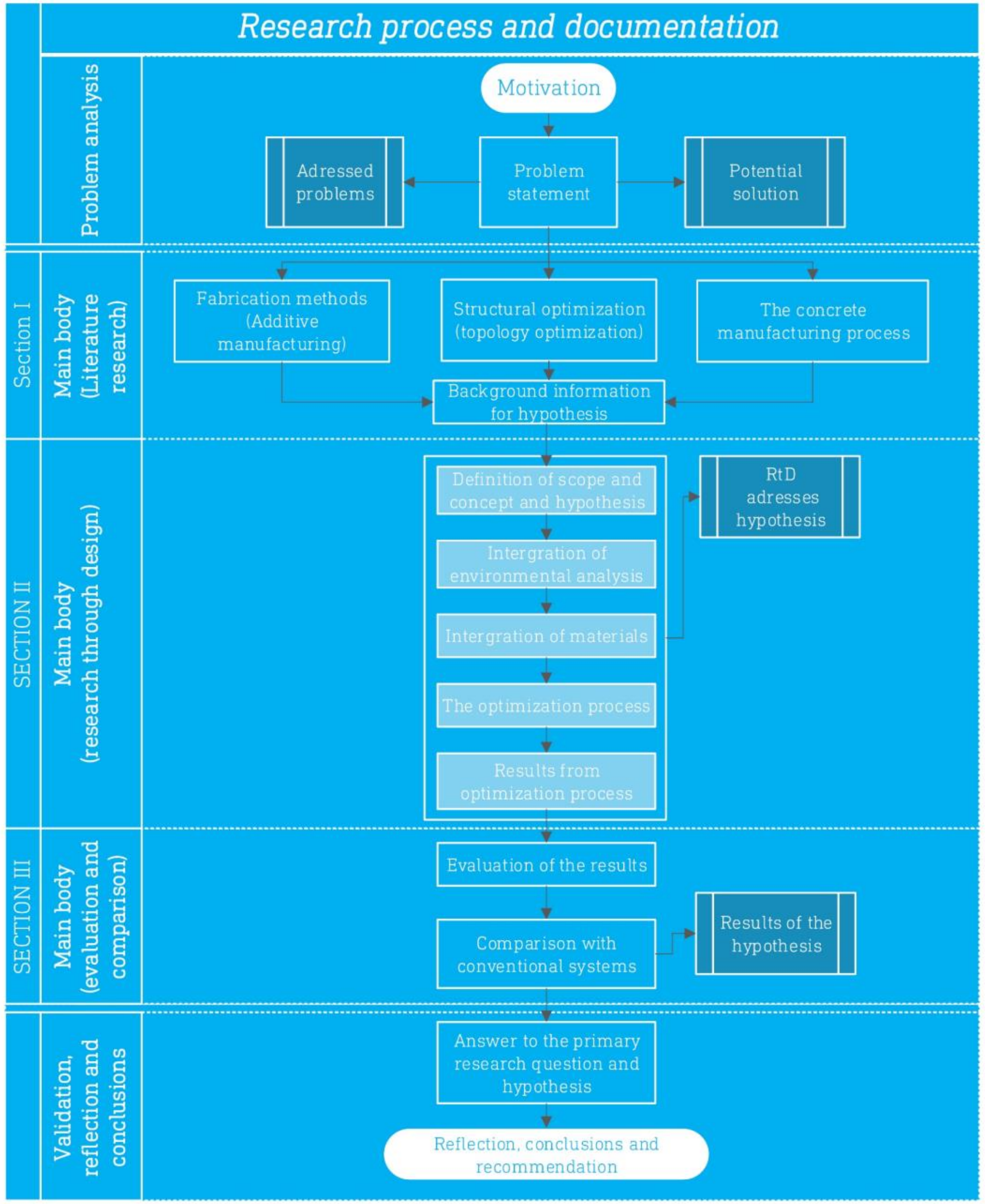
Source: (Andrew, 2019) / (Favier et al., 2018) / (Wight & MacGregor, 2009)

2.4% worldwide CO_2 Emissions

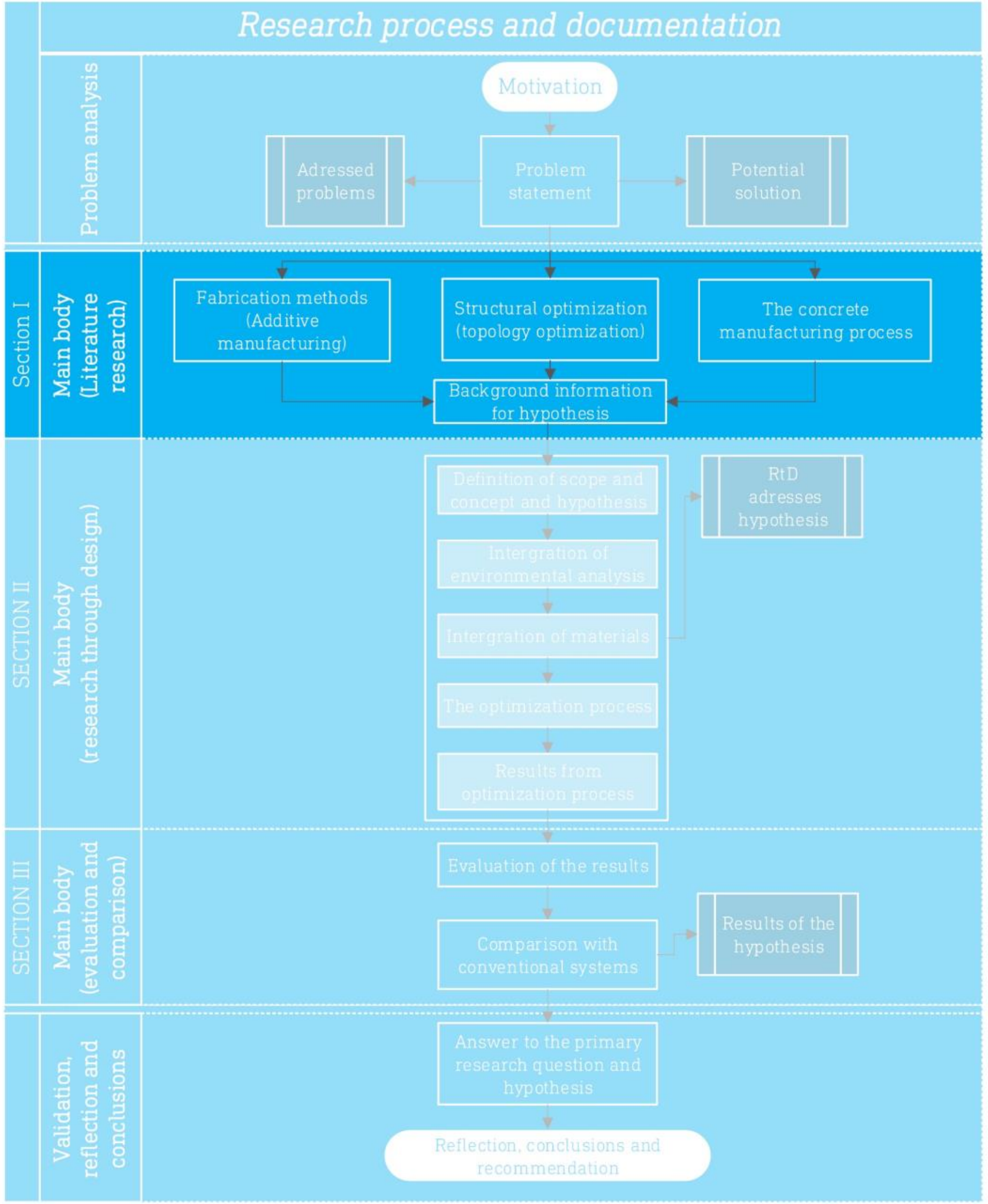
Is caused by concrete flooring systems

Research methodology

Research methodology

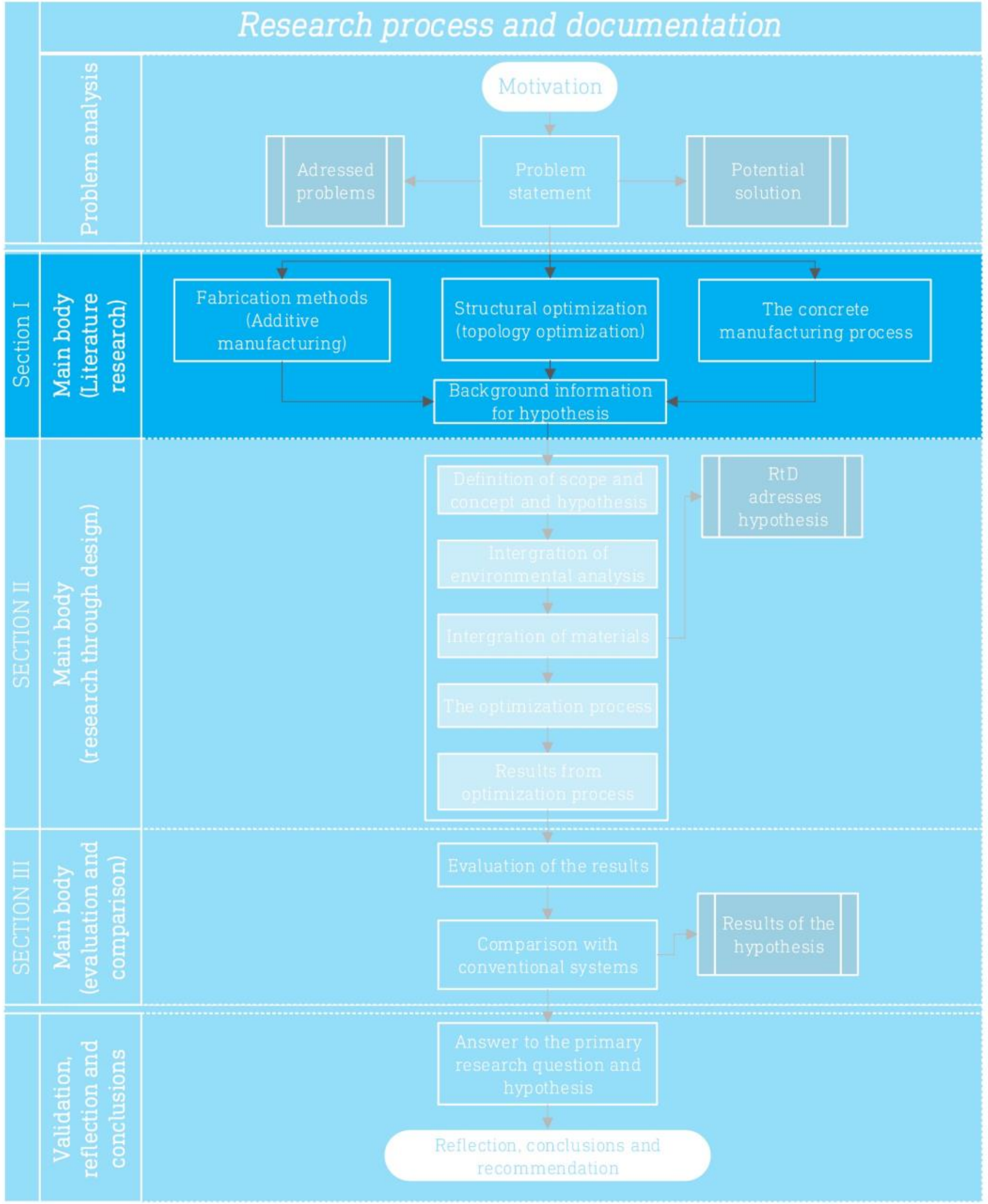


Fabrication methods



Fabrication methods

Structural optimization

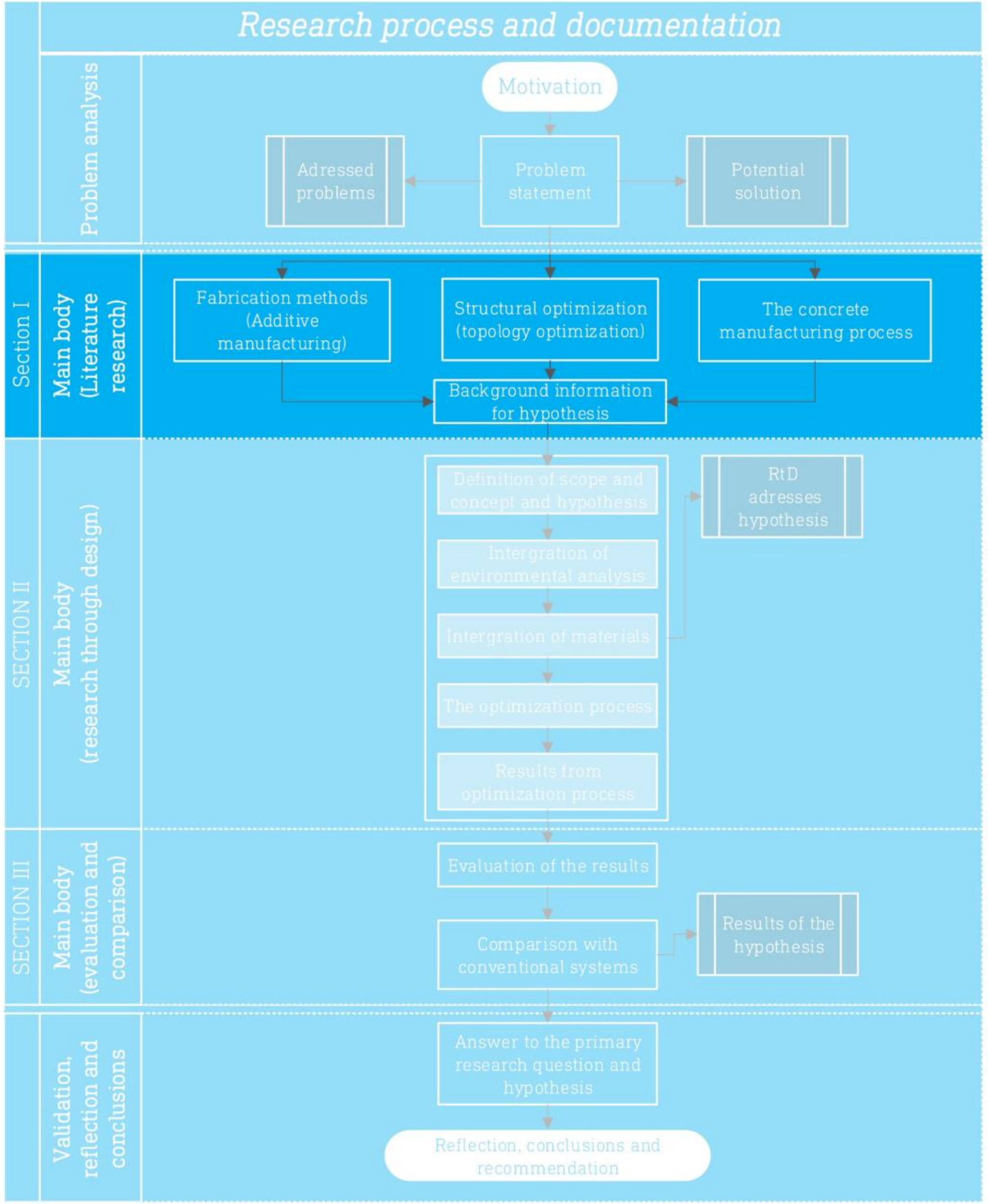


Research methodology

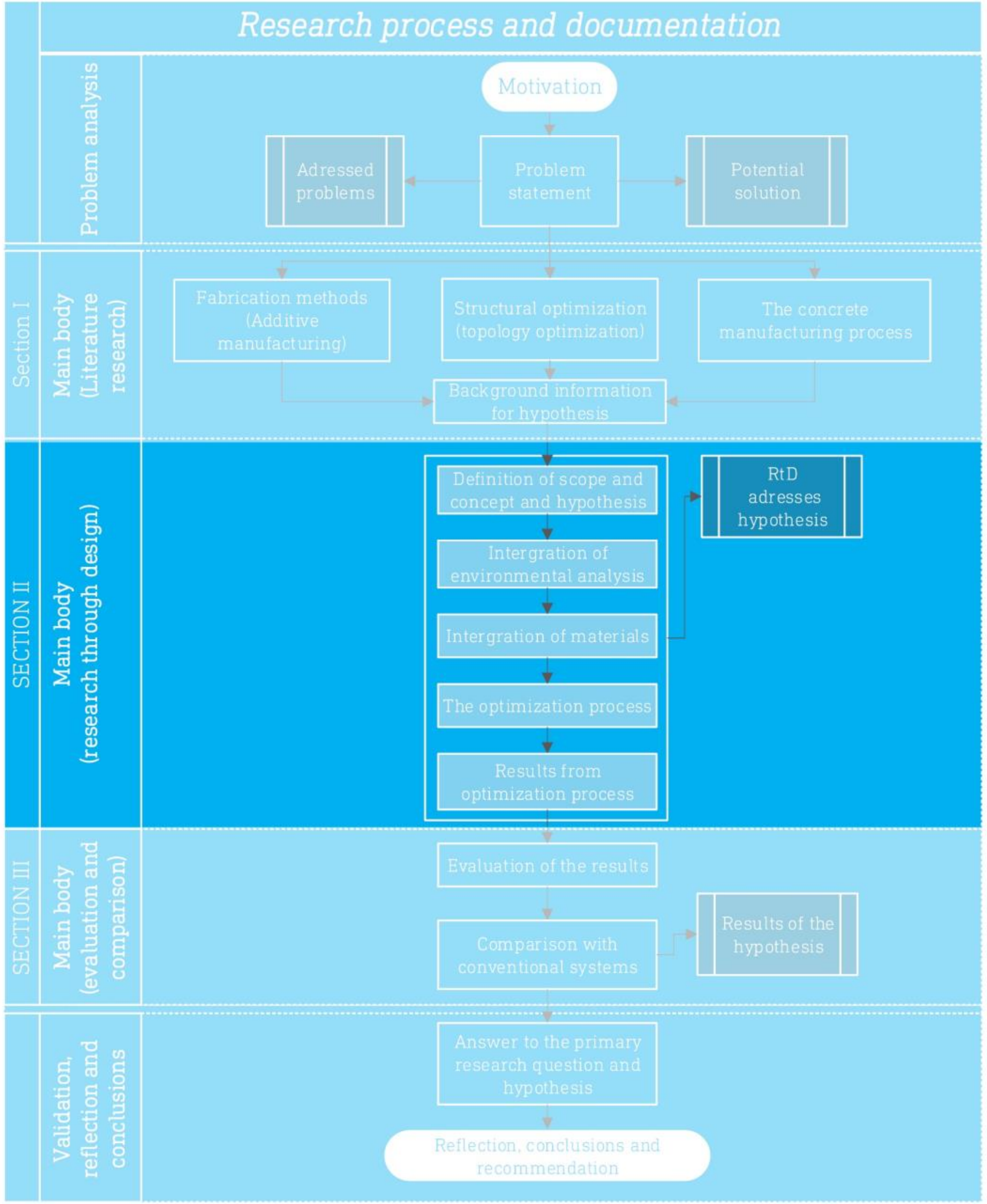
Fabrication methods

Structural optimization

Concrete manufacturing

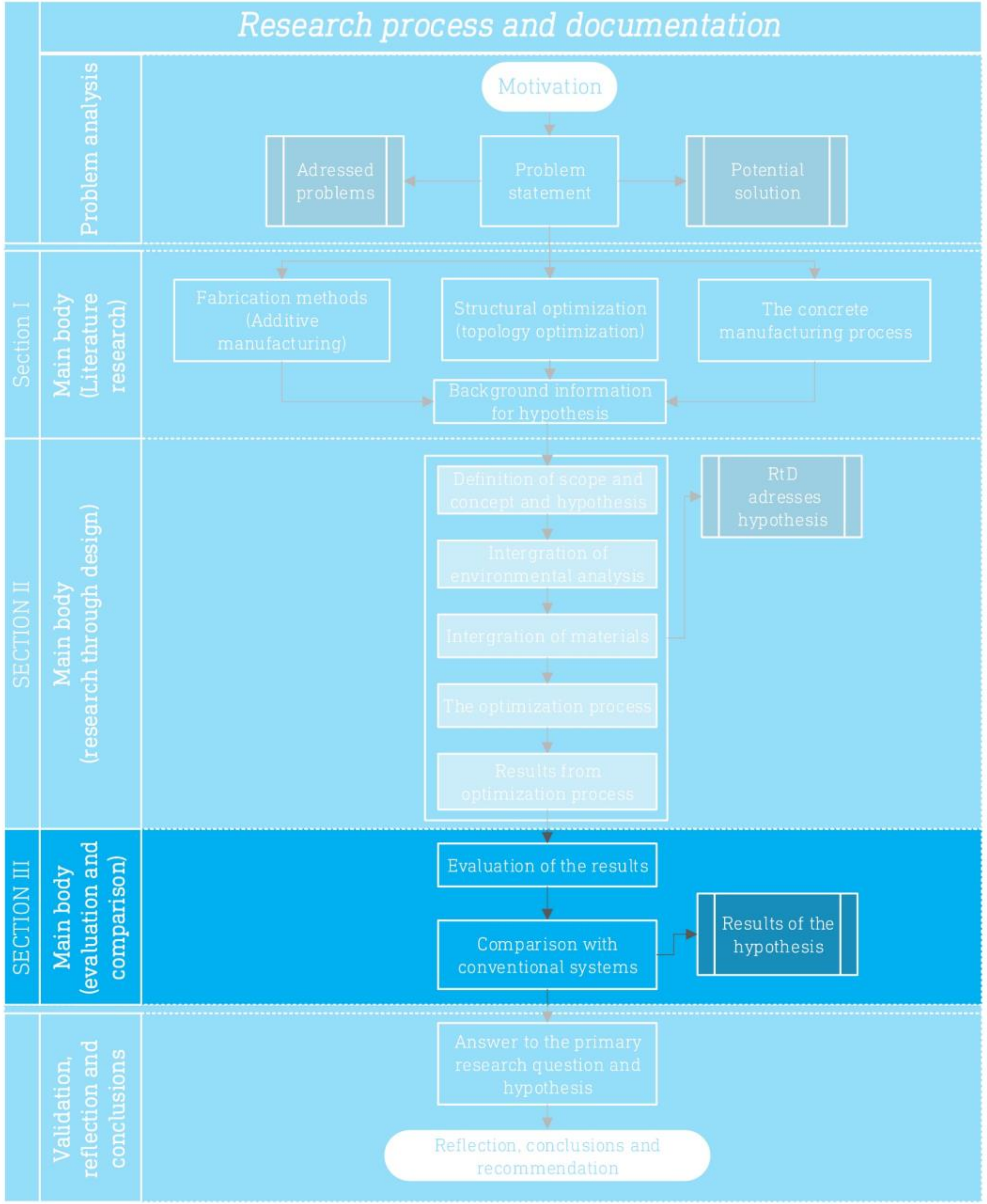


Hypothesis driven design



Hypothesis driven design

Evaluated with a Life Cycle Assessment



THE BODY OF THE RESEARCH

"Although reinforced concrete has been used for over a hundred years and with increasing interest during the last decades, few of its properties and potentialities have been fully exploited so far. Apart from the unconquerable inertia of our own minds, which do not seem to be able to adapt freely any new ideas, the main cause of this delay is a trivial technicality: The need to prepare wooden frames." – Nervi, 1956

"Although reinforced concrete has been used for over a hundred years and with increasing interest during the last decades, few of its properties and potentialities have been fully exploited so far. Apart from the unconquerable inertia of our own minds, which do not seem to be able to adapt freely any new ideas, the main cause of this delay is a trivial technicality: The need to prepare wooden frames." – Nervi, 1956

Main research question

In what manner can we use additive manufacturing and structural optimization in the building sector to address the environmental impact of concrete construction?

Why structural optimization and AM

Structural optimization provides a powerful method for generating the optimized models, while AM enables a cost-effective fabrication of geometrically complex shapes (J. Wu, Aage, N., Lefebvre, S., & Wang, C., 2017).

SECTION I
RESEARCH AS A BASIS FOR DESIGN

Main research question

Fabrication methods (AM)

Structural optimization (SO)

Concrete manufacturing (CM)

Focus on the hypothesis

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs

Fabrication methods (AM)

Process, material requirements

Sustainability of the material

Source: (Anton et al., 2020)

Fabrication methods: key findings

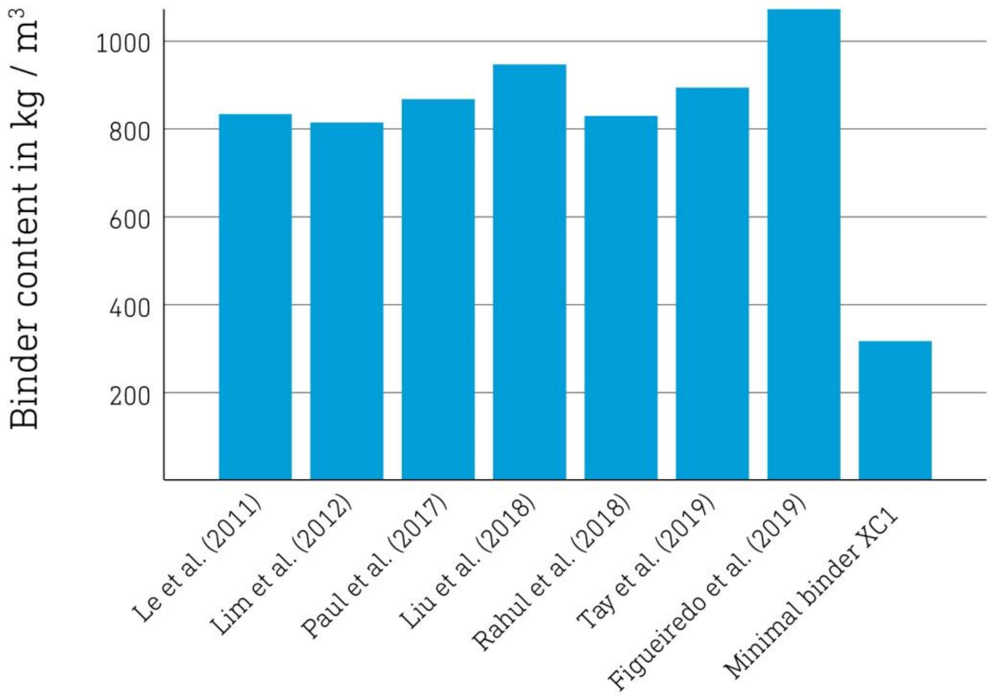
Fabrication methods (AM)
Sustainability of the material

85% of the emissions
is related to the binder in prefabricated concrete

Source: (Kong et al., 2020)

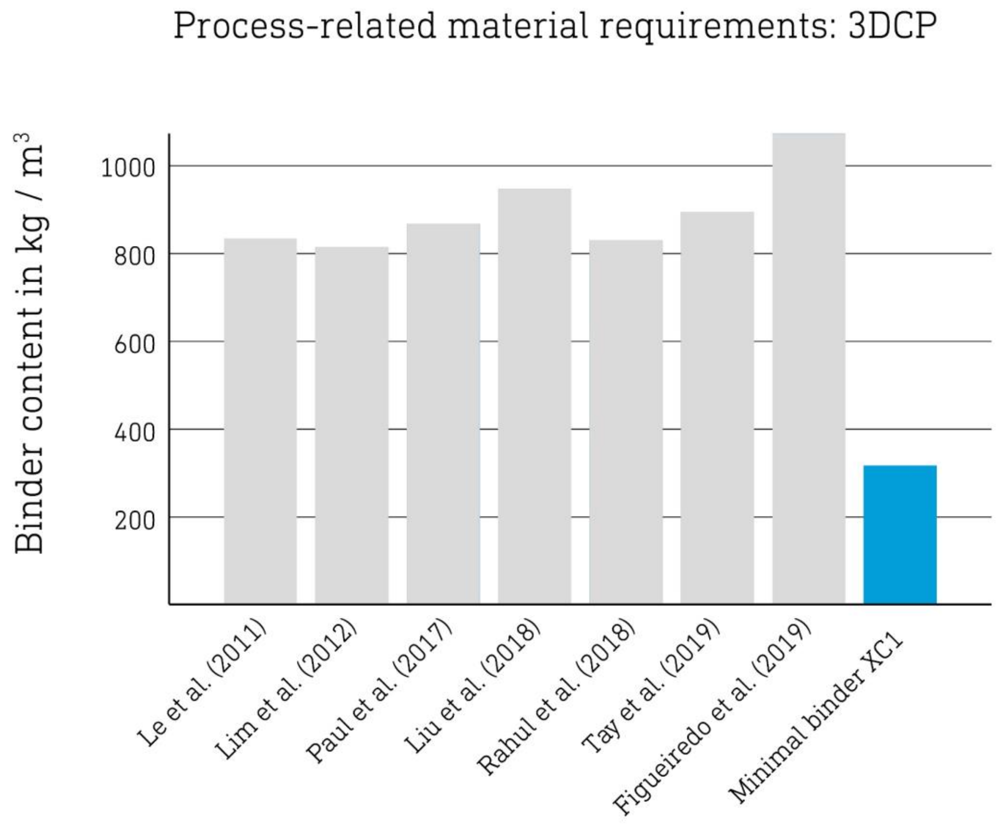
Fabrication methods (AM)
Sustainability of the material

Process-related material requirements: 3DCP



Fabrication methods (AM)

Sustainability of the material



Fabrication methods: key findings

Fabrication methods (AM)

Robustness and brittle behaviour

Difficulty of reinforcement

Robustness and brittle behaviour

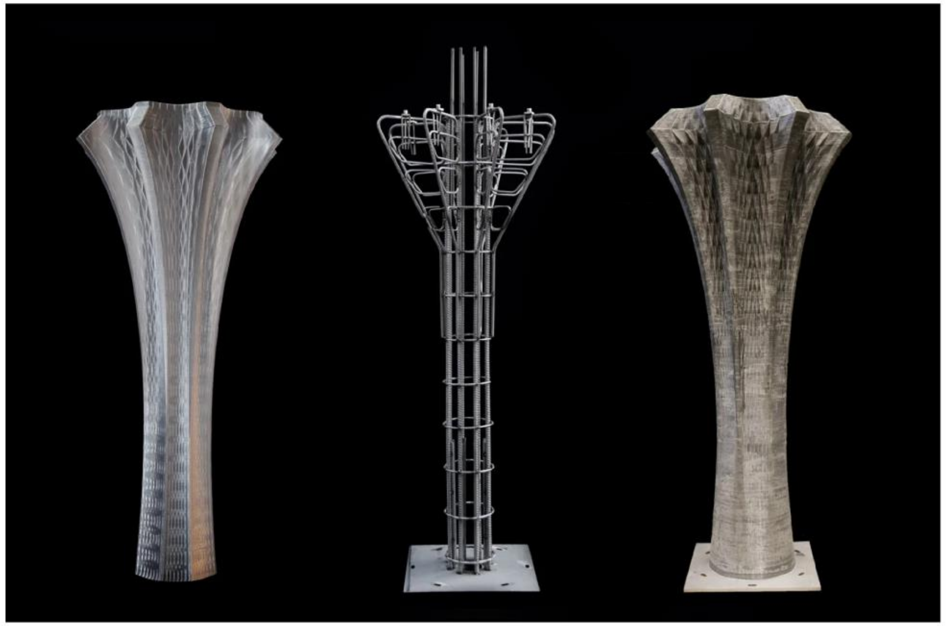
Fabrication methods (AM)
Robustness and brittle behaviour

Difficulty of reinforcement
Robustness and brittle behaviour

Source: (Menna et al., 2020)

Fabrication methods (AM)
Robustness and brittle behaviour

Difficulty of reinforcement
Robustness and brittle behaviour



Source: (Menna et al., 2020)

Fabrication methods: key findings

Fabrication methods (AM)
Conventional casting

Process, material requirements
Sustainability of the material

Difficulty of reinforcement
Robustness and brittle behaviour

Fabrication methods: key findings

Additive manufacturing is unlikely to adress the environmental impact of concrete construction

Fabrication methods: key findings

Process-related material requirements

Fabrication methods: key findings

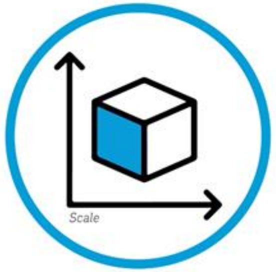
Process-related material requirements

Reinforcement

Fabrication methods: key findings

Process-related material requirements

Reinforcement

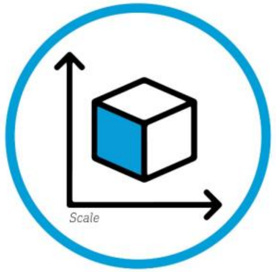


Scalability

Fabrication methods: key findings

Process-related material requirements

Reinforcement



Scalability

Life cycle cost

Structural optimization (SO)

Methods of structural optimization

Form finding of compression only structures

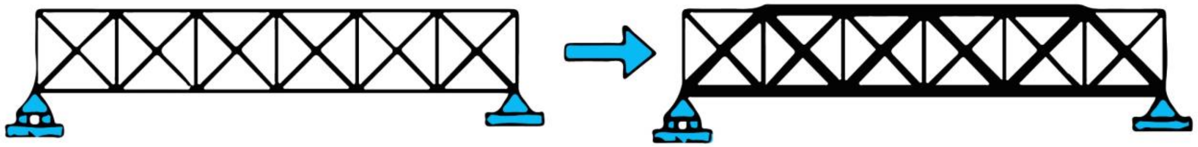
Black-box approach to concurrent optimization processes

Structural optimization (SO)

Methods of structural optimization

Structural optimization (SO)

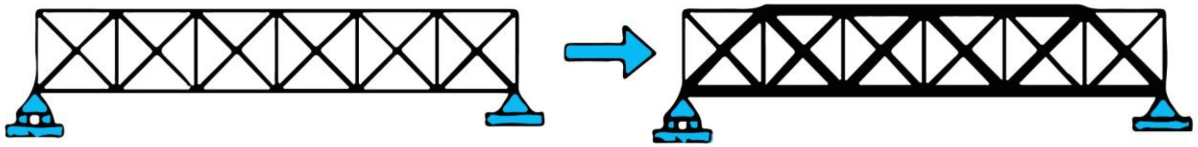
Methods of structural optimization



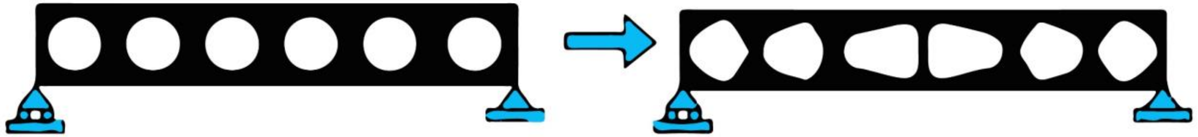
Size optimization

Source: (Gebisa & Lemu, 2017)

Structural optimization (SO)
Methods of structural optimization



Size optimization

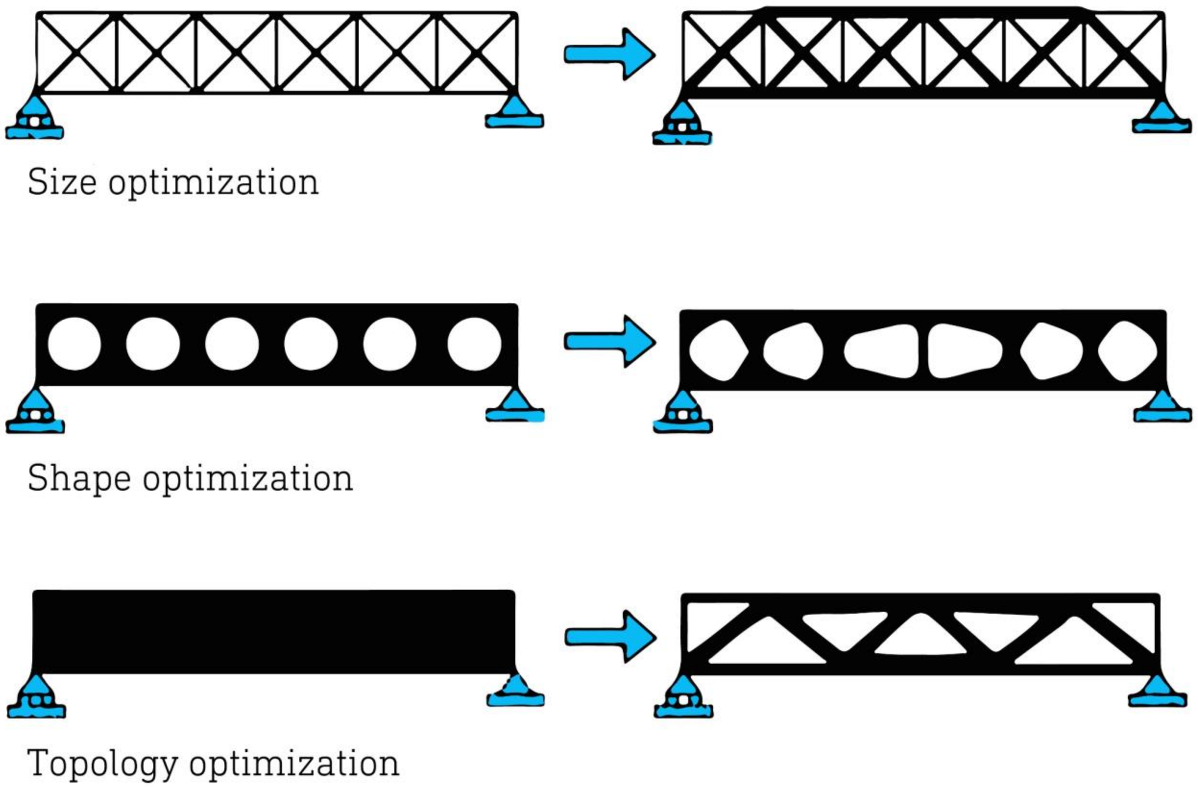


Shape optimization

Source: (Gebisa & Lemu, 2017)

Structural optimization (SO)

Methods of structural optimization



Source: (Gebisa & Lemu, 2017)

Structural optimization: key findings

Structural optimization (SO)
Methods of structural optimization

Material properties
Concrete is strong in compression

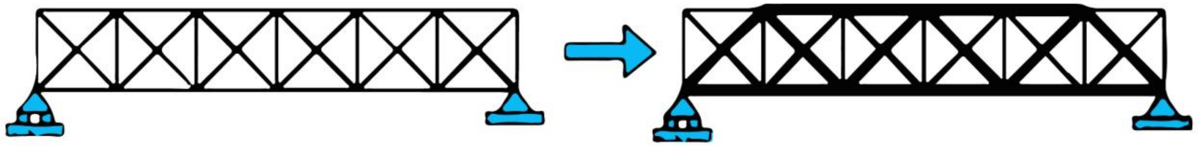
floorslab properties
Distributed Q-load

Structural optimization (SO)

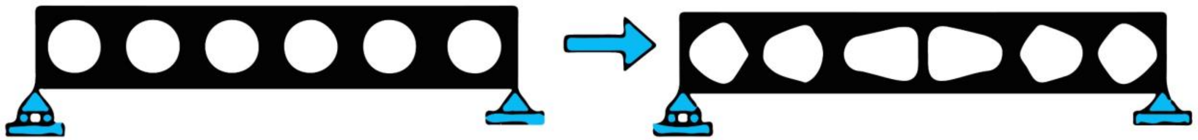
Methods of structural optimization

Structural optimization

for a compression dominant floor slab



Size optimization



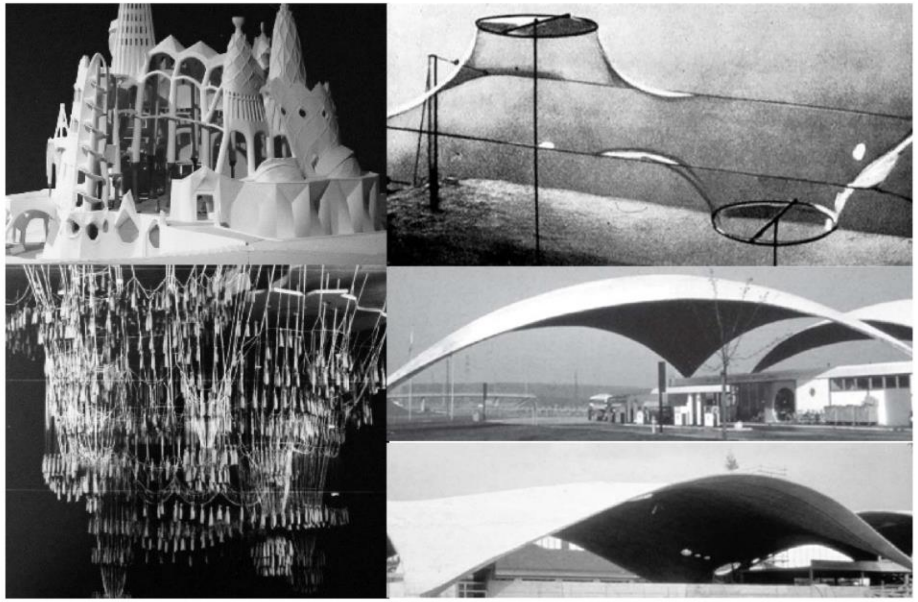
Shape optimization

Structural optimization (SO)

Form finding of compression only structures

Form finding of structures

for a compression dominant floor slab



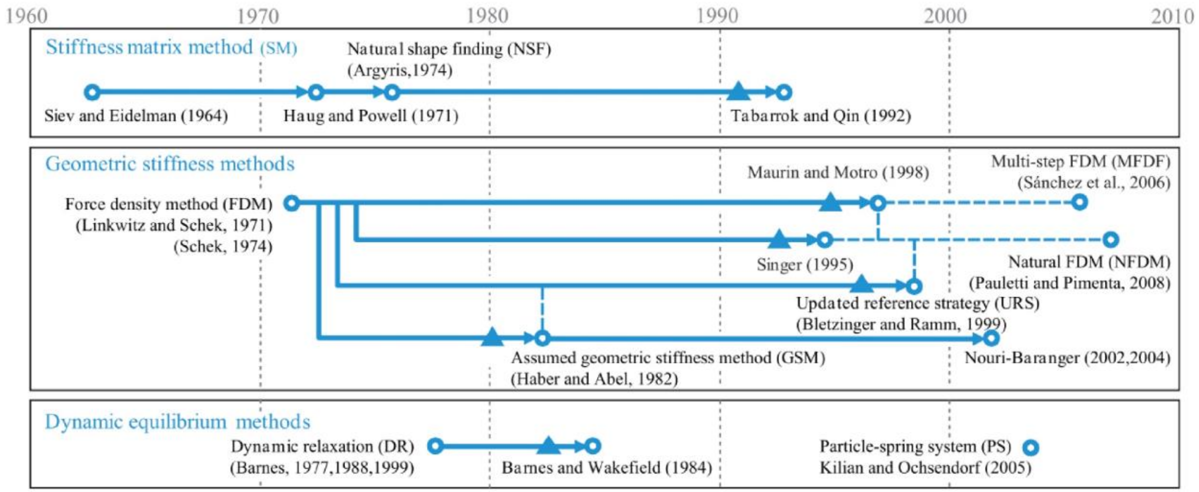
Source: (Matthias Rippmann, 2016)

Structural optimization (SO)

Form finding of compression only structures

Form finding of structures

With computational tools



Source: (Veenendaal & Block, 2012)

Structural optimization (SO)
Form finding of compression only structures

The variable shell thickness
The optimal floorslab has a variable height

Structural optimization: key findings

Structural optimization (SO)
Form finding of compression only structures

The variable shell thickness
The optimal floorslab has a variable height

Multiple loadcases are guiding
not able to have a concurrent optimization process

Structural optimization: key findings

Structural optimization (SO)

Form finding of compression only structures

The variable shell thickness

The optimal floorslab has a variable height

Multiple loadcases are guiding

not able to have a concurrent optimization process

Fabrication constraints

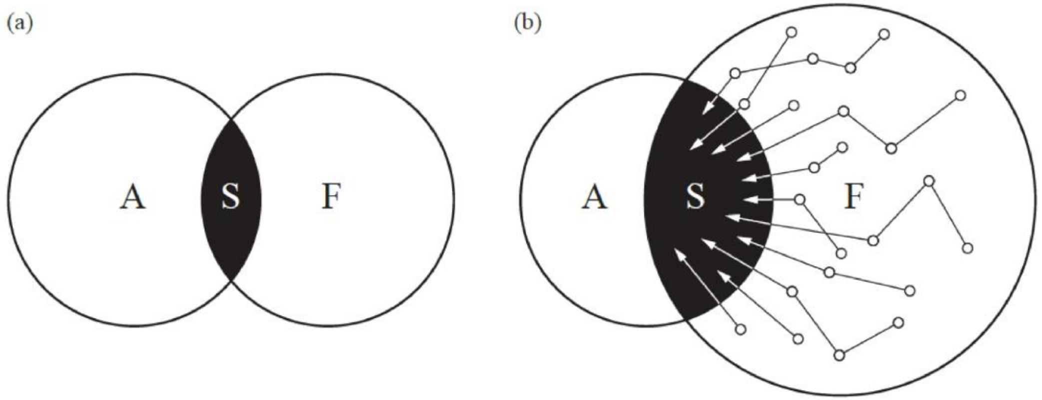
Cannot be intergrated directly in funicular methods

Structural optimization (SO)

Form finding of compression only structures

Form-finding as a tool

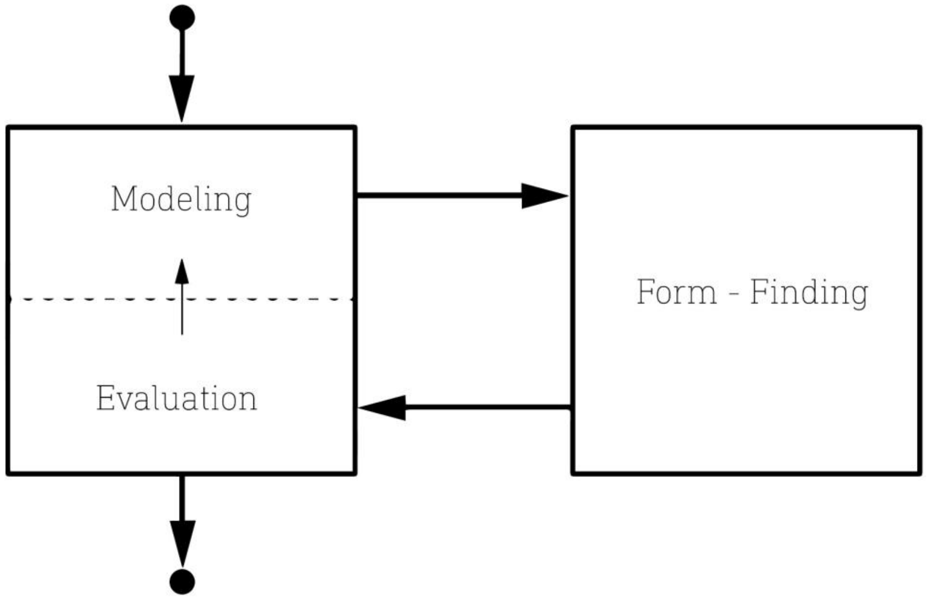
for shape optimization



Source: (Matthias Rippmann, 2016)

Structural optimization (SO)
Form finding of compression only structures

Form-finding as a tool
for shape optimization

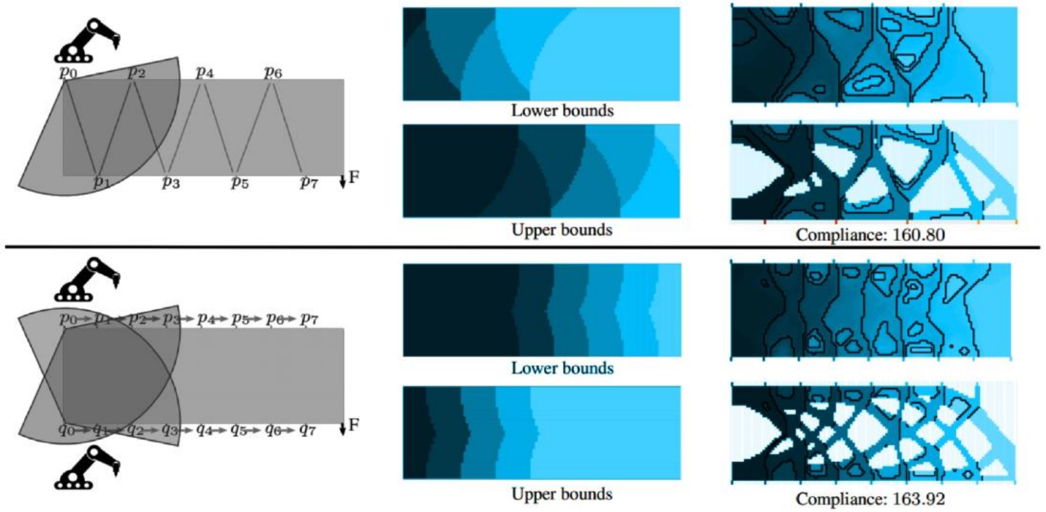


Structural optimization (SO)

Concurrent optimization

Concurrent optimization process

With computational tools



Source: (Wang et al., 2020)

Structural optimization: key findings

Structural optimization (SO)
Concurrent optimization

Concurrent optimization process
With computational tools

Why is there little research?
in concurrent optimization methods

Structural optimization: key findings

Structural optimization (SO)
Concurrent optimization

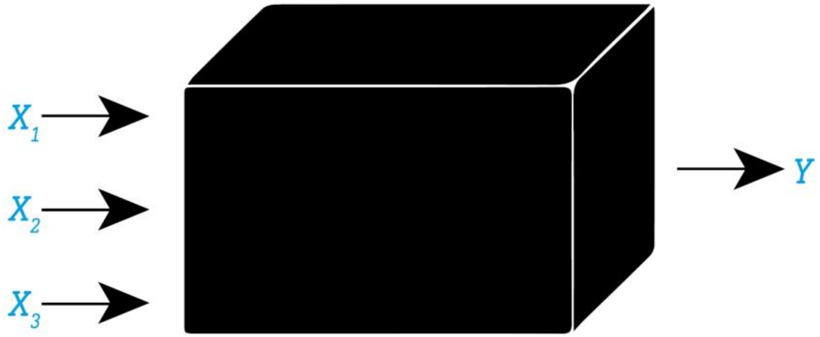
Concurrent optimization process
With computational tools

Why is there little research?
in concurrent optimization methods

No clear objective function
In multi-objective, fabrication-aware problems

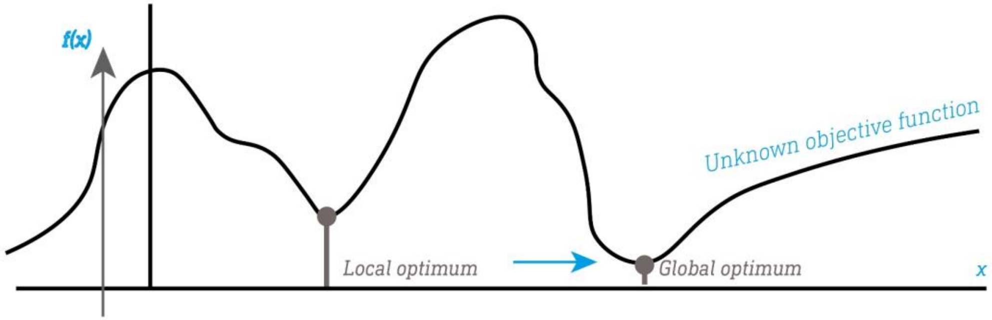
Structural optimization (SO)
Concurrent optimization

Concurrent optimization process
Using derivative free optimization



Structural optimization (SO)
Concurrent optimization

Derivative free optimization
to find the global optimum



Structural optimization: key findings

Structural optimization (SO)

Concurrent optimization

Derivative free optimization

to find the global optimum

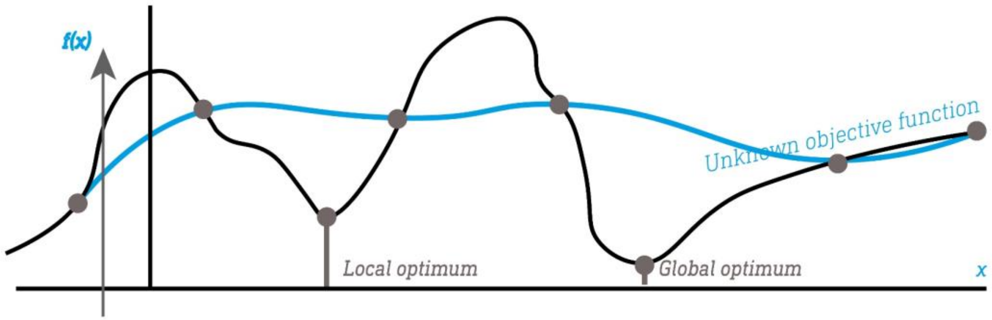
Metaheuristic methods

Direct-search methods

Model-based methods

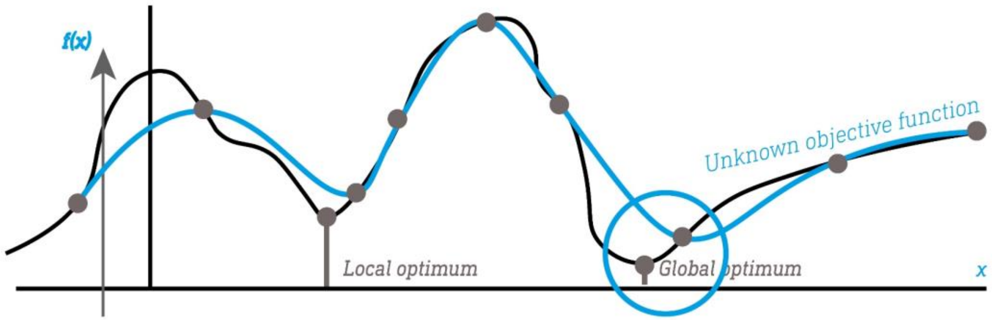
Structural optimization (SO)
Concurrent optimization

Model-based optimization
to find the global optimum



Structural optimization (SO)
Concurrent optimization

Concurrent optimization process
Using derivative free optimization



Floor slab optimization

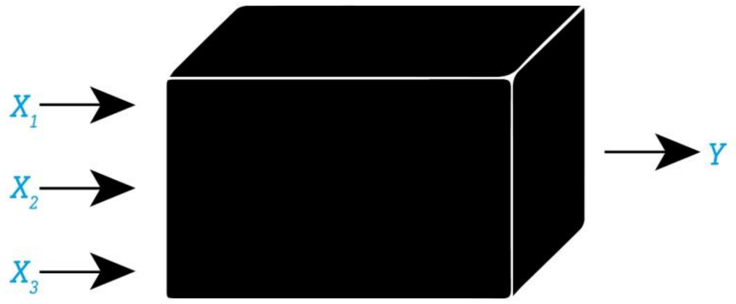
Structural optimization (SO)

Floor slab optimization

Structural optimization (SO)

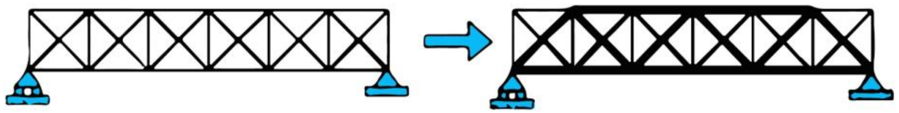
Derivative-free optimization process

using surrogate-model based optimization solvers

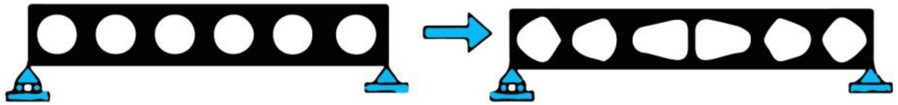


Floor slab optimization
Structural optimization (SO)

Shape and size optimization
To find the structural form



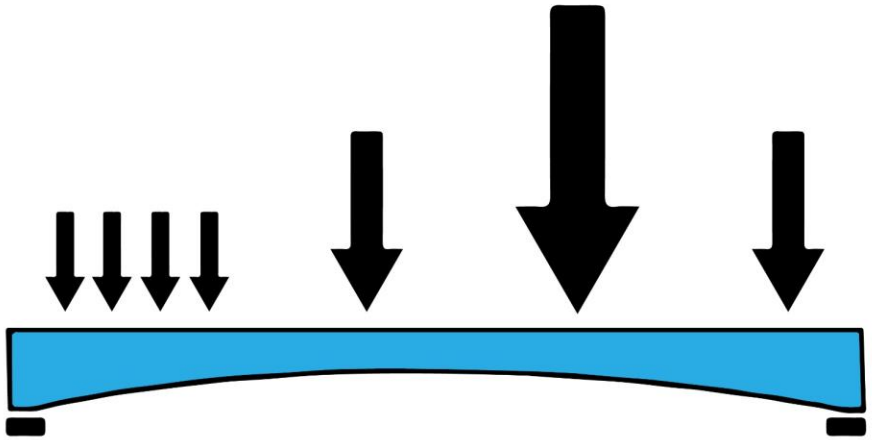
Size optimization



Shape optimization

Floor slab optimization
Structural optimization (SO)

Intergration of multiple loadcases
in the optimization process



Floor slab optimization
Structural optimization (SO)

Fabrication constraints
taken into account

Structural optimization: key findings

Floor slab optimization

Structural optimization (SO)

Derivative-free optimization process

using surrogate-model based optimization solvers

Shape and size optimization

To find the structural form

Intergration of multiple loadcases

in the optimization process

Fabrication constraints

taken into account

Structural optimization: key findings

Structural optimization will likely be highly effective, in adressing the environmental impact of floor slabs

Concrete emissions: key findings

Concrete manufacturing (CM)

Where are the emissions?

In concrete construction

What can we do?

to reduce the emissions

Concrete emissions: key findings

Concrete manufacturing (CM)

Environmental impact of concrete

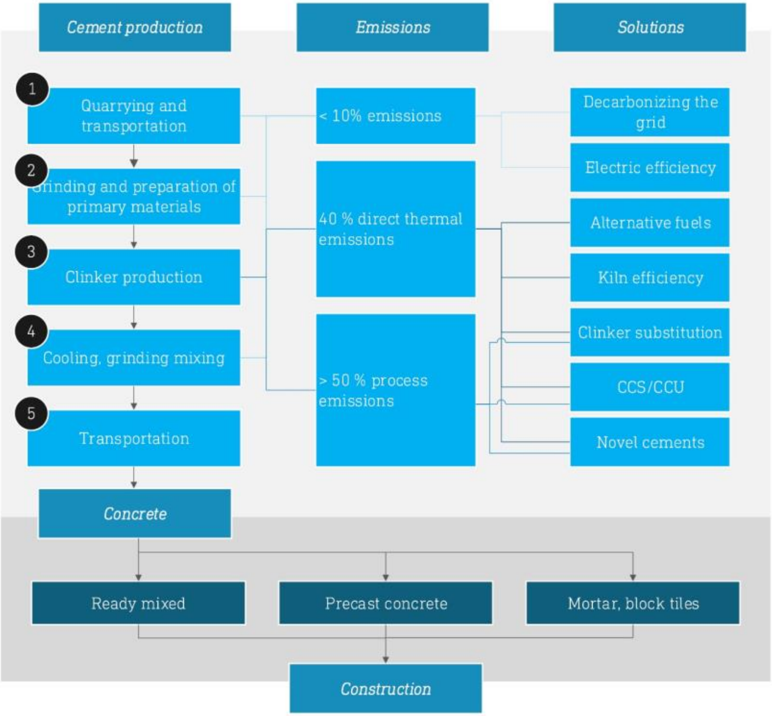
85% of the emissions

is related to the binder in prefabricated concrete

Source: (Kong, Kang, He, Li, & Wang, 2020)

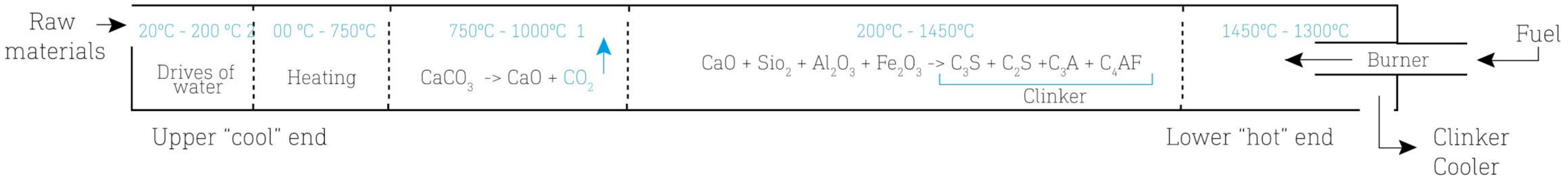
Concrete manufacturing (CM)
Environmental impact of concrete

85% of the emissions
is related to the binder in prefabricated concrete



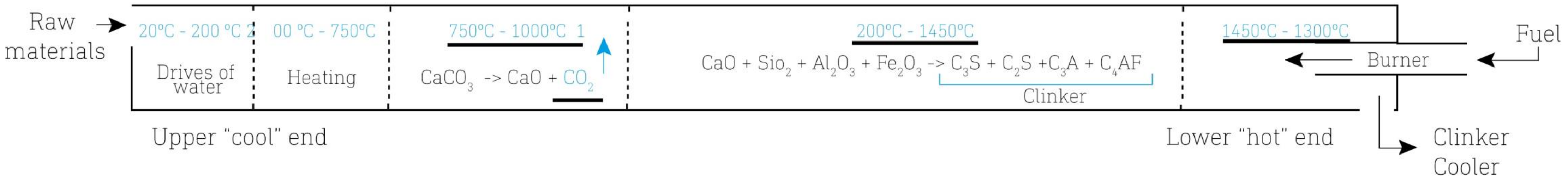
Source: (J. Lehne & F. Preston, 2018)

Concrete emissions: key findings



Source: (Van Oss & Padovani, 2002)

Concrete emissions: key findings



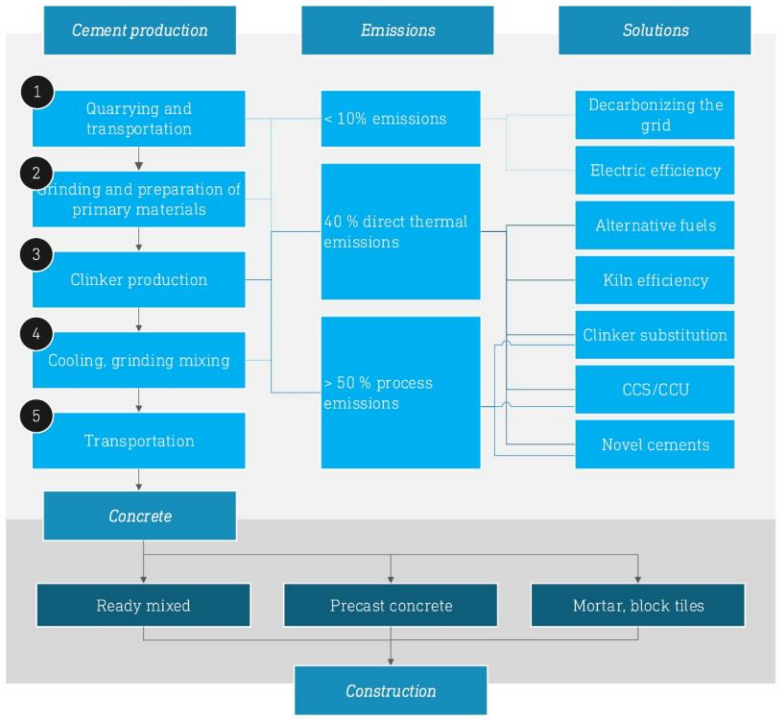
Source: (Van Oss & Padovani, 2002)

Concrete manufacturing (CM)

Environmental impact of concrete

85% of the emissions

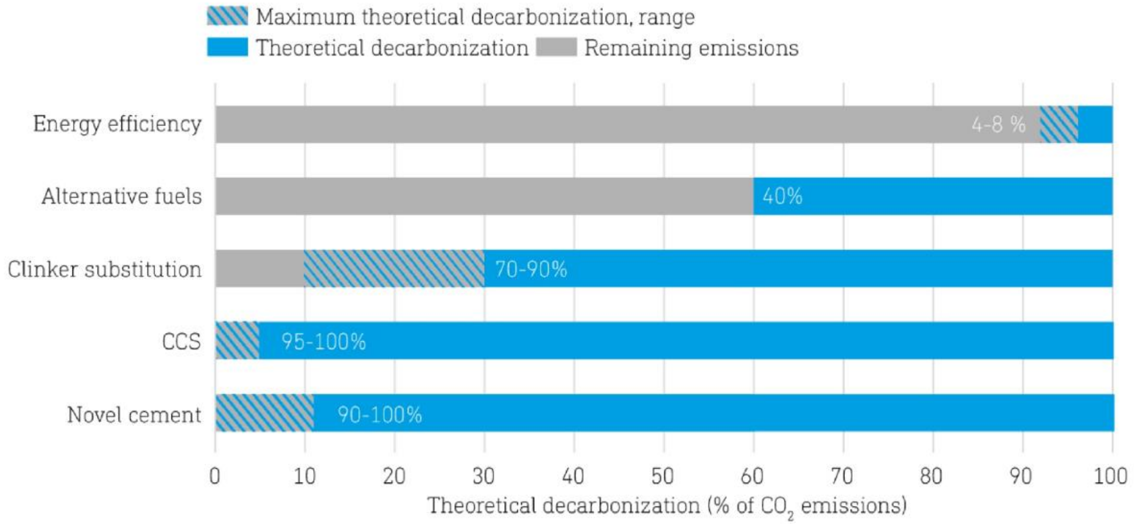
is related to the binder in prefabricated concrete



Source: (J. Lehne & F. Preston, 2018)

Concrete manufacturing (CM)
Reducing the environmental impact

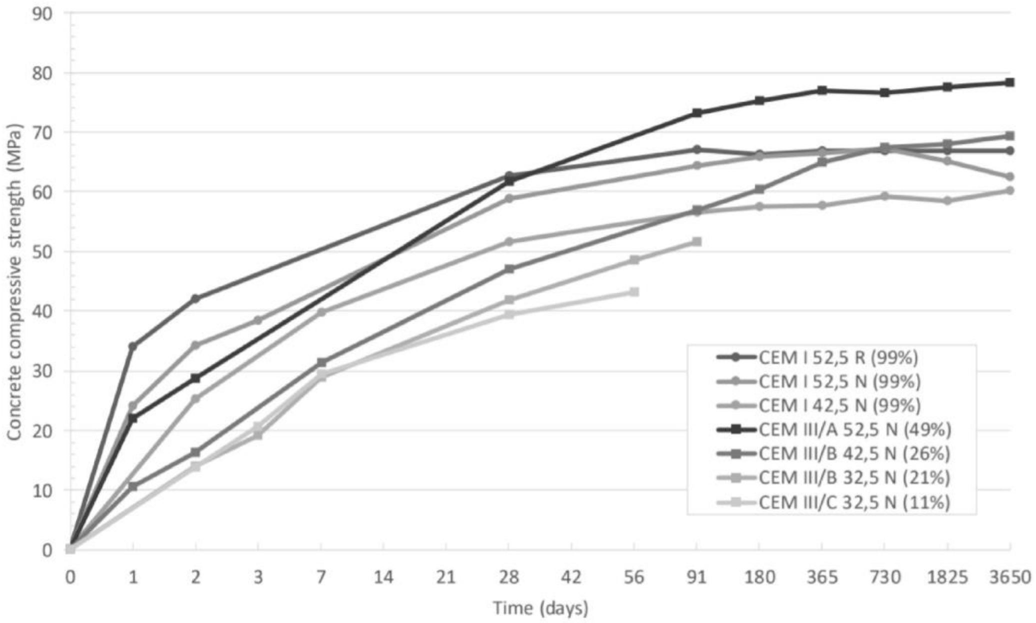
Reducing of the impact
What is the effectivity of the measures?



Source: (J. Lehne & F. Preston, 2018)

Concrete manufacturing (CM)
Reducing the environmental impact of the floorslab

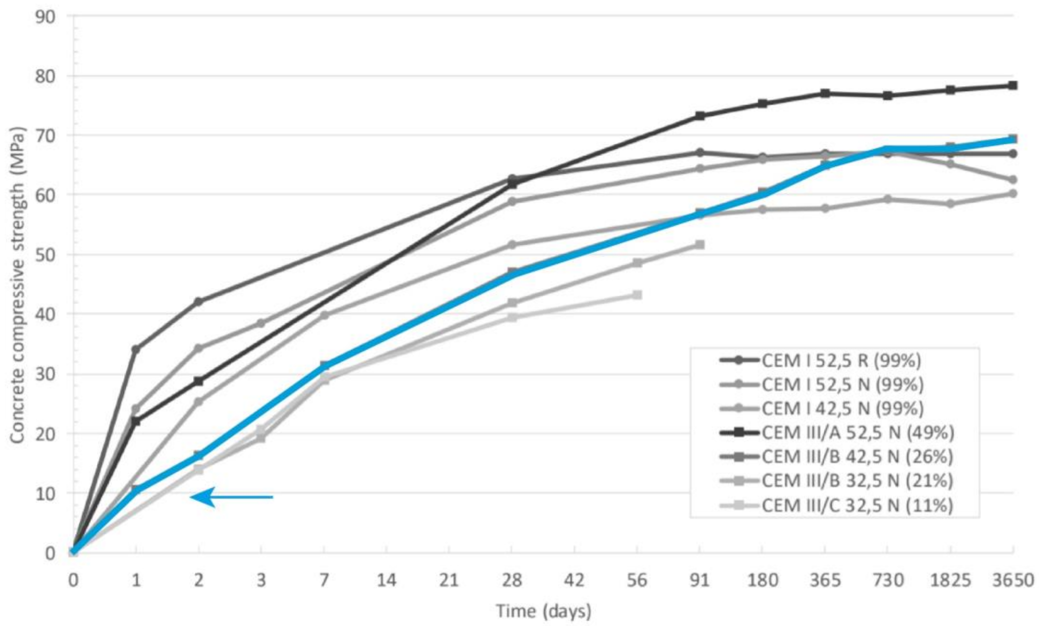
Use of clinker substitutes (SCMs)
in Portland clinker-based cement



Source: (Wijte, 2019)

Concrete manufacturing (CM)
Reducing the environmental impact of the floorslab

Use of clinker substitutes (SCMs)
in Portland clinker-based cement



Source: (Wijte, 2019)

Concrete emissions: key findings

Concrete manufacturing (CM)

Reducing the environmental impact of the floorslab

Use of clinker substitutes (SCMs)

in Portland clinker-based cement

More efficient use of clinker

by optimizing for lower strength concrete

SECTION II
HYPOTHESIS DRIVEN DESIGN

Hypothesis

Fabrication-aware, structurally optimized floor slabs can significantly reduce the environmental impact of concrete construction.

This adresses a current gap in literature

In a derivative-free optimization approach for concurrent structural design problems (e.g. taking into account fabrication constraints, and multiple loadcases)

Floor slab optimization

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs

1. Introduction of the flooring system
Thin-shells, shell theory, and critical aspect

2. Boundary conditions
loadcase, material intergration and assumptions

3. The optimization algorithm
Insight on the optimization process

4. Resulting floorslabs
The basis for the LCA analysis

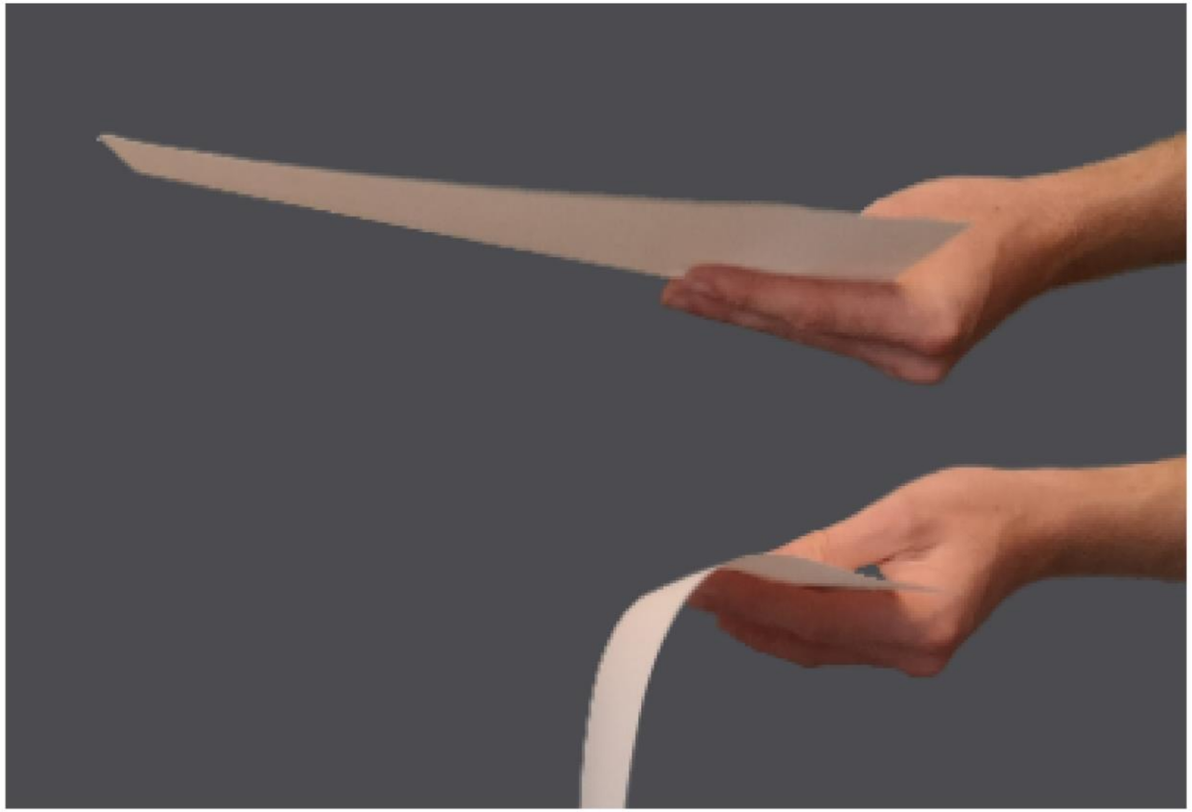
1. INTRODUCTION OF THE FLOORING SYSTEM

Strength through geometry

Source: (Block et al., 2020) / (Eisenbach, 2017) / (Boston pubilc library, 1889)

1. INTRODUCTION OF THE FLOORING SYSTEM

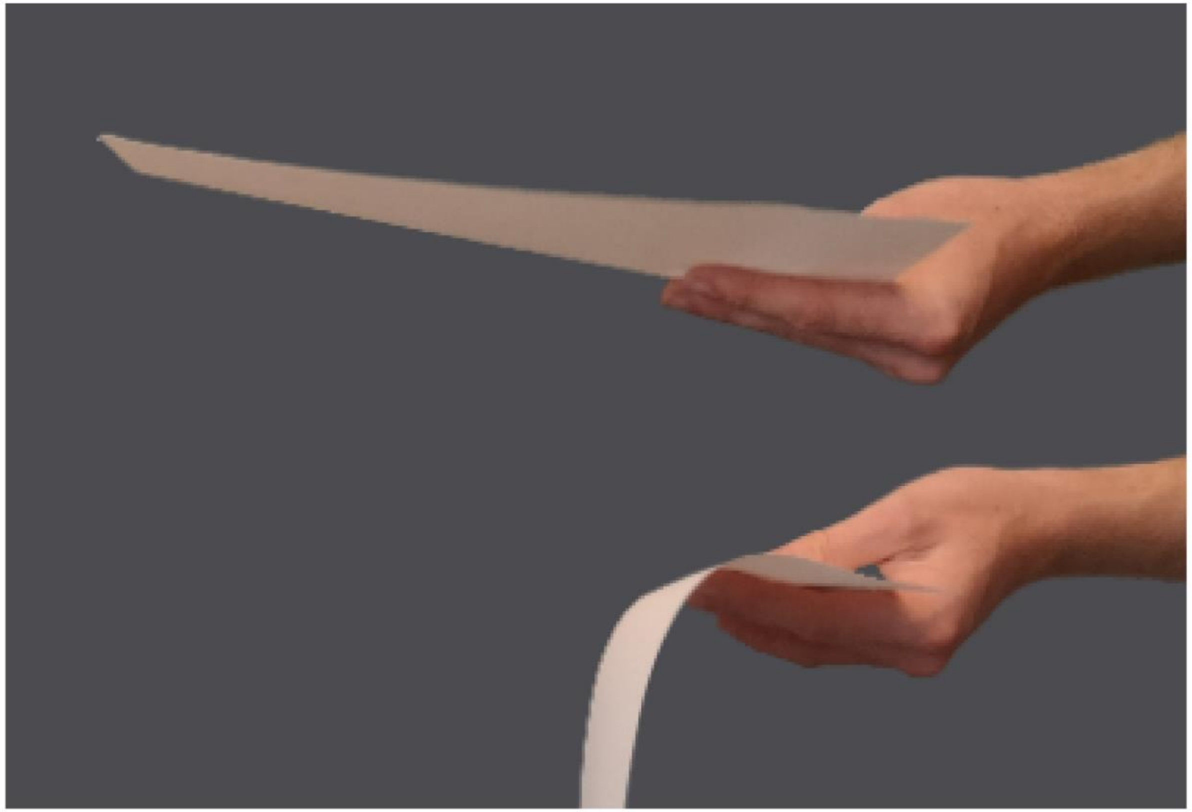
Strength through geometry

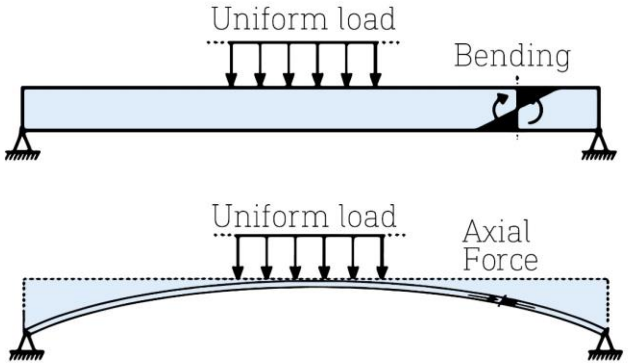


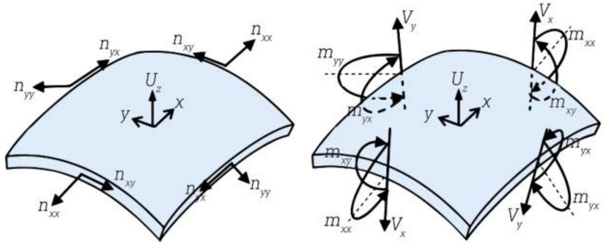
The concept

1. INTRODUCTION OF THE FLOORING SYSTEM

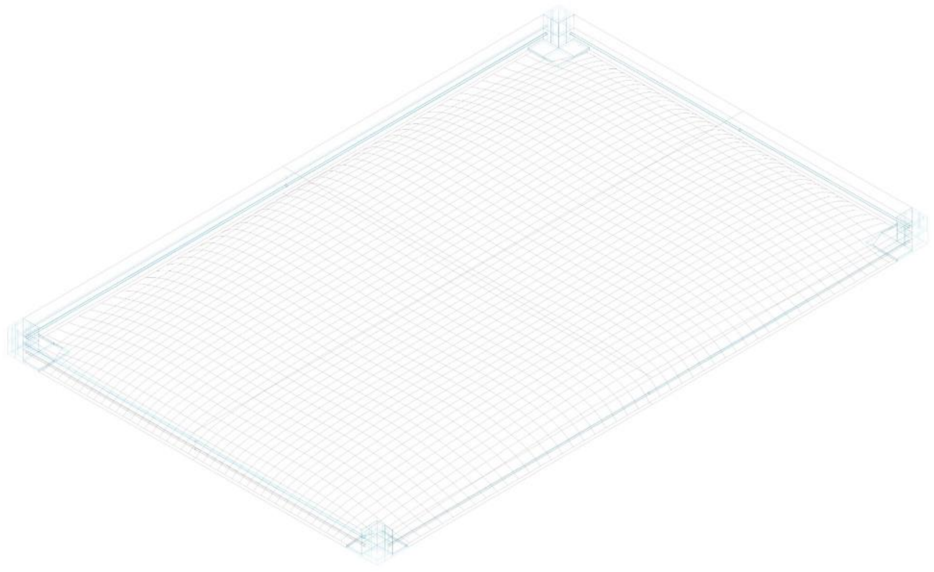
Strength through geometry

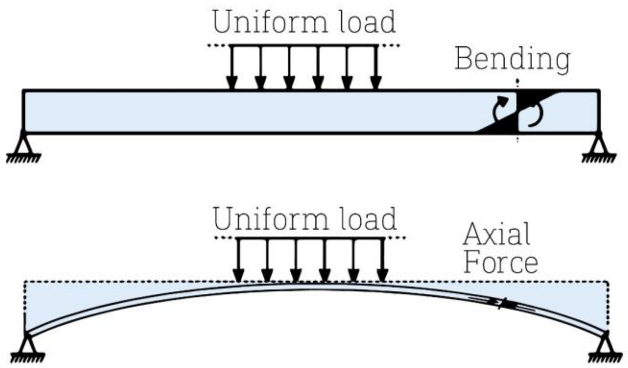


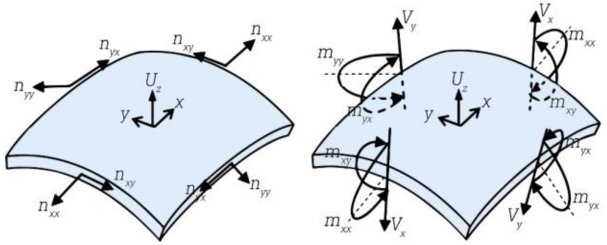




1. INTRODUCTION OF THE FLOORING SYSTEM





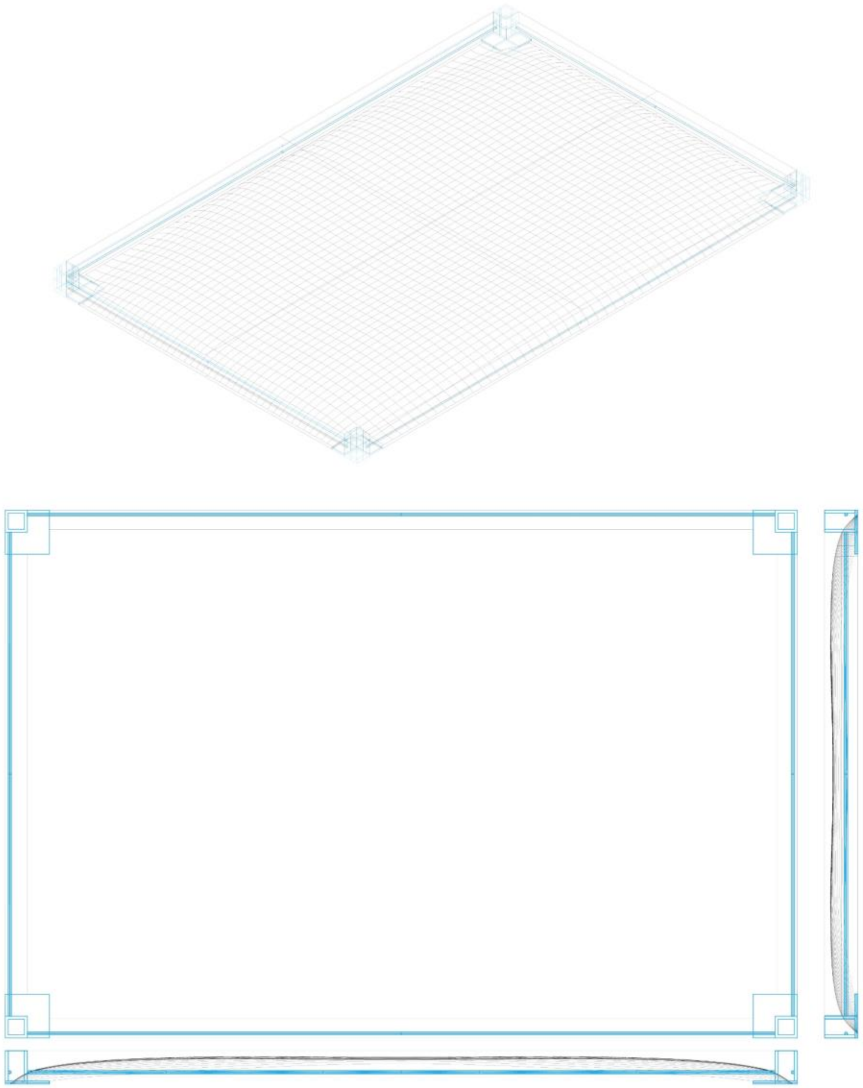


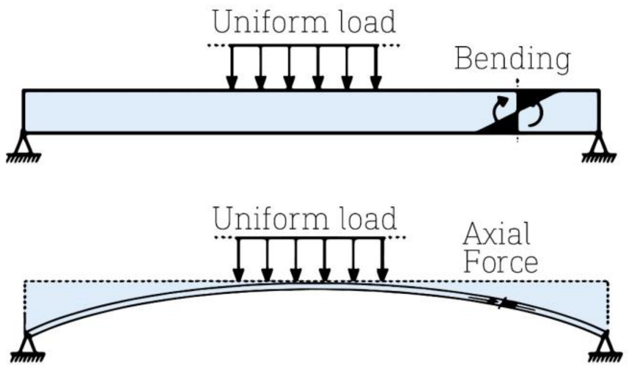
Membrane Forces

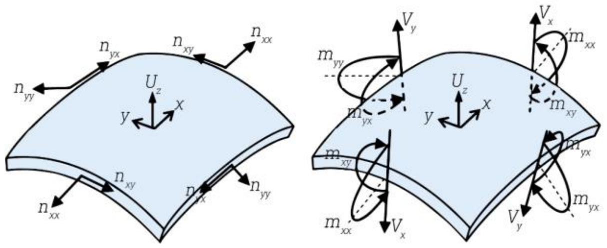
Moment and shear forces

The concept

1. INTRODUCTION OF THE FLOORING SYSTEM





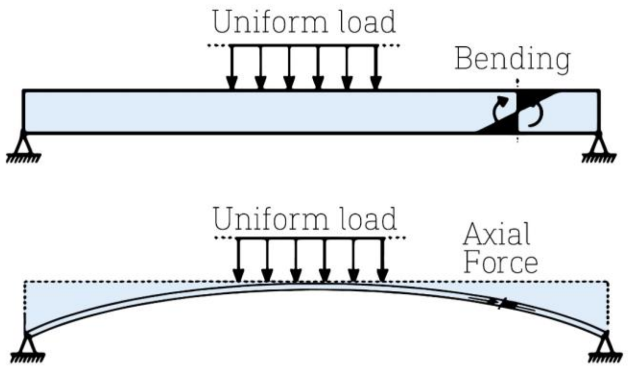


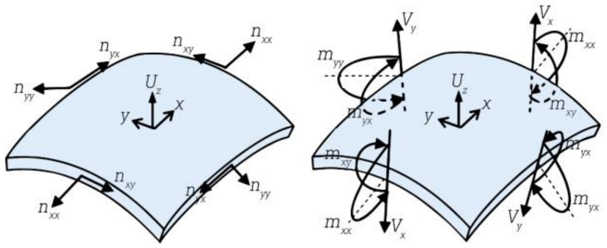
Membrane Forces   Moment and shear forces

1. INTRODUCTION OF THE FLOORING SYSTEM

Casting as the fabrication method

Due to material related emissions



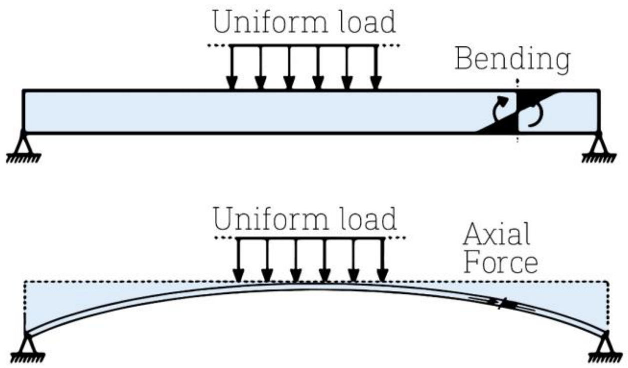


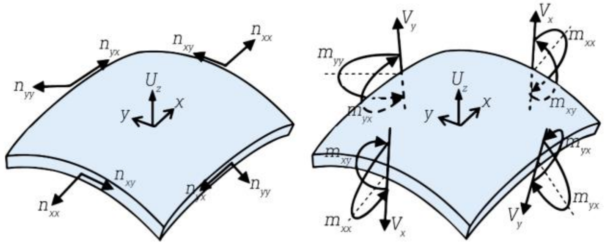
Membrane Forces   Moment and shear forces

1. INTRODUCTION OF THE FLOORING SYSTEM

Casting as the fabrication method
Due to material related emissions

Simplicity over complexity
in the fabrication process





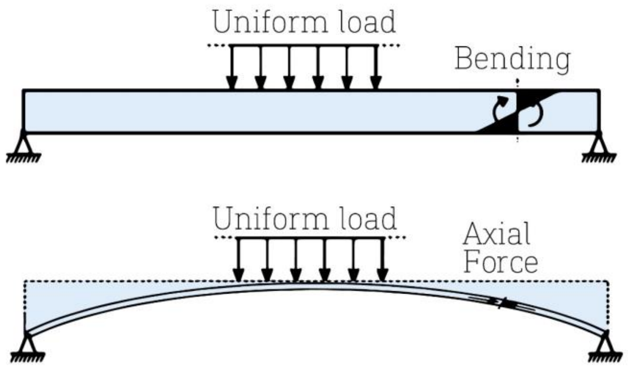
The concept

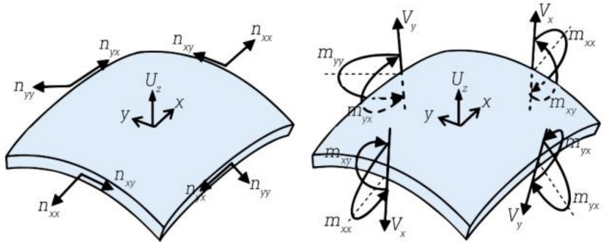
1. INTRODUCTION OF THE FLOORING SYSTEM

Casting as the fabrication method
Due to material related emissions

Simplicity over complexity
in the fabrication process

Prefabrication and modularization
Reusability of the formwork, and further optimization





Membrane Forces   Moment and shear forces

The concept

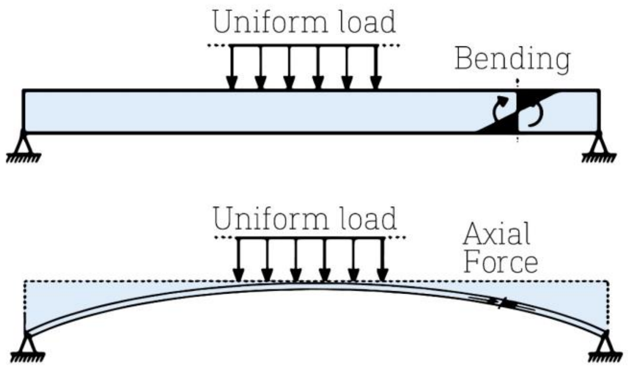
1. INTRODUCTION OF THE FLOORING SYSTEM

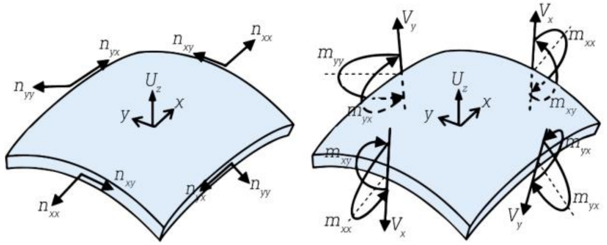
Casting as the fabrication method
Due to material related emissions

Simplicity over complexity
in the fabrication process

Prefabrication and modularization
Reusability of the formwork, and further optimization

Conform the building regulation
To allow for a more direct application





Membrane Forces

Moment and shear forces

The concept

1. INTRODUCTION OF THE FLOORING SYSTEM

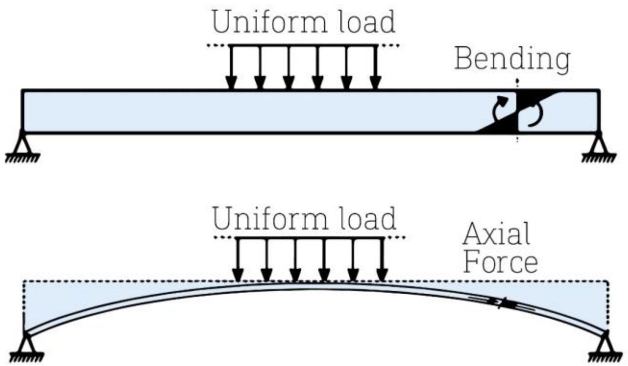
Casting as the fabrication method
Due to material related emissions

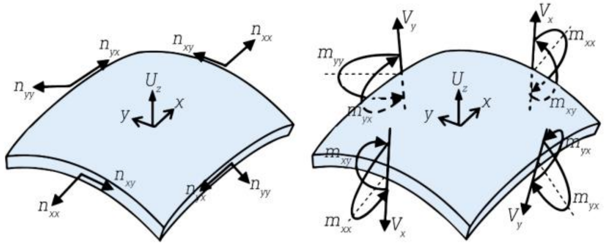
Simplicity over complexity
in the fabrication process

Prefabrication and modularization
Reusability of the formwork, and further optimization

Conform the building regulation
To allow for a more direct application

Focus on the LCA
in the hypothetical office building





Membrane Forces

Moment and shear forces

1. INTRODUCTION OF THE FLOORING SYSTEM

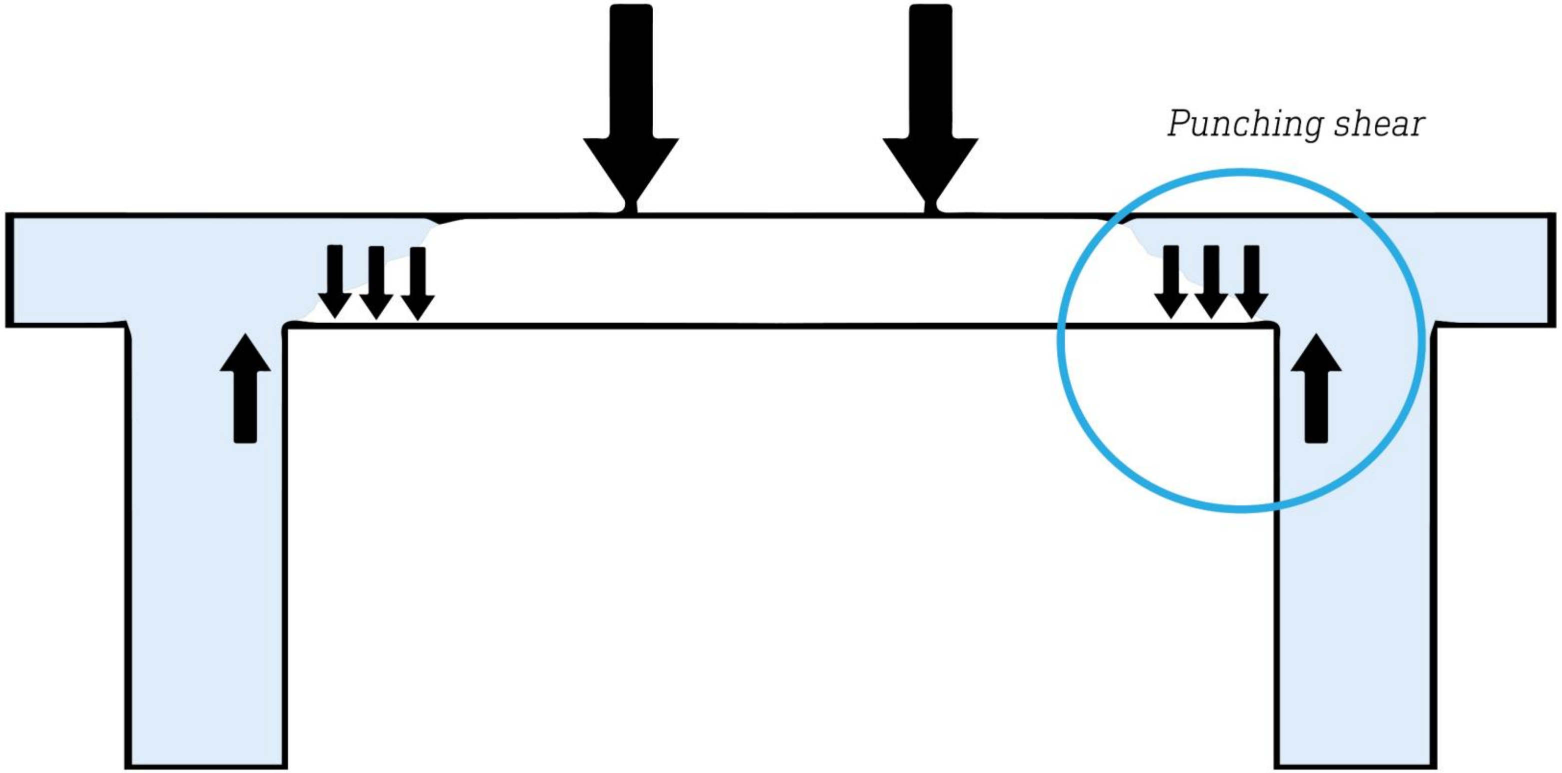
Punching shear
Four support points

Fire safety
Of the exposed steel

What will it look like?
the flooring system

1. INTRODUCTION OF THE FLOORING SYSTEM

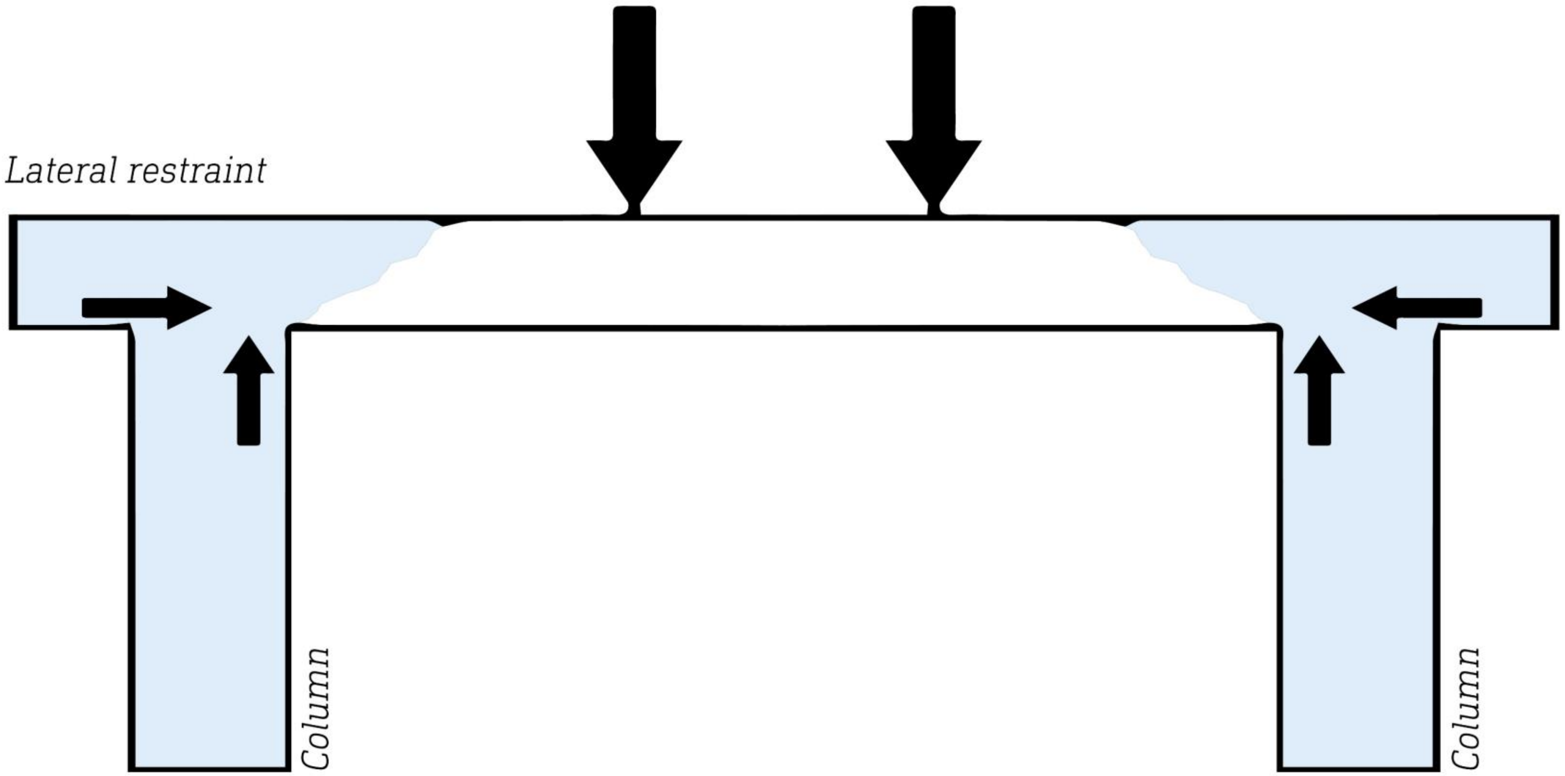
Punching shear
Four support points



Source: (Wijte, 2019)

1. INTRODUCTION OF THE FLOORING SYSTEM

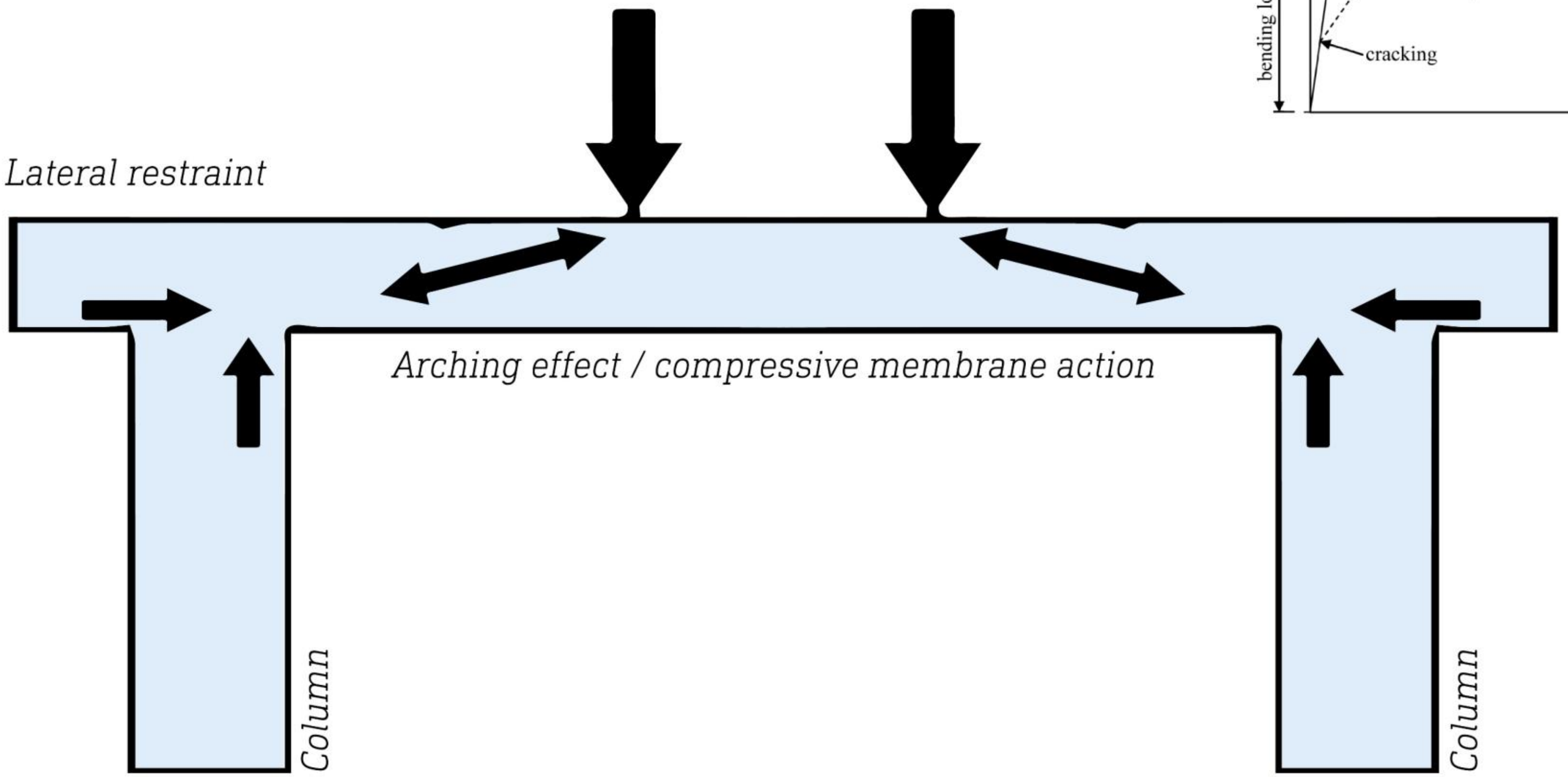
Punching shear
Four support points

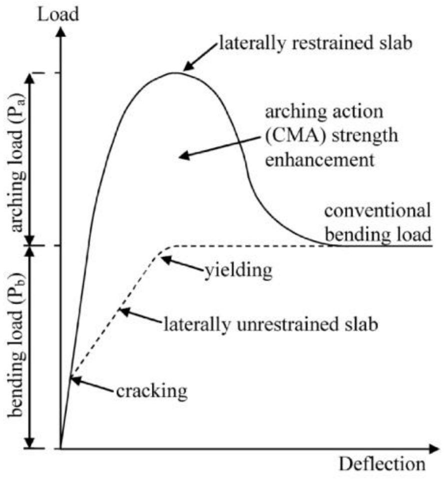


1. INTRODUCTION OF THE FLOORING SYSTEM

Punching shear

Four support points



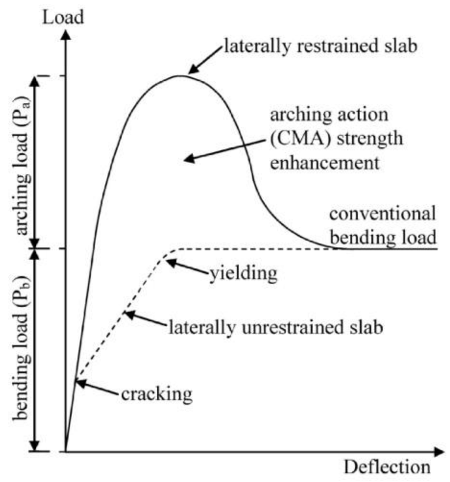


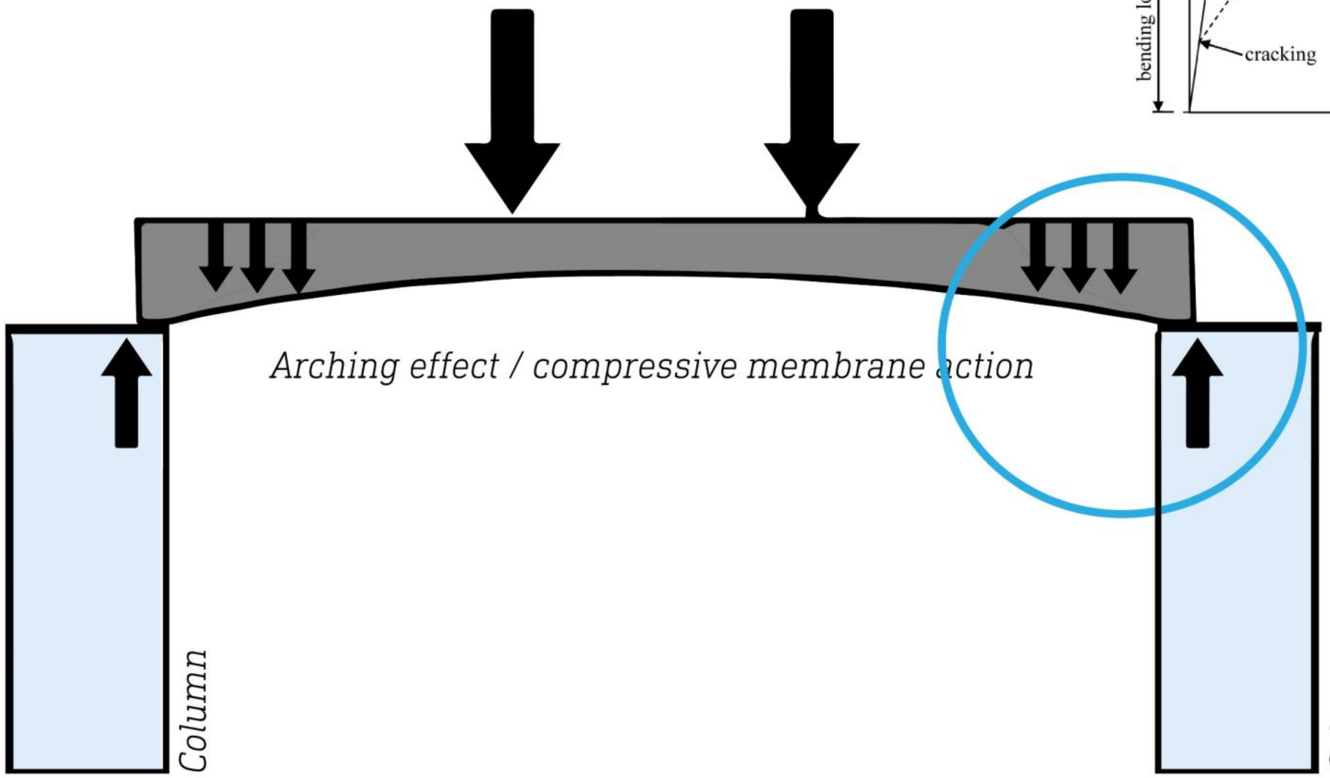
Source: (Rankin, et al. (1997)

1. INTRODUCTION OF THE FLOORING SYSTEM

Punching shear

Four support points

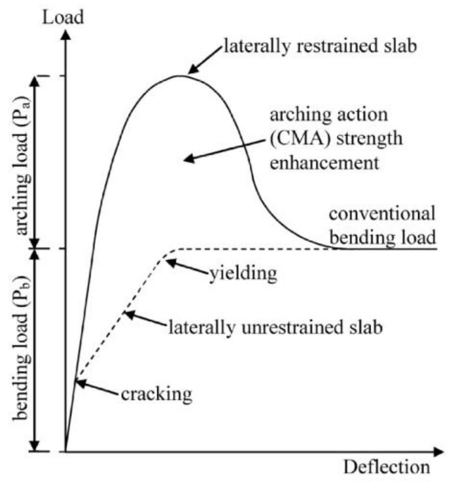


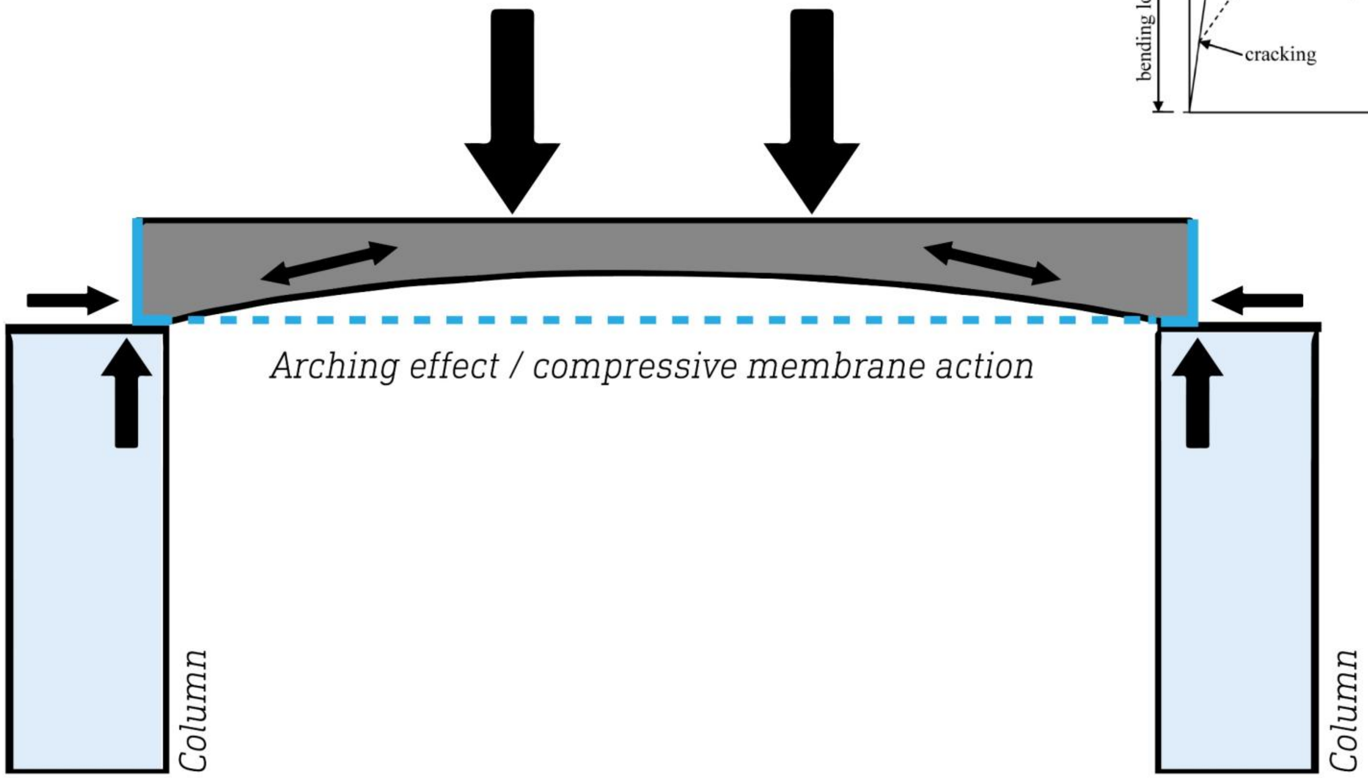


Source: (Rankin, et al. (1997))

1. INTRODUCTION OF THE FLOORING SYSTEM

Punching shear
Four support points

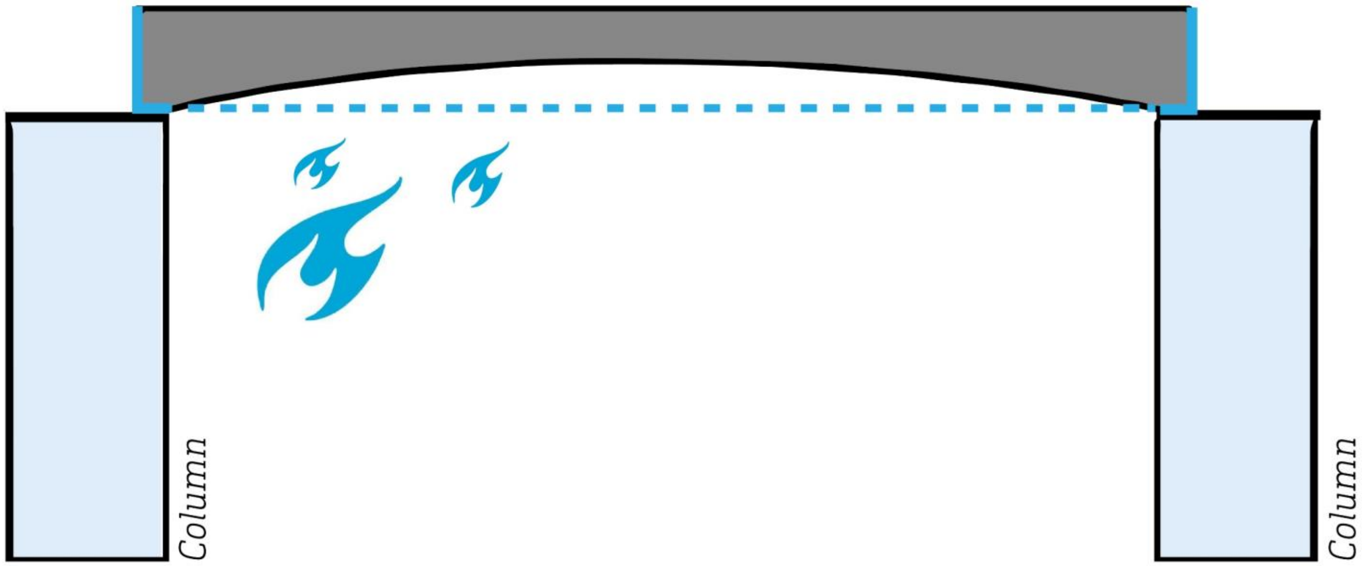




Source: (Rankin, et al. (1997)

1. INTRODUCTION OF THE FLOORING SYSTEM

Fire safety
Of the exposed steel

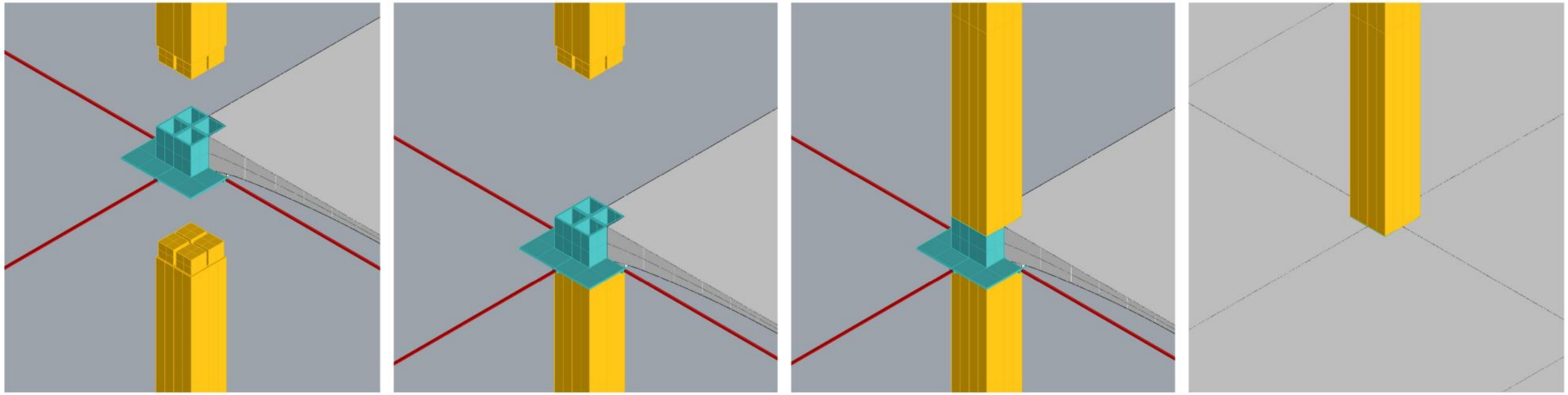


Source: (Rankin, et al. (1997)

1. INTRODUCTION OF THE FLOORING SYSTEM

Fire safety
Of the exposed steel

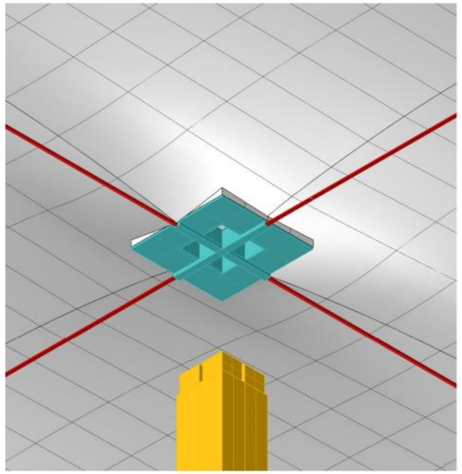
No exposed steel on the top side

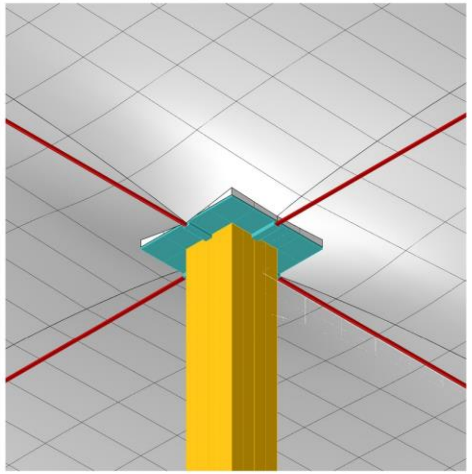


1. INTRODUCTION OF THE FLOORING SYSTEM

Fire safety
Of the exposed steel

Intumescent coating

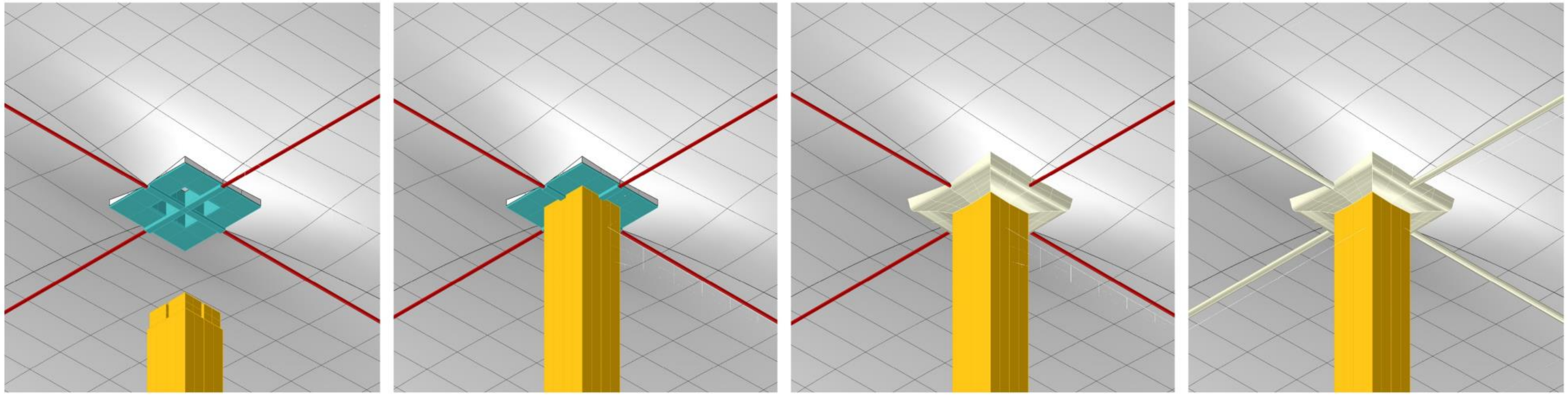




1. INTRODUCTION OF THE FLOORING SYSTEM

Fire safety
Of the exposed steel

Intumescent coating | *Covering it with an insulating material*



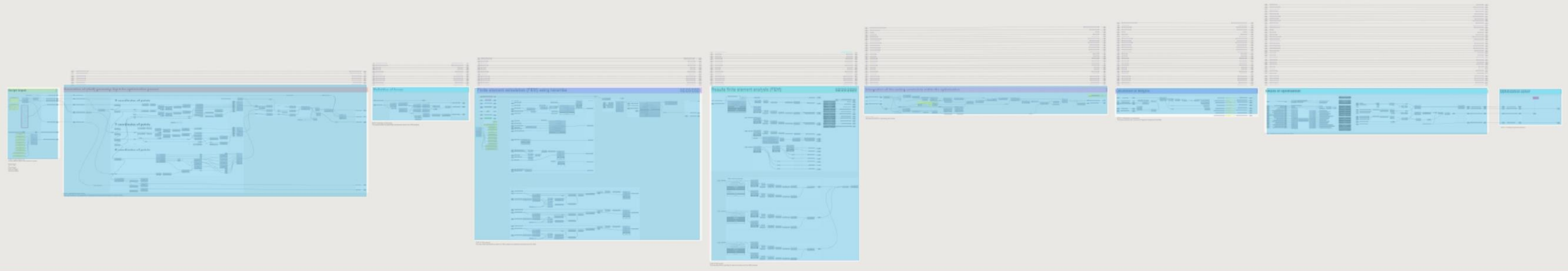
1. INTRODUCTION OF THE FLOORING SYSTEM

What will it look like?

the flooring system

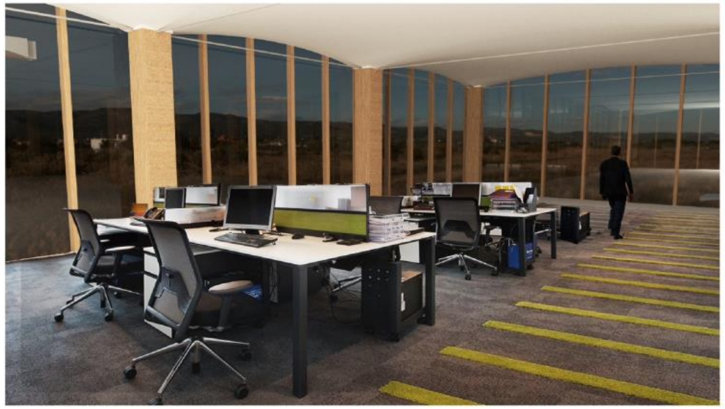
Floor slab optimization

In a derivative-free optimization approach for concurrent structural design problems (e.g. taking into account fabrication constraints, and multiple loadcases)



Focus on office buildings

as they are easier for transformation



The boundary conditions

1. INTRODUCTION OF THE FLOORING SYSTEM

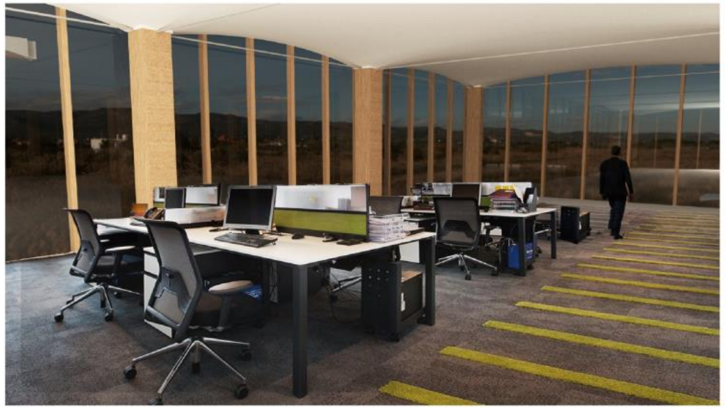
2. BOUNDARY CONDITIONS

Focus on office buildings

as they are easier for transformation

Eurocode, loading conditions

- *Total load of 5.37 kN/m^2 + self weight*



- *Offices CC2 2.5 kN/m^2*
- *Additional loading CC2 1.2 kN/m^2*
- *Safety factor permanent load 1.5*
- *Safety factor variable load 1.35*
- *Total load of 5.37 kN/m^2 + self weight*

The boundary conditions

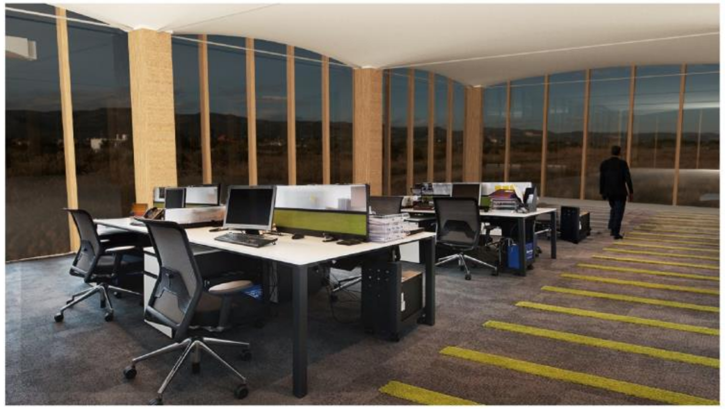
1. INTRODUCTION OF THE FLOORING SYSTEM

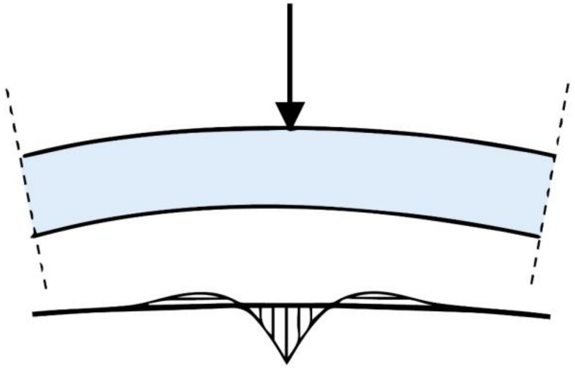
2. BOUNDARY CONDITIONS

Focus on office buildings
as they are easier for transformation

Eurocode, loading conditions
- Total load of 5.37 kN/m^2 + self weight

Intergration of critical point loads
As they are guiding in thin shells





Incidental point load, might result in tension

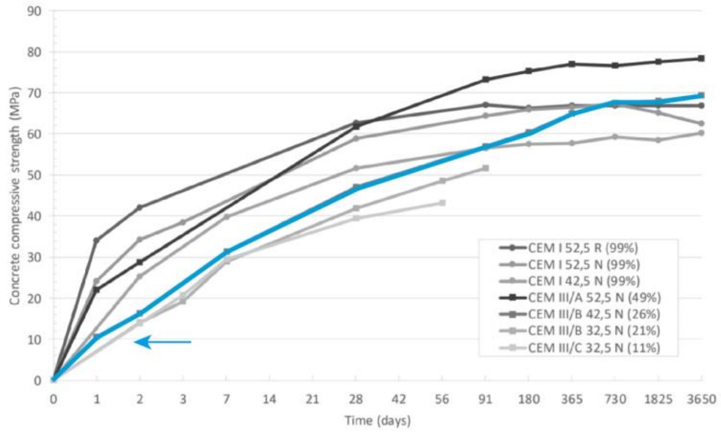
The boundary conditions

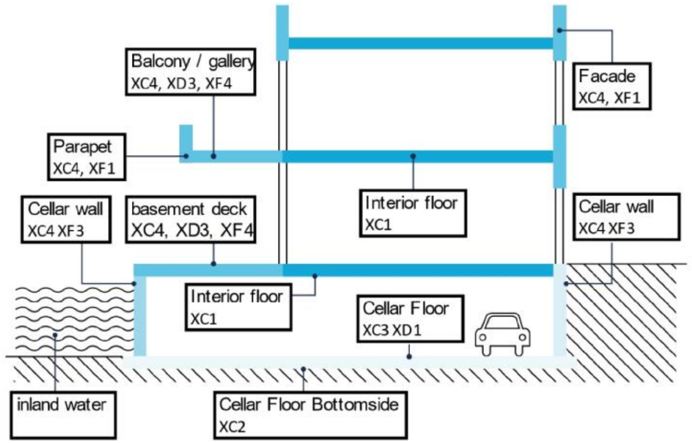
Focus on office buildings
as they are easier for transformation

Eurocode, loading conditions
- Total load of 5.37 kN/m² + self weight

Intergration of critical point loads
As they are guiding in thin shells

Intergration of material
in the optimization process





The boundary conditions

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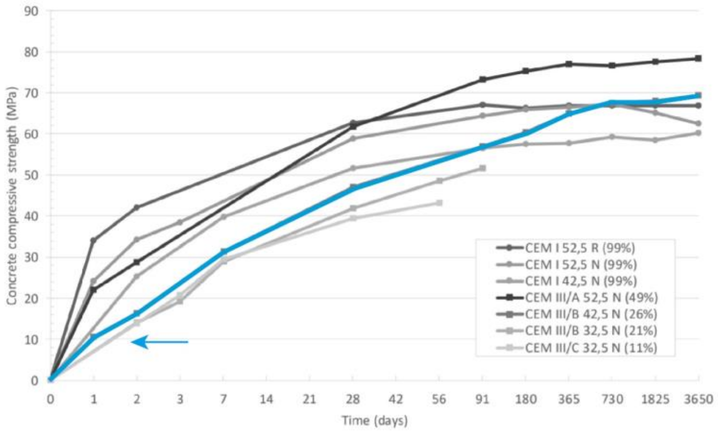

- Strength class = C20/25
- Exposure class = XC 1
- Consistency class = C2, S2, F2
- Maximal w/c factor = 0.65
- Design w/c factor = 0.63
- Minimal cement = 260 kg/m3
- Cement types used = CEM III/B 42,5 N
- Aggregate size = 4/16
- Plasticizer = 12%

The boundary conditions

1. INTRODUCTION OF THE FLOORING SYSTEM

2. BOUNDARY CONDITIONS

Focus on office buildings
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Eurocode, loading conditions
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Intergration of critical point loads
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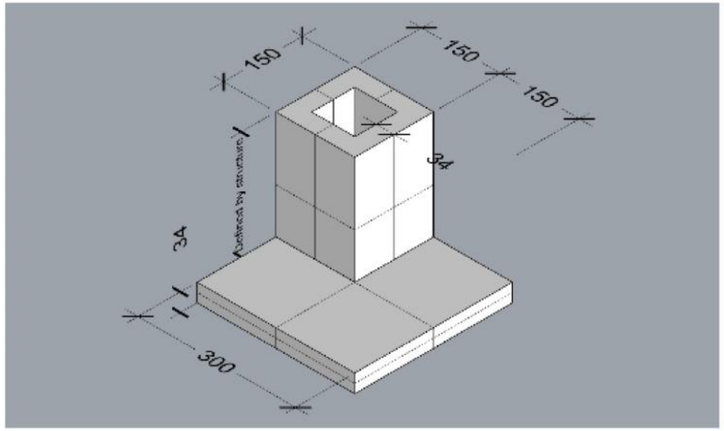
Intergration of material
in the optimization process

Assumptions in the process
uncracked concrete, linear finite element analysis,
steel shoe to prevent localized edge effects



1. INTRODUCTION OF THE FLOORING SYSTEM

2. BOUNDARY CONDITIONS

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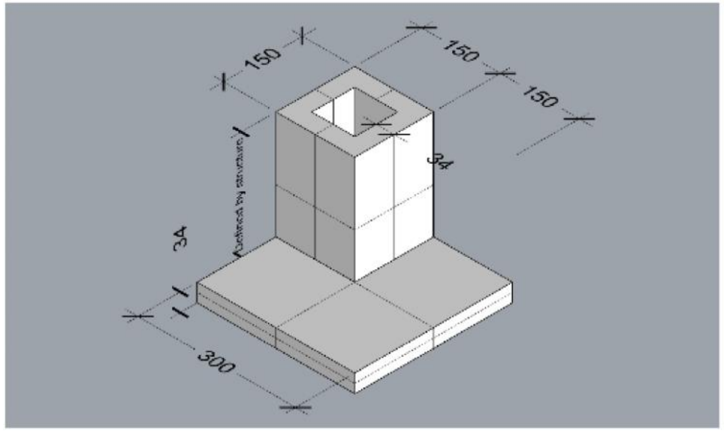
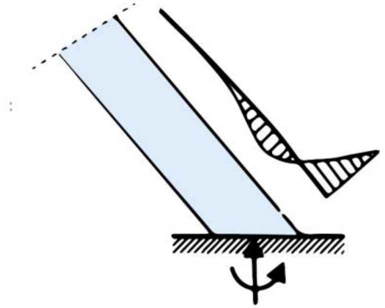
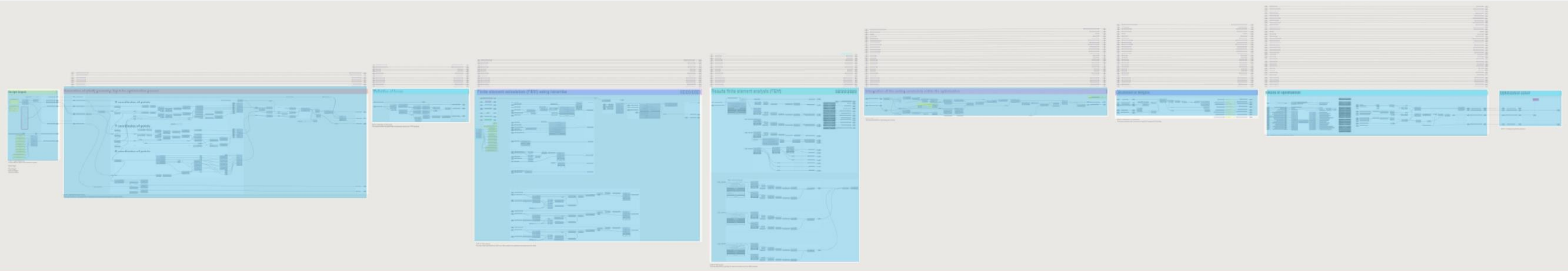




Distributing the load by enclosing the concrete

Script in Rhino Grasshopper



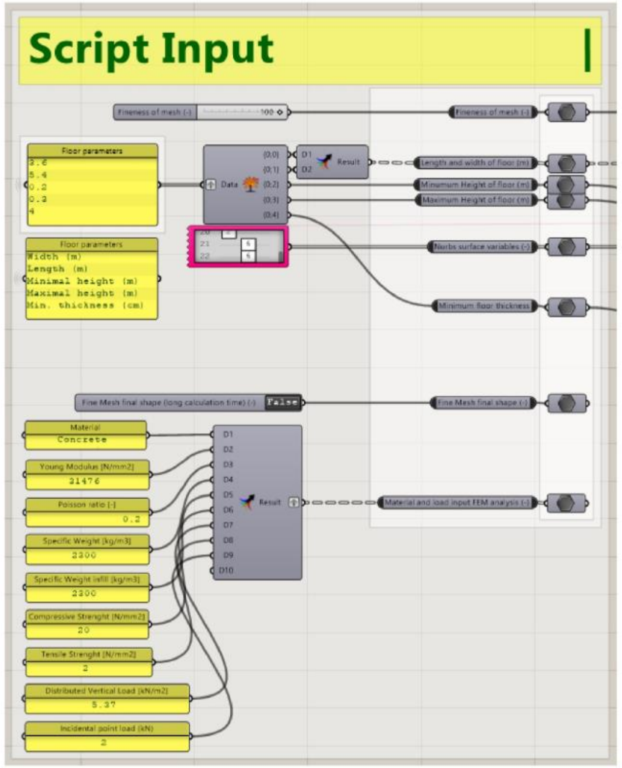
1. INTRODUCTION OF THE FLOORING SYSTEM

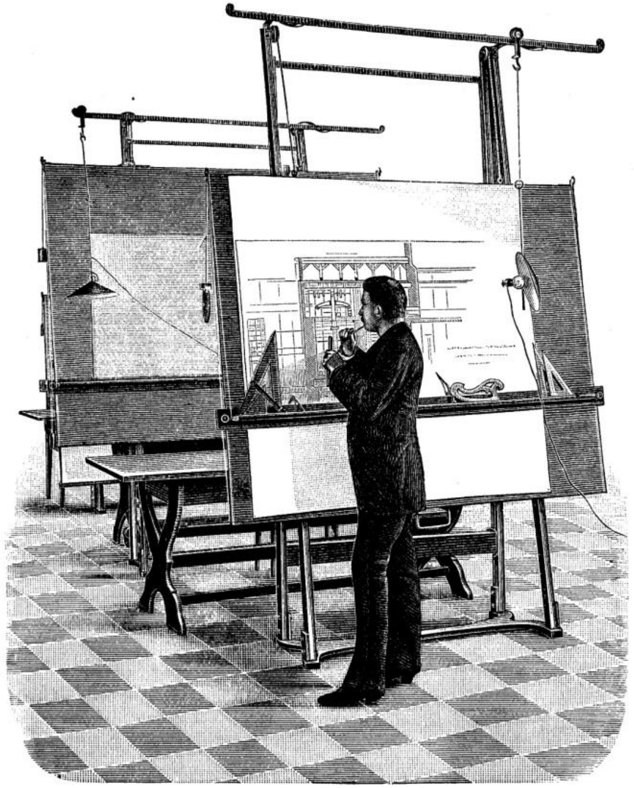
2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

STEP 1 Definition of the input

length, width, mesh size, height and material properties





Source: https://nl.wikipedia.org/wiki/Architect

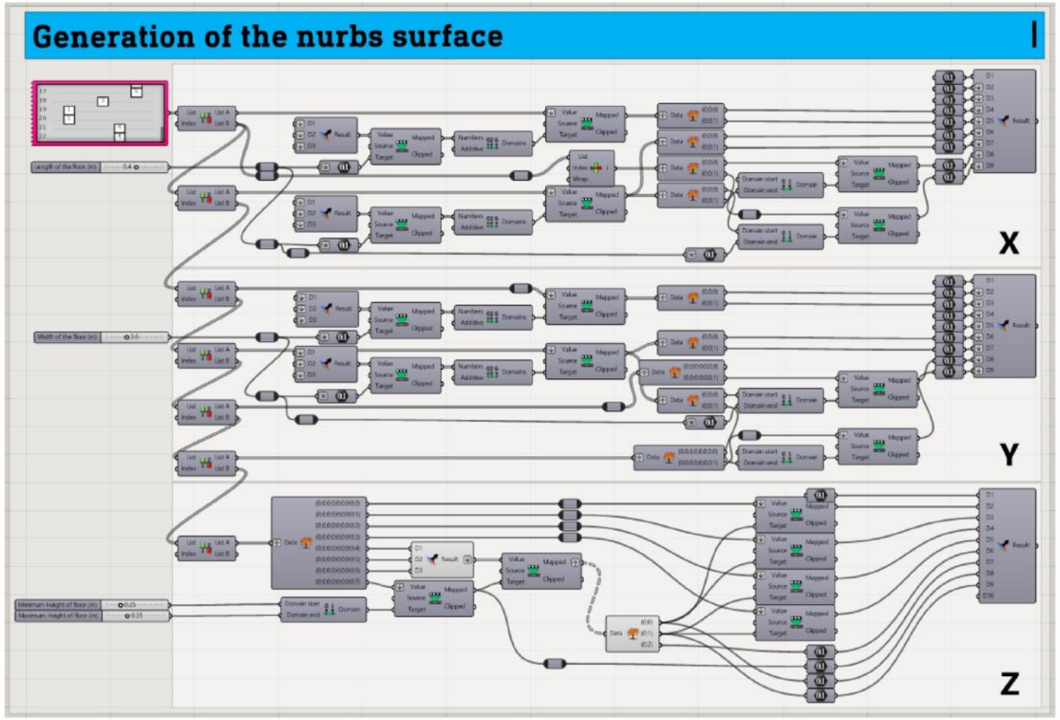
1. INTRODUCTION OF THE FLOORING SYSTEM

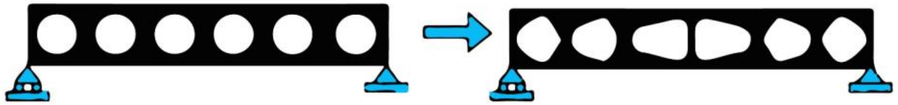
2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

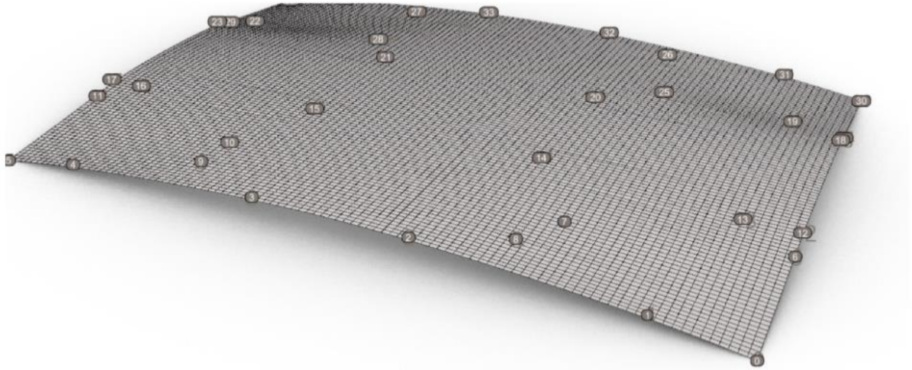
STEP 2 Shape optimization

length, width, mesh size, height and material properties



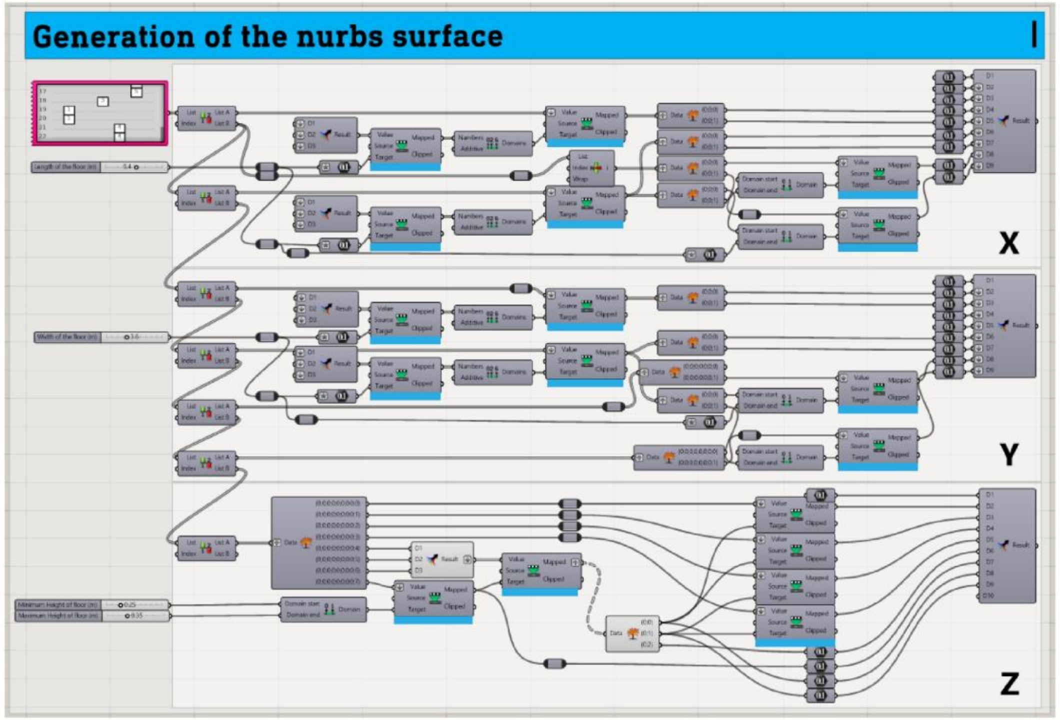


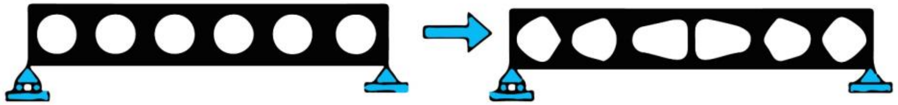
Shape optimization



STEP 2 Shape optimization

length, width, mesh size, height and material properties





Shape optimization

- Remapping of the variables, to influence the solution-space and thereby allow for faster convergence

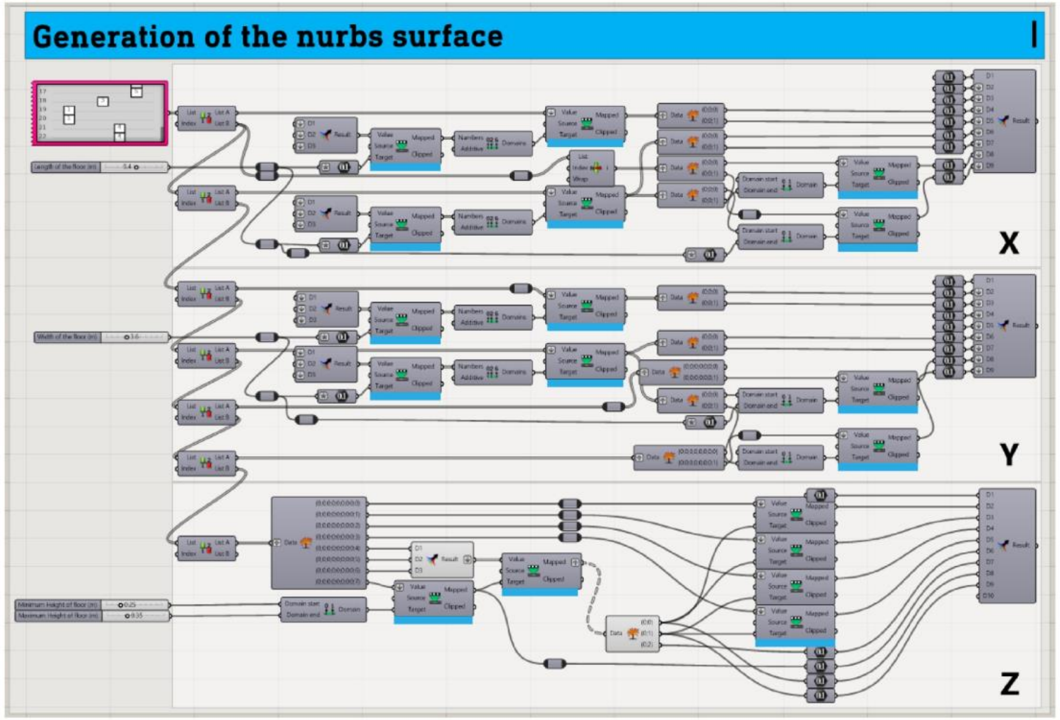
1. INTRODUCTION OF THE FLOORING SYSTEM

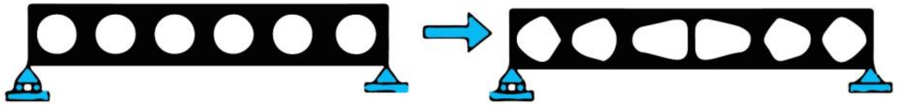
2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

STEP 2 Shape optimization

length, width, mesh size, height and material properties





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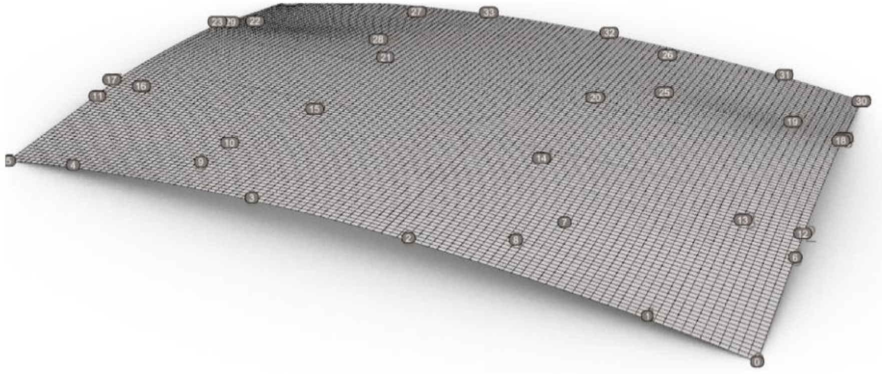


- *Remapping of the variables, to influence the solution-space and thereby allow for faster convergence*

- *Quad-Mesh is automatically generated, and forms the input for step three*

1. INTRODUCTION OF THE FLOORING SYSTEM

2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

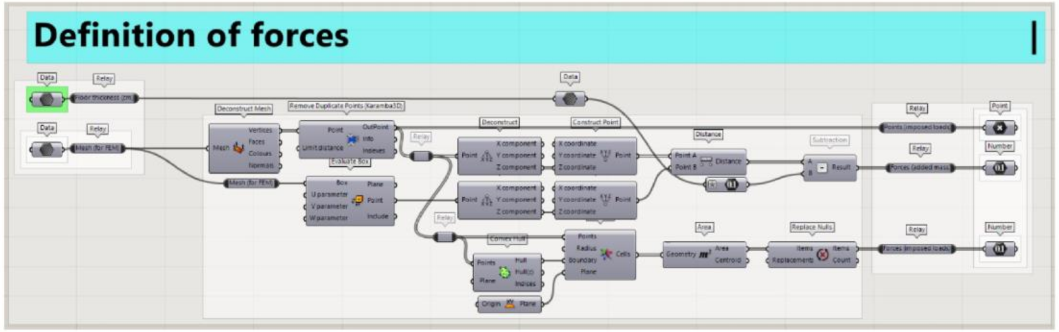
STEP 3 Intergration of self weight

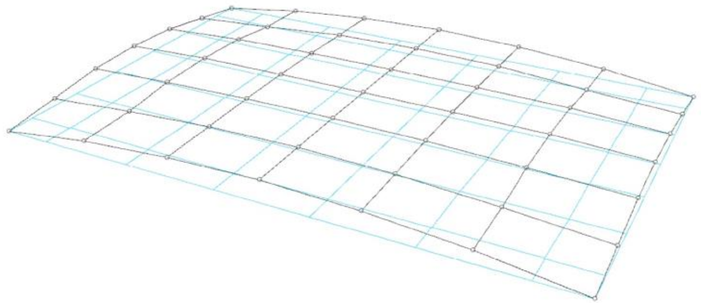
Intergration of the weight added by the casting constraints

- *Generation of the projected voronoi*

- *area of voronoi * height difference * SW of concrete in N*

- *Defines the added load on the structure*





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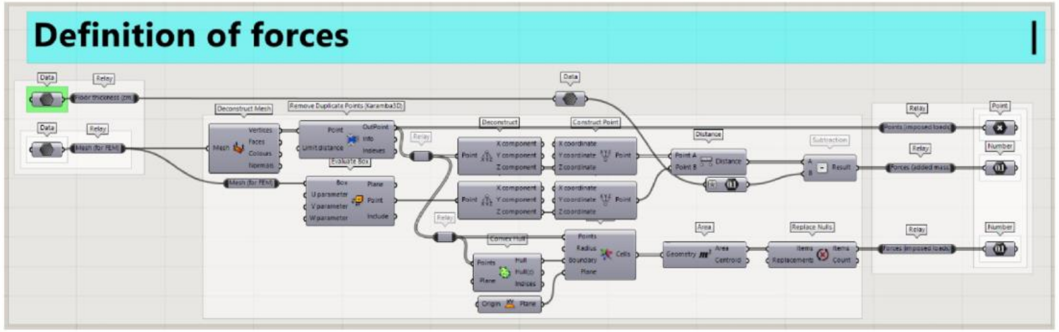
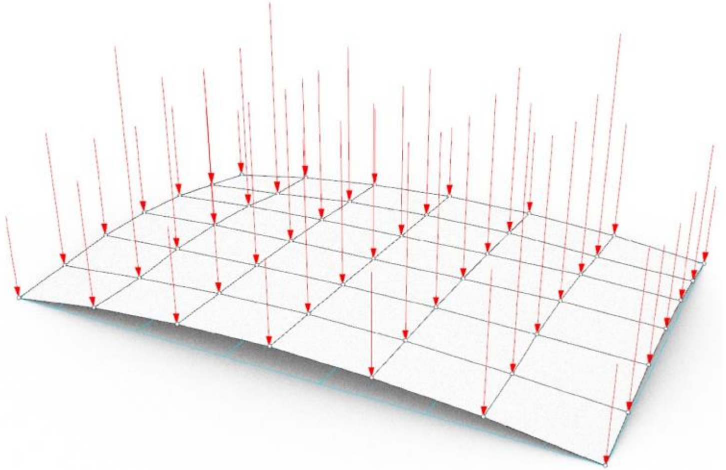




1. INTRODUCTION OF THE FLOORING SYSTEM

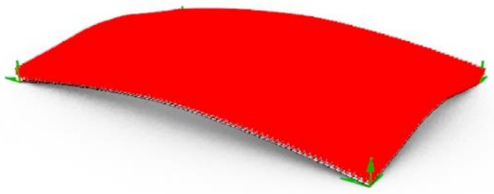
2. BOUNDARY CONDITIONS

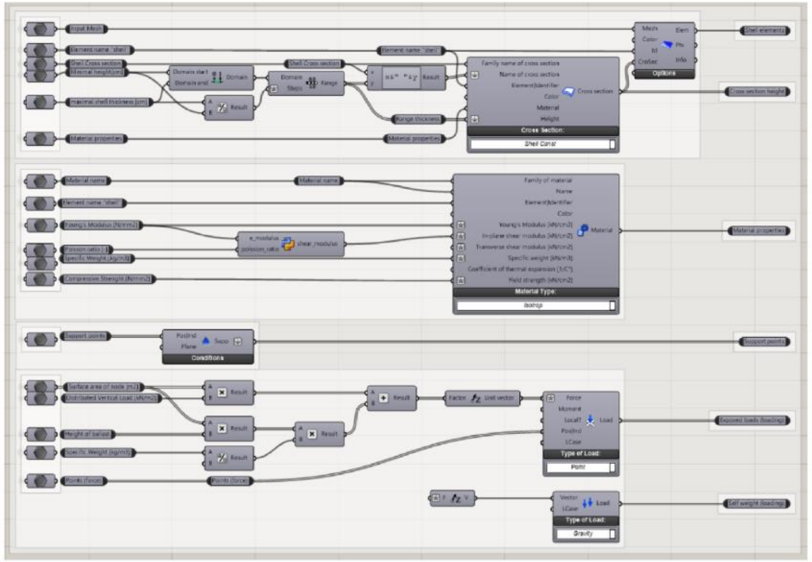
3. OPTIMIZATION SCRIPT

STEP 4 Finite element analysis
Using karamba3D

- *Generating the input in karamba3D, (e.g. support, load, variable shell thickness, material)*

- *Primary load-case (distributed Q-load)*



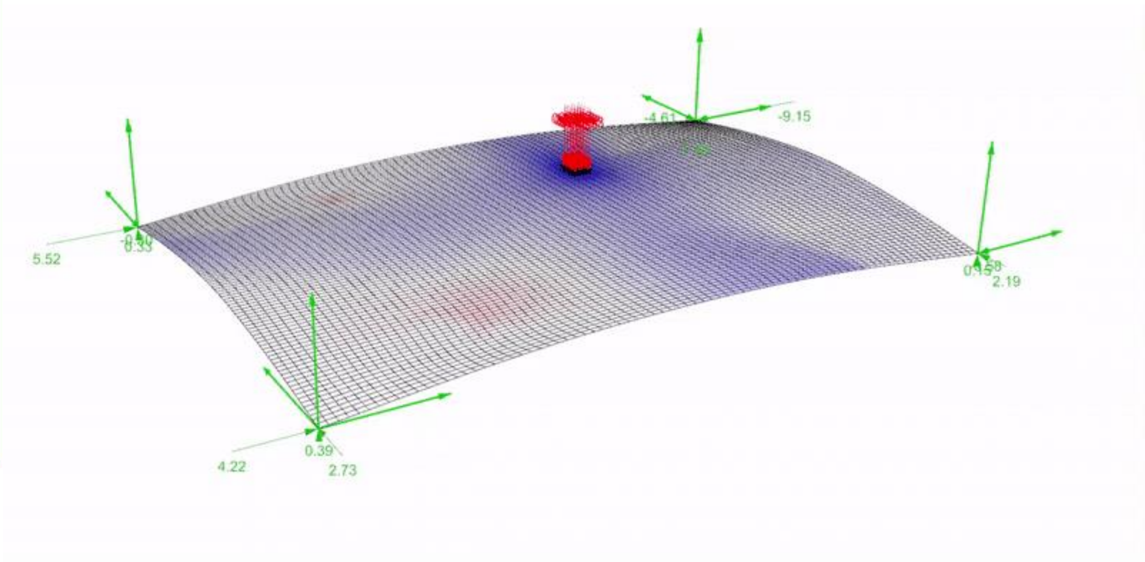


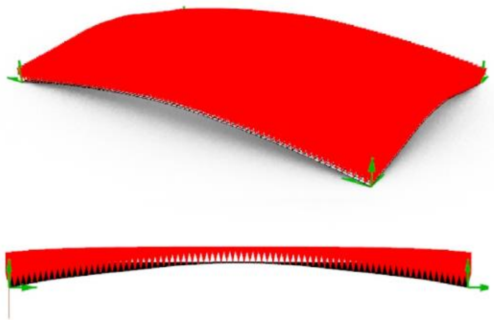
STEP 4 Finite element analysis

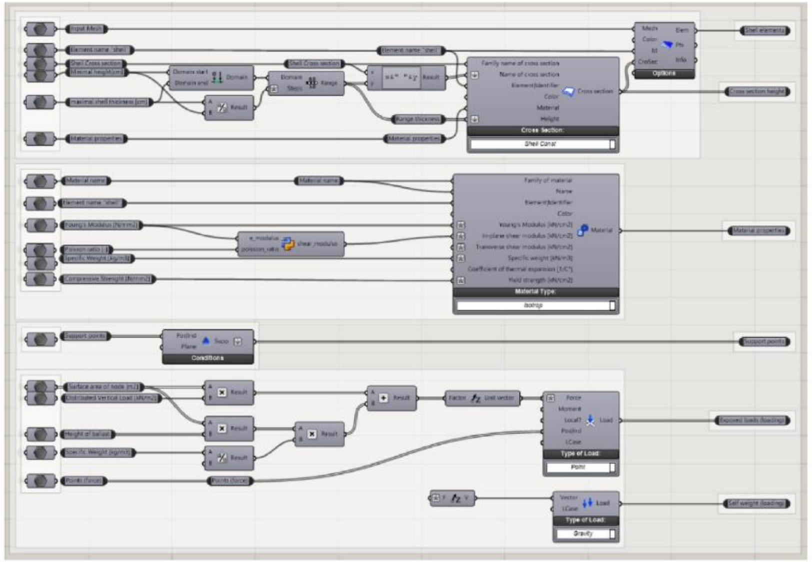
Using karamba3D

- Generating the input in karamba3D, (e.g. support, load, variable shell thickness, material)

- Primary load-case (distributed Q-load)







1. INTRODUCTION OF THE FLOORING SYSTEM

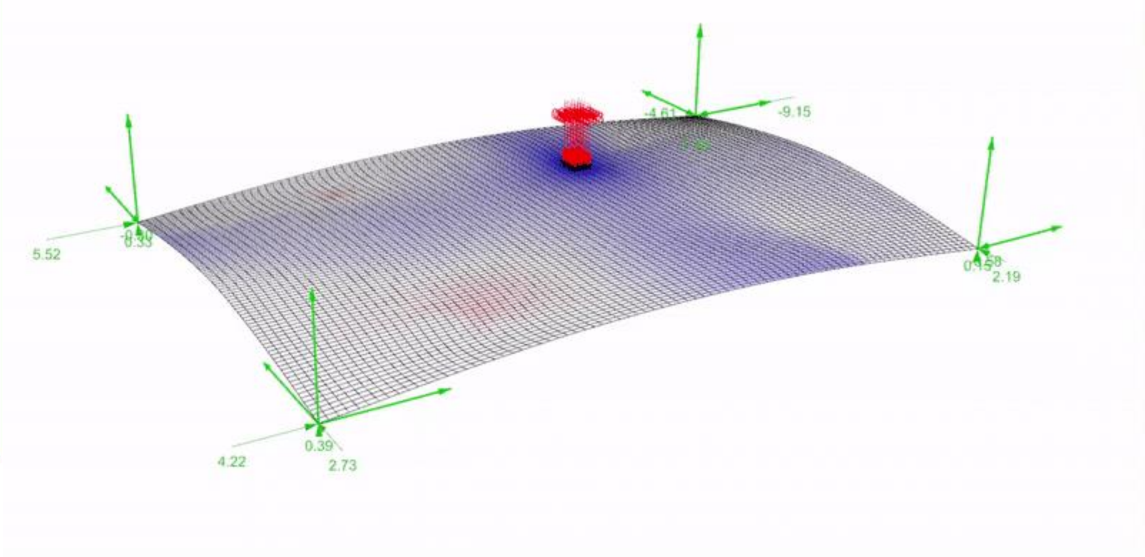
2. BOUNDARY CONDITIONS

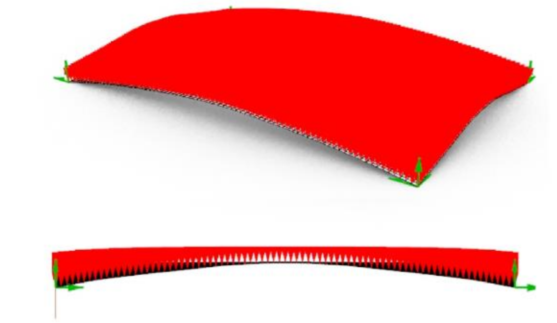
3. OPTIMIZATION SCRIPT

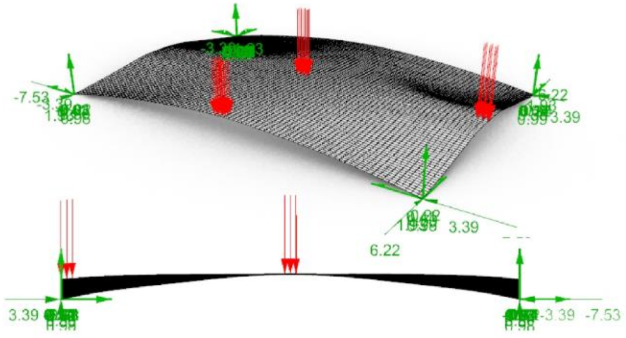
STEP 4 Finite element analysis
Using karamba3D

- Generating the input in karamba3D, (e.g. support, load, variable shell thickness, material)

- Primary load-case (distributed Q-load)







1. INTRODUCTION OF THE FLOORING SYSTEM

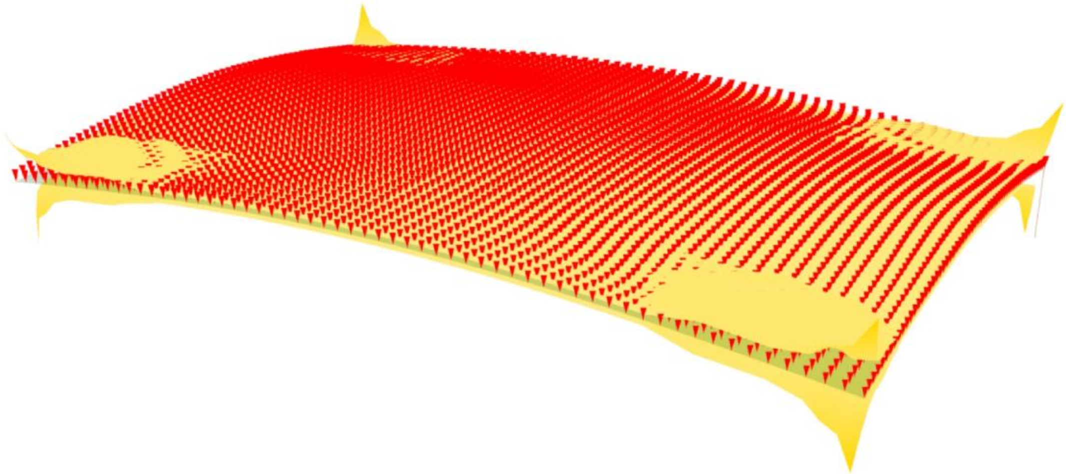
2. BOUNDARY CONDITIONS

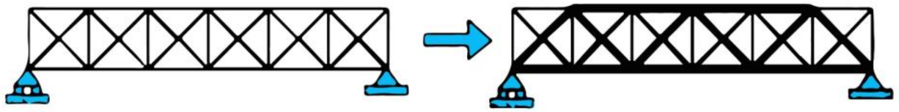
3. OPTIMIZATION SCRIPT

STEP 5 Size optimization

Based on the finite element results of the Q-load

- *five optimization steps, to optimize the compression stress*



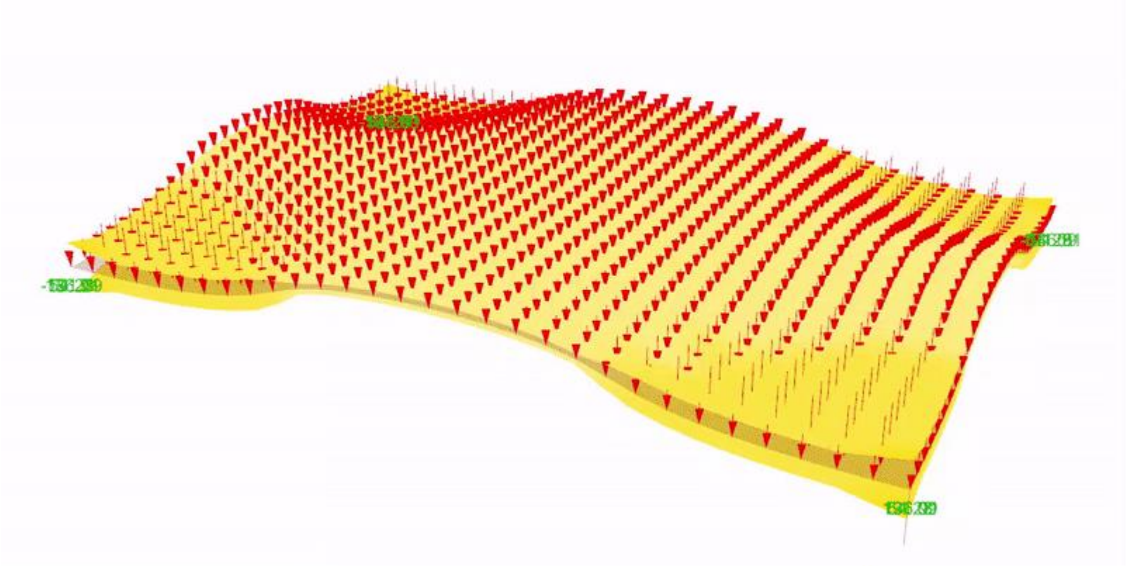


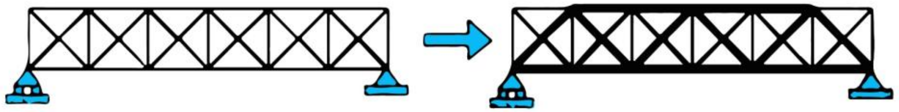
Size optimization

STEP 5 Size optimization

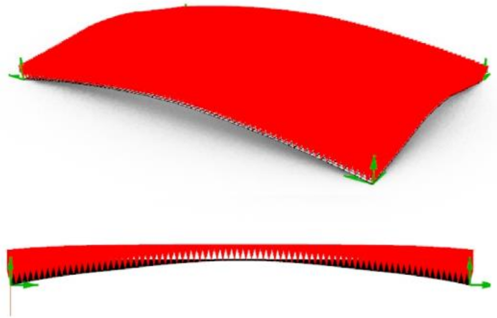
Based on the finite element results of the Q-load

- *five optimization steps, to optimize the compression stress*





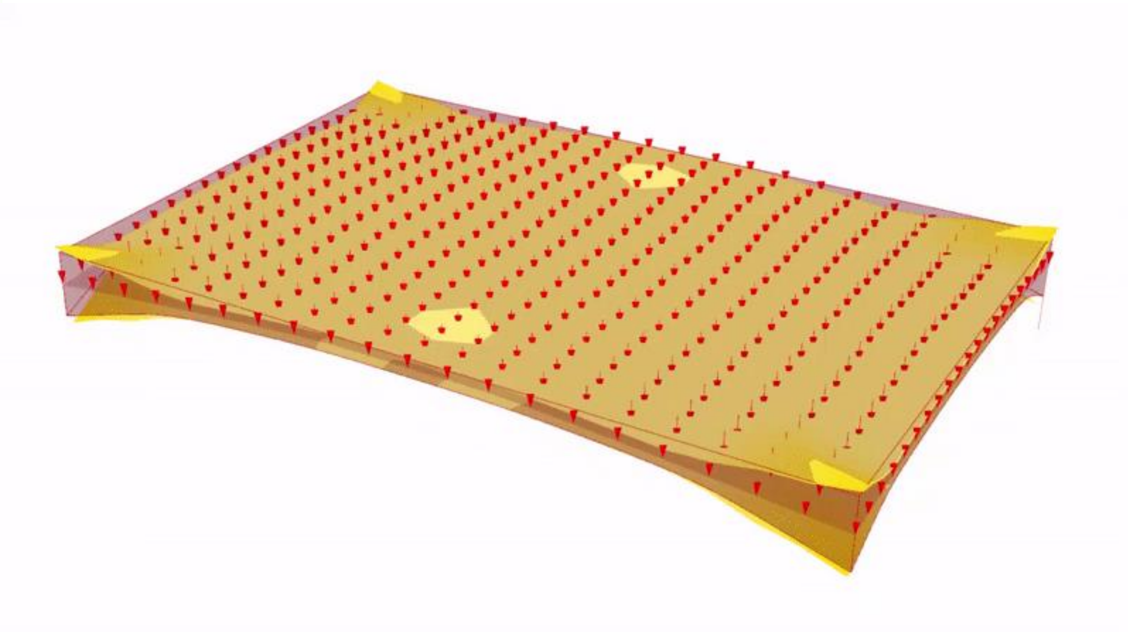
Size optimization



The Q-load defines the variable thickness

STEP 6 Fabrication-aware
rationalisation of the shell

- The variable mesh is converted to a nurbs surface, forming the basis of the final geometry.



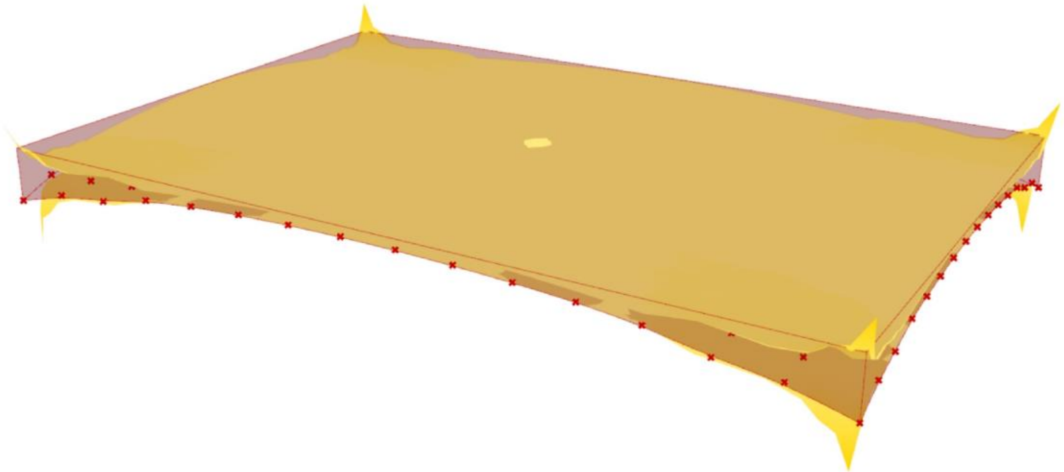
1. INTRODUCTION OF THE FLOORING SYSTEM

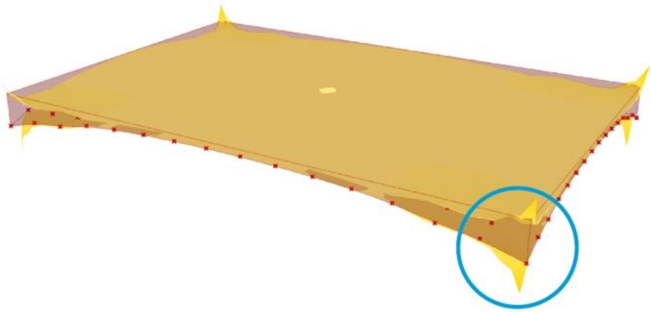
2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

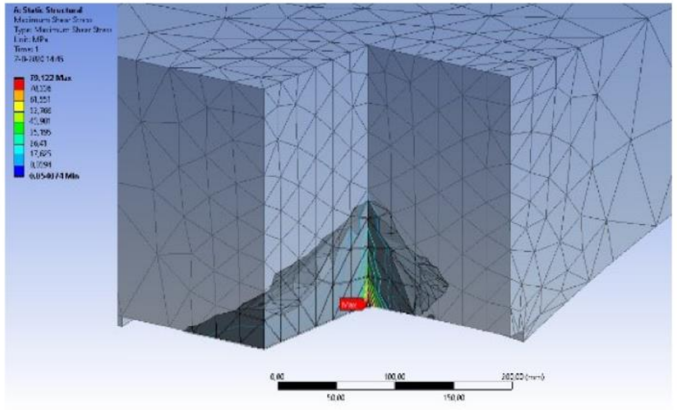
STEP 6 Fabrication-aware
rationalisation of the shell

- The stress singularities are due to the linear model, Steel shoes will be used for the localized edge effects.





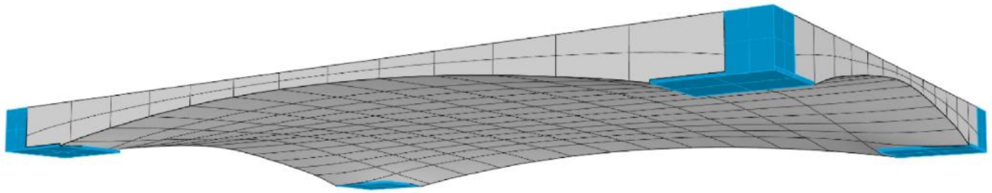
Solid FEM in Ansys

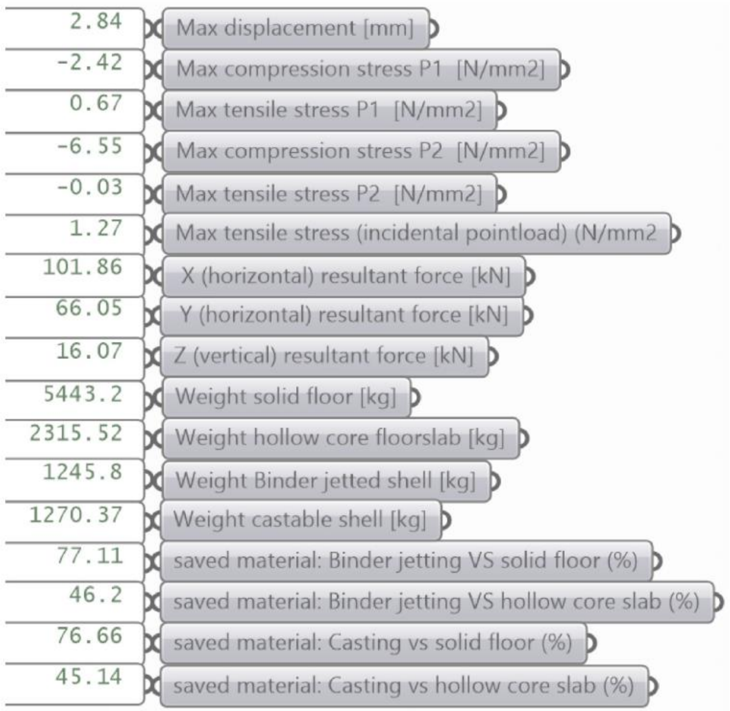


STEP 7 Generation of the results

unity checks

- Performing the unity checks on the tensile, compression and deflection limits.





1. INTRODUCTION OF THE FLOORING SYSTEM

2. BOUNDARY CONDITIONS

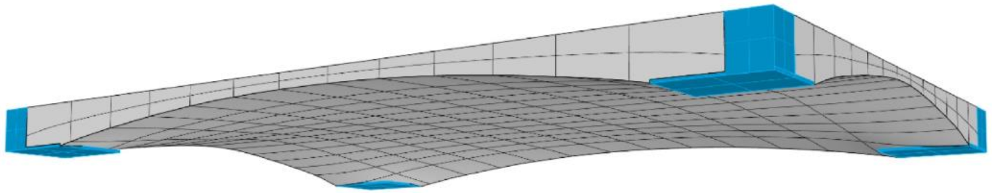
3. OPTIMIZATION SCRIPT

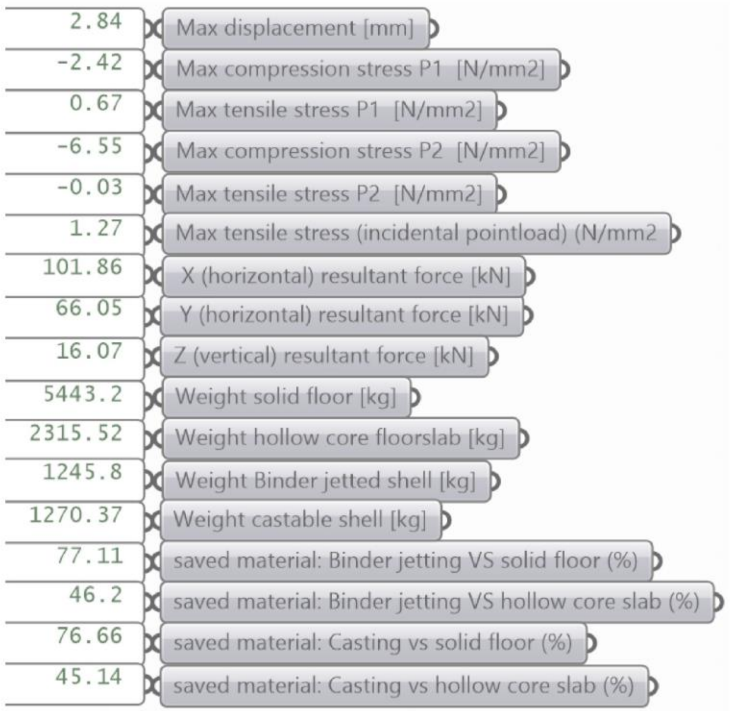
STEP 7 Generation of the results

unity checks

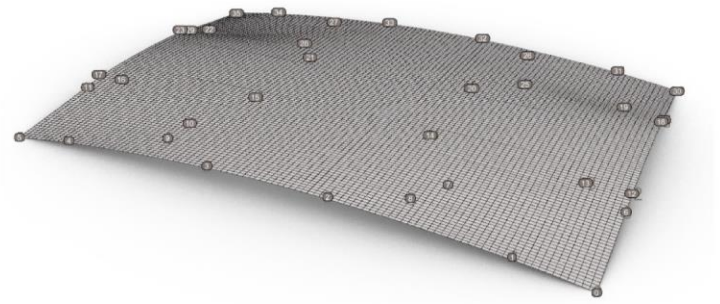
- Performing the unity checks on the tensile, compression and deflection limits.

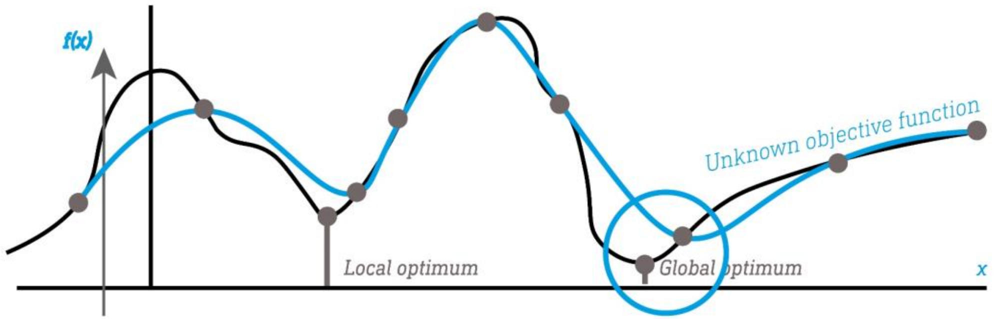
- Combining the results in the objective value





STEP 8 Model-based black-box
optimization strategy



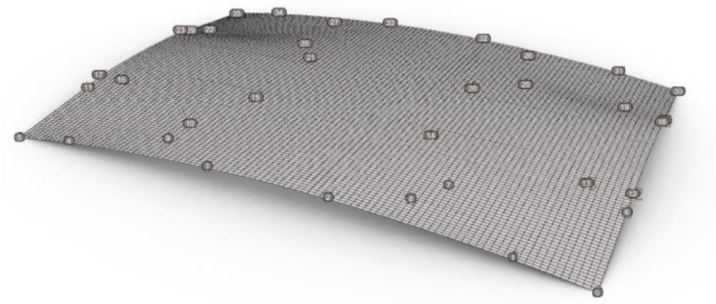


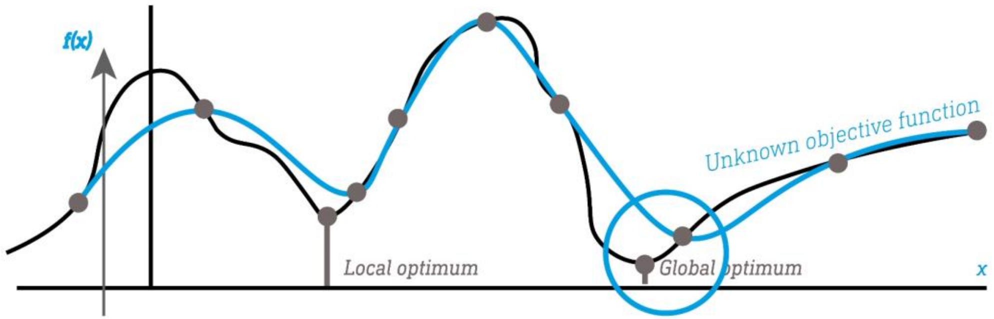
1. INTRODUCTION OF THE FLOORING SYSTEM

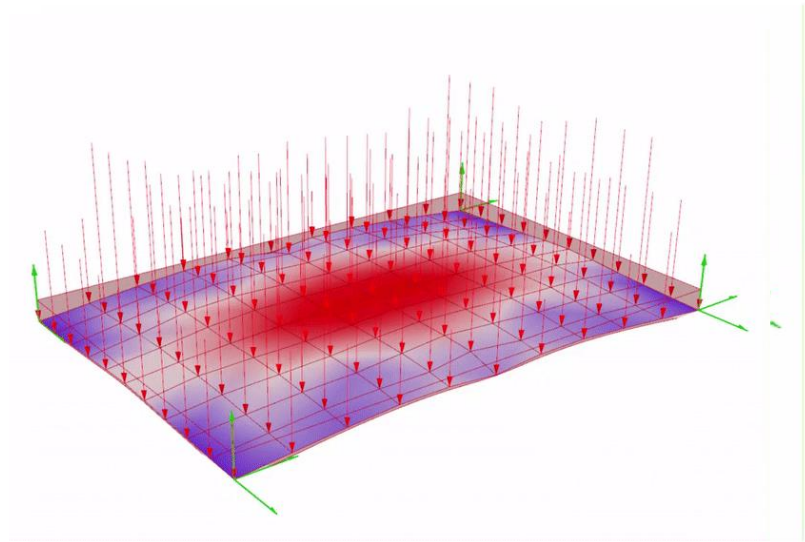
2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

STEP 8 Model-based black-box
optimization strategy







1. *INTRODUCTION OF THE FLOORING SYSTEM*

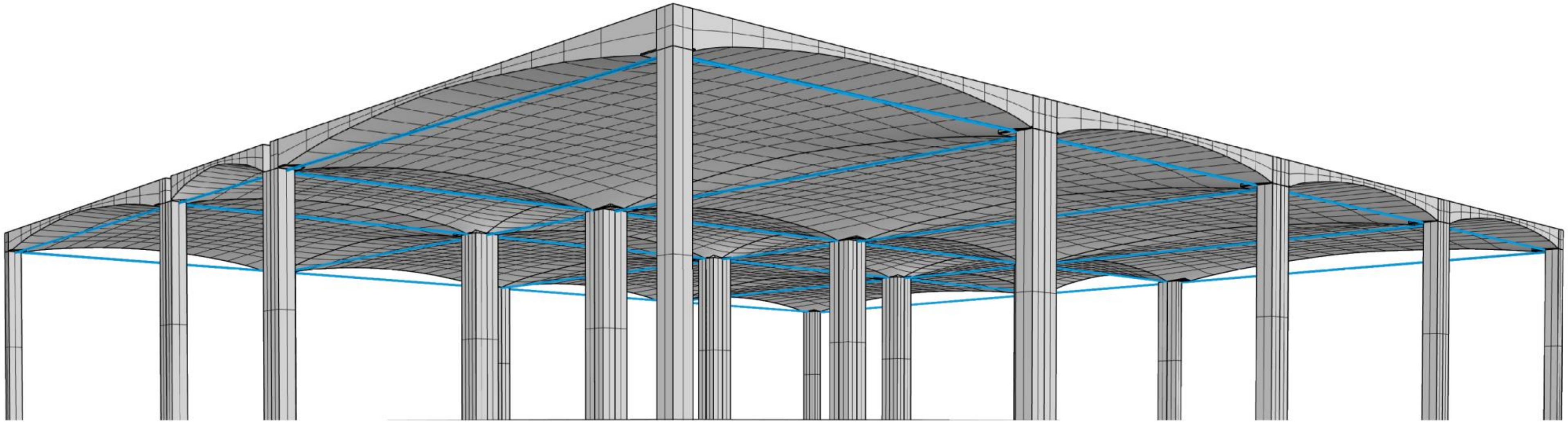
2. *BOUNDARY CONDITIONS*

3. *OPTIMIZATION SCRIPT*

4. *RESULTING FLOORSLABS*

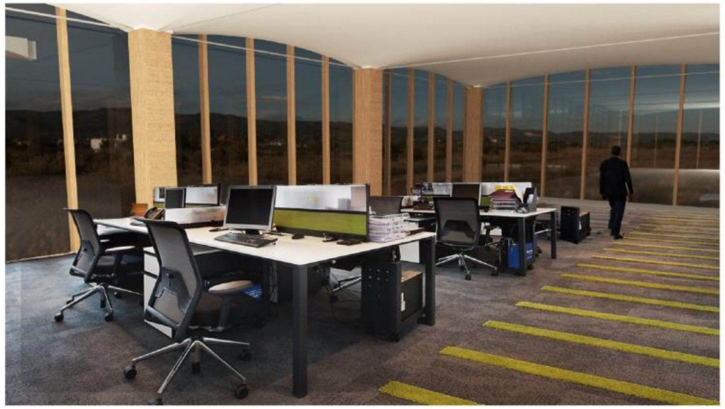
The resulting floorslabs

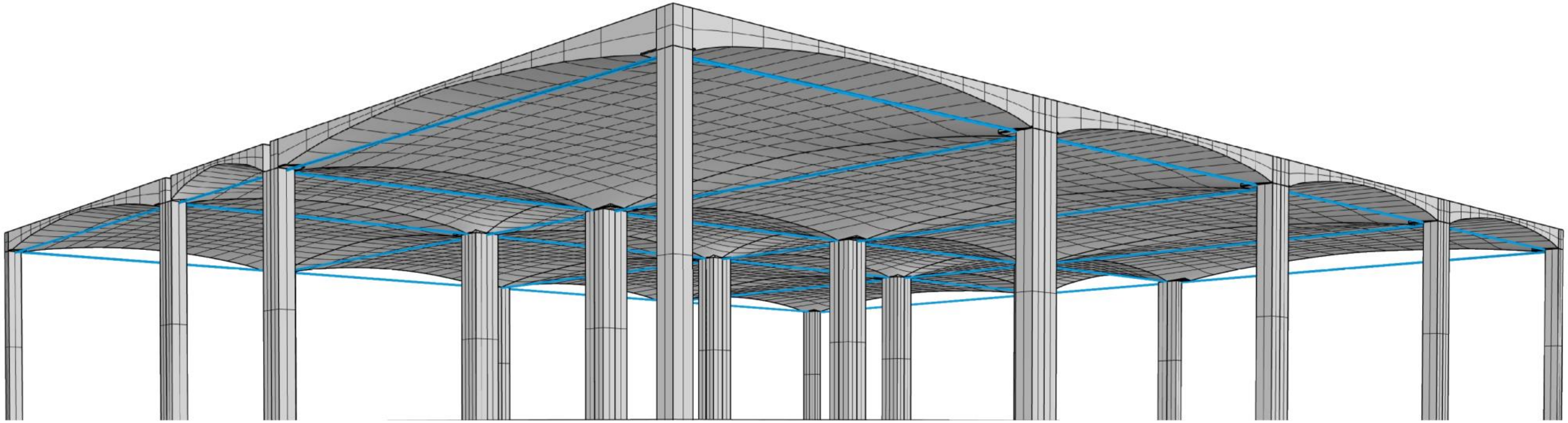
3600 x 2400 mm and 3600 x 5400 mm

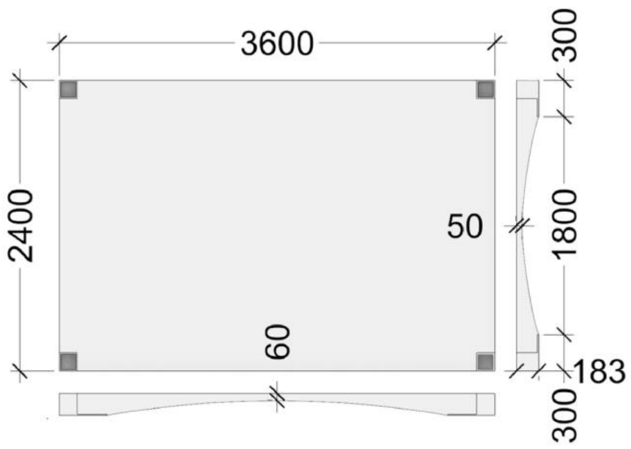


The resulting floorslabs

3600 x 2400 mm and 3600 x 5400 mm







The resulting floorslabs

3600 x 2400 mm

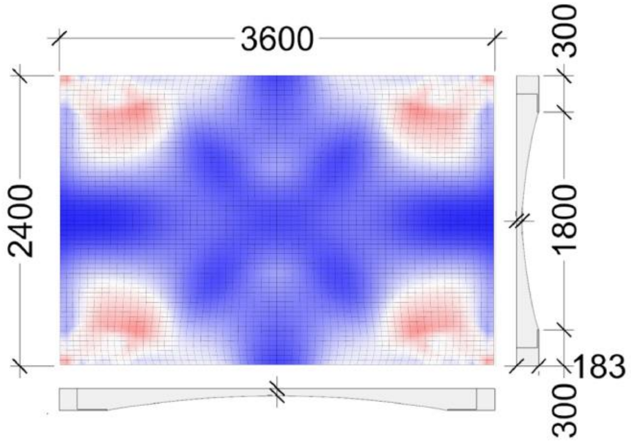
Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-2,91 N/mm2	Unity check	0.1455 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-10,5 N/mm2	Unity check	0.525 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1.48 N/mm2	Unity check	0,99 [-]	Critical UC (Passed)
Max tensile stress P2 [N/mm2]	0.45 N/mm2	Unity check	0.3 [-]	Passed UC > 1
Max tensile stress LC 1 [N/mm2]	1,06 N/mm2	Unity check	0.71 [-]	Passed UC > 1
Max tensile stress LC 2 [N/mm2]	1,02 N/mm2	Unity check	0.68 [-]	Passed UC > 1
Max tensile stress LC 3 [N/mm2]	1,37 N/mm2	Unity check	0.91 [-]	Passed UC > 1
X (horizontal) resultant force [kN]	96,75 kN	Diameter steel wire	12 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Y (horizontal) resultant force [kN]	61,99 kN	Diameter steel wire	9 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Z (vertical) resultant force [kN]	60.96 kN	Vertical load Z [kN]	58,2 kN	
Weight castable shell [kg]	1182,91 kg	Volume	0,514 m^3	
Reduction of weight vs hollowcore [%]	48,91%	Comparison floor	VBI 150mm	0,99 [-]
Reduction of weight vs solid floor [%]	70,24%	Comparison floor	200mm 2300kg concrete	

1. INTRODUCTION OF THE FLOORING SYSTEM

2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

4. RESULTING FLOORSLABS



The resulting floorslabs

3600 x 2400 mm

- Critical loadcase, P1 tensile stress due to distributed Q-load

Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-2,91 N/mm2	Unity check	0.1455 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-10,5 N/mm2	Unity check	0.525 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1.48 N/mm2	Unity check	0,99 [-]	Critical UC (Passed)
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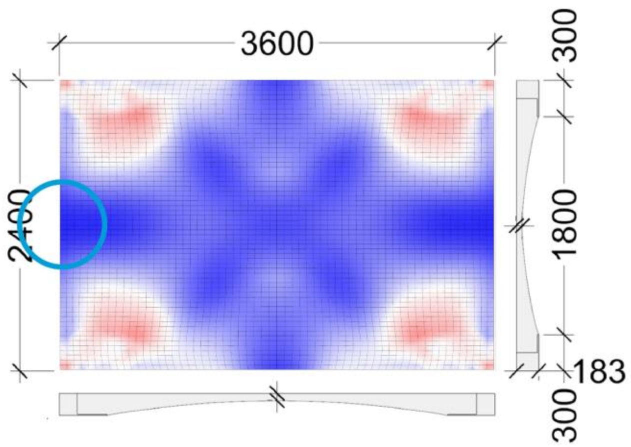
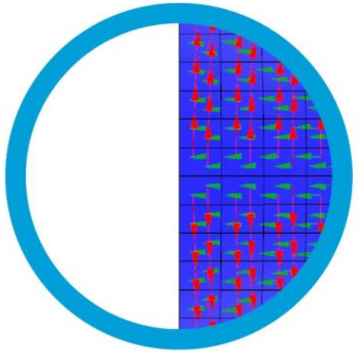
Max tensile stress LC 2 [N/mm2]	1,02 N/mm2	Unity check	0.68 [-]	Passed UC > 1
Max tensile stress LC 3 [N/mm2]	1,37 N/mm2	Unity check	0.91 [-]	Passed UC > 1
X (horizontal) resultant force [kN]	96,75 kN	Diameter steel wire	12 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Y (horizontal) resultant force [kN]	61,99 kN	Diameter steel wire	9 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Z (vertical) resultant force [kN]	60.96 kN	Vertical load Z [kN]	58,2 kN	
Weight castable shell [kg]	1182,91 kg	Volume	0,514 m^3	
Reduction of weight vs hollowcore [%]	48,91%	Comparison floor	VBI 150mm	0,99 [-]
Reduction of weight vs solid floor [%]	70,24%	Comparison floor	200mm 2300kg concrete	





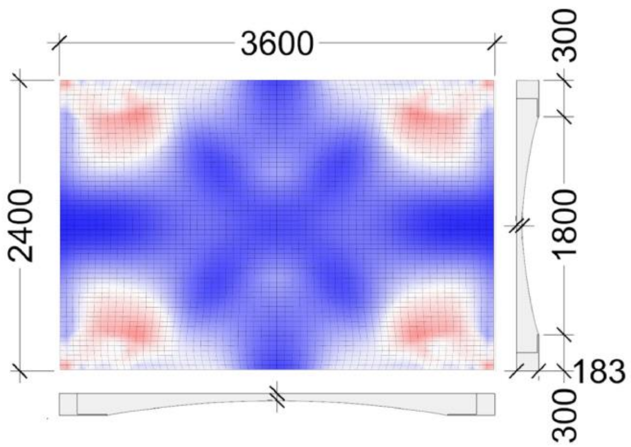
P1 tensile stress bottom layer

The resulting floorslabs

3600 x 2400 mm

- Critical loadcase, P1 tensile stress due to distributed Q-load

Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-2,91 N/mm2	Unity check	0.1455 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-10,5 N/mm2	Unity check	0.525 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1.48 N/mm2	Unity check	0,99 [-]	Critical UC (Passed)
Max tensile stress P2 [N/mm2]	0.45 N/mm2	Unity check	0.3 [-]	Passed UC > 1
Max tensile stress LC 1 [N/mm2]	1,06 N/mm2	Unity check	0.71 [-]	Passed UC > 1
Max tensile stress LC 2 [N/mm2]	1,02 N/mm2	Unity check	0.68 [-]	Passed UC > 1
Max tensile stress LC 3 [N/mm2]	1,37 N/mm2	Unity check	0.91 [-]	Passed UC > 1
X (horizontal) resultant force [kN]	96,75 kN	Diameter steel wire	12 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Y (horizontal) resultant force [kN]	61,99 kN	Diameter steel wire	9 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Z (vertical) resultant force [kN]	60.96 kN	Vertical load Z [kN]	58,2 kN	
Weight castable shell [kg]	1182,91 kg	Volume	0,514 m^3	
Reduction of weight vs hollowcore [%]	48,91%	Comparison floor	VBI 150mm	0,99 [-]
Reduction of weight vs solid floor [%]	70,24%	Comparison floor	200mm 2300kg concrete	



The resulting floorslabs

3600 x 2400 mm

- Critical loadcase, P1 tensile stress due to distributed Q-load

Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-2,91 N/mm2	Unity check	0.1455 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-10,5 N/mm2	Unity check	0.525 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1.48 N/mm2	Unity check	0,99 [-]	Critical UC (Passed)
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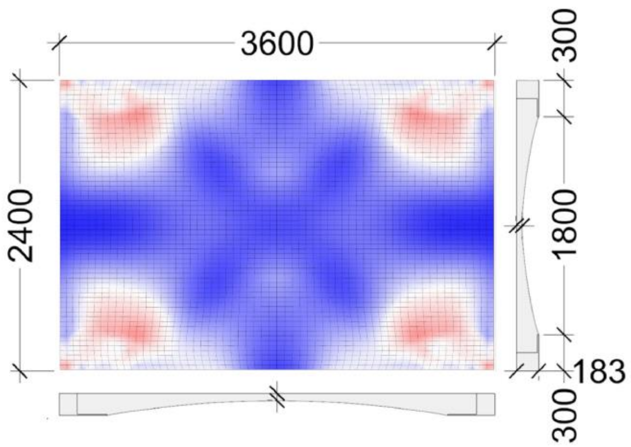
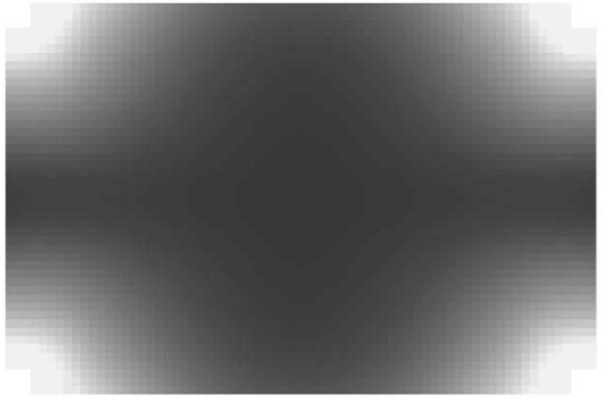
Max tensile stress LC 2 [N/mm2]	1,02 N/mm2	Unity check	0.68 [-]	Passed UC > 1
Max tensile stress LC 3 [N/mm2]	1,37 N/mm2	Unity check	0.91 [-]	Passed UC > 1
X (horizontal) resultant force [kN]	96,75 kN	Diameter steel wire	12 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Y (horizontal) resultant force [kN]	61,99 kN	Diameter steel wire	9 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Z (vertical) resultant force [kN]	60.96 kN	Vertical load Z [kN]	58,2 kN	
Weight castable shell [kg]	1182,91 kg	Volume	0,514 m^3	
Reduction of weight vs hollowcore [%]	48,91%	Comparison floor	VBI 150mm	0,99 [-]
Reduction of weight vs solid floor [%]	70,24%	Comparison floor	200mm 2300kg concrete	





Funicular floorslab Width: 3.6m, Length: 2.4m, Height: 0.18m

The resulting floorslabs

3600 x 2400 mm

- Critical loadcase, P1 tensile stress due to distributed Q-load

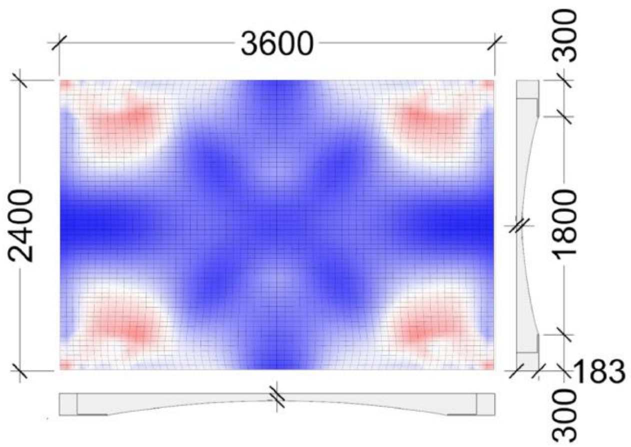
Results	Description	**Unity checks**	Description	Description
Max compression stress P1 [N/mm2]	-2,91 N/mm2	Unity check	0.1455 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-10,5 N/mm2	Unity check	0.525 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1.48 N/mm2	Unity check	0,99 [-]	Critical UC (Passed)
Max tensile stress P2 [N/mm2]	0.45 N/mm2	Unity check	0.3 [-]	Passed UC > 1
Max tensile stress LC 1 [N/mm2]	1,06 N/mm2	Unity check	0.71 [-]	Passed UC > 1
Max tensile stress LC 2 [N/mm2]	1,02 N/mm2	Unity check	0.68 [-]	Passed UC > 1
Max tensile stress LC 3 [N/mm2]	1,37 N/mm2	Unity check	0.91 [-]	Passed UC > 1
X (horizontal) resultant force [kN]	96,75 kN	Diameter steel wire	12 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Y (horizontal) resultant force [kN]	61,99 kN	Diameter steel wire	9 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Z (vertical) resultant force [kN]	60.96 kN	Vertical load Z [kN]	58,2 kN	
Weight castable shell [kg]	1182,91 kg	Volume	0,514 m^3	
Reduction of weight vs hollowcore [%]	48,91%	Comparison floor	VBI 150mm	0,99 [-]
Reduction of weight vs solid floor [%]	70,24%	Comparison floor	200mm 2300kg concrete	

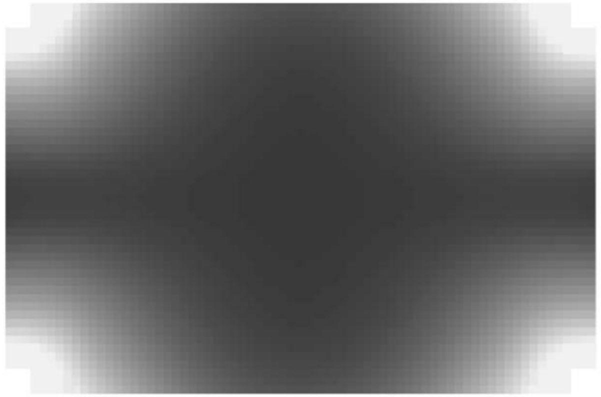
1. INTRODUCTION OF THE FLOORING SYSTEM

2. BOUNDARY CONDITIONS

3. OPTIMIZATION SCRIPT

4. RESULTING FLOORSLABS





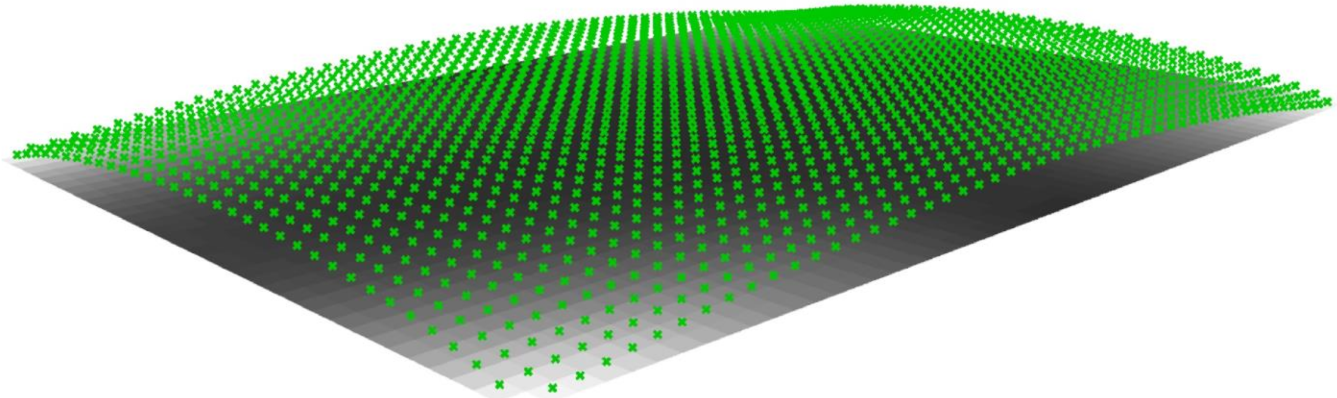
Funicular floorslab Width: 3.6m, Length: 2.4m, Height: 0.18m

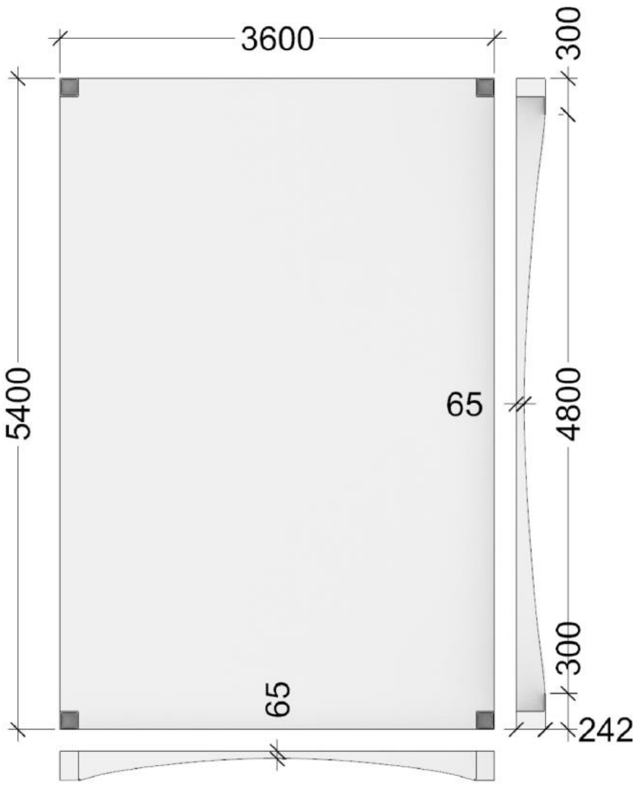
The resulting floorslabs

3600 x 2400 mm

- *Critical loadcase, P1 tensile stress due to distributed Q-load*

- *bitmap representation*

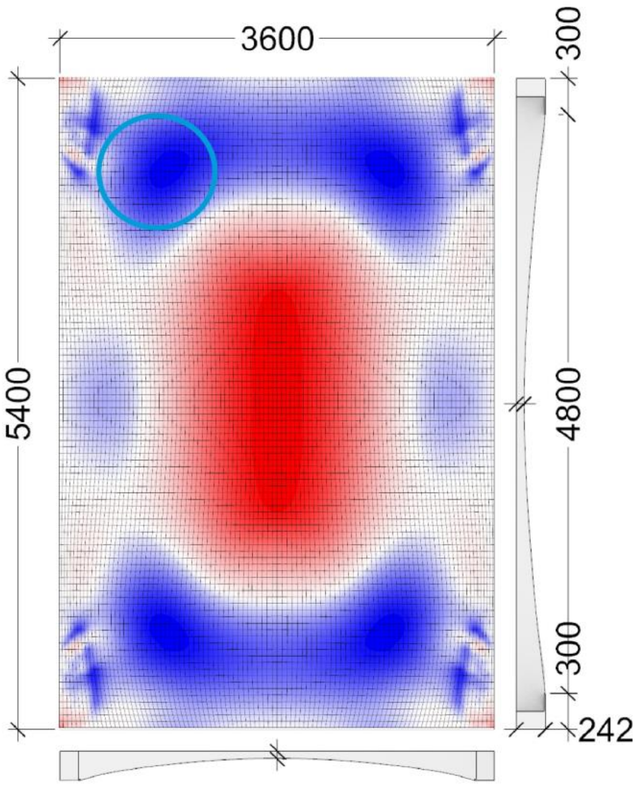




The resulting floorslabs

3600 x 5400 mm

Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-4,14 N/mm2	Unity check	0.207 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-16,7 N/mm2	Unity check	0.89 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1,47 N/mm2	Unity check	0.98 [-]	Critical UC
Max tensile stress P2 [N/mm2]	0,06 N/mm2	Unity check	0.04 [-]	Passed UC > 1
Max tensile stress LC 1 [N/mm2]	1,22 N/mm2	Unity check	0.81 [-]	Passed UC > 1
Max tensile stress LC 2 [N/mm2]	0,96 N/mm2	Unity check	0.64 [-]	Passed UC > 1
Max tensile stress LC 3 [N/mm2]	1,48 N/mm2	Unity check	0.99 [-]	Passed UC > 1
X (horizontal) resultant force [kN]	143,66 kN	Diameter steel wire	14 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Y (horizontal) resultant force [kN]	218,22 kN	Diameter steel wire	17 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Z (vertical) resultant force [kN]	36,25 kN	Total horizontal force	145 kN	
Weight castable shell [kg]	3313,61 kg	Volume	1.44 m^3	
Reduction of weight vs. hollow-core [%]	36,4%	Comparison of floor	VBI 150mm	
Reduction of weight vs. solid floor [%]	69,12%	Comparison floor	240 mm 2300kg concrete	



The resulting floorslabs

3600 x 5400 mm

- *Critical loadcase, P1 tensile stress due to distributed Q-load*

Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-4,14 N/mm2	Unity check	0.207 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-16,7 N/mm2	Unity check	0.89 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1,47 N/mm2	Unity check	0.98 [-]	Critical UC
Max tensile stress P2 [N/mm2]	0,06 N/mm2	Unity check	0.04 [-]	Passed UC > 1
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1. INTRODUCTION OF THE FLOORING SYSTEM

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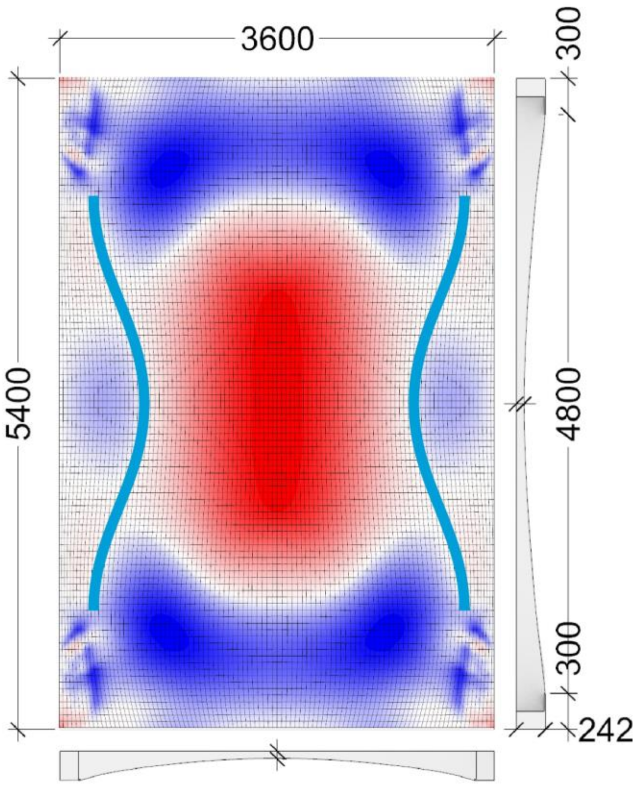
4. RESULTING FLOORSLABS



The resulting floorslabs

3600 x 5400 mm

- Critical loadcase, P1 tensile stress due to distributed Q-load

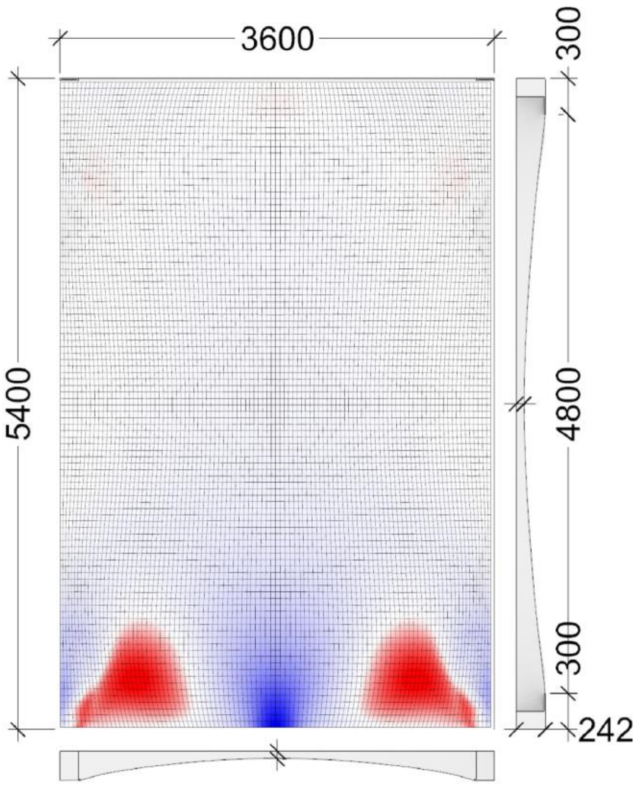
Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-4,14 N/mm2	Unity check	0.207 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-16,7 N/mm2	Unity check	0.89 [-]	Passed UC > 1
Max tensile stress P1 [N/mm2]	1,47 N/mm2	Unity check	0.98 [-]	Critical UC
Max tensile stress P2 [N/mm2]	0,06 N/mm2	Unity check	0.04 [-]	Passed UC > 1
Max tensile stress LC 1 [N/mm2]	1,22 N/mm2	Unity check	0.81 [-]	Passed UC > 1
Max tensile stress LC 2 [N/mm2]	0,96 N/mm2	Unity check	0.64 [-]	Passed UC > 1
Max tensile stress LC 3 [N/mm2]	1,48 N/mm2	Unity check	0.99 [-]	Passed UC > 1
X (horizontal) resultant force [kN]	143,66 kN	Diameter steel wire	14 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Y (horizontal) resultant force [kN]	218,22 kN	Diameter steel wire	17 mm	DIN3064 6x36 warrington-seale+steelcore cable (eurocable)
Z (vertical) resultant force [kN]	36,25 kN	Total horizontal force	145 kN	
Weight castable shell [kg]	3313,61 kg	Volume	1.44 m^3	
Reduction of weight vs. hollow-core [%]	36,4%	Comparison of floor	VBI 150mm	
Reduction of weight vs. solid floor [%]	69,12%	Comparison floor	240 mm 2300kg concrete	

1. *INTRODUCTION OF THE FLOORING SYSTEM*

2. *BOUNDARY CONDITIONS*

3. *OPTIMIZATION SCRIPT*

4. *RESULTING FLOORSLABS*



The resulting floorslabs

3600 x 5400 mm

- Critical loadcase, LC3 tensile stress due to distributed Q-load

Results	Description	Unity checks	Description	Description
Max compression stress P1 [N/mm2]	-4,14 N/mm2	Unity check	0.207 [-]	Passed UC > 1
Max compression stress P2 [N/mm2]	-16,7 N/mm2	Unity check	0.89 [-]	Passed UC > 1
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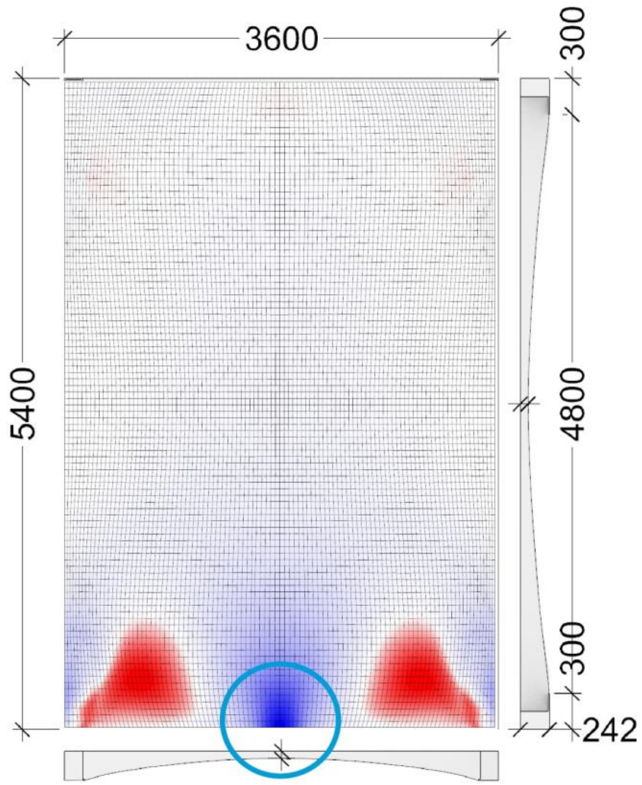
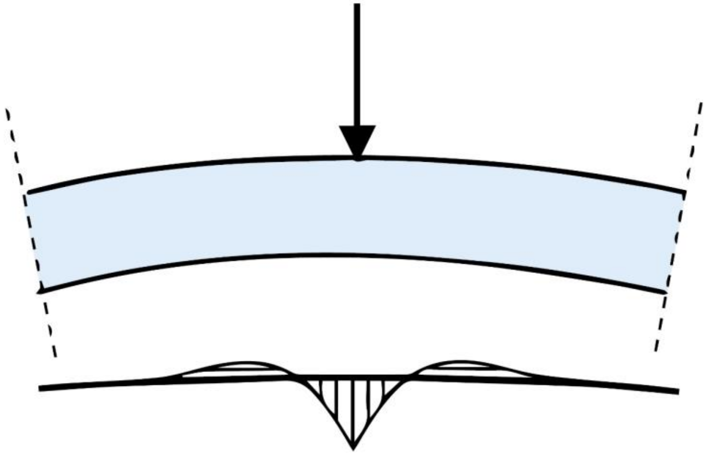
4. RESULTING FLOORSLABS

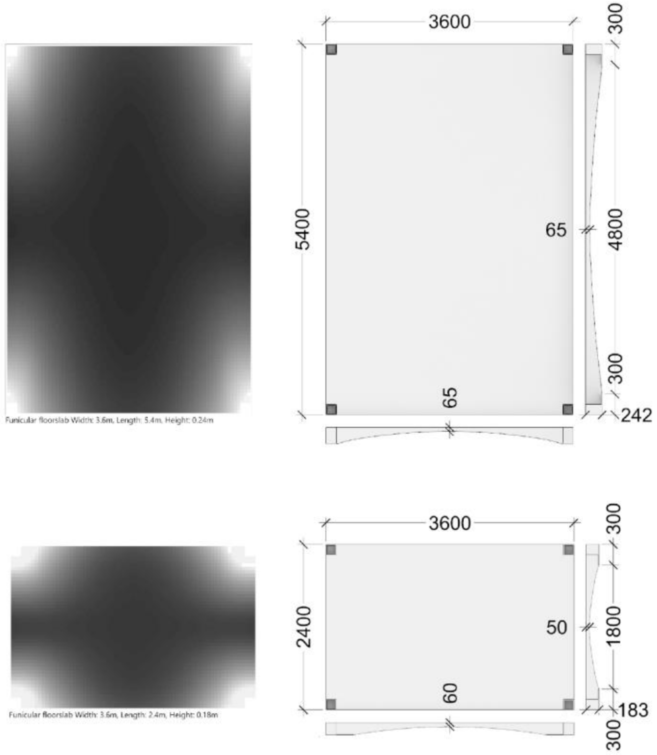


The resulting floorslabs

3600 x 5400 mm



Incidental point load, might result in tension



Tensile stresses are guiding

In thin-shell floorslabs

The results

1. INTRODUCTION OF THE FLOORING SYSTEM

2. BOUNDARY CONDITIONS

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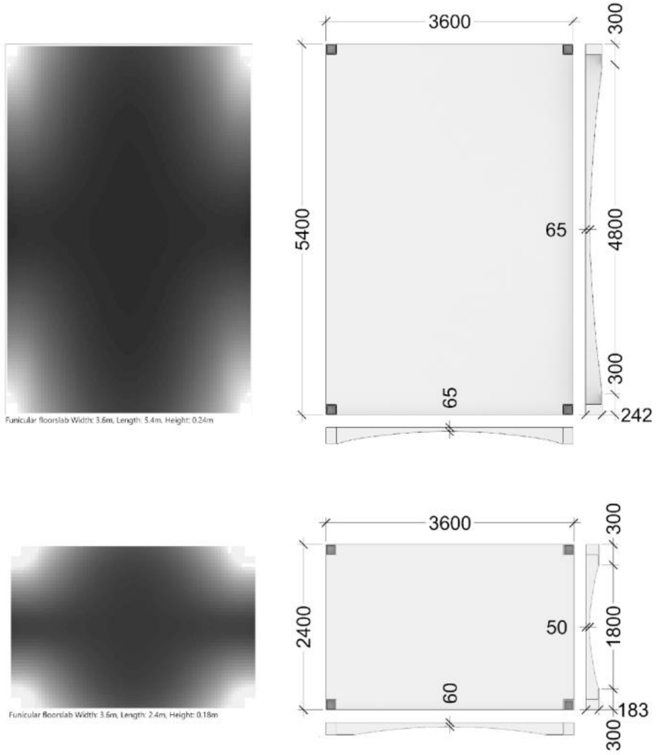

Tensile stresses are guiding

In thin-shell floorslabs

Reduction of 69% of weight

While intergrating fabrication constraints

The results

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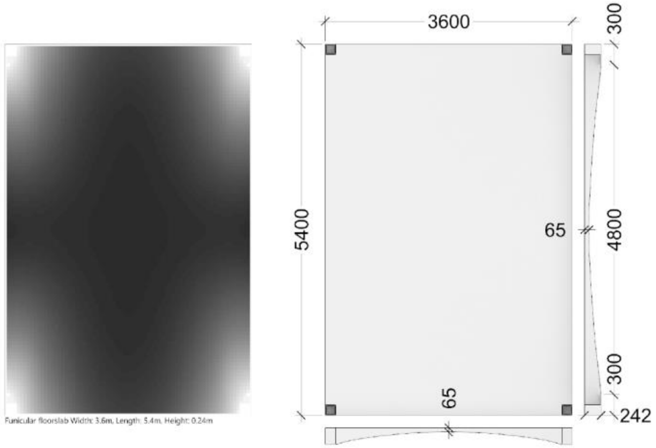
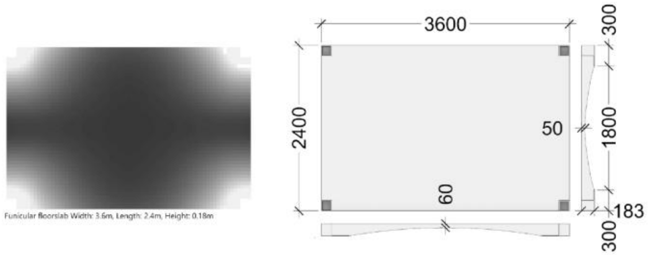




Tensile stresses are guiding

In thin-shell floorslabs

Reduction of 69% of weight

While intergrating fabrication constraints

Multiple loadcases are guiding

in the optimization process

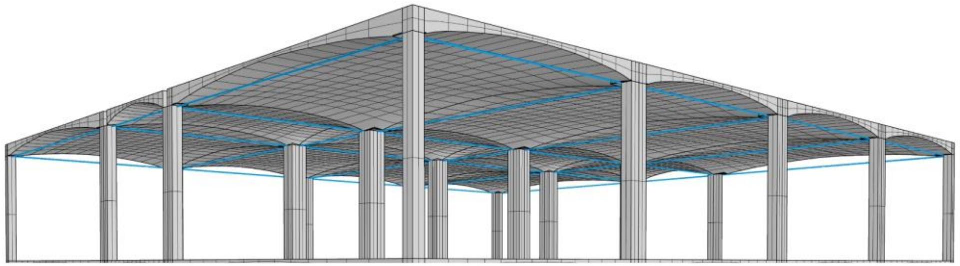
SECTION III
EVALUATION
OF THE HYPOTHESIS

Hypothesis

Fabrication-aware, structurally optimized floor slabs can significantly reduce the environmental impact of concrete construction.

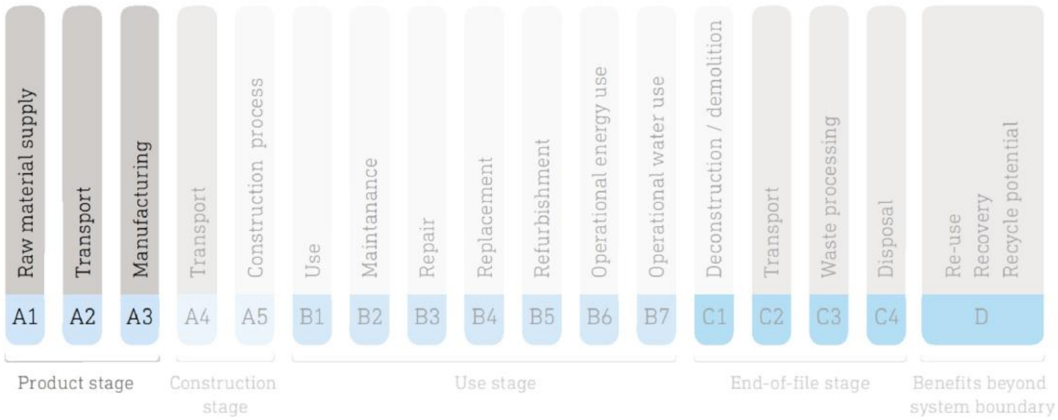
Evaluation of the hypothesis

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs



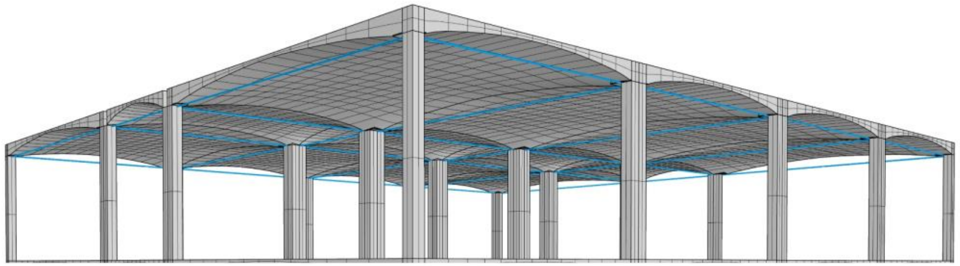
Life Cycle Assessment (LCA)

Of the product stage



Evaluation of the hypothesis

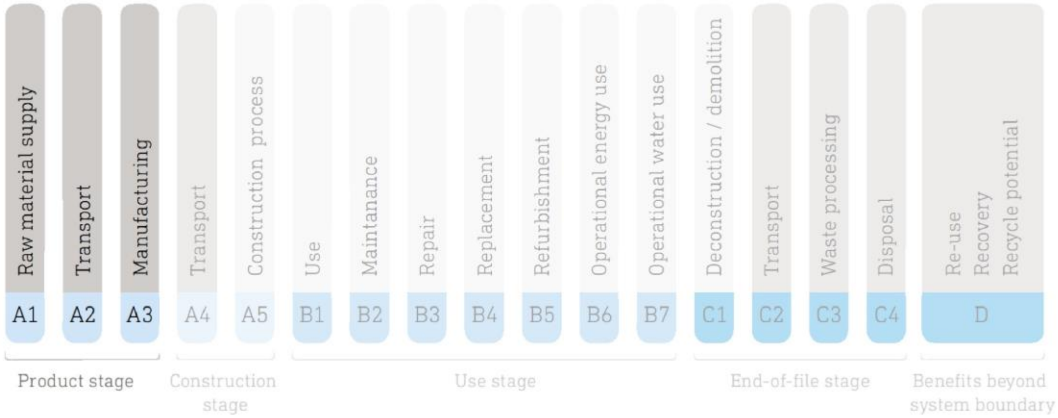
Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs



Life Cycle Assessment (LCA)

Of the product stage

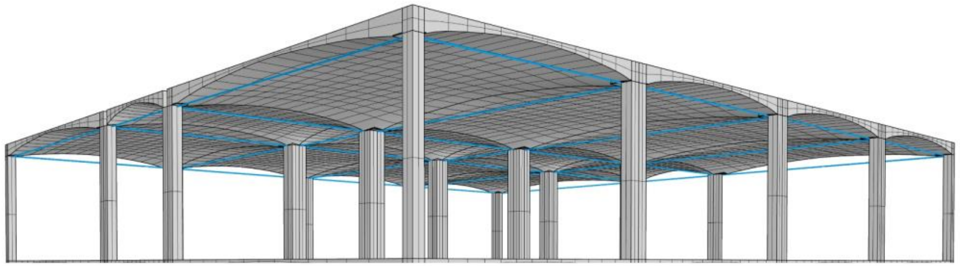
- The product stage, as it accounts for more than 80% of the embodied emissions



Source: (kong et al., 2020)

Evaluation of the hypothesis

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs



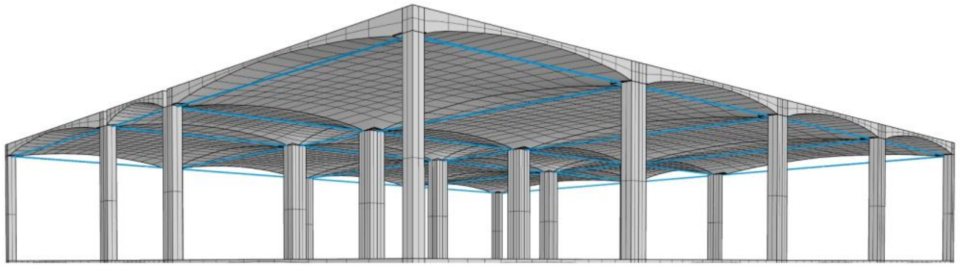
Life Cycle Assessment (LCA)

Of the product stage

Virtual office building

Evaluation of the hypothesis

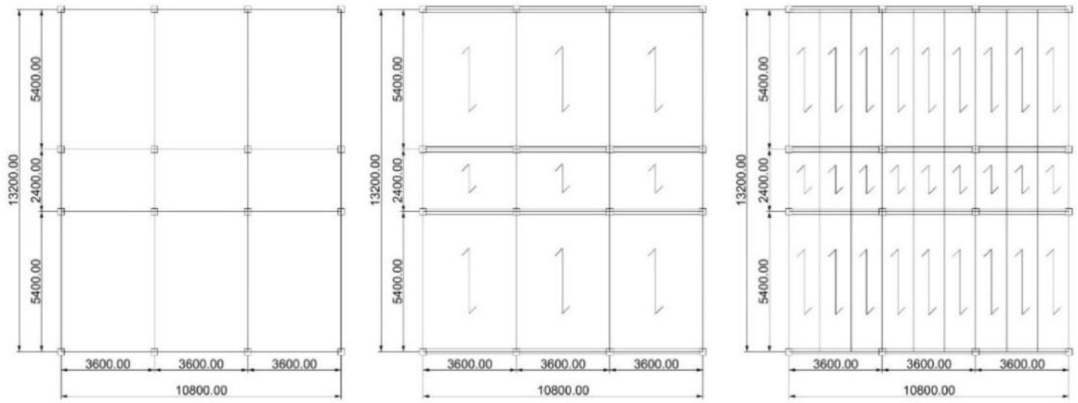
Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs



Life Cycle Assessment (LCA)

Of the product stage

Virtual office building



Evaluation of the hypothesis

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs

Life Cycle Assessment (LCA)

Of the product stage

Virtual office building

Ten flooring systems compared

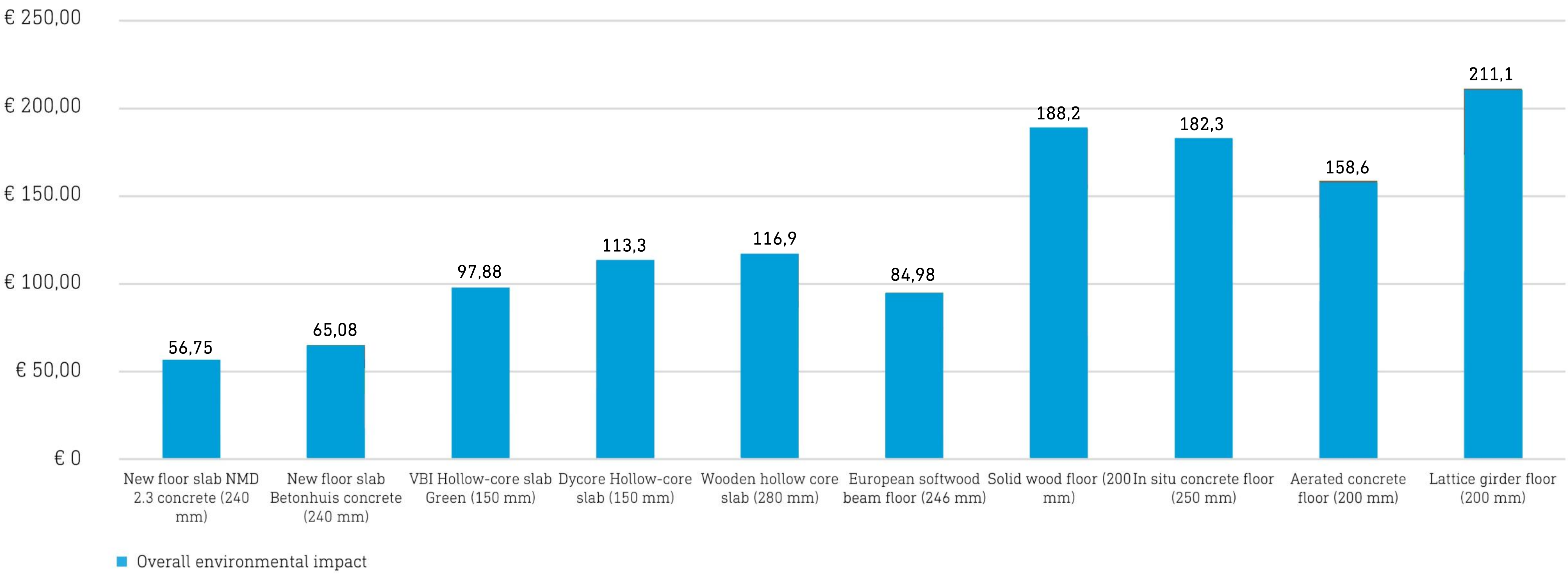
5400 mm span flooring systems

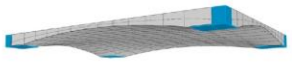
Ten flooring systems

5400 mm span flooring systems

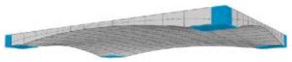
Ten flooring systems

Overall environmental impact in shadowcost (3600 mm x 5400 mm)





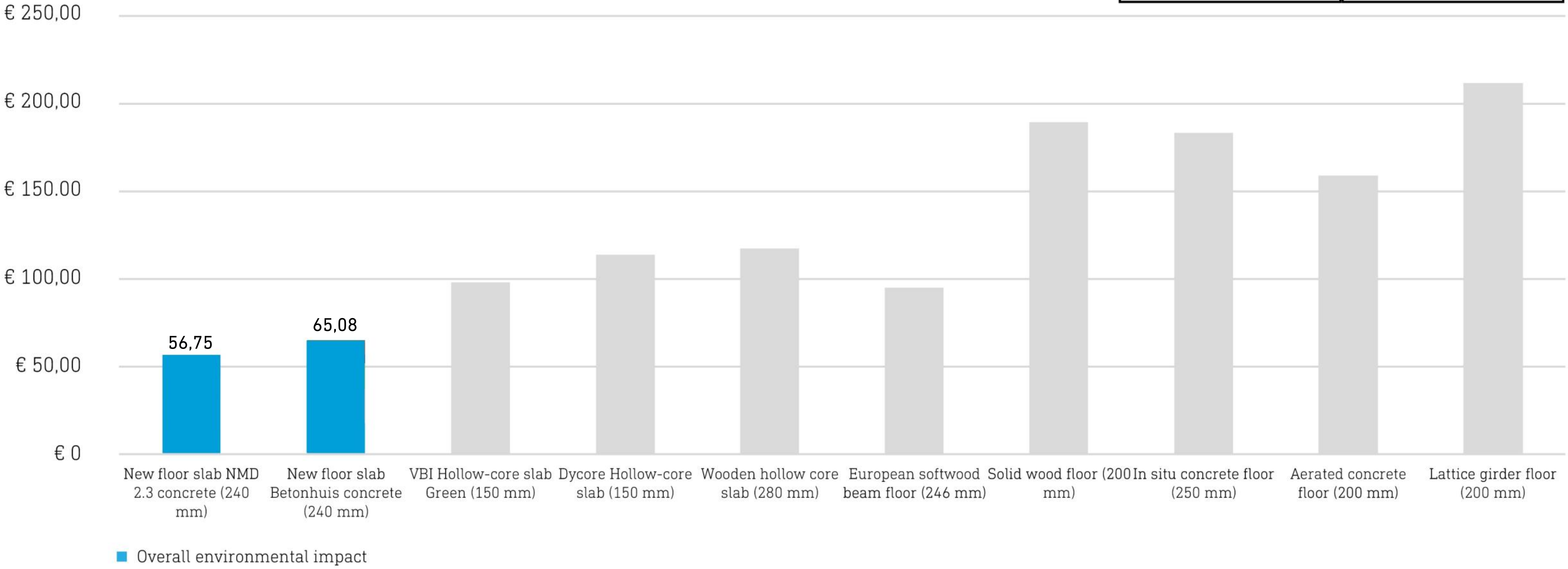
NMD 2.3 concrete



Betonhuis concrete

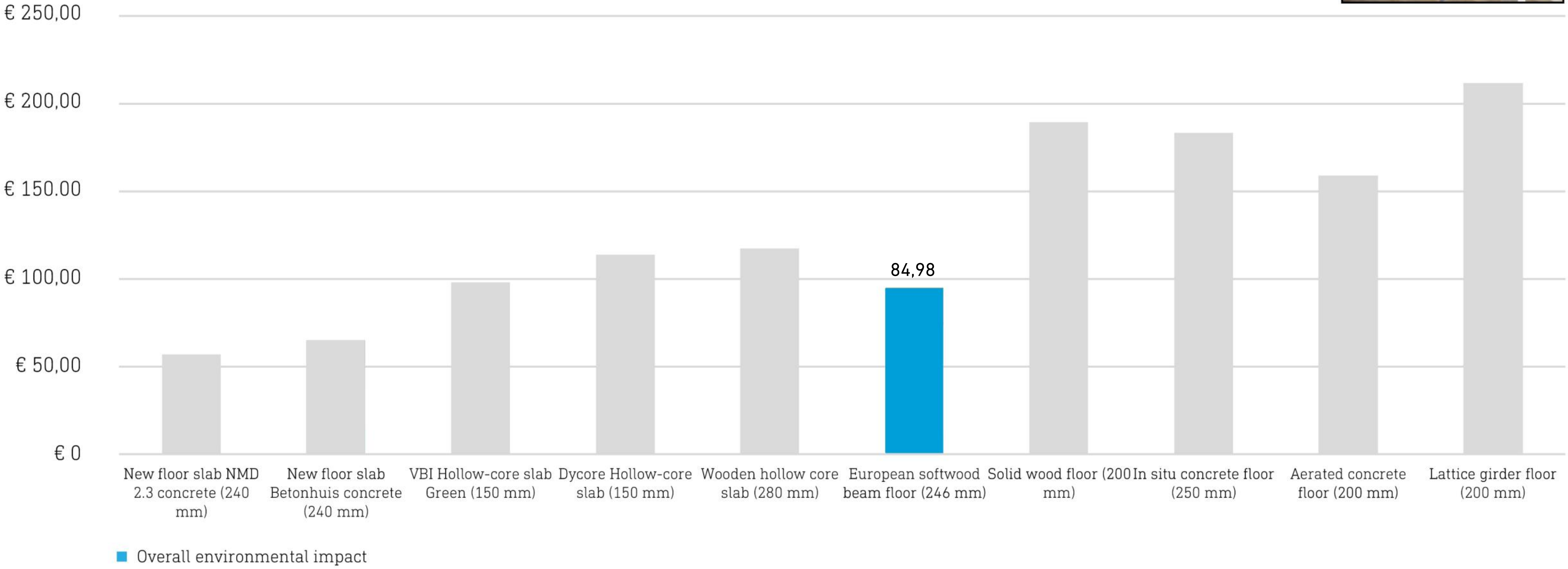
Ten flooring systems

Overall environmental impact in shadowcost (3600 mm x 5400 mm)

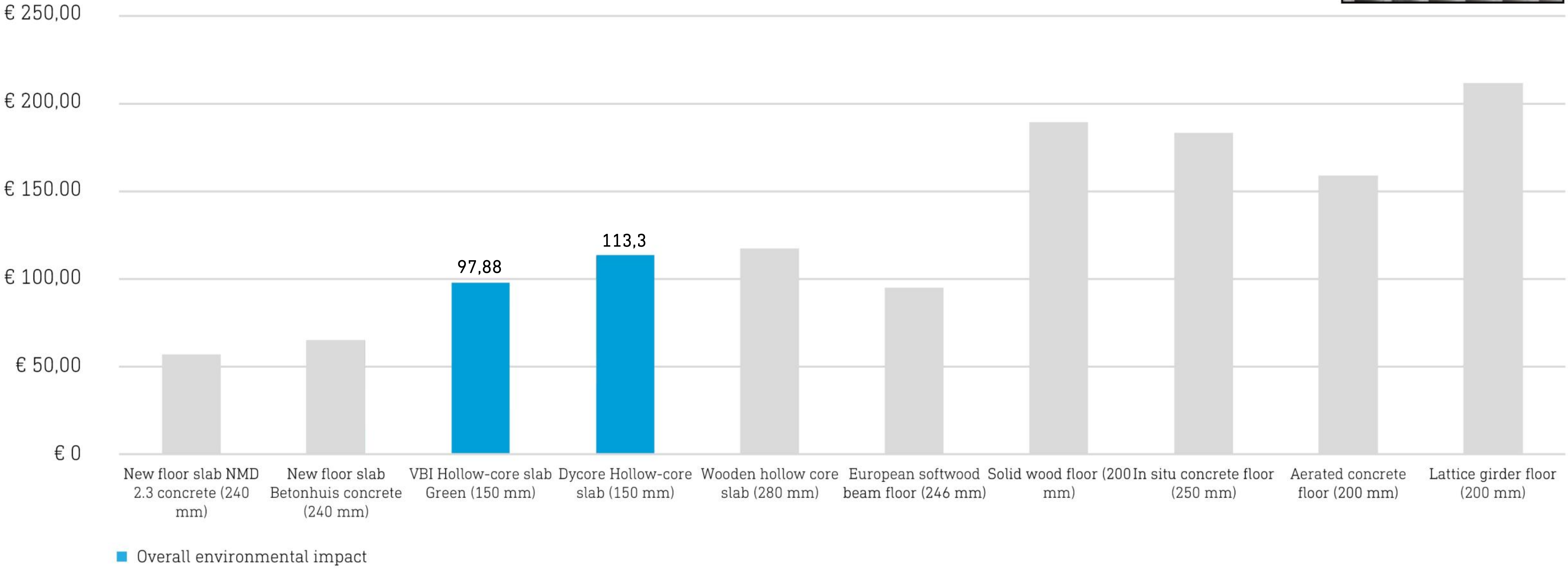


Ten flooring systems

Overall environmental impact in shadowcost (3600 mm x 5400 mm)

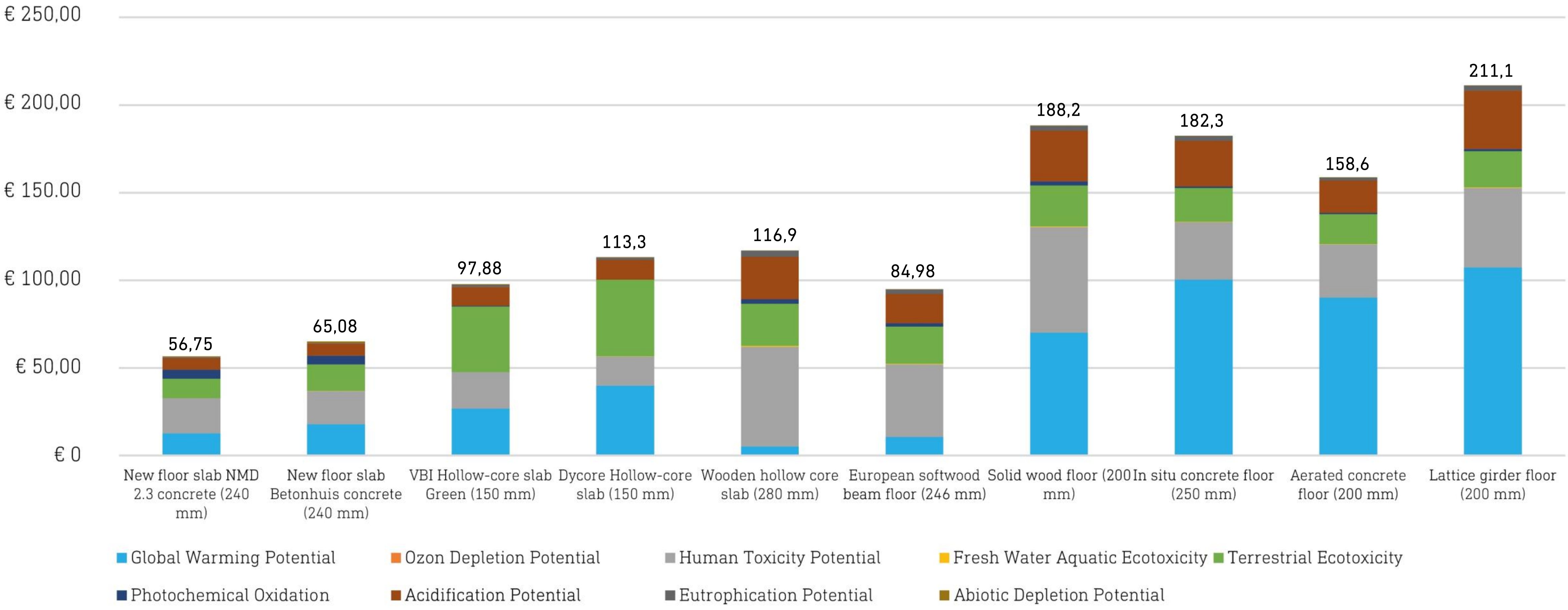


Ten flooring systems
Overall environmental impact in shadowcost (3600 mm x 5400 mm)



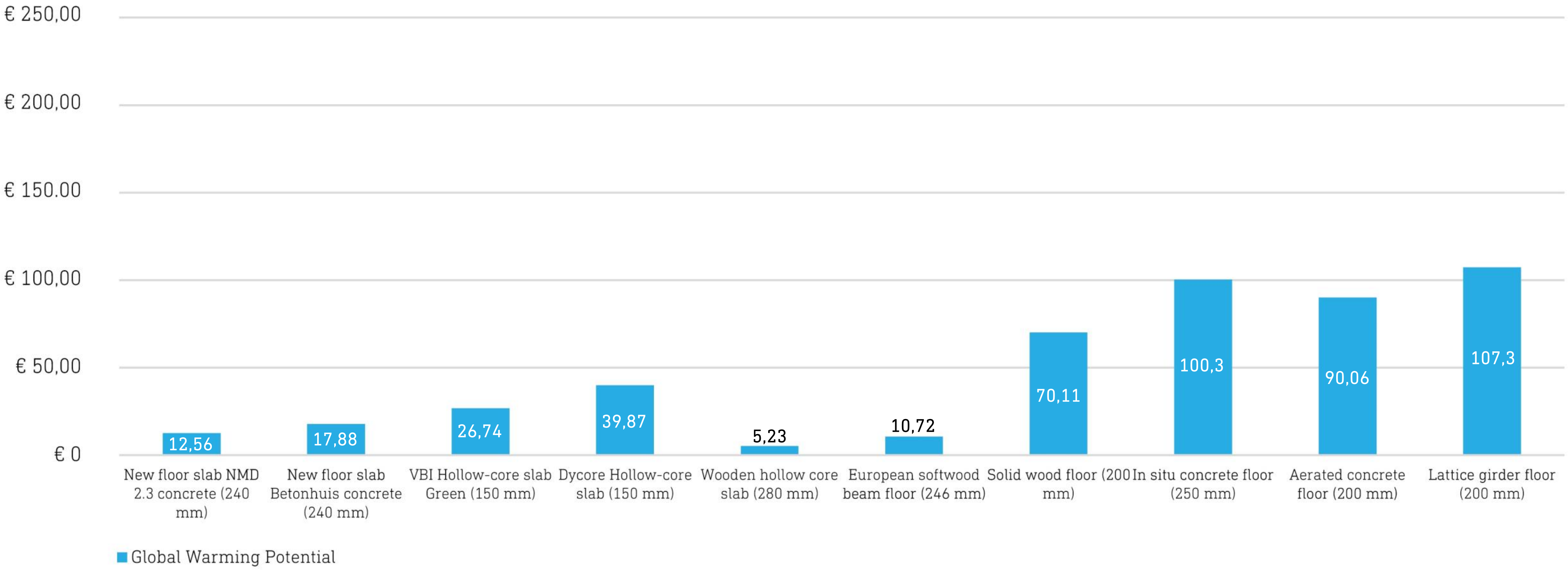
Ten flooring systems

Overall environmental impact in shadowcost (3600 mm x 5400 mm)



Ten flooring systems

Global warming potential in shadow cost (3600 mm x 5400 mm)



2.4% worldwide CO_2 emissions

Is caused by concrete flooring systems

0.32% to 1.3% to worldwide CO_2 emissions

Could be achieved with the proposed flooring system

Summary

Conclusion and Outlook

Main research question

In what manner can we use additive manufacturing and structural optimization in the building sector to address the environmental impact of concrete construction?

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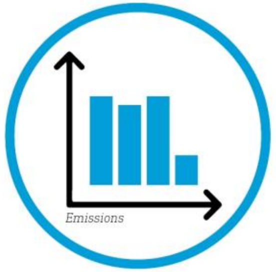
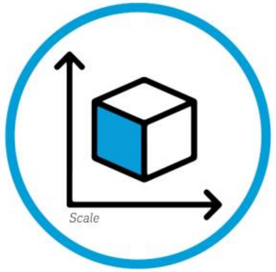


Process-related material requirements

Reinforcement

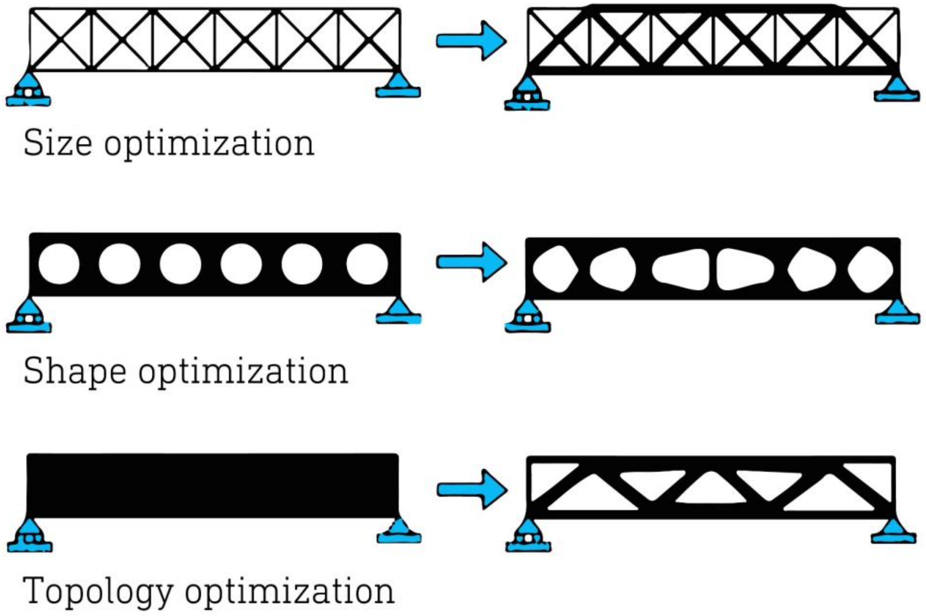


Scalability

Life cycle cost

Main research question

In what manner can we use additive manufacturing and structural optimization in the building sector to address the environmental impact of concrete construction?



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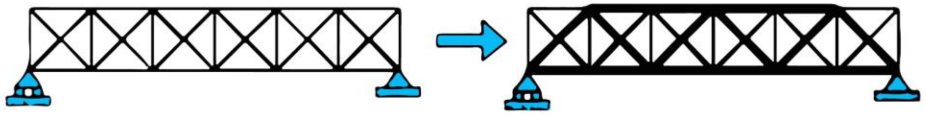
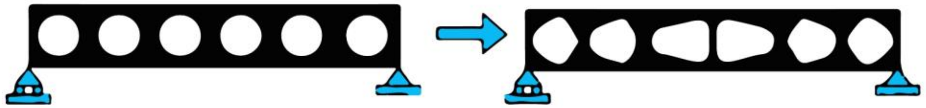
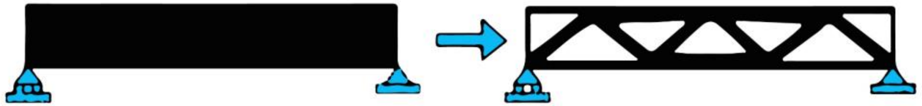


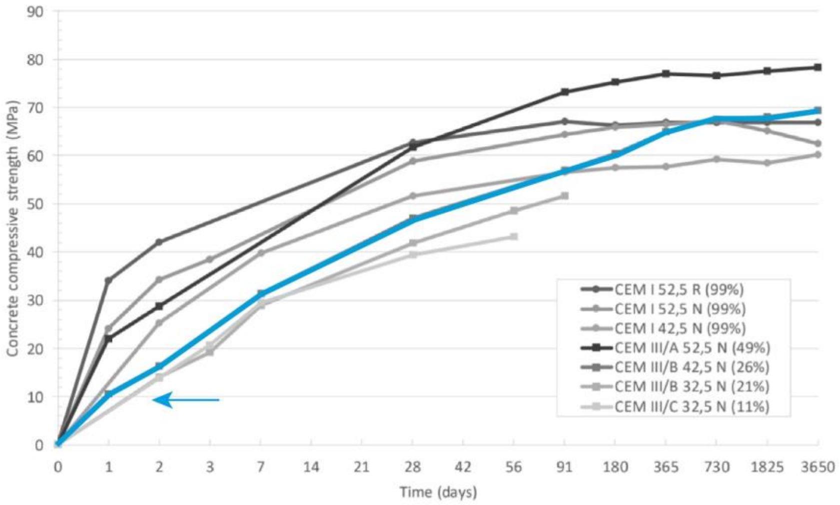
Size optimization



Shape optimization



Topology optimization



Main research question

In what manner can we use additive manufacturing and structural optimization in the building sector to address the environmental impact of concrete construction?

85% *of the emissions is the binder*

2.4% worldwide CO_2 emissions

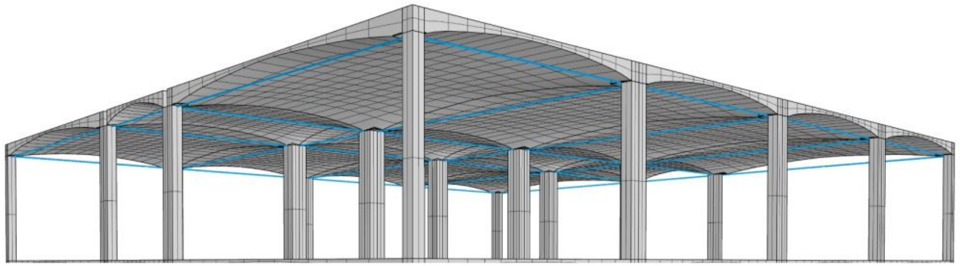
Is caused by concrete flooring systems

Hypothesis

Fabrication-aware, structurally optimized floor slabs can significantly reduce the environmental impact of concrete construction.

Hypothesis

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs

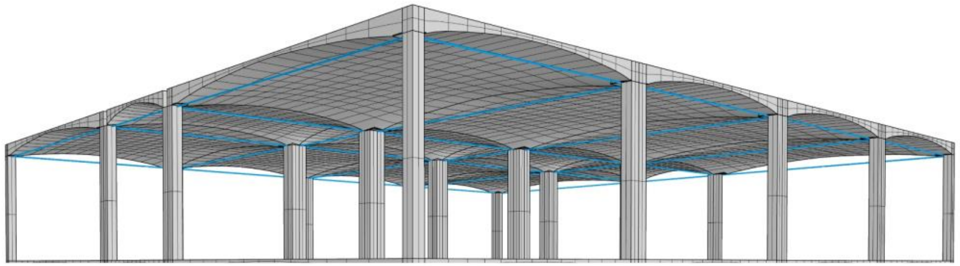


Research through design

- A derivative free optimimization approach allows for the succesful intergration of fabrication constraints and multiple loadcases in the optimization process.

Hypothesis

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs



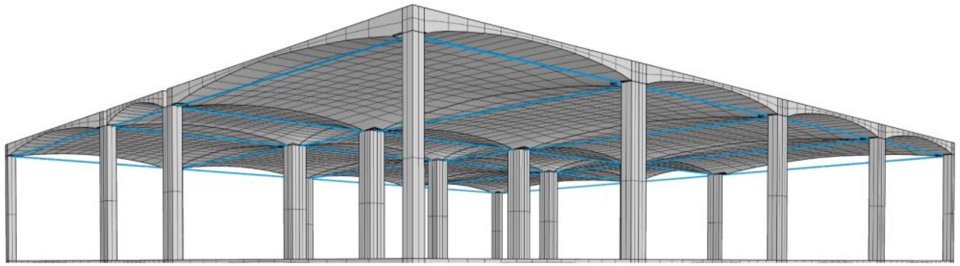
Research through design

- A derivative free optimimization approach allows for the succesful intergration of fabrication constraints and multiple loadcases in the optimization process.

This adresses a current gap in literature, on a derivative approach for concurrent structural design problems.

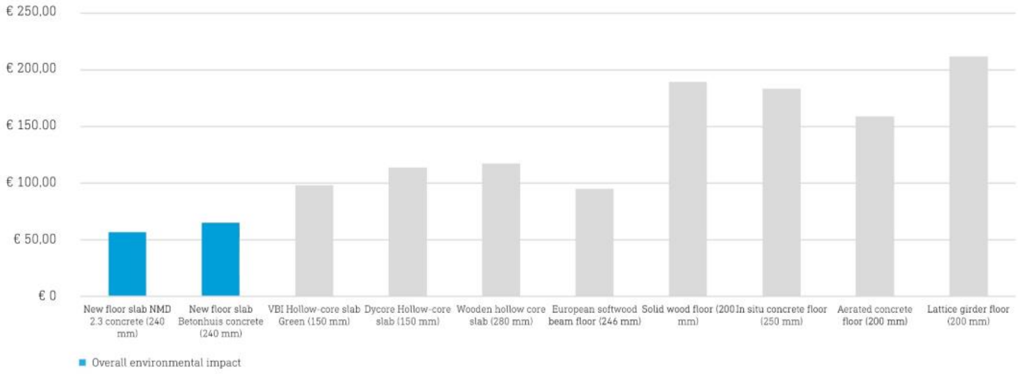
Hypothesis

Reducing the environmental impact of concrete construction through fabrication-aware, structurally optimized floor slabs



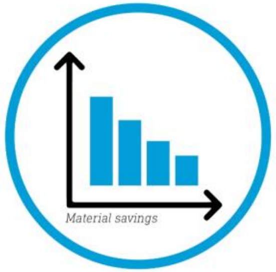
Research through design

- Thin-shell flooring systems which utilize membrane action, result in a significant reduction in both carbon and environmental footprint.



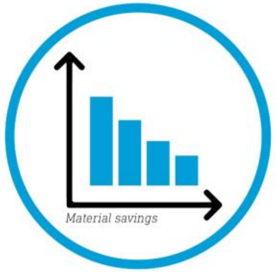
"Although reinforced concrete has been used for over a hundred years and with increasing interest during the last decades, few of its properties and potentialities have been fully exploited so far. Apart from the unconquerable inertia of our own minds, which do not seem to be able to adapt freely any new ideas, the main cause of this delay is a trivial technicality: The need to prepare wooden frames." – Nervi, 1956

Designing sustainable by designing with less material,



Material savings (Optimization)

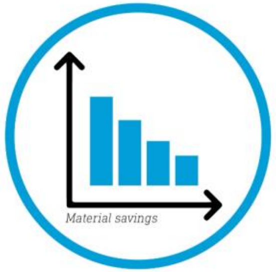
Designing sustainable by designing with less material, with a smaller impact,



Material savings
(Optimization)

Material emissions
(Material)

Designing sustainable by designing with less material, with a smaller impact, in an easy to construct way

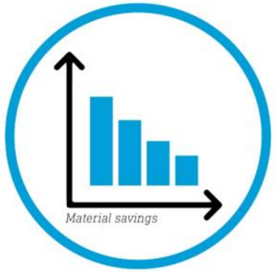


Material savings (Optimization)

Material emissions (Material)

Constructability (Process)

Designing sustainable by designing with less material, with a smaller impact, in an easy to construct way



Material savings
(Optimization)

+

Material emissions
(Material)

+

Constructability
(Process)

A step towards a more sustainable building sector

Thanks for listening