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Convective Concrete – Additive Manufacturing to facilitate activation of thermal mass

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Abstract

This paper reports on the research-driven design process of an innovative thermal mass concept: Convective Concrete. The goal is to improve building energy efficiency and comfort levels by addressing some of the shortcomings of conventional building slabs with high thermal storage capacity. Such heavyweight constructions tend to have a slow response time and do not make effective use of the available thermal mass. Convective Concrete explores new ways of making more intelligent use of thermal mass in buildings. To accomplish this on-demand charging of thermal mass, a network of ducts and fans is embedded in the concrete wall element. This is done by developing customized formwork elements in combination with advanced concrete mixtures. To achieve an efficient airflow rate, the embedded lost formwork and the concrete itself function like a lung. The convection takes place with separate pipes on both sides of the concrete's core to increase the charge/discharge of the thermal storage process. The first stage of the research, described in this paper, is to simulate the Convective Concrete at the component level, whereupon a mock-up is tested in a climate test set-up. The paper concludes with describing planned activities for turning this concept into a real building product.

1 INTRODUCTION

The use of thermal mass is usually considered as an effective strategy for achieving energy efficient building designs with high thermal comfort levels (Holmes and Hacker, 2008). This is normally done by applying construction types with high thermal storage capacity (e.g. concrete) on the inside of the thermal insulation layer (Knaack et al., 2007). Such heavyweight constructions have a slow response time. This thermal inertia helps to flatten temperature peaks, but the slow response is not advantageous at all times (Hoes et al., 2011; Loonen et al., 2013). Due to a lack of control possibilities regarding when and how much energy to exchange between interior zones and the constructions with thermal mass, these dynamic effects may actually also increase heating and cooling energy demand during intermittent operation or can cause unwanted discomfort, either due to too cold surface temperatures when the building is already occupied on winter mornings, or because the accumulated heat can sometimes not be sufficiently released, leading to potential indoor overheating issues in summer (Hoes and Hensen, 2016). Another shortcoming of thick concrete slabs is that actually only a small part of the heavyweight material (usually the first few centimetres) effectively plays a role in storing thermal energy. This forms a missed opportunity.

The goal of the research project that is reported in this paper is to explore new ways of making more intelligent use of thermal mass in buildings. This is accomplished through the research-driven design process of an innovative building envelope concept: Convective Concrete. This paper first introduces the underlying principles of Convective Concrete. In the second phase, the simulation-based and experimental activities that are used to inform the design specifications for Convective Concrete are addressed. The paper concludes with presenting future most promising application areas and future perspectives for high-performance buildings with Convective Concrete.

2 THE CONVECTIVE CONCRETE CONCEPT

The idea behind Convective Concrete is inspired by the concept of hollow-core ventilated slabs, of which its potential has been investigated by Zmeureanu & Fazio (1988), and a more recent energy-active façade that uses capillary tubes, described by Maier, Gilka-Bötzow & Schneider (2015). The hollow-core ventilated slabs are concrete floor elements that play an active role in the thermal comfort of buildings, by being part of the ventilation system in order to precondition the ventilation air. Most of these systems have been applied in offices. Analyses show that an increased airflow rate through the hollow core slab floors during the night can decrease the inner cooling load by 28.4 – 44.2 W/m^2 in comparison to a standard mechanical climate system (Zmeureanu & Fazio, 1988). Warwick et al., (2007) monitored an office building in Sheffield, UK with hollow-core ventilated slabs and found that an airflow rate of 0.3 m/s (6.2 air changes per hour) within the slab is sufficient to completely eliminate the occurrence of summer discomfort. Simulations show that ventilated hollow core slab floor elements can provide a temperature below 28 degrees centigrade for 90% of the occupied time in an office situated in Italy (Corgnati & Kindinis, 2007). The energy-active façade is an ultra-high-performance concrete slab that is combined with concrete foam for insulation and capillary piping on both sides, to allow energy to be exchanged from inside the building to the outside and vice versa (Maier et al., 2015). Another design iteration of the hollow-core slab principle has been proposed in the form of ventilated internal double walls (VIDW) (Fraisse et al., 2006). Simulation studies show that the application of such a wall element can be very effective for improving thermal comfort conditions in warm summer periods (Fraisse et al., 2010). Despite the promising potential of VIDW, practical manifestations (e.g. prototypes or mock-ups) cannot be found in scientific literature.

Convective Concrete initially targets the residential building market. The goal is to mitigate residential overheating during summer periods by reducing the temperature of constructions through active heat exchange between the building construction (hollow-core concrete slabs) and cool outside air at night. Even though air has a relatively low volumetric heat storage capacity compared to e.g. water, it is used as a transport medium in this project, because of:

— Its widespread availability at favorable temperatures;
— Can be combined with earth tubes;
— Easy construction an installation process: plug-and-play;
— Provides standalone elements that do not need to be connected to additional systems;
— Can function passively without mechanically forced convection due to the buoyancy effect;
— No risk for leakages, punctures or frost damage;
— Low weight and therefore less structural requirements.

To accomplish the on-demand charging of thermal mass, a network of ducts with attached fans, as back-up to the buoyancy effect to ensure a sufficient amount of air flowing through the Convective Concrete, needs to be embedded in the concrete wall element. This is done by developing customized formwork elements in combination with advanced concrete mixtures.

Additive Manufacturing (AM) is used, because it is a good method for this kind of rapid prototyping. Customized and free-form parts can be produced easily. AM of lost formwork differs from the approach of direct concrete printing, but allows for a traditional processing of the concrete itself. To benefit most from AM as production technology, the free-form and customized parts needed for the Convective Concrete are printed in wax, using Fused Deposition Modeling (FDM), an AM process based on material extrusion, that can be melted after the concrete is hardened. The building volume and resolution of FDM printers can be adapted to the desired size and layer thickness easily.

To achieve an efficient convective flow, the embedded lost formwork and the concrete itself should function like a lung. The convection takes place with separate pipes on both sides of the concrete's core to increase the charge/discharge of the thermal storage process with help of fans, in the event of lack of buoyancy effect and with the help of valves, to control when the slabs are ventilated. There will not be any openings through the slabs themselves, because that would cause thermal bridges. The concrete mixture with matching characteristics (density, porosity and lambda value) will be fabricated on the basis of input from computational simulations.
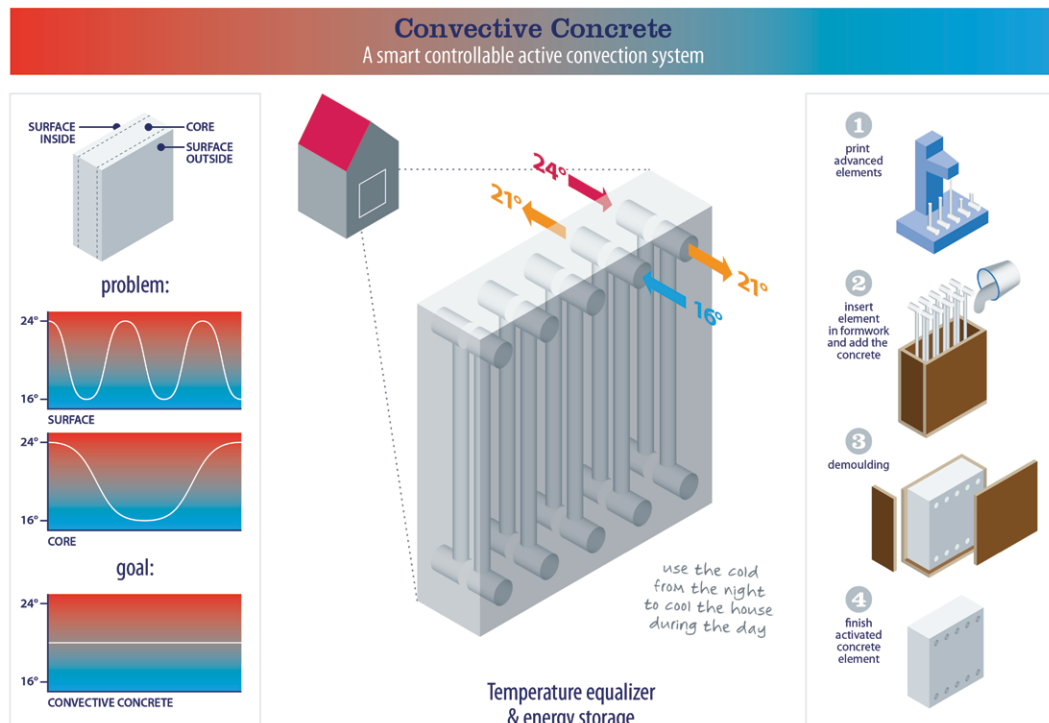
FIG. 1 Convective Concrete concept.

By integrating these additively manufactured smart voids and piping for convection within the customized concrete elements, it is possible to compensate for the emissions from concrete production during the usage phase. Carbonation is a process which binds CO_2 (CaO and CO_2 react to form CaO_3) to the concrete during the usage phase. With Convective Concrete, the rate of carbonation can be increased since the surface area doubles in the models used for the first simulations and since the amount of carbonation is directly related to the surface area. The speed of carbonation relates to the way the concrete is exposed and the concrete's strength class. From those parameters a k – value can be obtained (Lagerblad, 2005). Althoug the k – value differs with every concrete mixture and only a thin layer of concrete is able to bind the CO_2 over a certain time interval, the surface area that is able to bind the CO_2 will increase significantly, due to the internal piping in Convective Concrete.

2.1   MOCK-UP

The first stage of the research is to simulate the Convective Concrete at the component level, whereupon a mock-up is tested in a climate test set-up. If the simulations and the obtained results of the physical mock-ups match with the simpler geometries, the geometry of the tested mock-ups can develop over time. Form and routing shall become more complex to increase the efficiency of the heat exchange and to increase the amount of surface that is able to bind CO_2.The research is an iterative process to measure the different geometries of the embedded formwork used. The first layout used is an internal tubing system in which the channels on both sides of the concrete are not connected. There is no cross-ventilation and the element functions as a heat exchanger. The cool outside air ventilates the Convective Concrete during the night which allows the concrete to absorb unwanted internal heat gain during the day. The geometry is on basis of the computational design described in paragraph 3. In Fig. 1 this layout in combination with an abstract principle of Convective Concrete is shown.

Additive Manufacturing is in the project used to print the internal voids. For the internal repeating formwork of the first layout, which has a simple geometry, a positive form has been printed to make a mold, which can be used to cast the wax elements. Future, more complex, geometries will be printed directly in wax. Combining both, direct and indirect production methods by use of AM facilitates the desired mass customization. By using AM in this beneficial way, to improve performance based on location and its demand, the heat storage and exchange can be optimized. This flexibility in form without additional costs is where the main advantage is, compared to more conventional types of ventilated slabs.

3   COMPUTATIONAL DESIGN SUPPORT

During the design process of an innovative façade element such as Convective Concrete, many parameters can be considered but not all can be extensively tested via the making of a mock-up. However, computational simulations can help us to make decisions on some variables in order to select the most promising properties to further analyze with the mock-up (Loonen et al., 2014). In this case, a two-dimensional dynamic heat transfer model is used via the simulation program Energy2D to make decisions on the shape and layout of the air channels in the Convective Concrete as well as the properties of the concrete mixture itself. The goal is to model the system in a whole building energy simulation program, EnergyPlus, to evaluate the performance of the system in relation to weather and occupant influences, and to determine its most efficient operation mode.

3.1   ANALYSIS OF DYNAMIC 2D HEAT TRANSFER

The software program Energy2D is used to solve the dynamic Fourier heat transfer equations for the Convective Concrete case. Energy2D is a relatively new program (Xie, 2012) and is not yet widely used as a building performance simulation tool. To gain more confidence in the predictions with Energy2D, an analytical validation study was therefore carried out first, inspired by the approach described in Hensen and Nakhi (1994). Those analytical solutions and the simulation results of the dynamic response to a 20°C temperature step change on the surface of a concrete construction with the following properties were compared for this research:

Properties and symbol	Value and Unit
Thickness t	0.1 m
Conductivity λ	0.045 W/(m ×K)
Density ρ	50 kg/m3
Specific heat c	840 J/(kg ×K)
Convective heat transfer coefficient h_c	3 W/(m2×K)

TABLE 1 Construction properties

The exact solution of the surface temperature of a plane wall with surface temperature was determined as follows according to Incropera et al.:

$$T_s = T_\infty + (T_i - T_\infty) \sum_{n=1}^{\infty} (C_n \exp(-\zeta_n^2 Fo) \cos(\zeta_n x^*)) \text{[Eq.] (1)}$$

Where:

$$C_n = \frac{4 sin\zeta_n}{2\zeta_n + sin(2\zeta_n)} \qquad \text{[Eq.] (2)}$$

and the discrete values of ζ_n (1-4) are positive roots of the following equation:

$$\zeta_n tan\zeta_n = Bi = 3,33. \qquad \text{[Eq.] (3)}$$

The appropriate values of ζ_n for this problem become:

$$\zeta_1 = 1,217; \zeta_2 = 3,850; \zeta_3 = 6,739; \zeta_4 = 9,751. \qquad \text{[Eq.] (4)}$$

With Biot number,

$$\frac{h \cdot L_c}{k} = 3,33 \qquad \text{[Eq.] (5)}$$

thermal diffusivity:

$$\alpha = \frac{k}{\rho c} = 1,07 \cdot 10^{-6} \ m^2/s' \qquad \text{[Eq.] (6)}$$

and the Fourier number:

$$Fo = \frac{\alpha \cdot t}{L_c^2} = 4,29 \cdot 10^{-4} \cdot t \quad \text{[Eq.] (7)}$$

As can be seen in Fig. 2, the simulation results never divert from the exact solution more than 0.45°C and it is therefore considered acceptable to further use this model.
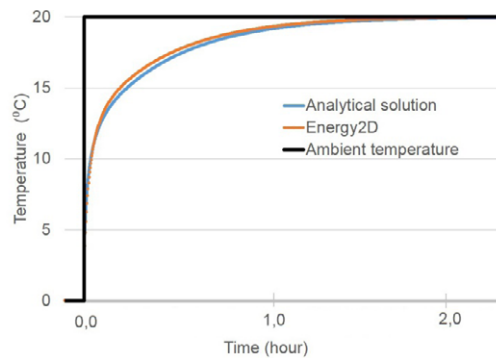
FIG. 2 Validation study, showing a comparison between simulated and analytically calculated results.
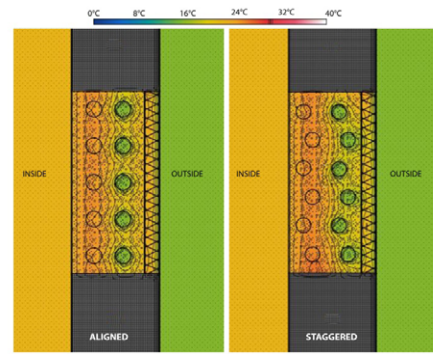

FIG. 3 Aligned and staggered distribution of air channels.

3.2   TIME CONSTANT

The Energy2D model is also used to characterize the thermal time constant of different concrete mixtures in order to select the mixture that will first be used for the initial Convective Concrete mock-up. In this study, the temperature for a point in the middle of a 20 cm thick concrete wall is simulated and the wall is subjected to a 10°C temperature step decrease. The thermal time constant is defined as the time required for this point to change e^{-1} = 36,8% of the total difference between its initial and final temperature. The thermal time constant was evaluated for 70 existing types of concrete with different density and thermal conductivity. The heat capacity of the 70 types of concrete was always 840 J/kgK. Fig. 4 shows the simulation at two stages: t=0 when the concrete is at a temperature of 25°C and the surrounding at a temperature of 15°C and after 3 hours when the temperature in the wall is decreasing.
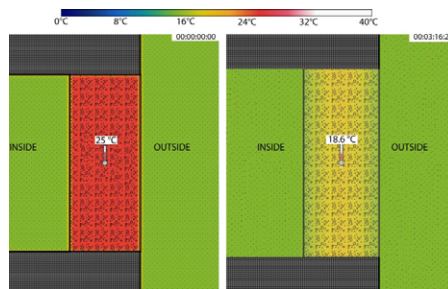

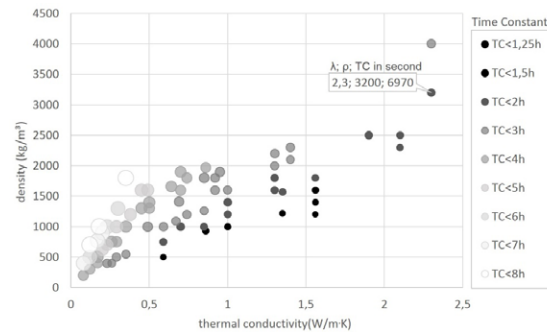FIG. 4 Example of time constant simulation.

FIG. 5 Thermal time constant of 70 concrete types.

Fig. 4 allows us to select a concrete mixture that has a high density for high storage capacity purposes while having a relatively quick thermal response with a time constant in the order of 2 hours. As can be seen in Fig. 5, the selected concrete mixture has a density of 3200 kg/m^3, a thermal conductivity of 2.3 W/m.K and a time constant of one hour and 56 minutes. Fig. 5 presents all the examined concrete types according to their thermal conductivity (x-axis) and their density (y-axis). The diameter of the circle represents the time constant recorded during the simulation for every concrete type while the shades of grey categorizes the results in different sections of time. The smaller the diameter and the darker the grey, the shorter the time constant.
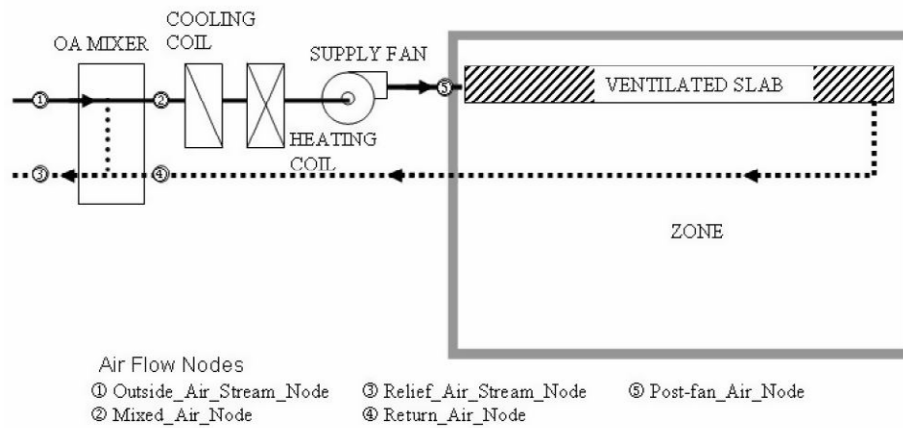
FIG. 6 Schematic section representing the operation of the ventilated slab model in EnergyPlus. (U.S. Department of Energy, 2016).

3.3 NEXT STEP WITH ENERGYPLUS

While the performance of the mock-up will be measured under controlled conditions, the timespan of the project does not allow to implement and monitor the performance of the system in a real building. This situation can instead be modeled in a whole building energy simulation software. No model pre-exists to simulate the innovative Convective Concrete system, however, some existing models have enough similarities and flexibility to replicate the effects of the Convective Concrete. In this study, the ventilated slab model developed by Chae and Strand in EnergyPlus (Chae & Strand, 2013) is used.

Since the Convective Concrete does not directly circulate the air of the room, the "Slab Only" mode which is displayed in a schematic manner in Fig. 6 is selected. Also no heating or cooling coils are implemented as the Convective Concrete uses outdoor air directly.

The first results show promising performance of the system but operation modes and control settings still need to be further investigated. As can be seen on Fig. 7 Convective Concrete has the potential to decrease the operative temperature in a simple square zone of 25 m^2 by more than 2^{0}C. The zone simulated has all its surfaces exposed to the outside except for its ground floor, a window is implemented on the South oriented wall and the East, North and West wall are equipped with Convective Concrete. In this example the control to turn on the system is based on the operative temperature and is set to 22^{0}C. When both the operative temperature is more than 22^{0}C and the outdoor air temperature is lower than the temperature of the Convective Concrete, outdoor air is circulated in the element and goes out warmer as the concrete is cooled down.
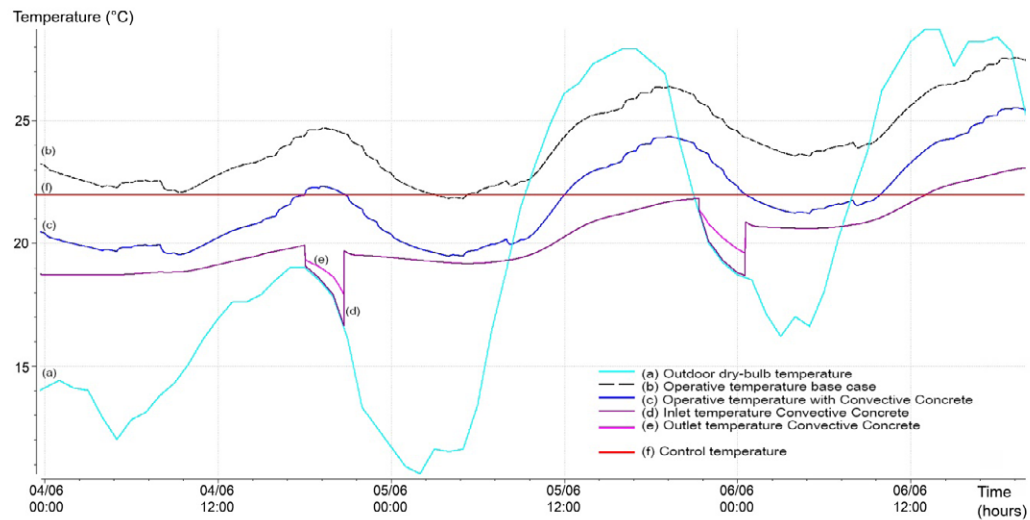
FIG. 7 First results of the whole building simulation for the 4th, 5th and 6th of June.

4 FUTURE WORK

The simulations show the potential of the Convective Concrete. Future work consists of producing the different concrete mixtures, building mock-ups to test and to compare the results of the simulations and the physical models.

4.1 PHYSICAL MODEL

Concerning the concrete mixture, the focus is placed on the density and the thermal conductivity value which need to be the same as in the simulation to be able to compare the simulations and the mock-ups. The test facility is an insulated box with two rooms, one on each side of the sample, a so called hot-box as described in NEN-EN-ISO 8990:1997. A lamp is used to warm up a room while a Peltier element is used to cool it down. Once the temperature is stabilized, these rooms can represent different conditions on both sides of the Convective Concrete (e.g. overheated room inside and cold summer night outside). To measure the heat conduction through the Convective Concrete, heat flux sensors are used in combination with temperature sensors on both sides of the element and in the rooms.

With the temperature sensors, the U value can be calculated roughly by:

$$U = \frac{1}{R_{se}(1 + \frac{dT_o}{dT_i})} \qquad \text{[Equ] (8)}$$

dTo is the temperature difference between the inside wall surface and the outside air temperature
dTi is the temperature difference between the inside wall surface and the inside air temperature
RSe are the surface resistances of the exterior

The heat flux sensors will be used for an accurate measurement, which will be compared to the obtained values calculated over the temperature sensors.

4.2   POTENTIAL APPLICATIONS

Buildings that require a constant inner temperature benefit most from Convective Concrete. Climates where the night temperature falls below the day comfort temperature are those benefitting most of the system (Bernard, 2002). While in his research Bernard focusses on CoolDeck that eliminates the influence of false ceilings and walls, Convective Concrete inner walls can be used as well for energy storage, but also the influence of cavities in front of the element activated need to be eliminated. Cross ventilation during the night needs to be used to cool down these inner walls, making not only massive façades useful as activated concrete, but internal mass as well. With these innerwalls also the walls in between of row housing. Here forced horizontal ventilation can be used to activate the Convective Concrete. The separated inner and outer channels make Convective Concrete a closed loop heat exchanger with a thermal buffer in between.

To further decrease cooling energy use, the outer channels can also be connected with earth tube heat exchangers. During the summer the lower temperature is used to cool the outside channels and in winter it can be used only when the earth tube's temperature is higher than the core temperature of the concrete, when heating is needed. Cooling will always work as long as the earth tube delivers cooler air as the inside room temperature.

5   CONCLUSIONS

Although real mock-ups still need to be tested before the performance can be determined, the Convective Concrete shows its potential in the simulations. The concrete can store the energy on day/night cycles allowing a more constant inner temperature, which leads to a better thermal comfort within the built environment. In the next steps of the project, the physical models will be tested and with an iterative process the different geometries will be tested to obtain information on the parameters that influence the thermal exchange; Flow speed, internal surface geometry and the geometry of the channels inside the concrete. The technology to print the outcome of parametric models is available. As soon as the outcomes of the simulations match the physical models, parametric models can be designed, after which optimized internal formwork for the Convective Concrete can be printed and the façade and internal walls can be applied in the built environment. The final product can be in the form of prefabricated concrete slabs, but also in the form of the inserts that are placed in on-site built formwork.

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