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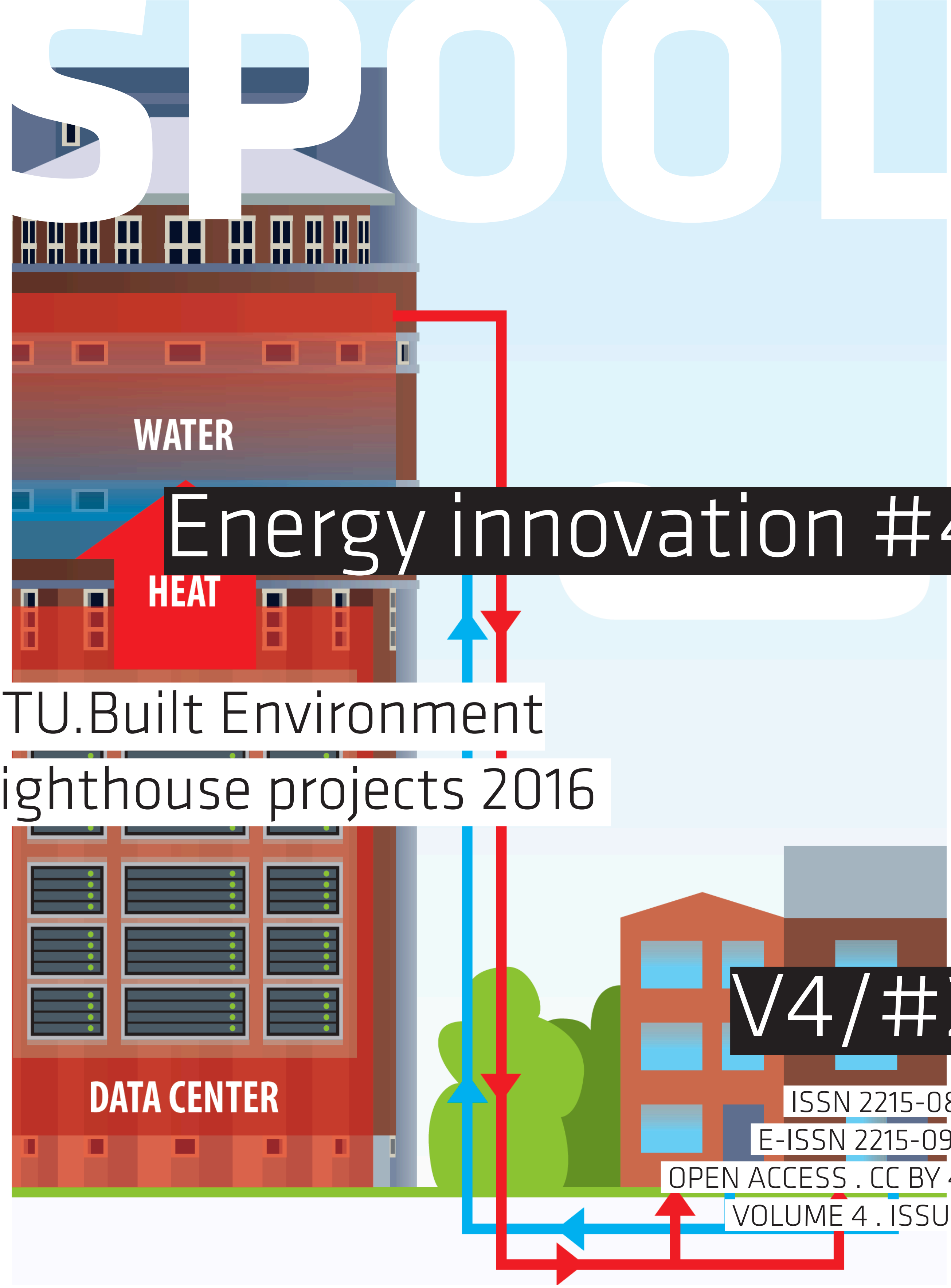

Energy innovation #4

4TU.Built Environment Lighthouse projects 2016

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Energy Innovation #4

Projects

SPOOL - Journal of Architecture and the Built Environment

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Bio based bridge

primary structural elements

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[3] *Centre of Expertise Bio-Based Economy*
[4] *NPSP BV*

Abstract

The project aims to design, produce and realise a small, but fully bio-based composite pedestrian bridge at the campus of TU/e. So far, few bio-based building projects have been realised world-wide, but they focussed either on non-structural elements or they partially used building materials based on fossil materials.

The application of bio-based materials in the built environment is an extremely promising approach towards a more circular economy and a sustainable environment, which is one of the National Science Agenda's themes: "Energy and raw materials: Circular economy". Recent developments have shown that bio-based materials can provide a useful approach for recyclable objects. Until now, fully bio-based primary structural elements have not been used and the applications are limited to experiments with facades components. Building industry clients are generally hesitant to put new technologies into practice without a proof of concept and therefore this pedestrian bridge is a big step forward.

Keywords

bridge structure; bio-based composite materials; vacuum-infusion

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1 Rijk, B., Teuffel, P., Smits, J., Gkaidatzis, R., Böttger, W., Hoogendoorn, A. Lepelaar, M. (2017). Bio-based briddge: Primary structural elements. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

> The main research question was whether and how these bio-based composite materials could be used in structural loadbearing (bridge and building) applications.

The main goals of the research project on bio-based materials were: investigating options for further reduction in the use of fossil fuels, preventing further depletion of raw materials and increasing options for a transition towards a more circular economy. For the unit Structural Design at the University in Eindhoven: TU/e , the main research question was whether and how these bio-based composite materials could be used in structural loadbearing (bridge and building) applications. Until recently bio-based composites have already been sparsely used in façade applications and also some structures with limited bio-based materials are known, but a bridge fully made out of bio-based composite materials had not yet been realised.

TU/e (acting as the project leader) submitted the research project proposal at the end of 2015 for the 4TU lighthouse call. The project was awarded in early 2015 and with the other project members: the university in Delft: TUD, as well as the Dutch Centre of Expertise Biobased Economy (universities of applied science Avans and HZ)) and a company NPSP bv, the projected started in early 2016.

The initial ambition was to realise a bridge with a span of about 8 m. This ambition was raised towards realising a bridge of 14 m. This way is became possible to cross the width of the river Dommel at the TU/e campus in Eindhoven. With the help of the TU/e real estate agency a location was found at an already existing small steel footbridge. This way the already existing bridge abutments could be reused.

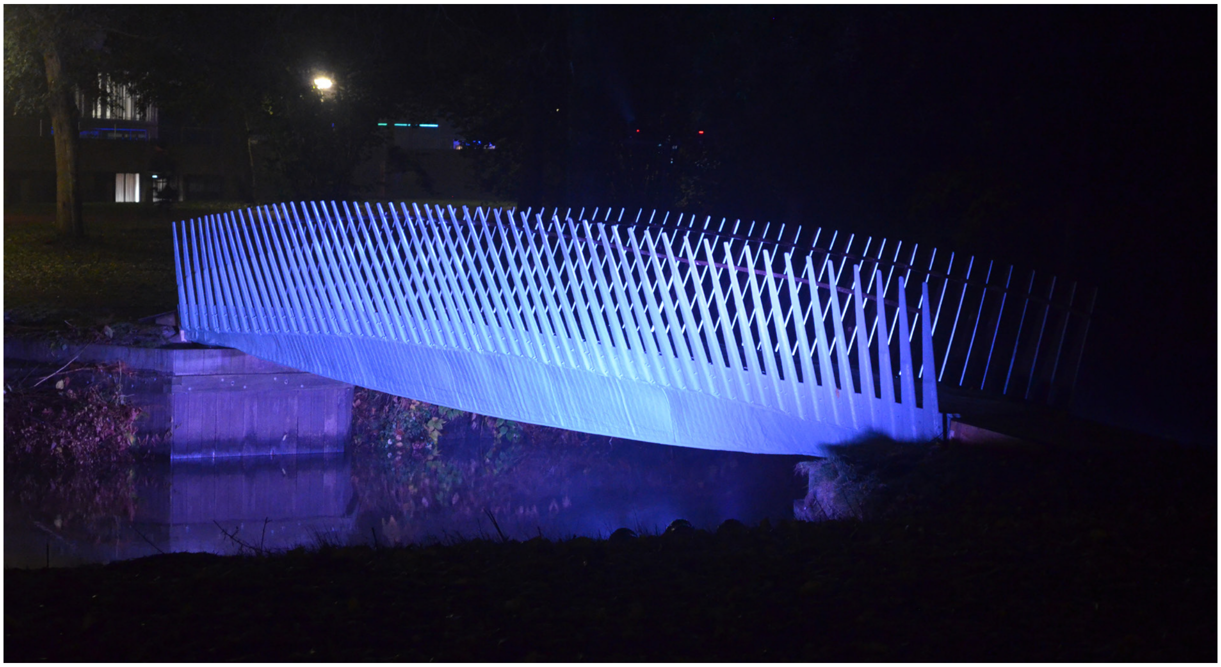

FIGURE 1 Photo: Tom Veeger

Rijk, B., Teuffel, P., Smits, J., Gkaidatzis, R., Böttger, W., Hoogendoorn, A. Lepelaar, M. (2017). Bio-based briddge: Primary structural elements. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Design and elaboration

The bridge, first in its kind, has been made fully out of bio-based materials: Flax and hemp fibres in a bio-based resin and round an internal shape of PLA bio-foam. Obviously the bridge had to fulfil the normal structural requirement in terms of safety and usability, like any other bridge. Also a normal building permit by the municipality of Eindhoven was required. The research, the design as well as the production and installation has entirely become possible through the enthusiastic collaboration of many students involved in all parts of the project. The project team-members together with students started off in joint design sessions, with generating design ideas in sketches and models. In further sessions the most promising designs were further investigated and elaborated. In student projects the designs were optimised using Rhino/ Grasshopper programs, materials were tested on strength and stiffness in the TU/e's structural laboratory in order to model the material behaviour as close as possible and to arrive at safe design values of strengths. Using these values as well as other sources the preliminary structural design calculations were made. In a later stage when more information became available simple beam-models were replaced by more complicated Final Element Models (FEM). From the final design the detailed production drawings were made.

The chosen production method was Vacuum-infusion. Simply put, this meant that layers of fibres (flax and hemp) were glued around a shape of bio-foam, this was then put in a large bag and brought under a vacuum. This causes a liquid bio-(epoxy) resin to be sucked into the product. This resin has been mixed with a hardener and causing a chemical reaction. With the fibres this in fact becomes the solid bio-composite.

The exo-thermal reaction of the hardener in the resin heaths up the internal foam core. Earlier tests and making a 2 m, 1:1 scale production test model showed that the temperatures could become too high causing the foam core to melt. For this reason it was decided to work with prefabricated lamellas of 10 mm in the top and bottom flanges of the bridge beam as well as using insulating layers of cork material. Thus a closed bridge section was created of 20 mm thickness at top and bottom flanges of the beam and only 10 thickness at its web sides. It means that the resulting bridge beam is very light-weight in comparison to other, for example concrete, bridges. The whole bridge including its rather heavy railing weighs 2,6 tons.

To monitor the bridge beam's structural behaviour during its Service Life, glass-fibre sensor technology, called Fibre Brag Grating (FBG), in to the top and bottom flange of the bridge is integrated. Elongation of the glass fibre sensor, caused by a change in temperature or by an external load, causes a shift in the reflected light spectrum that is sent through the glass fibre at the sensor positions. This shift in spectrum is a precise measure for the local elongation and has an accuracy of 1 micrometre per meter. With students using these techniques the elongations of the 28 sensors is being monitored. Additional load tests static as well as dynamic (Eigen-frequencies, damping behaviour) are carried out.

The earlier mentioned 2 m test model, as well as the final bridge, have been produced at the Avans Composite Laboratory at Spark Rosmalen, Netherlands. The bridge has been produced by students of 4 different educational levels, from University towards vocational training (TU/e, TUD, Hogeschool Avans, het Koning Willem 1 college and Bossche Vakschool).

Finally the structural strength and safety was tested and proofed successfully in attendance of the Building inspectors of the Municipality of Eindhoven. The load test adding 500 kg/m2 in large water containers was without problems and it also showed the accuracy of the theoretical models in the prediction of the deflections.

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[3] Rijk, B., Teuffel, P., Smits, J., Gkaidatzis, R., Böttger, W., Hoogendoorn, A. Lepelaar, M. (2017). Bio-based briddge: Primary structural elements. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

FIGURE 2

FIGURE 3

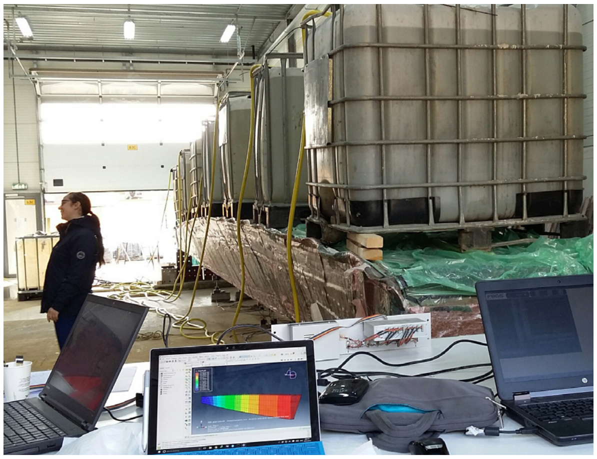

FIGURE 4

FIGURE 5

> The initial ambition was to realise a bridge with a span of about 8 m. This ambition was raised towards realising a bridge of 14 m.

With the help of many students and many others involved, the bridge was installed, on time, during the so-called Dutch Design Week event (DDW) in October 2016 . Alderman Mary-Anne Schreurs opened the bridge for public use and also declared that the city of Eindhoven would like to have a second bridge in the development of their City area “Mariënhage”. This project is now well under way, resulting in further research and developments. Research on moisture and creep influences as well the monitoring of the bridge itself are currently being performed.

Support

- Avans University of Applied Sciences
- HZ University of Applied Sciences
- SPARK campus, Rosmalen

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[5] Rijk, B., Teuffel, P., Smits, J., Gkaidatzis, R., Böttger, W., Hoogendoorn, A. Lepelaar, M. (2017). Bio-based briddge: Primary structural elements. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Cast Formwork System

customised self-construction for local informal conditions

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[2] *Eindhoven University of Technology*

Abstract

CAST Formwork Systems (CFS) is a concrete formwork system based on CNC milling technology. It enables self-construction in informal areas to build up safe, incremental housing up to four storeys high. Ordinary formwork systems are complex to use, often too expensive for the low- to mid-low income group and only suited to one shape of building plot. The CFS-system is not only cheaper, it can be customized to all shapes of building-plots and is both safe and easier in use.

Keywords

concrete; CAST Formwork Systems (CFS); concrete formwork system; CNC milling technology; housing

Remmerswaal, N., Bilow, M., Moonen, F., Blok, R. (2017). Cast Formwork System: Customised self-construction for local informal conditions. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

The problem

We live in an urban era; the Global Health Organization estimates that in 2050 almost 75% of the world population will live in cities. The biggest urban growth will take place in ‘informally built parts of the city’, often known as slums. These areas are formed when the government can no longer deal with the rapid growth of the urban population and city inhabitants start constructing their own living quarters. While densification in these ever growing mega-cities is sorely needed, the inhabitants often lack the building knowledge needed to construct safe housing over two stories high. Dangerous situations occur since these self-constructed houses are often not able to withstand the earthquakes and yearly flooding these poorly situated areas are exposed to.

The goal

The immediate objective is to provide a safe building method in the informal areas of Indonesian cities. These informal areas are called ‘Kampung’ and are an excellent example of self-build areas, 80% of Indonesian cities consist of these kampungs. They are more than just places to sleep, these Kampung thrive on a very close knit community and are full of economic activities. A governmental top-bottom approach in handling these areas often consists of tearing down the whole Kampung and build high rises in its place. This ‘block attack’ destroys not only the community but also denies the city inhabitants their economic opportunities. The CAST Formwork System proposes a bottom up approach where the inhabitants can independently build up safe housing in accordance with local practice.

Origins

The company CAST Formwork System (CAST) came forth from the thesis ‘Tra-Digital Hybrids’ written by Nadia Remmerswaal. In July 2015 she graduated from the Faculty Architecture at TU Delft as best graduate of her year with this thesis. In her graduation project, she delved into enabling safe, self-build constructions in informal neighborhoods, the Kampungs of Bandung, Indonesia.
Research shows that 80% of the build environment of Indonesian cities is self-build, in Indonesia this results in 100 million Kampung inhabitants, and it is expected that before 2050 we will see 50 million more Kampung inhabitants. This enormous city growth is not limited to Indonesia, but will happen in mega-cities worldwide. These DIY areas are prone to earthquakes and flooding, and residents often do not have enough building knowledge to build sustainable structures to withstand these natural disasters. After witnessing this in the cities of Indonesia, Remmerswaal tried to find a technical solution in her architectural graduation to enable safe self-construction in these areas.
After graduating Remmerswaal sought funding in the form of scientific financing and participated in several competitions to develop the project further. The project won the ASN Bank World Prize

“Veiligheid & Sociale cohesie”, prize money €8000, the STW Open Mind funding, €50,000 and the 4TU Lighthouse funding, €50,000. The project has been renamed ‘CAST Formwork System’, CAST an abbreviation of ‘casting concrete’ and Remmerswaal started developing the project in February 2016.
The objectives of the project are to create both a workable prototype and a workable revenue model. Both are be completed in February 2017 when the project financing ends.

The formwork is specifically designed for self-build areas, to be used by residents themselves.

FIGURE 1

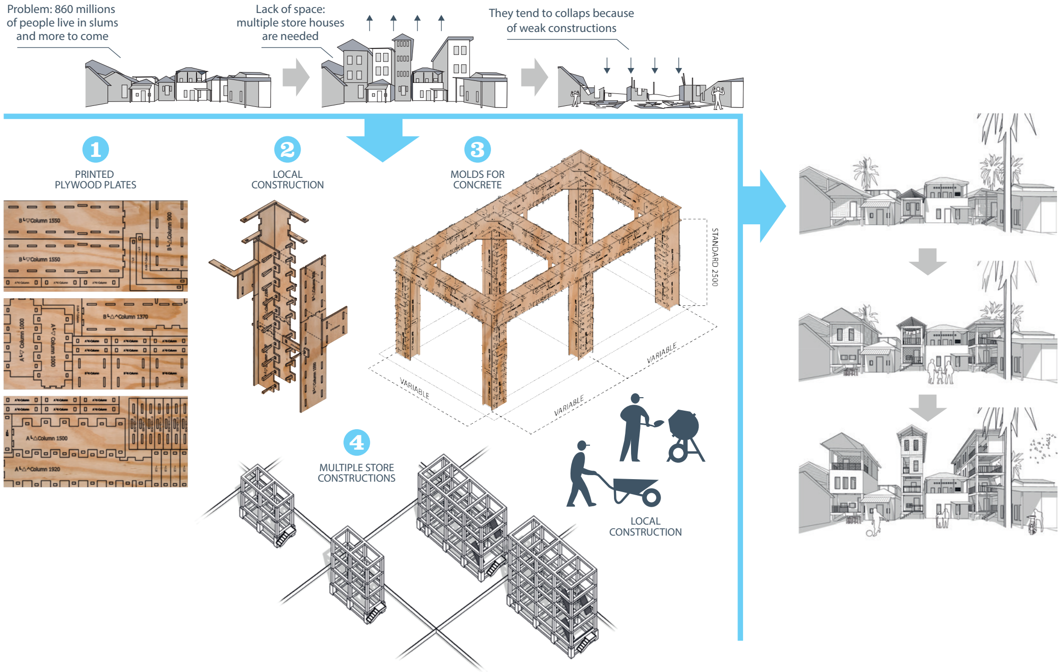

FIGURE 2 Graphical abstract

A concrete frame of 3 x 7 x 3 meter was realized within two weeks.

The technique

CAST Formwork System is a formwork system based on CNC milling technology. The CAST system makes up the mould in which the concrete can be cast. The resulting concrete frame forms a durable structure and safe concrete skeleton. The formwork is specifically designed for self-build areas, to be used by residents themselves. The system is made from special wood: Betonplex, this hardwood triplex has a smooth, very durable coating that makes de-casting the formwork easy. Betonplex is being produced locally in Indonesia. The elements are never bigger than 1,5 meter, and can be easily transported into the Kampung using a handcard. It is designed to be as simple as possible, so that it can be put together by people with limited construction knowledge.

After the assembly of the formwork, the concrete is cast and when dry the formwork can be reused a minimum of 8 times. Normal formwork systems are often complex to use, need cranes or trucks to be transported or assembled, are too expensive for the low to middle-low income group in self-construction areas and only suitable for one form construction plot. CAST strives to be an inexpensive alternative that is easily adapted to multiple building plot configurations. Since not a single house in the Kampung, or self-build areas around the globe for that matter, are equal, this is an essential important aspect of the system.

With CAST Formwork System it is safe to build up to multiple levels, right now this is often impossible, inadequate construction knowledge prevents the buildings to reach over 2 building stories. With the CAST-system, it would be possible to expand the dwelling in an incremental manner: the first year the foundations and first story is constructed, and when inhabitants have gathered sufficient funding a second story can be constructed several years on. This incremental building method is essential as these informal neighborhoods often lack the financial resources to construct a four-story house all at once. This incremental construction method makes it possible for a household to spread the investment over several years.

The next step

In December 2016 a CAST-Formwork prototype has been tested at the Green Village in Delft. A concrete frame of 3 x 7 x 3 meter has been realized within two weeks. While some technical adjustments have to be made, the team considers the test a great success. The next step is to do more local testing in Indonesia in January 2017, and to present the formwork at the 'Week van de Bouw' in February 2017. A pilot project is being developed in Bandung Indonesia, if sufficient funding is found, 6 pilot homes will be built with the CAST Formwork System in May 2017.

Remmerswaal, N., Bilow, M., Moonen, F., Blok, R. (2017). Cast Formwork System: Customised self-construction for local informal conditions. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Support

- Jongeneel B.V.
- Cementbouw
- Van Gelder Group
- The Green Village
- Riset 8 kota Indonesia

FIGURE 3

FIGURE 4

FIGURE 5

Convective Concrete

additive manufacturing to facilitate activation of thermal mass

Dennis de Witte [1], **Ulrich Knaack** [1], **Marie de Klijn-Chevalerias** [2], **Roel Loonen** [2], **Jan Hensen** [2], **Gregor Zimmerman** [3]

[1] *Delft University of Technology*
[2] *Eindhoven University of Technology*
[3] *G.tecz Engineering GmbH*

Abstract

Convective Concrete is about a research-driven design process of an innovative thermal mass concept. 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 use of the available thermal mass effectively. Convective Concrete explores new ways of using thermal mass in buildings more intelligently. 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.

Keywords

concrete; thermal storage capacity; thermal mass; Additive Manufacturing

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de Witte, D., Knaack, U., de Klinj-Chevalerias, M., Loonen, R., Hensen, J., Zimmerman, G. (2017). Convective concrete: Additive manufacturing to facilitate activation of themal mass. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

To accomplish this on-demand charging of thermal mass, a network of ducts and fans is embedded in the concrete wall element.

The use of thermal mass is usually considered as an effective strategy for achieving energy efficient building designs with high thermal comfort levels. This is normally done by applying construction types with high thermal storage capacity (e.g. concrete) on the inside of the thermal insulation layer. 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. 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. 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.

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 and 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 of 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, needs to be embedded in the concrete wall element. The fans act as back-up to the buoyancy effect to ensure a sufficient amount of air flowing through the wall. This is done by developing customized formwork elements in combination with advanced concrete mixtures.

Additive Manufacturing (AM) is researched, 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. However, for the first prototypes wax casting was used.

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de Witte, D., Knaack, U., de Klinj-Chevalerias, M., Loonen, R., Hensen, J., Zimmerman, G. (2017). Convective concrete: Additive manufacturing to facilitate activation of themal mass. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Additive manufacturing of lost formwork differs from the approach of direct concrete printing, but allows for traditional processing of the concrete itself.

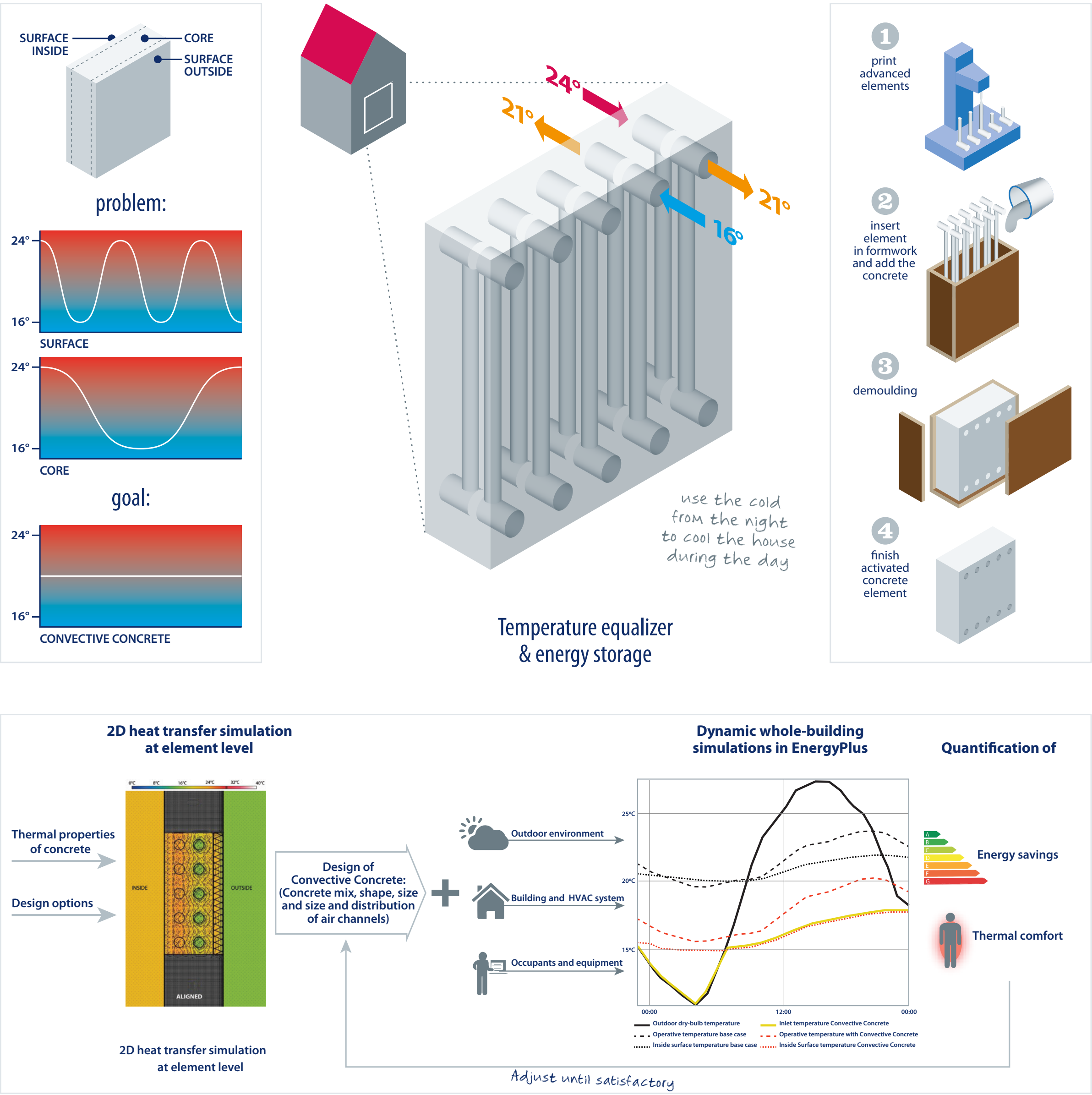

FIGURE 1 Graphical abstract

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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.

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 a prefabricated concrete slabs, but also in the form of the inserts itself that is are placed embedded in the on-site built formwork.

FIGURE 2

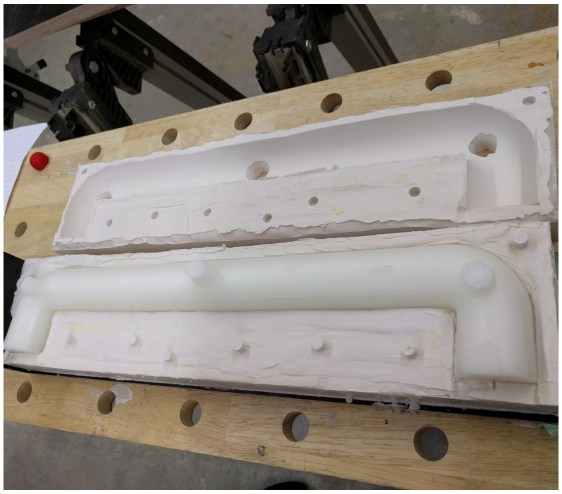

FIGURE 3

FIGURE 4

FIGURE 5

Double curved concrete printing

printing on non-planar surfaces

Roel Schipper [1], **Chris Borg Costanzi** [1], **Freek Bos** [2], **Zeeshan Ahmed** [2], **Rob Wolfs** [2]

[1] *Delft University of Technology*
[2] *Eindhoven University of Technology*

Abstract

It is no secret that there have been some great advances in the realm of concrete additive manufacturing. However, one of the major drawbacks of this fabrication technique is that the elements must be self-supporting during printing. While most other additive manufacturing materials can overcome this by using a secondary printed support structure, alternative strategies have to be developed for materials such as concrete.

This 4TU project explores the possibilities of combining concrete additive manufacturing with a temporary support surface. By printing on a free-form surface, more intricate geometries can be realized. A number of potential applications have been outlined, however the principle focus is combining concrete additive manufacturing and casting. The end result is a partially-printed pavilion using a completely digital design-to-fabrication workflow.

Keywords

casting concrete; 3D concrete printing; Additive Manufacturing; adaptable mould

Schipper, R., Borg Costanzi, C., Bos, F., Zeeshan, A., Wolfs, R. (2017). Double curved concrete printing: Printing on non-planar surfaces
SPOOL, 4(2). doi:10.7480/spool.2013.1.624

FIGURE 1

Concrete that shows great potential for large-scale additive manufacturing.

Although additive manufacturing (AM) is a fabrication technique which has been around for the past 20 years or so, it is only now that we are starting to see its applications emerge into the built environment. Whilst metals, plastics and other composite materials are also being explored for their use in the Built environment, it is concrete that shows great potential for large-scale additive manufacturing. Concrete Printing techniques already allow for the rapid fabrication of large-scale structures with minimal material waste, as already exhibited by Winsun and the fabrication of 1,100 Sqm Apartments in Jiangsu, China.

Whilst this does indeed allow for the rapid fabrication of concrete structures, most elements printed remain as 2.5D rather than 3D. This is due to the fact that extruded material must be self-supporting during printing in order to avoid collapse, imposing somewhat of a geometrical restriction. Most other printing materials can overcome this by printing a temporary support structure, however this is not the case with fluid materials such as concrete. Instead, a temporary surface is proposed as a means of support to printed concrete.

The adaptable mould developed at TU Delft served as a means to provide such a surface. Consisting of a silicone surface connected to a bed of adjustable pins, double-curved surfaces can be produced in a similar fashion to milled surfaces. The main difference being that no material waste is generated since new surfaces are defined by adjusting the pin-bed. Prior to the 4TU Project, this system was used for casting free-form concrete panels. The combination 3D concrete printing and an adaptable mould resulted in a hybrid manufacturing technique consisting of two complimentary fabrication techniques.

Schipper, R., Borg Costanzi, C., Bos, F., Zeeshan, A., Wolfs, R. (2017). Double curved concrete printing: Printing on non-planar surfaces SPOOL, 4(2). doi:10.7480/spool.2013.1.624

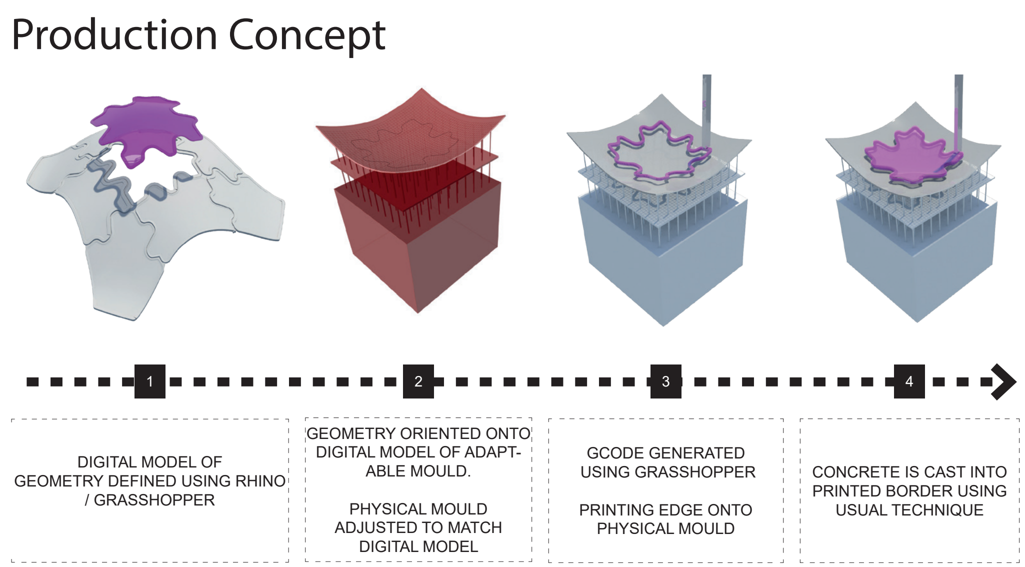

FIGURE 2 Graphical abstract

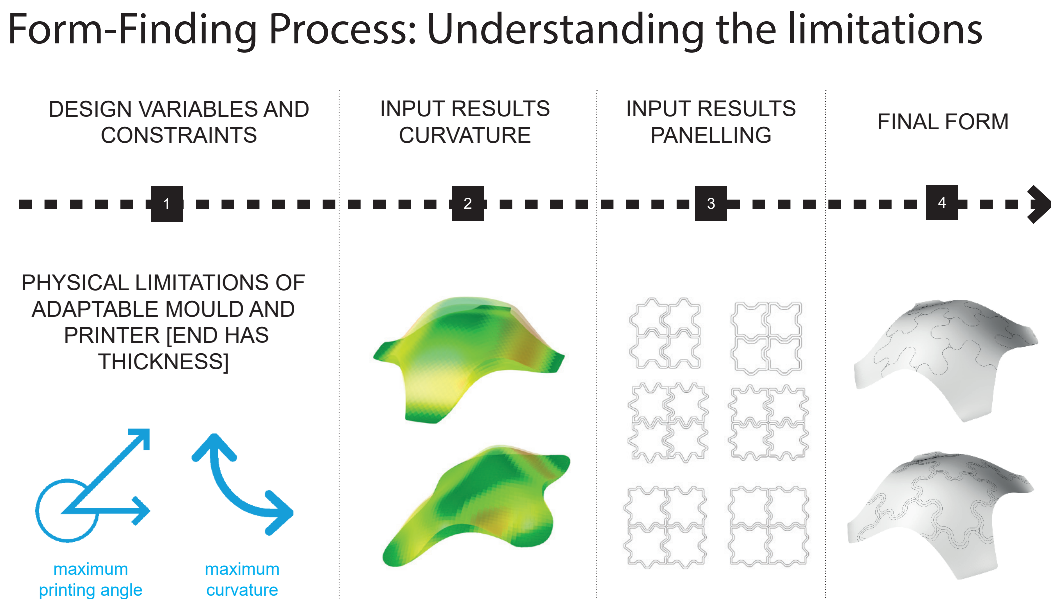

FIGURE 3 Graphical abstract

Three potential areas of research were identified through this combination. Firstly, the potential for fully-printed concrete panels. For this, It is proposed to use differential growth algorithms to generate print paths over any given surface. The second potential identified was the printing of structural ribs following stress-lines to provide reinforcement to panels. However, the chosen theme was a combination of 3D Printing and casting concrete. In this, complex geometries are defined by printing a boundary into which concrete is cast. The advantage to this approach is that complex, free-form concrete panels can be realized without the need for complicated moulding systems.

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Complex geometries are defined by printing a boundary into which concrete is cast.

Design Overview

In order to study the proposed manufacturing concept, a shell structure consisting of complex interlocking geometry was designed and printed. The basic principle of realizing the design consists of first creating a digital model of the structure using parametric design tools. Each individual panel is then digitally oriented onto an adaptable mould and G-code is generated by dividing splines that define the perimeter of the object. Once the physical mould is adjusted to match the digital mould, the Gcode is sent to the printer and the geometry is printed. Finally, concrete is cast into the printed shape and left to cure for 24 hours after which it is demoulded.

Fabrication Process

Both the 3D Printer and adaptable mould have their own set of physical limitations. Thus, a number of variables and constraints were set by studying the two technologies. Firstly, the maximum slope angle on which concrete can be printed was found to be 40 Degrees, after which material had a tendency to curl up and distort. This value was used to limit the maximum curvature of the form-found shell structure. Due to the printer's incapability to print right angles, a minimum turning radius was also determined and was used to generate the tessellations for printed geometry. The end result is a 2.5 m x 2.5 m shell with a maximum slope of 35 degrees and minimum turning radius of 150 mm, consisting of a total of 9 Print-And-Cast panels.

In order to have a design process which consists of a single file from design to fabrication, a custom g-code generator was created using Grasshopper 3D. This was also necessary because slicing techniques used in traditional additive manufacturing could not be used since a later-wise approach was not used. Instead, the geometry is defined as a spline and is divided into a number of points depending on curvature of the curve. These points are then expressed in terms of their relative co-ordinates and communicated with the Printer. An additional bespoke script was generated to take into account collisions of the Printer Nozzle with the Surface. This was required because printing was not done perpendicular to the surface meaning that the physical nozzle had a tendency to collide with steep surfaces. The way this was corrected was by determining the intersection between the nozzle and surface at every co-ordinate and raising the point such that no intersections occurred. The corrected print path is then defined by interpolating the raised points which is then converted into G-Code.

Final Structure

The final structure is printed in a single print pass taking approximately 20 minutes to complete as shown in the image below. After the individual panels are printed, plasticizer is mixed in with printed concrete and cast inside the panels. These are left to cure for 24 hours and demoulded as an inverted shell structure. This is later temporarily propped up and held together through mortar joints.

Schipper, R., Borg Costanzi, C., Bos, F., Zeeshan, A., Wolfs, R. (2017). Double curved concrete printing: Printing on non-planar surfaces SPOOL, 4(2). doi:10.7480/spool.2013.1.624

FIGURE 5

FIGURE 4

FIGURE 6

The end result is a 2.5m x 2.5m shell consisting of a total of 9 Print-And-Cast panels.

Challenges and conclusions

The project was limited to a relatively small 2.5 m x 2.5 m shell structure and the geometries printed were kept relatively simple so as to focus on refining the design process. However, given that the physical constraints of the printing process have been established it is easily imaginable that scalability and increase of geometrical complexity can be achieved if boundary conditions are maintained. Moreover, the project focused on combining printing and casting, however other directions such as generating print paths which follow stress-lines could serve as future areas of research using the same basic design process.

Schipper, R., Borg Costanzi, C., Bos, F., Zeeshan, A., Wolfs, R. (2017). Double curved concrete printing: Printing on non-planar surfaces
SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Fibrous smart material

adaptive, low–energy, real–time responsive interior environments

Nimish Biloria [1], **Javid Jooshesh** [1]

[1] *Delft University of Technology*

Abstract

The project is an inter-disciplinary initiative for the 'designed engineering' of heterogeneous fibres with variable material behaviors to create real-time responsive interior environments (furniture systems). These smart furniture systems will embody properties of real-time adaptive temperature control, real-time structural adaptability and real-time physiological support of the human body. These properties shall be fully self-regulated (devoid of external power sources) via engineering multi-layered fibre compositions, which can sense the forces exerted by the human body and accordingly alter their physical properties. The scale of operation is chosen deliberately, considering the time-span of one year within which we will produce a fully operational 1:1 physical prototype and scientific material-research guidelines. A research through design approach with 3 iterations shall be adopted in this research: working on the yarn (U Twente + EURECAT), textile (TUE) and product (TUD). Each iteration will consist of the development of a prototype, the creation of future usage scenarios + business possibilities, and a workshop to envision future requirements. In this project, prototypes and material output will be co-designed with material scientists, architects, textile and industrial designers and will be used to assess 1) design challenges, 2) business opportunities, and 3) technical feasibility of scalable multi-performative interior systems for applications such as healthcare and future office environments.

Keywords

heterogeneous fibres; smart furniture systems; mutli-layered fibre compositions; real-time structural adaptability

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Biloria, N., Jooshesh, J. (2017). Fibrous smart material: Adaptive, low–energy, real–time responsive interior environments. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

> These smart furniture systems will embody properties of real-time adaptive temperature control, real-time structural adaptability and real-time physiological support of the human body.

For the purpose of the research, a decision was made to choose the La Chaise Lounge designed by Charles & Ray Eames as an inspirational form. This voluminous lounge piece has a captivating elegance and allows a wide range of sitting and reclining positions. La Chaise has long since established itself as an icon of organic design. The selected chaise lounge geometry is tested as a boundary region while considering the active load of one person sitting on it. The topology of the fragment is later optimised based on supports and loads. In this process, the material from the parts that are less needed is removed till the initial supporting matter is defined. Following this step, according to the principal stress lines in different axises which indicate compression, tension and shear forces are extracted to be traced for creating the desired topology. The coordination of the point indices and the magnitude of moment and force vectors are calculated to identify the exact spots to manipulate the material distribution based on the defined cross section, material properties and directionality. .

FIGURE 1 Graphical abstract

For understanding the composite structural behavior it was necessary to find an understanding of the relations between fibre arrangements and strength characterisation. The density and directionality of the fibres mainly specify the interaction between the fibres and determines different structural strengths. For this end, we conducted a robotic winding based cylinder experiment. The cylinder model was analysed as one union composite shell to observe the non-linear static stress flow over the model through finite element methods.

The resulting model indicated the stiffness distribution over the mesh varying between a range of 0.3 as minimum stiffness required to 1.0 as maximum stiffness required from one end to another. The stiffness factors are then interpreted into winding angle and the helix pitch which creates the new mesh topology corresponding to the directionality and density of fibres. The significance of the study is to predict how the fibers with certain configurations can interact and how composite strength values are affected by number of piles and directions. In this study, the winding angle value is the key parameter to gain a full control upon the local thickness and material deposition which feeds directly from stiffness factors.
The structural strength statistics from the cylinder experiment are analysed and recorded. The experiment is followed by a prototype of a fragment from the concave area from the geometry. For winding technique it is important to consider measures to prevent fibres being offset in these areas. As a result, a waffle section containing grippers are designed to guide the fibres through the gripper teeth which allows the fibres to be positioned while they are under tension. The project is on-going and based on the robotic fabrication and material properties based feedback is now progressing into the next phase of 1:1 physical prototyping.

Support

- Eindhoven University of Technology
- University of Twente
- EURECAT
- Atelier Robotic

FIGURE 2

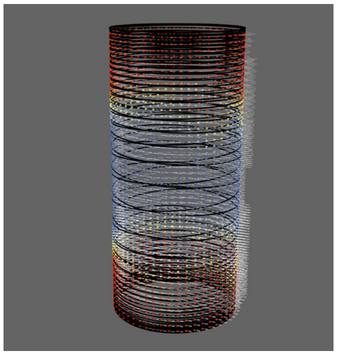

FIGURE 3

FIGURE 4

FIGURE 5

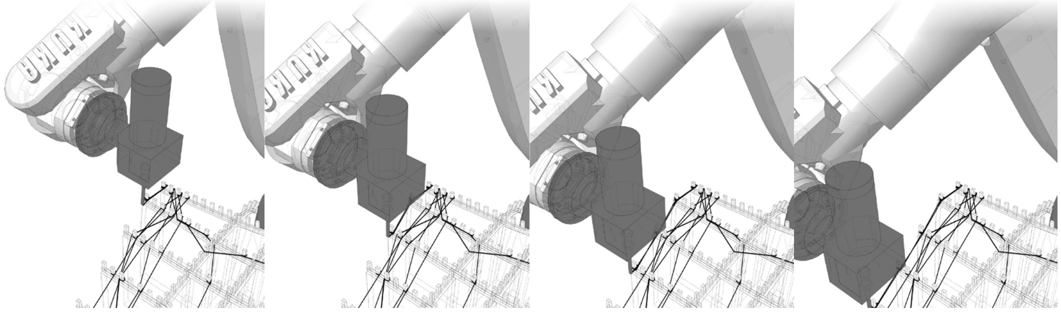

FIGURE 6

Optimizing 3D concrete printing

exploring potentials and limitations of materials and production

Jeroen Coenders [1][3], **Maarten Mathot** [1][3], **Pascal Martens** [1], **Freek Bos** [2], **Rob Wolfs** [2], **Anke Rolvink** [3], **Puck Middelkoop** [3]

[1] *Delft University of Technology*
[2] *Eindhoven University of Technology*
[3] *White Lioness technologies*

Abstract

The application of new Computer Aided Manufacturing (CAM), digital fabrication and additive manufacturing techniques in the construction industries is expected to bring major change to these industries. Driven by a foreseen reduction of construction time and labor cost, simplification of logistics and an increase of constructible geometrical freedom, many experiments are performed both at academia and in practice.

Beyond these economical and architectural objectives, digital fabrication in construction can be used to reduce the environmental footprint of the industry. The increased level of control offered by digital fabrication enables the use of advanced computational optimisation techniques. With these optimisation techniques buildings can be designed which, for instance, combine an optimal thermal performance with a minimum use of materials, while still complying with all codes and standards.

In order to fully utilise this potential of digital fabrication, the capabilities and limitations of the manufacturing process need to be taken into account during optimisation. By combining the concrete 3D printing knowledge of Eindhoven University of Technology, the optimisation expertise of the BEMNext lab at Delft University of Technology and software development by White Lioness technologies, the 'Optimising 3D concrete printing' Lighthouse project has made the first steps towards more knowledge on integrated optimisation and manufacturing.

Keywords

optimised 3D concrete printing; Computer Aided Manufacturing; digital manufacturing; Additive Manufacturing

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Coenders, J., Mathot, M., Martens, P., Bos, F., Wolfs, R., Rolvink, A., Middelkoop, P. (2017). Optimizing 3D concrete printing: Exploring potentials and limitations of materials and production. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Context

Additive Manufacturing (AM) techniques are employed to overcome limitations of traditional manufacturing in terms of precision and/or constructability and allow for application of digital fabrication on a multitude of scales and materials. The difference between an object on a designer's screen and the physical, manufactured artifact can be orders of magnitude smaller with an additive manufacturing powered process in comparison to a conventional manufacturing process.

It is this narrowing of the gap between computational design and physical artifact which enables better use of advanced optimisation techniques in design. For years optimisation algorithms have been used to acquire the best performing designs, with respect to different metrics, whilst still complying with standards and regulations. A common example is a minimisation of material used, for which topology optimisation algorithms are well suited.

One of the main limitations on the widespread adoption of optimisation in the construction industries lies in the conditions on the construction site. As optimised designs often approach the boundaries of what is possible or allowed, they are more vulnerable to construction errors. Additionally, the scale on which the geometry can be optimised is limited by the often manual process employed on the construction site.

By use of additive manufacturing in construction some of the main limitations on use of design optimisation can be removed, enabling the design and construction of further optimised, more environmentally friendly buildings and infrastructure.

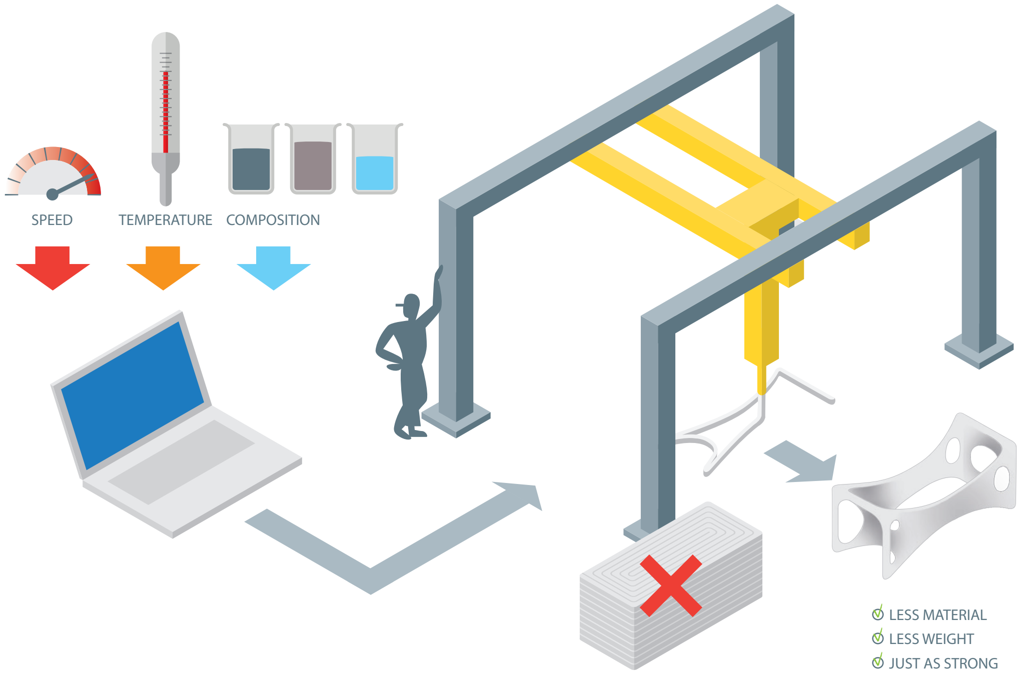

FIGURE 1 Graphical abstract

The first steps towards an environment in which geometries can be optimised whilst taking the properties and limitations of a 3D concrete printer and the resulting material properties into account.

Project

The 4TU.Bouw Lighthouse project on “Optimising 3D concrete printing” aims to make the first steps towards an environment in which geometries can be optimised whilst taking the properties and limitations of a 3D concrete printer and the resulting material properties into account. These additive manufacturing specific features are key to ensuring the optimised geometry can indeed be printed and that the resulting artifact behaves as expected. Once again, as optimised geometries are often on the limit of the materials potential, the correctly modelled behaviour is even more important in optimisation than in conventional design techniques.

FIGURE 2

Printer properties

Whilst additive manufacturing has an increased geometrical freedom in comparison with many conventional construction techniques, there still are boundaries to what can and cannot be printed. In the "Optimising 3D concrete printing" project the following aspects are identified and considered:

- Vertical cantilevering angle between layers;
  Without the use of a support material the layers can only cantilever a few degrees, both in the printing direction, as well as perpendicular to that direction.
- Printing direction;
  In this project the printing direction is kept constant. Layers are printed next to each other and on top of each other.
- Nozzle width and layer height;
  The nozzle width and the layer height can be chosen at the start of the optimisation.

As the actual values of these parameters are printer- and/or material specific, they are kept as free variables in the optimisation environment where possible.

Material properties

The printing process has influence on the material properties of the resulting concrete artefact. From the concrete mix, which has to be compliant with the printer, to the depositing method, speed and direction a lot of printer specific parameters influence the material properties. In the "Optimising 3D concrete printing" project the following aspects are explored and tested:

- (An)Orthotropic behaviour
  The tests performed on the bulk material indicate that the mixture behaves in an orthotropic manner. This constant behaviour is incorporated in the optimisation.
- Non-linear behaviour of the mixture;
  Concrete-like materials do not behave elastic under loading. The cracked properties of the concrete are used in the optimisation.

Optimisation

Based on the material- and printer properties found, a custom topology algorithm has been developed. The topology optimisation algorithm strives to save material by iteratively filter the densities of the elements to obtain a structure that is as stiff as possible for a predefined fraction of the initial volume. By checking, during the iterations, that the geometry is printable and taking into account the material properties of the printed concrete during analysis, a structurally optimised, printable geometry is generated.

Coenders, J., Mathot, M., Martens, P., Bos, F., Wolfs, R., Rolvink, A., Middelkoop, P. (2017). Optimizing 3D concrete printing: Exploring potentials and limitations of materials and production. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Results

The “Optimising 3D concrete printing” project has advanced the insight in the properties of both concrete 3D printers and the resulting 3D printed artifacts. Additionally, it has resulted in the first optimisation environment in which these capabilities and limitations are taken into account, enabling the use of additive manufacturing for the realisation of structurally sound, optimised concrete structures. As a proof of concept a topological optimised, concrete, printable floor slab is generated using the optimisation environment, and consequently 3D printed.

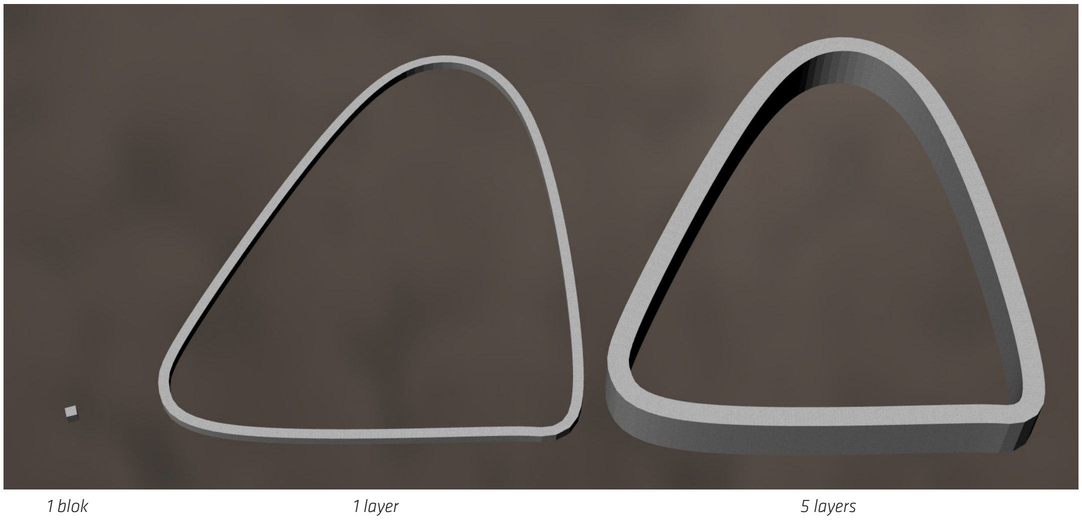

FIGURE 3

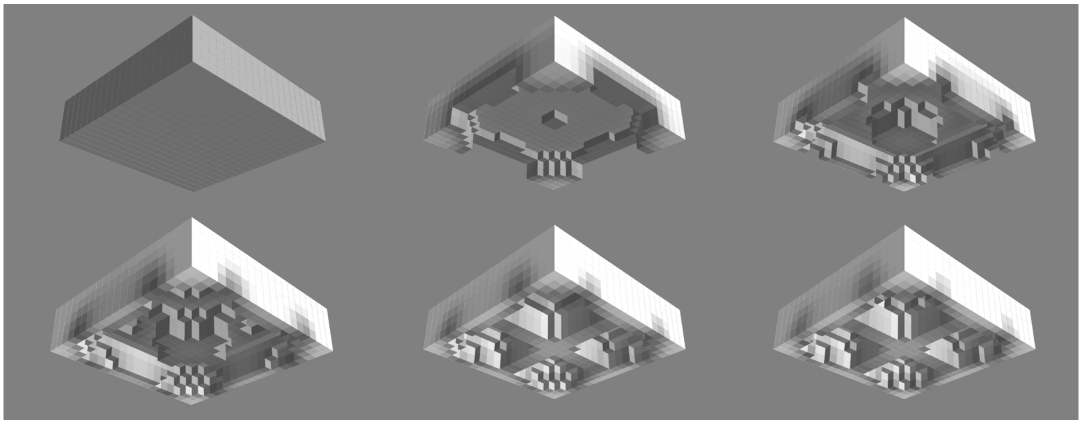

FIGURE 4

Public space for refugees

community facilities in the context of permanent temporariness

Juliette Bekkering [1], **Sjef van Hoof** [1], **Kornelia Dimitrova** [1], **Eefje Hendriks** [1], **Michiel Riedijk** [2], **Rick Krosenbrink** [2], **Peter van Sorgen** [3]

[1] *Eindhoven University of Technology*
[2] *Delft University of Technology*
[3] *Koninklijke Landmacht*

Abstract

At this moment in history, a staggering 60 million refugees rely on international help - the highest number of displaced persons ever. A large variety of solutions have been developed that cater for primary needs. However, long-term public and community facilities have been neglected.

This project is addressing the necessity of dignifying community facilities in the context of permanent temporariness in refugee camps. Twelve plans for public buildings are developed, each with a different program. During the coming spring, certain parts of these projects will be built in scale 1:1, as part of the building exercises of the battalion of genie troops.

In order to develop these prototypes, a variety of camp types, public building types and techniques have been researched and analysed. All together these studies have been assembled in a catalogue, intended as a toolbox for designing public buildings for refugees.

Keywords

long term public facillities; refugee camps; design toolbox

Bekkering, J., van Hoof, S, Dimitrova, K., Hendriks, E., Riedijk, M., Krosenbrink, R., van Sorgen, P. (2017).
Public space for refugees: Community facilities in the context of permanent temporariness. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

The permanency of these camps asks for long term solutions for community facilities, public space and public buildings.

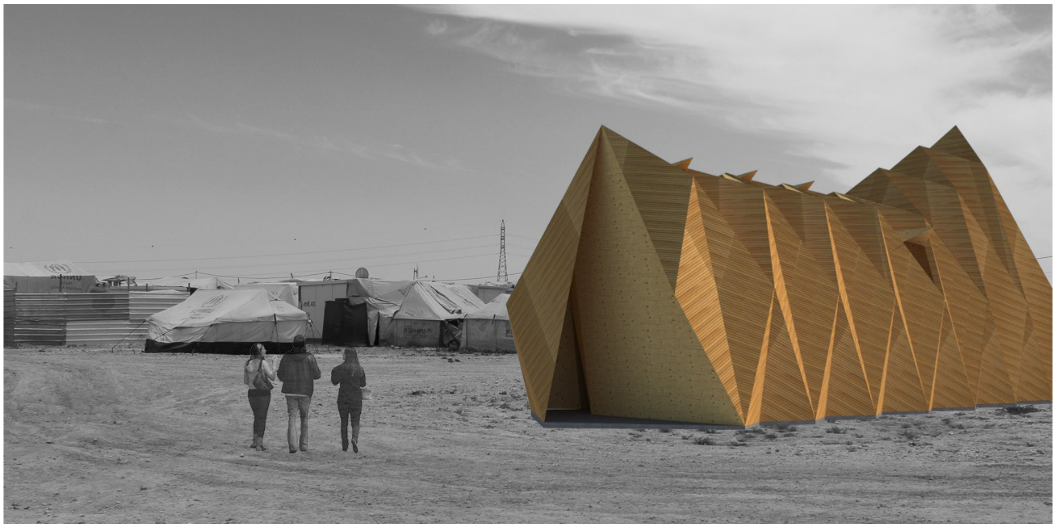

FIGURE 1

At this moment in history, due to war and conflict, drought or flooding caused by climate change, we are confronted with over 60 million refugees - the highest number of displaced persons ever. To house displaced persons a large variety of solutions have been developed that cater primary needs. However, long-term public and community facilities have been neglected as an important mean of creating an environment of hope and dignity.

With the graduation studio “Public Buildings for Refugees” we aim to develop designs and prototypes of public buildings that can empower the life of displaced persons. Although refugee-camps are envisioned to provide short-term accommodation, the reality shows that people tend to stay there for years. The average stay in refugee camps has been estimated by UNHCR on 17 years. The permanency of these camps asks for long term solutions with not only housing but adequate community facilities, public space and public buildings to empower personal socio-economical development and enforcement of communities. Within this Lighthouse grant we will design solutions for these public buildings.
Currently, 12 plans for public buildings are being developed, each with a different program. During the coming spring, certain parts of these projects will be built in scale 1:1, as part of the building exercises of the battalion of genie troops. These will serve as prototype tests for the techniques and designs developed within this research.

In order to develop a prototype of a so-called “Public Building for refugees”, a thorough research and analysis of existing camps of different kinds around the world has been done; a spectrum of architectural typologies of public buildings that could empower the life of the inhabitants in camps has been analysed and coinciding building methods and building technologies of varying form, from temporal to semi-permanent till permanent buildings have been studied. All together these studies have been assembled in a catalogue book. With the catalogue we aim to give an overview and broader vision of different topics that are of relevance while designing public buildings for refugees.

Bekkering, J., van Hoof, S, Dimitrova, K., Hendriks, E., Riedijk, M., Krosenbrink, R., van Sorgen, P. (2017).
Public space for refugees: Community facilities in the context of permanent temporariness. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

This book will form a base for designers willing to dig into the issue of public buildings in refugee camps.

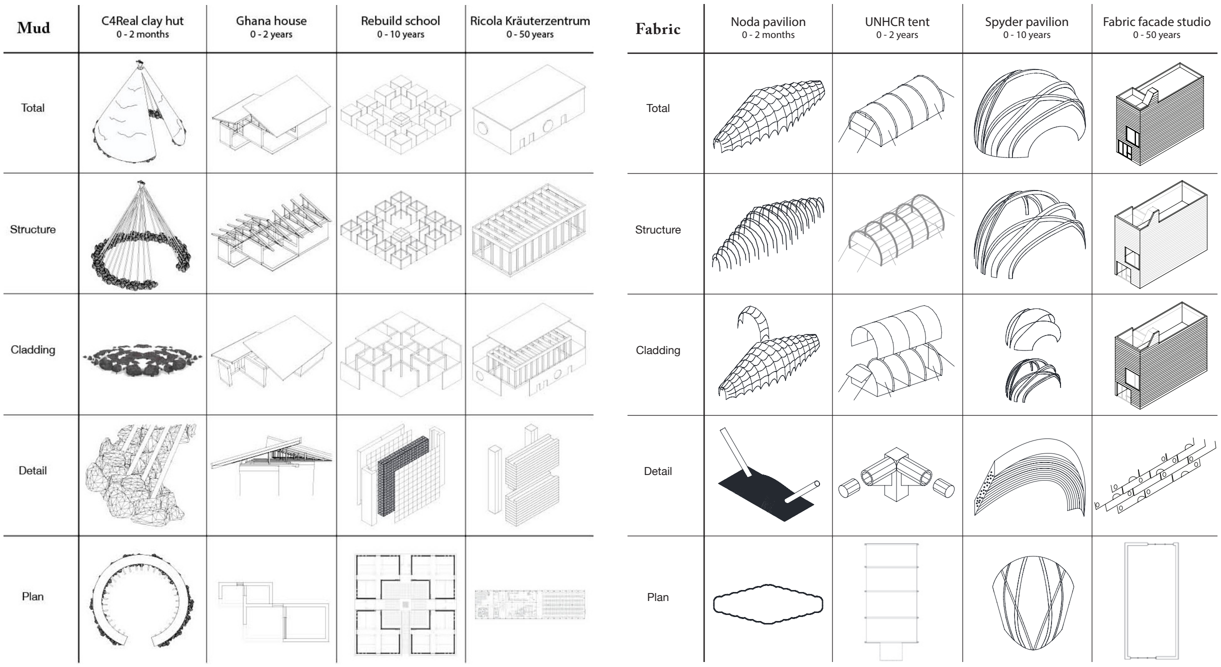

FIGURE 2

The ambition of the book is to frame a base point for a designer that is willing to dig into the issue of public buildings in refugee camps. More specifically, this catalogue breaks the topic in three parts: Urban, Building and Detail.

The Urban part provides an analysis of different camp typologies. Although other types of camps are included, the main focus is on refugee camps. More specific, the chapter offers insight in the structure of the camps and the way this typology has developed. The Building part provides information about different public buildings. Public functions discussed are health centres, community centres, schools, bus stops and market places. The main focus is on the influence of time on the specific typology. The Detail part provides an overview of seven different building materials - earth, cardboard, bamboo, wood, fabric, metal, plastic - with the analysis of built examples in different time spans. At this scale the aim is to clarify the properties and possibilities of each material in a range from temporal to permanent building.

Finally, the goal of the catalogue is to serve as a toolbox, from which a designer can grab elements when for instance designing a hospital. Then the detail part can be used to explore the possibilities of different materials.

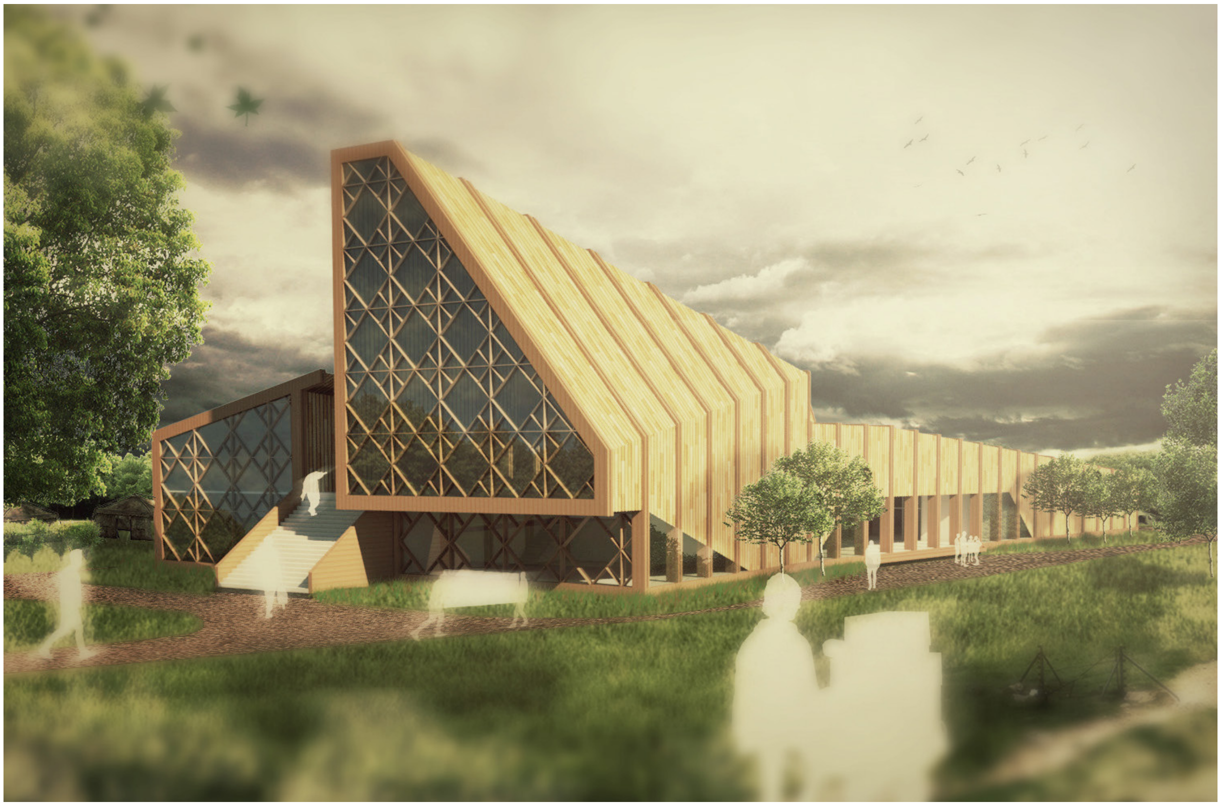
FIGURE 3

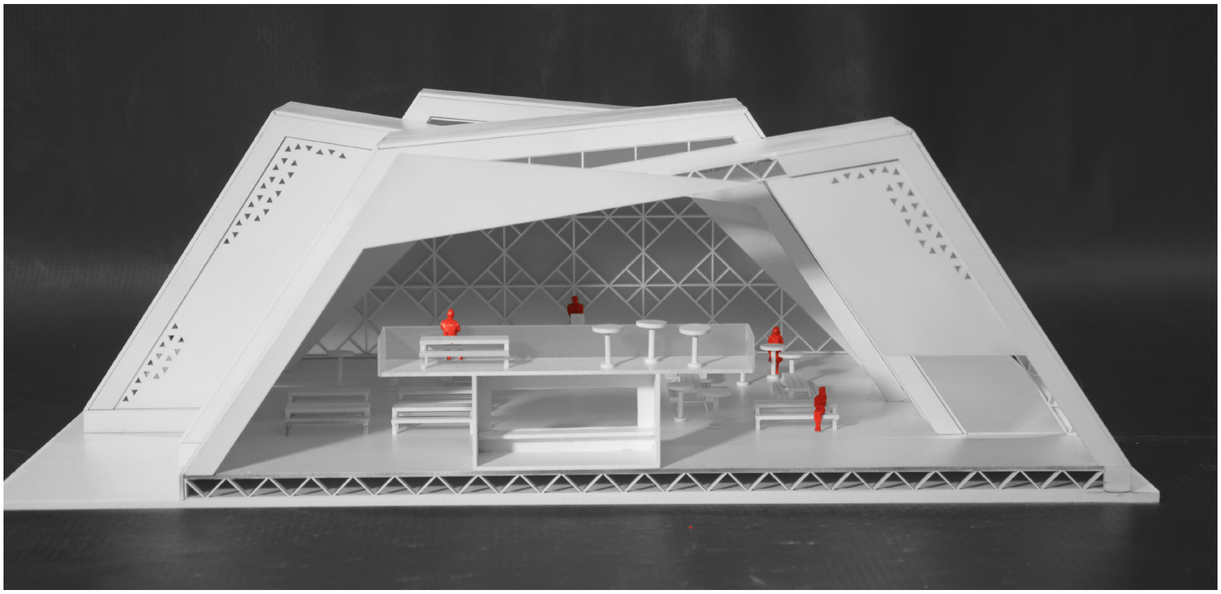
FIGURE 4

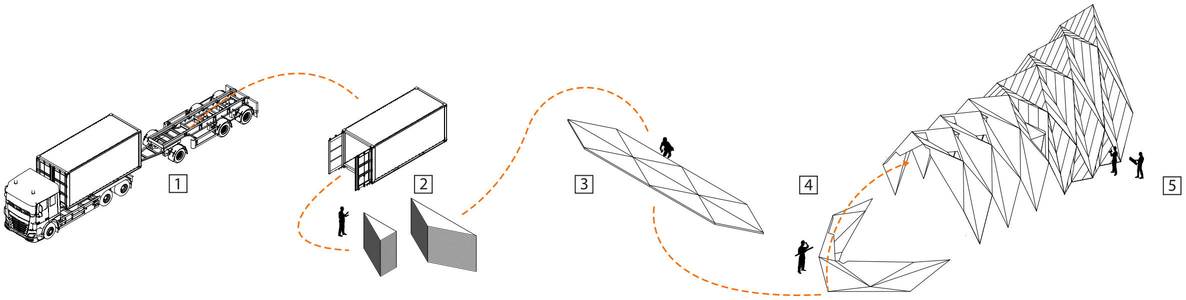

FIGURE 5 Building process

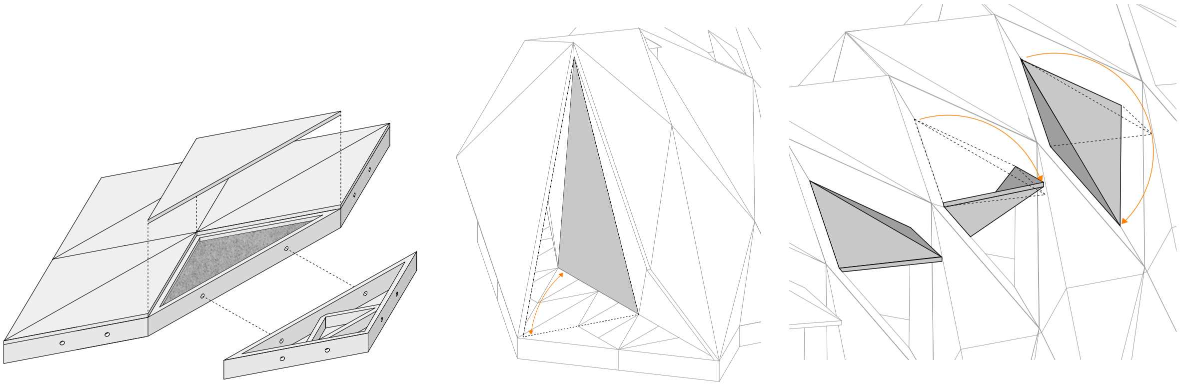

FIGURE 6 Connectable floor tiles, door fragment & window fragment

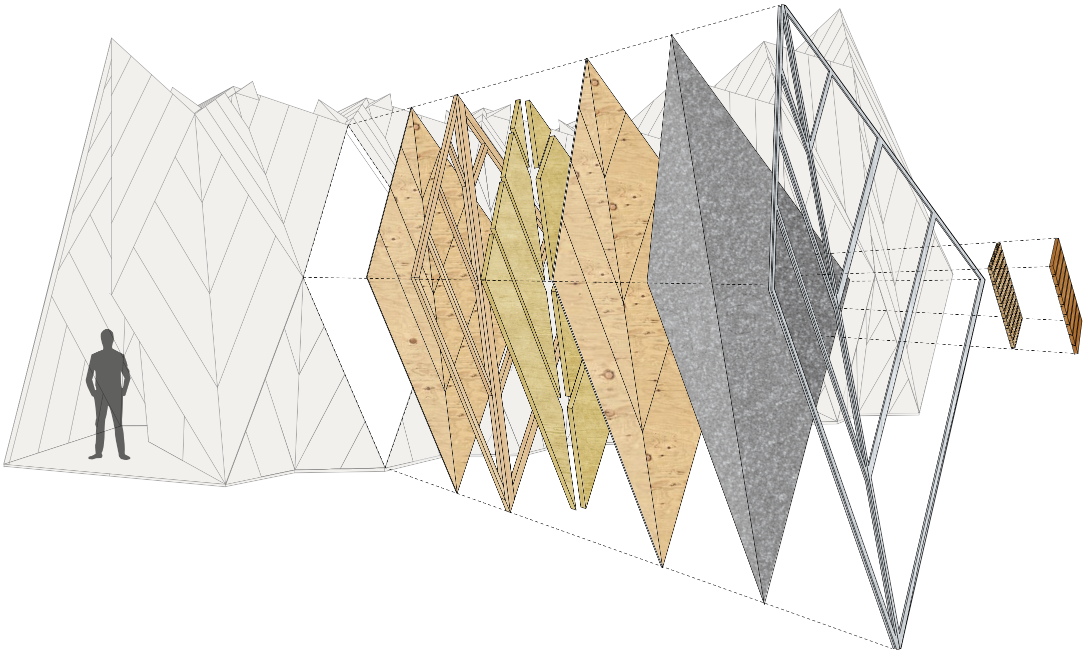

FIGURE 7 Facade built-up

Bekkering, J., van Hoof, S, Dimitrova, K., Hendriks, E., Riedijk, M., Krosenbrink, R., van Sorgen, P. (2017).
Public space for refugees: Community facilities in the context of permanent temporariness. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Restorative glass

reversible, discreet restoration using structural glass components

Faidra Oikonomopoulou [1], Telesilla Bristogianni [1], Lida Barou [1], Rob van Hees [1], Rob Nijsse [1], Fred Veer [1], Henk Schellen [2], Jos van Schijndel [2]

[1] *Delft University of Technology*
[2] *Eindhoven University of Technology*

Abstract

The application of structural glass as the principal material in restoration and conservation practices is a distinguishable, yet discreet approach. The transparency of glass allows the simultaneous perception of the monument at both its original and present condition, preserving its historical and aesthetical integrity. Concurrently, the material's unique mechanical properties enable the structural consolidation of the monument. As a proof of concept, the restoration of Lichtenberg Castle is proposed. Solid cast glass units are suggested to complete the missing parts, in respect to the existing construction technique and aesthetics of the original masonry. Aiming for a reversible system, the glass units are interlocking, ensuring the overall stability without necessitating permanent, adhesive connections. This results in an elegant and reversible intervention.

Keywords

structural glass; restoration; preservation; solid cast glass

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Oikonomopoulou, F., Bristogianni, T., Barou, L., van Hees, R., Nijsse, R., Veer, F., Schellen, H., van Schijndel, J. (2017).
Restorative glass: Reversible, discreet restoration using structural glass components. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

The transparency of glass allows the simultaneous perception of the monument at both its original and present condition, preserving its historical and aesthetical integrity.

This research investigates the potential of structural glass as a principal material in restoration and conservation practices in order to highlight and safeguard our built heritage; a distinguishable, yet discreet approach. Current restoration treatments with traditional materials bear the risk of conjecture between original and new elements, while the ambition to enhance the structural integrity of the endangered structures, often results in visually invasive and irreversible solutions that can impair the authentic image of the monuments. In this context, glass could be the answer to this on-going debate between restoring and preserving, a promising restoration solution able, on the one hand to consolidate the historic buildings and on the other hand to reveal their stratification. The transparency of glass enables the simultaneous perception of both the original and ruinous state of the monument, giving a material and immaterial appearance that relates the structure to both the past and the present setting. But equally important, owing to the mechanical properties of glass, the glass addition can contribute to the structural preservation of the monument.

As a case study, the restoration of the Lichtenberg Tower in Maastricht is proposed. The Lichtenberg Tower - the oldest castle ruin in the Netherlands - has undergone numerous phases of destruction, decay, rebuilding and renovation in the course of eight centuries. The scars of time and human intervention are evident in the monument's brickwork which forms a beautiful collage of different materials and building rhythms. Last century's reinforcement and preservation acts, however, burdened the monument with a prevailing steel structure- alien to its nature.

FIGURE 1

Oikonomopoulou, F., Bristogianni, T., Barou, L., van Hees, R., Nijsse, R., Veer, F., Schellen, H., van Schijndel, J. (2017).
Restorative glass: Reversible, discreet restoration using structural glass components. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

This solid cast glass interlocking masonry consists of glass elements resembling the original stone texture.

In this proposal, all foreign elements such as steel anchors, rods, and staircases, as well as the contemporary brickwork, are removed in favour of glass components that fill the missing parts and prevent the monuments' walls from drifting apart and collapsing. The innovative contribution of this glass restoration approach, besides allowing for a transparent addition, lies in the development of a completely reversible system, complying with the conservation guidelines suggested by the Venice Charter. To avoid any permanent bonding between the existing structure and the glass intervention, dry connections are proposed between the glass and the historic matter. Solid cast glass units are suggested, in respect to the existing construction technique and aesthetics of the original limestone masonry, to reinforce the monument by replacing the missing parts. To ensure the overall stability of the façade, the cast glass units follow an interlocking geometry, sparing the necessity of permanent, adhesive connections. The high stiffness and compressive strength of glass result in a lightweight glass wall of minimal thickness that ensures the desired structural consolidation without burdening the monument.

Different interlocking systems were explored to conclude to the optimum shape. As a proof of concept, the interlocking units are cast in the TU Delft Glass Lab, resulting to a 1:2 scale prototype. The aesthetic value of this solid cast glass interlocking masonry is articulated with glass elements resembling the original stone texture, while at the same time allowing for the perception of the surroundings. Three different sizes of bricks are designed to follow the gradient of different masonry styles, as this has been formed over the centuries. To evaluate the degree of cooperation of the units, testing in shear has been performed, manifesting the potential of the dry-assembly system as a compatible and elegant design approach for the preservation of our heritage. For the safe dry-assembly of the glass bricks, a transparent PET interlayer is proposed, specially thermoformed to match the interlocking surface.

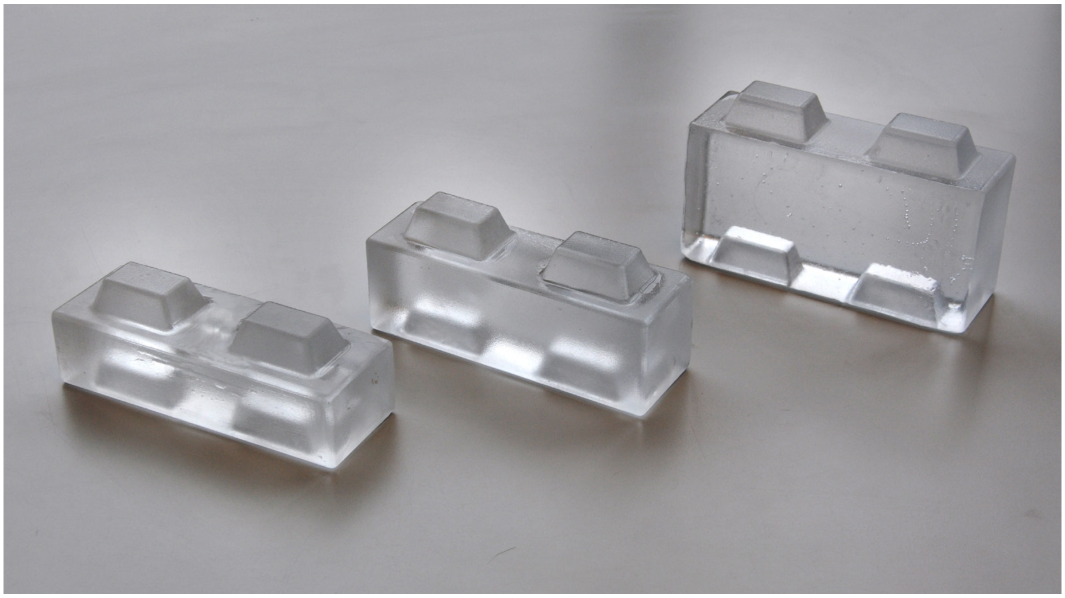


FIGURE 2

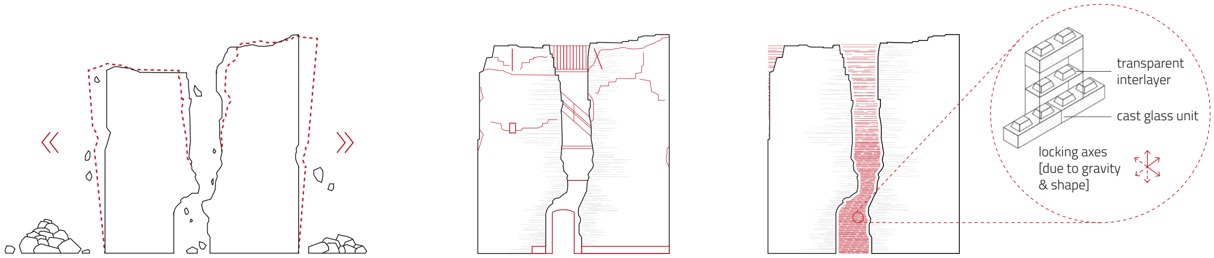
Oikonomopoulou, F., Bristogianni, T., Barou, L., van Hees, R., Nijsse, R., Veer, F., Schellen, H., van Schijndel, J. (2017).
Restorative glass: Reversible, discreet restoration using structural glass components. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

The connection between the glass masonry system and the historic wall is also designed to be discreet and reversible and any use of adhesives is prevented. Various scenarios were evaluated and tested in full scale prototypes, concluding to the proposal of a connective element that matches the exact shape of the wall on one side, and the interlocking geometry of the glass bricks on the other. Steel rods are anchored at key locations along the cracked historic wall in order to fix the special connective elements. The crack of the monument is 3D-scanned by a FARO® Focus phase difference laser scanner and the obtained pointcloud is converted to a 3D model. Based on this accurate 3D model, the connectors are developed. The connective components are proposed to be 3D-printed in plastic or 3D-milled in wood, in order to achieve accuracy, but more research is to be conducted to determine the most optimum material choice.

Regarding the interior of the monument, an all-glass ascending path to the top of the tower is created using float glass components. The transparent staircases and floors result to the least intrusive visual impact. The overall approach respects the rich history of the monument and highlights it, in a discreet transparent manner.

Support

- Poesia
- ABT



PROBLEM
Monument under threat of total collapse

CURRENT SOLUTION
Visually intrusive treatments

PROPOSED TRANSPARENT SOLUTION
Structural consolidation using cast glass

FIGURE 3 Problem, current solution and proposed transparent solution

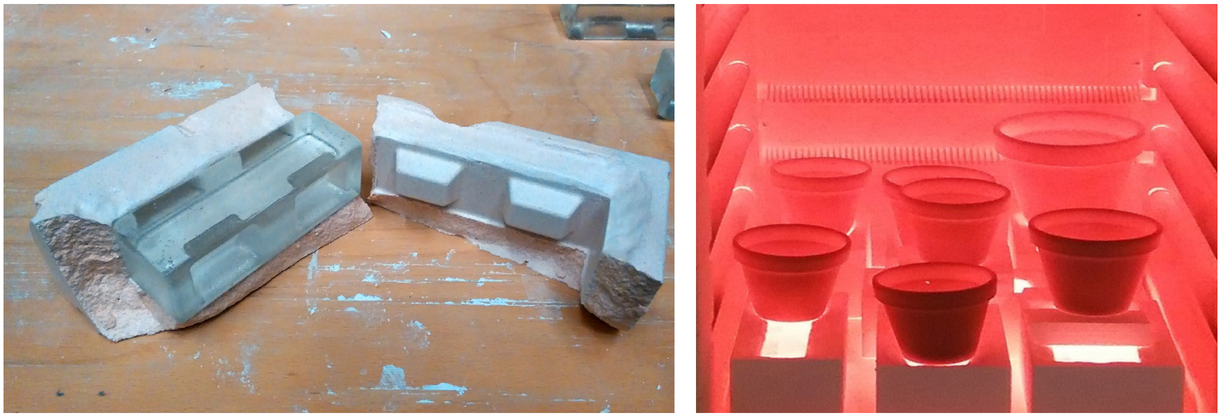


FIGURE 4

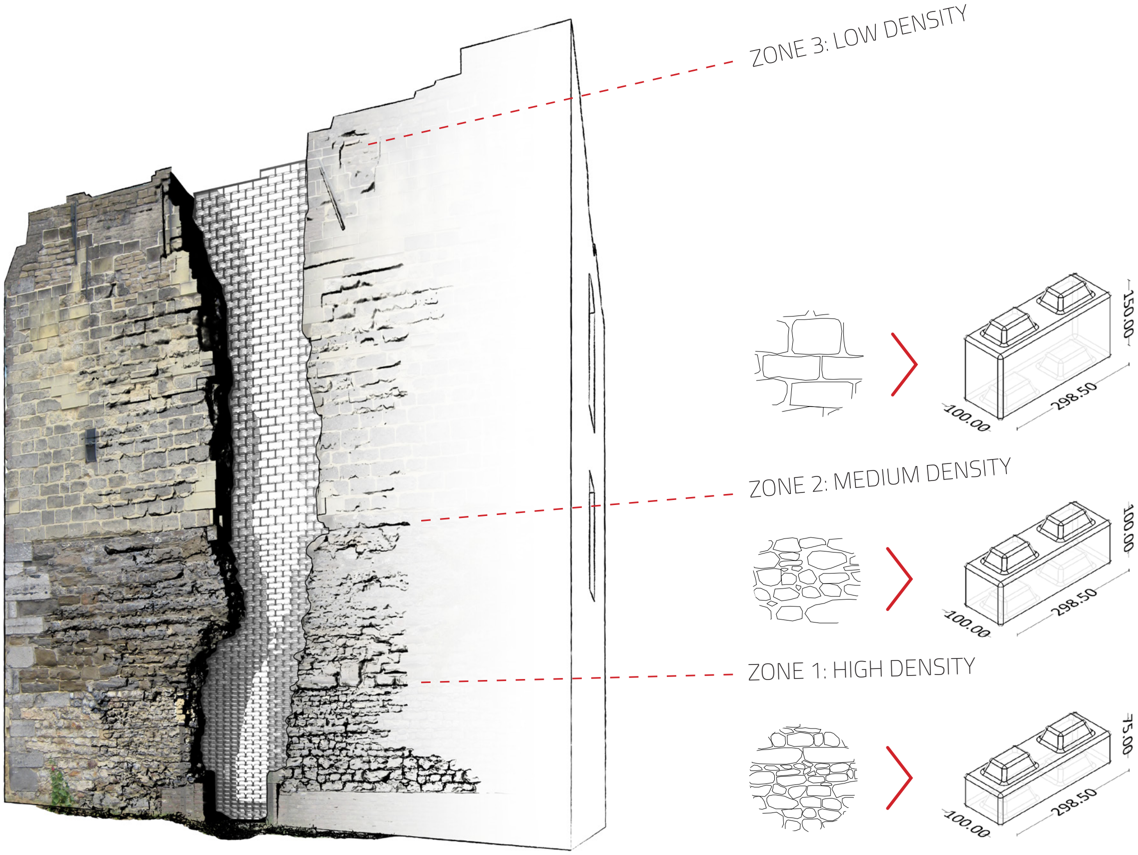


ILLUSTRATION OF THE NEW GLASS FACADE

The case study of Hoeve Lichtenberg Castle in Maastricht

FIGURE 5

Smart sensors in asphalt

monitoring key process parameters during and post construction

Seirgei Miller [1], **Joyraj Chakraborty** [1], **Jurian van der Vegt** [1],
Daan Brinkerink [1], **Sandra Erkens** [2], **Xueyan Liu** [2], **Kumar Anupam** [2],
Berwich Sluer [3], **Mohamad Mohajeri** [3]

[1] *University of Twente*
[2] *Delft University of Technology*
[3] *Boskalis B.V.*

Abstract

The Fibre Bragg Gratings (FBG) technology based on integrated photonics, offers specific benefits including thermal mapping, damage detection, shape- and distributed sensing. This makes it useful for determining pavement behaviour during extreme weather conditions e.g. freeze-thaw cycles when harsh winter conditions could damage the asphalt surfacing layer. However, the harsh construction environment and traffic loading highlights the high-risk challenge of installing the sensor into the asphalt layer in a non-invasive manner so that the key parameters are accurately measured during and after construction.

Keywords

smart sensors; Fibre Bragg Gratings technology; asphalt construction process

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Miller, S., Chakraborty, J., van der Vegt, J., Brinkerink, D., Erkens, S., Liu, X., Anupam, K., Sluer, B., Mohajeri, M. (2017).
Smart sensors in asphalt: Monitoring key process parameters during and post construction. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

This project focuses on the integration of FBG into the asphalt construction process so that the technology's benefits can be realised for constructed asphalt layers. Accurately monitoring key process parameters during and after construction using the appropriate sensor technology should contribute to extending the service life (durability) of asphalt pavements.

FBG sensors have previously been successfully used to monitor strain and other parameters in asphalt. While previous projects have mainly focused on the installation of the fibre optic technology sensors after construction has been completed, this project takes on the challenge of installing the FBG sensors in a non-invasive manner during the harsh asphalt construction process. This in itself raises significant challenges given high asphalt temperatures during construction, heavy roller compactor loading and the resulting shear stresses between aggregates which could damage the sensors during the construction process.

An initial part of the project included devising a set of functional requirements for the sensor system keeping in mind the harsh conditions that the system had to operate in during the construction process and afterwards during the service life of the asphalt layer. More importantly, to serve as a health condition monitoring system for constructed asphalt layers in the future, issues of system robustness, data accuracy, data redundancy, flexible installation and mounting, data transfer and data storage needed to be addressed in the design. To this end, several laboratory experiments were set up at Technobis, the fiber optic supplier and at local contractor, Boskalis. A first series of experiments focused on getting to know the workings of the FBG sensors and testing a few of the functional requirements in a "dry" set up. The "dry" set up typically consisted of sensors mounted inside moulds that were filled with various raw aggregates or with cold mix asphalt. This enabled checks to be made on the mounting of the sensors and the accuracy of the temperature and strain data with little danger of losing any sensors during this phase of testing. A second series of experiments focused on trialling several sensor set ups in Hot Mix Asphalt. More importantly, it focused on the protection of the FBG sensors given the very high asphalt temperatures and heavy compaction loading during construction. The protection of sensors has repeatedly been raised as a challenging issue to deal with in an extensive literature review. Several protection measures including Fibre Reinforced Polymer (FBR), steel tubing and carbon fibre reinforced epoxy resin coatings have been shown to provide adequate protection. Strain compatibility of the sensor to the package is important due to the actual strain measurement of the surrounding environment. In short, proper protection of the sensors was confirmed as key to the successful implementation of the FBG technology during both phases of laboratory testing.

In a parallel exercise, several FBG sensors have been installed in an existing porous asphalt (ZOAB) layer at TU Delft's linear accelerator LINTRACK facility. The purpose is three-fold. Firstly, to assess the influence of sealing fluids such as epoxy or bitumen on the accuracy of the temperature and strain measurements. Secondly, to compare the accuracy of the collected strain data with the data collected from a previously installed strain gauge. Lastly, the collected temperature data should provide more insights the behaviour of the porous asphalt layer during freeze-thaw cycles in typical Dutch winters.

The results thus far, show that the FBG sensor is a feasible technology to monitor strain and temperature progression during asphalt construction and afterwards during the service life of the asphalt layer.
The sensor is able to withstand high asphalt mix temperatures up to 200°C. It also appears feasible for accurately monitoring asphalt temperature during winter periods when freeze-thaw cycles may damage and reduce the performance of the asphalt layer. Laboratory tests using a 2ton "baby" roller compactor show that the sensor is able to deliver accurate strain measurements even under heavy loading. The strain measurements when combined with the temperature measurements, can be used to develop compaction and other performance models. Also, the strain measurements can be used to make explicit vehicle (axle) loading and therefore provide opportunities for assessing long-term damage due to for example, the overloading of trucks.

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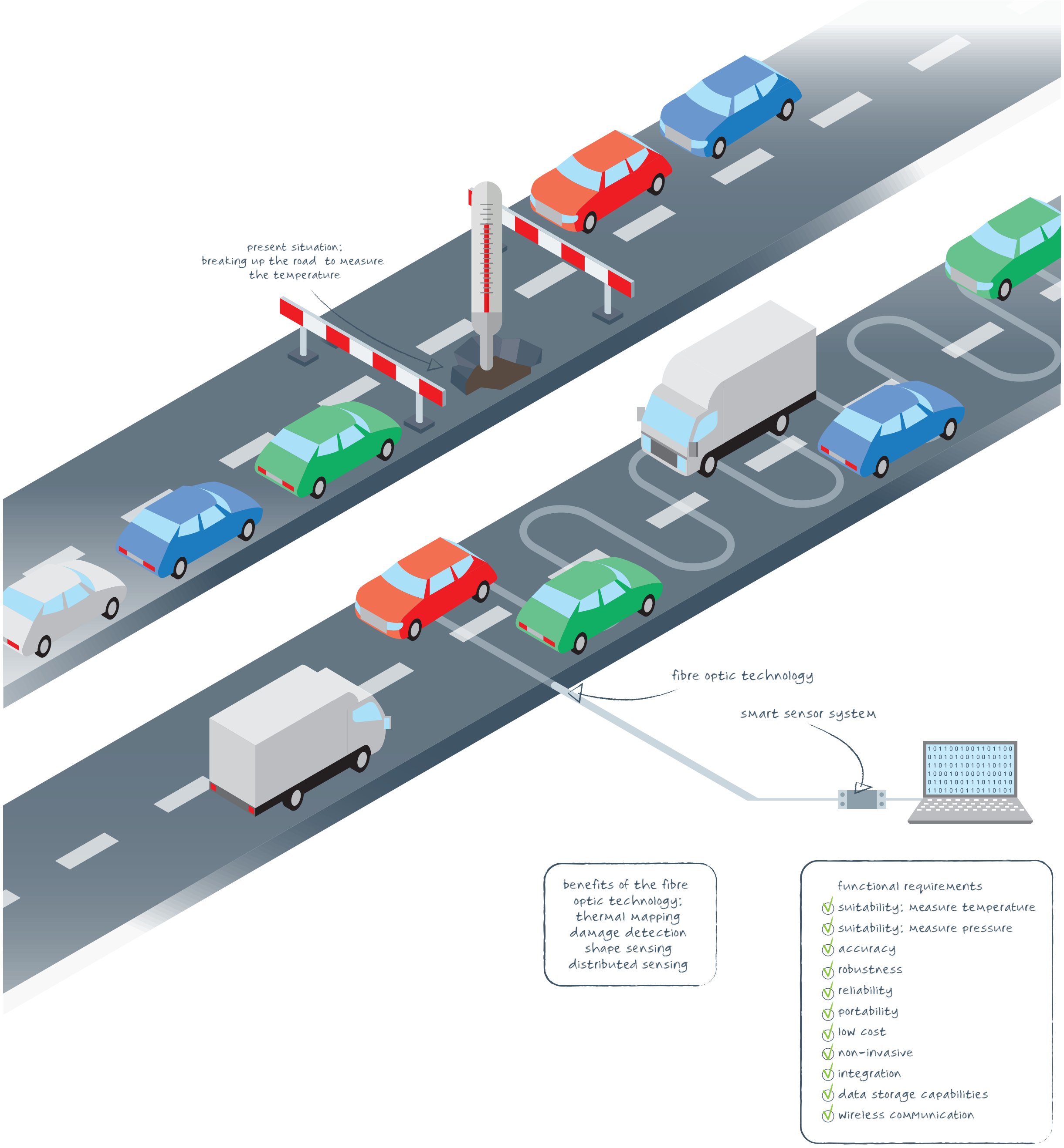

FIGURE 1 Graphical abstract

However, while the technology is promising, the study has highlighted a serious limitation. Fiber optic sensors are fragile, break easily under loading and therefore need suitable protection if they are to be installed during the harsh construction process. While several protection measures were tested during this study, more work is needed to find an appropriate protection method that guarantees the accuracy of both strain and temperature measurements. The results of ongoing long-term testing at TU Delft's LINTRACK facility, will show whether post-construction installation has any effect on the accuracy of the collected data and whether cutting grooves into the asphalt layer after construction has been completed is a feasible method of installation for collecting accurate temperature and strain data during the service life of the asphalt layer. The study will also address issues of damage to the asphalt layer given the invasive manner of installing the sensors after construction has been completed.

Applying appropriate sensor technology in the asphalt construction process requires predictable and reproducible sensor performance given the nature of the asphalt construction process. Placing any sensor in the asphalt layer during construction is both challenging and promising. It is challenging since it needs to be done in a non-invasive manner and in such a way that it does not disturb the very properties being measured. Promising, since if done properly, it opens up opportunities for measuring a range of properties during and after construction given the rapid development of sensor technology. The benefits of thermal mapping, damage detection, shape- and distributed sensing, makes it useful for determining pavement behaviour during service life of the asphalt pavement and for working towards increasing the service life and therefore, the durability of asphalt layers. The work into studying suitable sensors, sensor modalities and wireless communication will continue given the results of this project.

Support

- Technobis Group

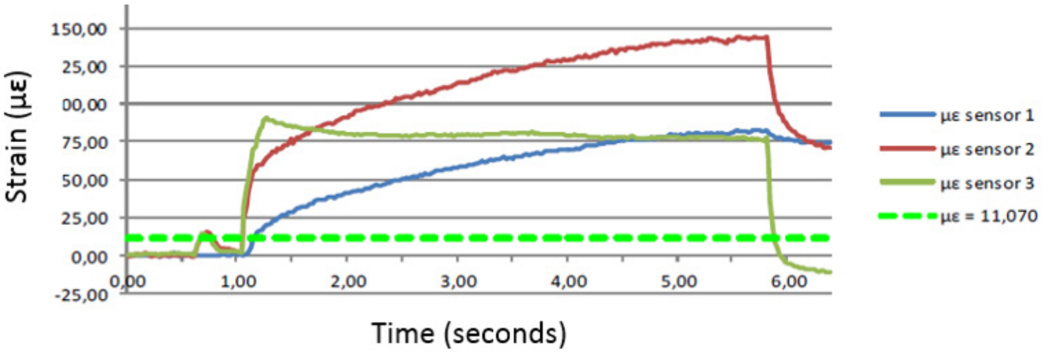

FIGURE 2 Typical asphalt strain measurements using Fibre Bragg Gratings

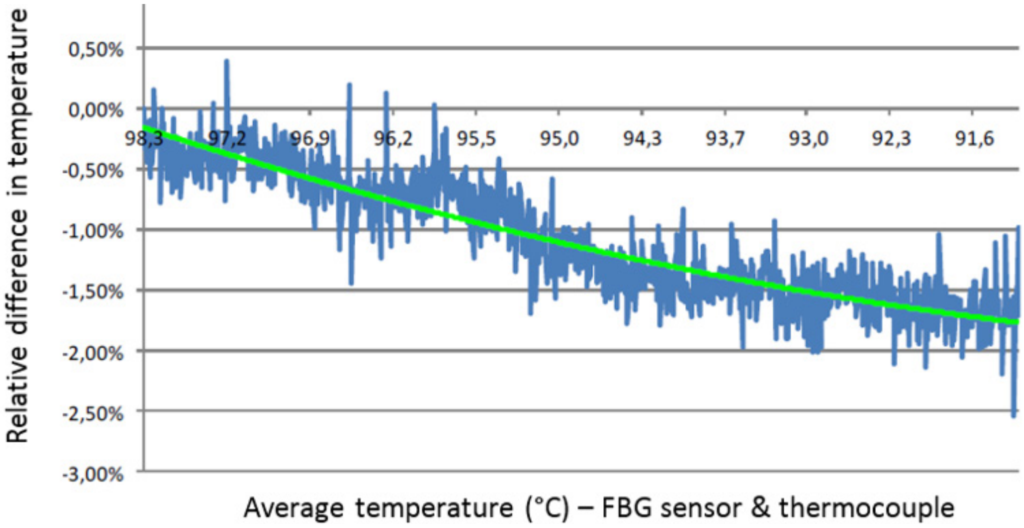

FIGURE 3 Typical asphalt temperature measurements using Fibre Bragg Gratings

Solar bikes: user acceptance

understanding user experience, preference and acceptance

Pauline van den Berg [1], **Theo Arentze** [1], **Karst Geurs** [2]

[1] *Eindhoven University of Technology*
[2] *University of Twente*

Abstract

Car traffic causes carbon emissions and air pollution and has negative effects on public health and quality of life in cities. Solar bikes are an innovative, sustainable transport option that can offer a substitute for car travel. Solar bikes are electric bikes with solar cells that are powered by the sun. This expands their range compared to regular e-bikes as the bikes are charged during the trip and at the destination without electricity. The aim of this project is to understand people's preferences, conditions for acceptance and experiences with the solar bike. Insight in preferences and experiences will assist urban policy makers in identifying which interventions in the built environment can stimulate the acceptance and use of solar bikes.

Keywords

solar cells; solar bikes; user experience; survey data collection

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van den Berg, P., Arentze, T., Geurs, K. (2017). Solar bikes: user aceptance: Understanding user experience, preference and acceptance. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Solar bikes are electric bikes with solar cells that are powered by the sun.

Cycling has several benefits compared to motorized travel: it is cheap, environmentally friendly, and it is good for public health. Policy makers therefore promote cycling, even in the Netherlands, where cycling is already quite popular compared to other countries. In the Netherlands around a quarter of all trips are made by bike. However, bikes are mainly used for short distances up to 7.5 kilometers, while the average commute distance is 17.5 kilometers.

E-bikes may be a feasible transport mode for these longer trips between 7.5 and 17.5 kilometers. The pedal support of e-bikes allows cycling longer trips compared to a regular bike. E-bike ownership and use has rapidly increased over the last decade.

A new type of e-bike, the solar bike, has recently been developed at Eindhoven University of Technology. The solar bike is an electric bike with solar panels in the front wheel that charges through sunlight. The solar bike thus has the advantage of a larger range and independency of charging compared to a regular e-bike.

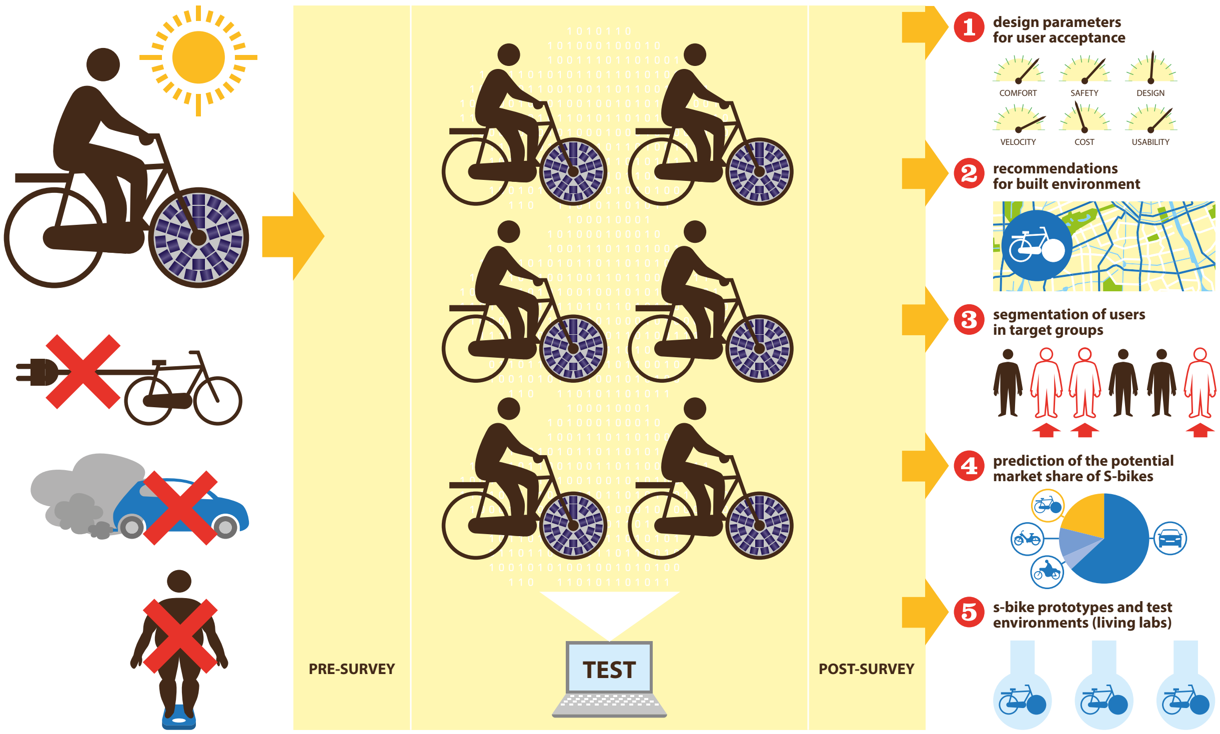

FIGURE 1 Graphical abstract

van den Berg, P., Arentze, T., Geurs, K. (2017). Solar bikes: user aceptance: Understanding user experience, preference and acceptance. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

In this 4TU.Bouw Lighthouse project, Eindhoven University of Technology and University of Twente study which factors affect the acceptance of the solar bike. This is done in three steps. First, a survey is used to collect data on people's perceptions of the solar bike, and under which conditions they would purchase and use a solar bike. The second part of the study consists of a field test in which participants will test the solar bike for one week. In the final part the participants who used the solar bike will be asked about their experiences in a survey as well as in focus group discussions.

In the first part of this project data have been collected using an online survey. The survey has been distributed through different channels, such as Facebook, LinkedIn and an email to the employees of the two univeristies. This has resulted in a sample of 317 respondents. A bit more than half (57%) of the respondents were men. Regarding age, 29% was below 30; 41% was between 30 and 49; and 30% was 50 years or over. Because the survey was distributed at the univerisities, higher educated people are overrepresented in the sample (89%).

Two thirds of the sample indicated that they considered purchasing a solar (very) unlikely. For 18% this would be neither likely nor unlikely, and 13% would probably buy a solar bike. The results showed that the oldest age group was more positive about the solar bike. Non-working and retired people were also more positive, and students were least positive. People who are more interested in innovative products are also more likely to purchase a solar bike.

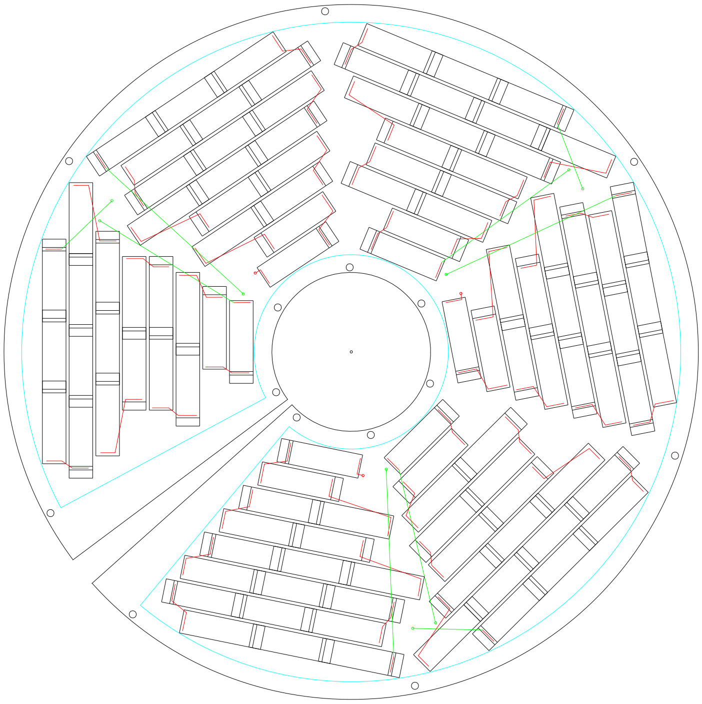

FIGURE 2

FIGURE 3

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van den Berg, P., Arentze, T., Geurs, K. (2017). Solar bikes: user aceptance: Understanding user experience, preference and acceptance. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

In this project we study which factors affect the acceptance of the solar bike.

In addition, the results of a choice experiment show that travel distance has the largest impact on the intention to buy a solar bike. People are most likely to purchase a solar bike when they have a commute distance between 7 and 12 kilometers, and least likely when they have a shorter commute distance.

The second most important factor is the quality of the cycling infrastructure. The better the infrastructure, the more likely people are to purchase a solar bike. People are also more inclined to purchase a solar bike when they can park the bike in a secured parking, when the quality of public transport is lower, and when car parking is more expensive. The characteristics of the solar bike itself also play a role. People are more inclined to buy a solar bike when it is cheaper and has a lighter weight.

Based on these results a number of policy recommendations can be given. As cycling has environmental and health benefits compared to car traffic, policy makers should stimulate cycling, alsof or longer distances. Good quality cycling infrastructure increases the intention to cycle, and to purchase and use a solar bike. Municipalities could therefore invest in the maintenance or improvement of bike lanes in order to stimulate cycling. As paid car parking has a positive effect on cycling, policy makers could also introduce this as a boost for cycling.

The developers of the solar bike could aim their marketing and sales strategy on the preferences of the main target group, consisting of people aged 50 and over. This could increase the acceptance of the solar bike.

The next steps in the project will be the field test and the evaluation survey and focus groups. The field tests will start in March 2017. This part of the project will reveil the actual experiences with the solar bike. It will also give insight in the question whether people's perceptions of the solar bike change as a result of testing the solar bike.

FIGURE 4

FIGURE 5

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van den Berg, P., Arentze, T., Geurs, K. (2017). Solar bikes: user aceptance: Understanding user experience, preference and acceptance. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Sound absorbing glass

transparent solution for poor acoustics of monumental spaces

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[1] *Delft University of Technology*
[2] *Eindhoven University of Technology*
[3] *SiO2 glas*
[4] *De Laurenskerk ,Rotterdam*

Abstract

Monumental buildings are demolished when they lose their traditional function. These historical monuments can be maintained by repurposing them for modern use, like lectures and musical events. This results in a demand for different acoustic conditions. However, monuments are subject to strict building intervention regulations; any intervention concerning changes to the original elements are often prohibited. This creates a demand for demountable and adaptable product design, repurposing monumental buildings by alleviating acoustical problems without distorting the view towards the monumental elements.

This research focused on developing sound absorption panels based on the micro-perforation principle: manufacturing these in thin glass panels, evaluating their influence on strength and transparency, optimizing sound absorption (perforation diameter and ratio) using a tailor-made computational model, and creating a pattern of perforations that optimizes strength.

Keywords

sound absorbing; glass panels; micro-perforation; sound absorption glass panel

Struiksma, A., Tenpierik, M., Snijder, A., Veer, F., Botterman, B., Hornikx, M., van der Water, H., Migchielsen, F. (2017).
Sound absorbing glass: Transparent solution for poor acoustics of monumental spaces. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Sound absorbing glass provides a transparent solution for bad acoustics in spaces in which the aesthetics must not be visually affected.

To come to a product that can improve the acoustic surroundings in monumental buildings without affecting the beautiful sights, different aspects needed to be studied. The starting point became a microperforated (transparent/glass) panel (MPP) in front, backed by a closed air cavity and an unperforated transparent back panel. By manufacturing micro- perforations (≤ 1 mm diameter) in a thin transparent panel, sound absorption can be achieved due to viscous thermal dissipation inside these perforations, flow distortion effects at both sides of the panel and the acoustic resonances in the air cavity. During this study many of such panels with different perforation diameters, perforation ratios, cavity sizes, panel thicknesses and combinations of differently sized perforations were tested in an impedance tube. This measures the normal incidence sound absorption: the amount of sound that is being absorbed of a certain frequency (range). We discovered that by solely using a single perforation diameter only a small frequency range was absorbed. Even though sound absorption is nearly perfect in that small range, our goal is to broaden this range in order to create improved acoustic surroundings for multiple, very different, types of events with accordingly different ranges of sound.
To come up with transparent sound absorbing panels with the highest sound absorption coefficient and the broadest frequency range, a mathematical model was developed. This model requires the following input parameters: perforation diameter, perforation ratio, depth of air cavity and the thickness of the panel. The model was validated making use of the measurements done in the impedance tube showing good correspondence, even for combinations of different perforation diameters and ratios within one panel. Making use of the validated computational model, optimum values for the input parameters are obtained, which will be used in the production of specified panels for a specific location.
The production process of the panel had as a starting point: the use of glass, being the most transparent material available, and the thickness of the panel to be 2 mm, due to the limiting structural properties of float glass.

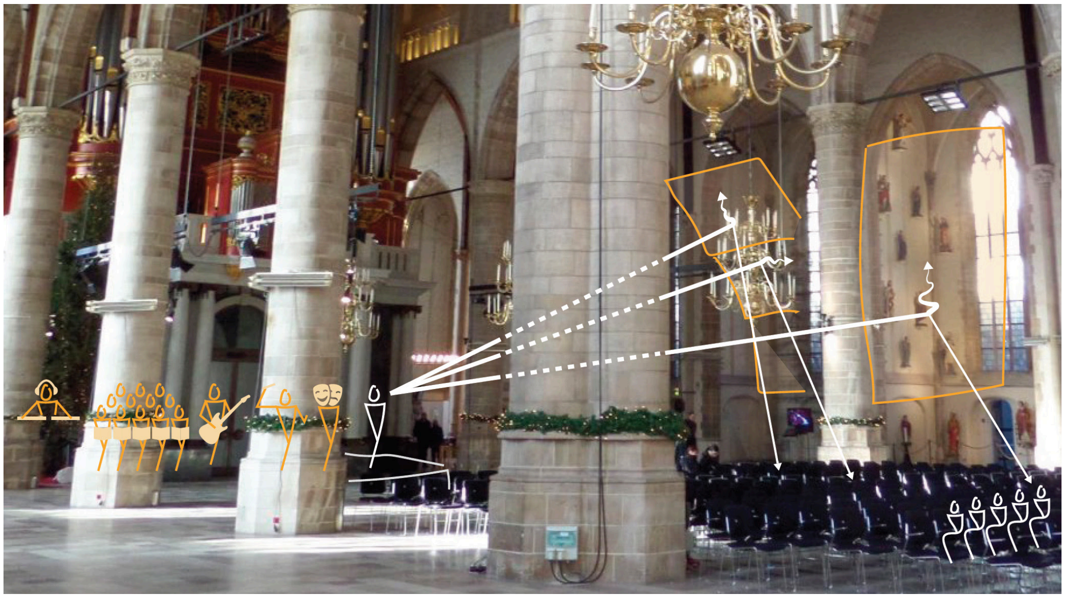

FIGURE 1

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We tried three techniques to make micro perforations in glass, but hydrogen fluoride etching led to uncontrollable perforation sizes and shapes. But, there are two feasible ways to manufacture micro-perforations (≤ 1 mm diameter) in a glass panel: drilling or using a high-end pulse laser-cutting technique. These techniques are both as precise as leaving only 150 μm chip size around the cut, but the cost differs about 4:1.

Perforations in glass panels cause stresses to course around these perforations throughout the glass panel, making its failure behaviour unpredictable and therefore its possible application not so obvious. The final product will contain many perforations, but failure will occur at the weakest point. So, to see that effect, a singular weak point (hole) was tested through computational finite element method (FEM) and a strength-experiment. The experiment is still ongoing.

Another aspect of the finalised product is its transparency. This aspect entails two different scales: the smaller scale of the glass panel with the perforations and the larger scale, that of the entire composite panel and its support structure. The larger scale is dependent on the amount of 'edges' that obstruct the view behind the panel, i.e. frames, connections, cabling. Although the fixings and some connections could be made from the same transparent material as the panel, the structural components are inherently from different and opaque materials, so the less the better.

The smaller scale, that of the panel and the perforation itself and the pattern of the perforations, entails using a colourless glass or polymer with no light reflectance. Colourlessness can be influenced by the chemical composition of the material and the reflectance of the panel can be diminished by adding an AR-coating. Looking at the perforation itself any manufacturing technique 'scratches' the material and thereby leaves a white edge inside the perforation. However, those perforations can then be treated by flame polishing or acid etching. This would not only make the edges transparent again, but also alleviates the tension in the edges, giving back some strength to the panel itself.
Even though the edges of the holes can be transparent, light breaks differently inside the glass than inside the perforation. This entails that perforations do slightly affect view quality: having a negative impact on the amount of detail visible of the image behind the panel.

FIGURE 2

FIGURE 3

Struiksma, A., Tenpierik, M., Snijder, A., Veer, F., Botterman, B., Hornikx, M., van der Water, H., Migchielsen, F. (2017).
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> By manufacturing micro-perforations in a thin transparent panel, sound absorption can be achieved.

The present study shows promising results to bring sound absorbing glass into the building industry. Research is ongoing to reach the optimum integral design of the panel taking into account the sound absorption, transparency, strength and production costs. Besides creating different acoustic surroundings for different types of events in beautiful monumental spaces, the possibilities for application in other types of buildings and building-objects are endless.

FIGURE 4

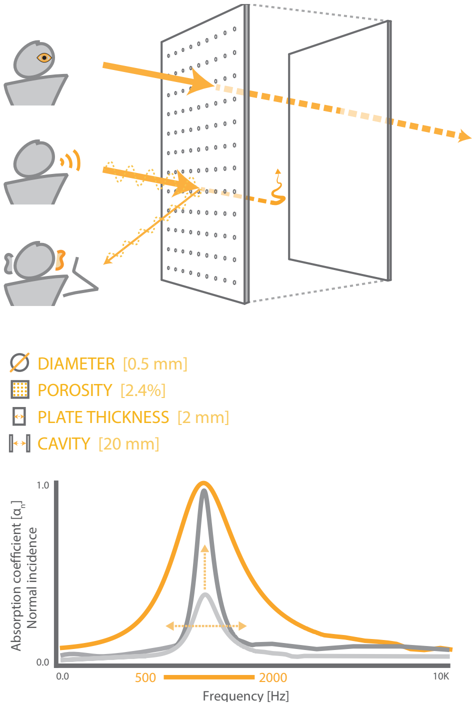

FIGURE 5

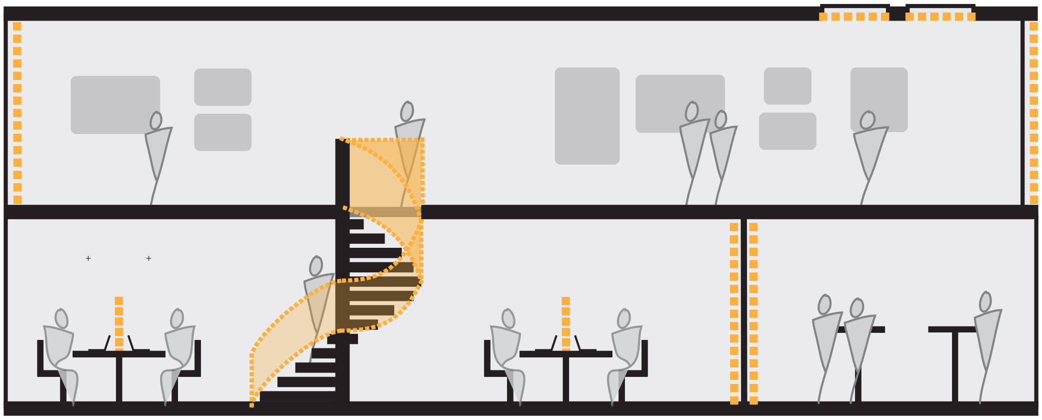

FIGURE 6

Spong3d

3D printed facade system enabling movable fluid heat storage

Maria Valentini Sarakinioti [1], **Michela Turrin** [1], **M. Teeling** [1], **Paul de Ruiter** [1], **Mark van Erk** [1], **Martin Tenpierik** [1], **Thaleia Konstantinou** [1], **Ulrich Knaack** [1], **Arno Pronk** [2], **Patrick Teuffel** [2], **Arthur van Lier** [2], **Rens Vorstermans** [2], **Eline Dolkemade** [2], **Marie de Klijn** [2], **Roel Loonen** [2], **Jan Hensen** [2], **Dick Vlasblom**

[1] *Delft University of Technology*
[2] *Eindhoven University of Technology*
[3] *KIWI Solutions*

Abstract

Spong3D is an adaptive 3D printed facade system that integrates multiple functions to optimize thermal performances according to the different environmental conditions throughout the year. The proposed system incorporates air cavities to provide thermal insulation and a movable liquid (water plus additives) to provide heat storage where and whenever needed. The air cavities have various dimensions and are located in the inner part of the system. The movable liquid provides heat storage as it flows through channels located along the outer surfaces of the system (on the indoor and outdoor faces of the façade). Together, the composition of the channels and the cavities form a complex structure, integrating multiple functions into a singular component, which can only be produced by using an Additive Manufacturing (AM; like 3D printing) technology.

Keywords

3D printed facade system; thermal performance; movable fluid heat storage; Additive Manufacturing

Sarakinioti, M.V., Turrin, M., Teeling, M., de Ruiter, P., van Erk, M., Tenpierik, M., Konstantinou, T., Knaack, U., Pronk, A., Teuffel, P., van Lier, A., Vorstermans, R., Dolkemade, E., de Klijn, M., Loonen, R., Hensen, J., Vlasblom, D. (2017). Spong3d: 3D printed facade system enabling movable fluid heat storage. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

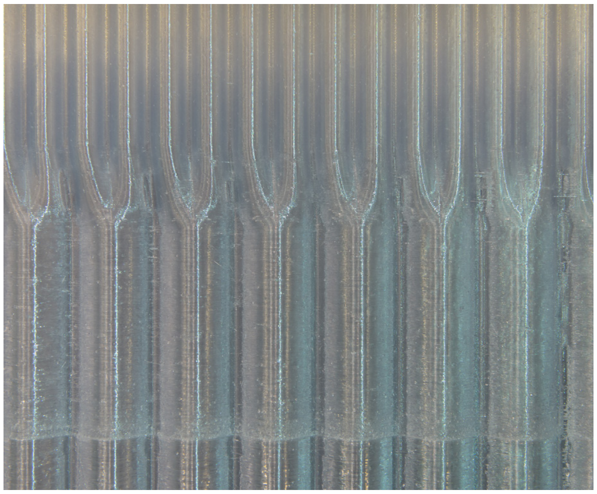

FIGURE 1

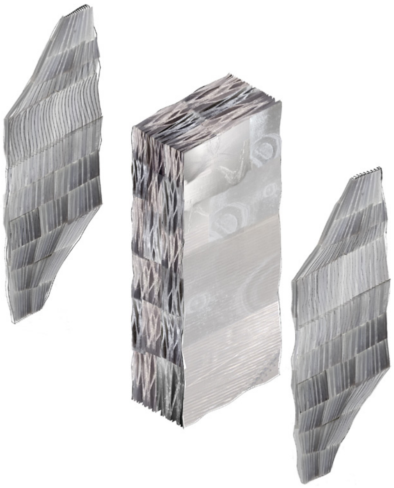

FIGURE 2

The aim of this research is a proof of concept of Spong3D. Spong3D is an adaptive façade system that controls the heat exchange during the year between the interior and exterior conditions of the building. It incorporates two sub-systems. The first system consists of a porous inner core with air cavities to provide thermal insulation. The second one contains a series of outer channels that enable the flowing of liquid. The liquid acts as movable thermal mass to provide adaptive heat storage. Based on necessity, the liquid can be transferred from one side of the façade to the other to absorb and release the heat. The overall adaptive system proposes an integrated component fabricated with additive manufacturing.

The development of the proof of concept was organized according to sub-goals. First, the research aimed at understanding and quantifying the thermal potentials of the 3d printed porous structures; enhancing their capacity for thermal insulation and heat storage. Moreover, the research discovered additional needed properties, specifically issues related to the 3D printing process, such as flow resistance, water tightness, structural robustness and printing time for production. Finally, the research investigates the effects of the façade system in a room environment.

The optimization of thermal performances occurred through an iterative, cyclical process. Several samples with different geometric configurations of porous structures were designed and tested in order to maximize thermal insulation, allow appropriate heat absorption in the liquids, minimize the flow resistance, achieve acceptable water tightness and minimize the production time. In order to design the test-samples, preliminary choices were made by taking into account that the porosity of the material determines the thermal resistance of the façade. The higher the porosity, the less solid (and conductive) material there is, and therefore higher thermal resistance. Thus, the first set of samples was based on ordered cellular structures like polyhedra, which performed well for thermal criteria and structural robustness, but caused challenges with regard to the printing process. In order to reduce the time required for the printing process and the risk of possible failures during production, the size of the cells were then scaled in all directions except the ones related to the heat transfer perpendicular to the facade. The size of the insulating cavities in that direction was constrained to 15 mm in order to prevent internal convection since this would cause the thermal resistance to be reduced. As such, the geometry was adjusted to create smoothly curved cavities that remain 15 mm only in the direction of the heat transfer but are larger in the other two directions. This adjustment showed positive results not only reducing the printing time, but also to creating a stiff, yet lightweight structure. Moreover, the smoothness of the geometry allowed for a more stable printing process.

An adaptive façade system that controls the heat exchange during the year.

The external layer (where the liquid flows) requires water-tightness and a fluid shape of the channels to allow for minimal pressure drop and uniform flow. Several samples with different configurations were tested for flow resistance and the best performing shape was selected. The current shape of the channels is inspired by natural configurations that transfer fluids such as blood vessels, the veins of leaves and three dimensional bionic structures. Though further investigation is needed, the current shape is promising with regard to the circulation of the liquid. The channels should also allow for appropriate heat absorption into the liquid. To accommodate this need, the current models were produced with Fused Deposition Modelling (FDM) printing, using PETG, a transparent 3D printing material that has relatively low thermal conductivity. Further investigations may consider the calibrated combination of translucent and dark materials.

To control the movement of the liquid through the overall system, each façade panel consist of two external layers that integrate two reversed pumps for water circulation. The water can be stored in a tank in the center of the panel. In a cooling situation, the liquid is first placed on the inside to absorb internal heat gain and is then pumped to the outside layer to discharge the heat to the cool night sky. In the alternative case, for heating purposes, the liquid is placed outside to absorb any solar heat gain during daytime and is then pumped to the inside to release this heat inside the building. The pumps are also connected with the water tank to store the water inside the tank when necessary.

The structural behavior of the overall system was analyzed by investigating the impact of the wind load to the façade panel and calculating the deformations. The result is a curtain wall system that transfers the loads to the main structure of the building. The structural analysis did not reveal major structural challenges. However, deeper studies on the structural behavior of the 3D printed material are required especially when considering extreme thermal conditions and durability.

Finally, the thermal impact of the overall system on a room was simulated. The investigation focused on two scenarios, a summer day and a sunny winter day. Energy simulations showed that a cooling rate of 25 W/m2 could be obtained during typical summer conditions. This is more or less equivalent to 50% of the internal heat gains in a conventional office environment. Similarly, 4.8 kWh of thermal energy could be harvested for a typical 12 m^2 office space on a sunny winter day, which accounts for approximately 70% of the typical corresponding heating demand.

A large 1:1 (full scale) prototype was produced. One important aspect of this research was to study the feasibility to produce a façade panel within particular time constraints. This was one of the main challenges that influenced the design and the production process. The design process prioritized configurations that have low printing time and specific settings were applied to ensure a speedy printing process.
The production process occurred in collaboration with KIWI Solutions. The investigation of the 3D printing technology was based on the latest available production technologies, using 3D printers for larger objects and innovative materials.

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59 Sarakinioti, M.V., Turrin, M., Teeling, M., de Ruiter, P., van Erk, M., Tenpierik, M., Konstantinou, T., Knaack, U., Pronk, A., Teuffel, P., van Lier, A., Vorstermans, R., Dolkemade, E., de Klijn, M., Loonen, R., Hensen, J., Vlasblom, D. (2017). Spong3d: 3D printed facade system enabling movable fluid heat storage. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

> The models were produced with 3D printing, using PETG, a transparent material with relatively low thermal conductivity.

In conclusion, the main outlook of this research is a proof of concept for a façade system that can adapt its thermal behavior to different environmental conditions, regulate the temperature inside the building and reduce the environmental impact through innovative production technologies. Despite the challenges faced so far, the project showed promising results regarding the development of tailored products with complex shapes by using 3D printing technology. In the case of Spong3D, it was possible to successfully generate a façade system with high complexity that achieves high levels of thermal comfort. Additionally, by using 3D printing technology the project uses material resources more strategically and minimalizes waste material throughout the production process.

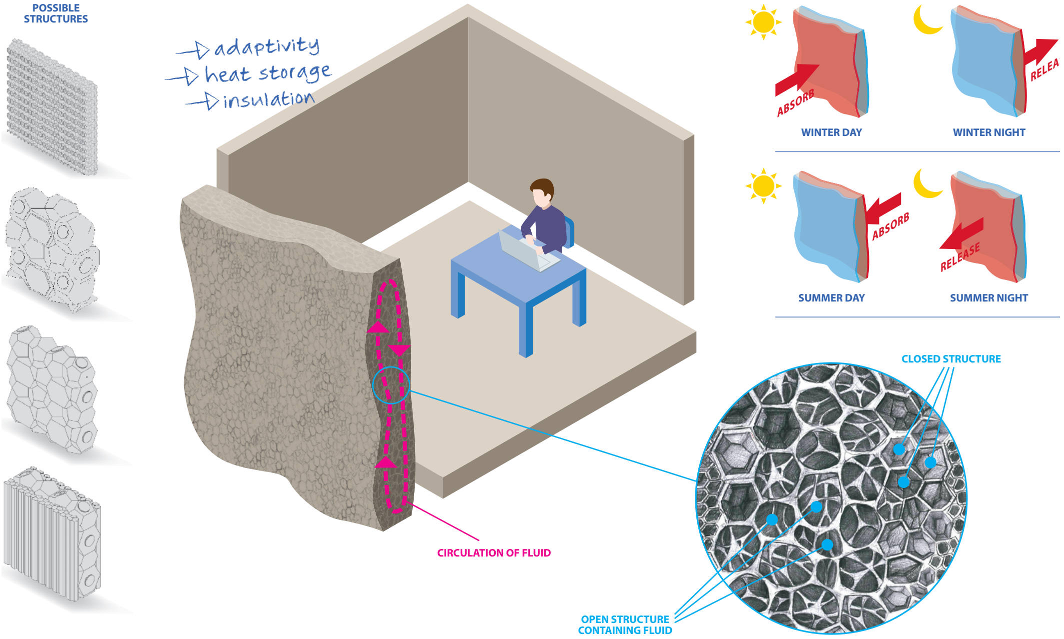


FIGURE 3 Graphical abstract

FIGURE 4

FIGURE 5

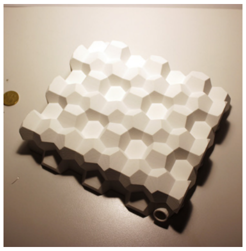


FIGURE 6

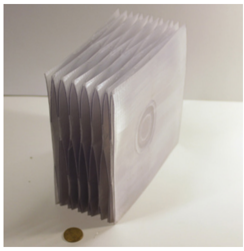


FIGURE 7

Spying the underground

visualizing subsurface utilities' location uncertainties with fuzzy 3D

Léon olde Scholtenhuis [1], **Sisi Zlatanova** [2], **Xander den Duijn** [2], **Anna-Maria Ntarladima** [2], **Evangelos Theocharous** [2]

[1] *University of Twente*
[2] *Delft University of Technology*

Abstract

Spying the Underground refers to the buried utilities that are often hidden from the eyes of citizens and city engineers. Since they are difficult to localize and measure from street level, utility plans are the only models that convey geometry information about them. Nowadays, Augmented Reality (AR) techniques allow us to display three-dimensional (3D) virtual utility models over a surface level camera image. To achieve this, 3D information needs to be added to existing utility models. Therefore, we developed a data model that allows storage of depth and geometry information. Based on this, we developed a fuzzy model that will visualize a fuzzy shape that indicates the uncertainty related to the location of each utility. We developed all this while generating 3D models for subsurface utilities at Oostplein Rotterdam.

Keywords

Augmented Reality; subsurface utilities; 3D modeling; virtual utility model

olde Scholtenhuis, L., Zlatanova, S., den Duijn, X., Ntarladima, A., Theocharous, E. (2017). Spying the underground: Visualizing subsurface utilities' location with uncertainties with fuzzy 3D. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

The resulting 'fuzzy 3D utility model' concept was tested in the field by implementing it in an Augmented Reality (AR) application.

Three-dimensional utility infrastructure models enrich the spatial view on the subsurface and support the design, construction, and maintenance of networks. Although some geographical information systems (GIS) can store utility data in 3D, most existing utility plans are currently composed of 2D schematic lines. One reason for this is the absence of and uncertainty in available depth information of utility networks. With the use of limited additional location information, it is possible to already move 2D utility plans toward more accurate 3D models. This project, therefore, developed a 3D utility data model that uses various sources of available data to visualize location uncertainties. The resulting 'fuzzy 3D utility model' concept was tested in the field by implementing it in an Augmented Reality (AR) application.

For the proof of concept for our fuzzy 3D utility model, we analyzed the distinctive ways that are used in practice to store depth information. We consulted the people responsible for maintenance of the Rotterdam buried subsurface utilities, and we analyzed practical design guidelines such as the 'Rotterdam Handboek Leidingen'. As a next step, we developed a conceptual model to describe subsurface utilities. We, therefore, extended an existing conceptual city model called CityGML Utility ADE. Software developer Recognize then helped us to implement this model in AR. This application was used to visualize the utility data of the Oostplein square in Rotterdam.

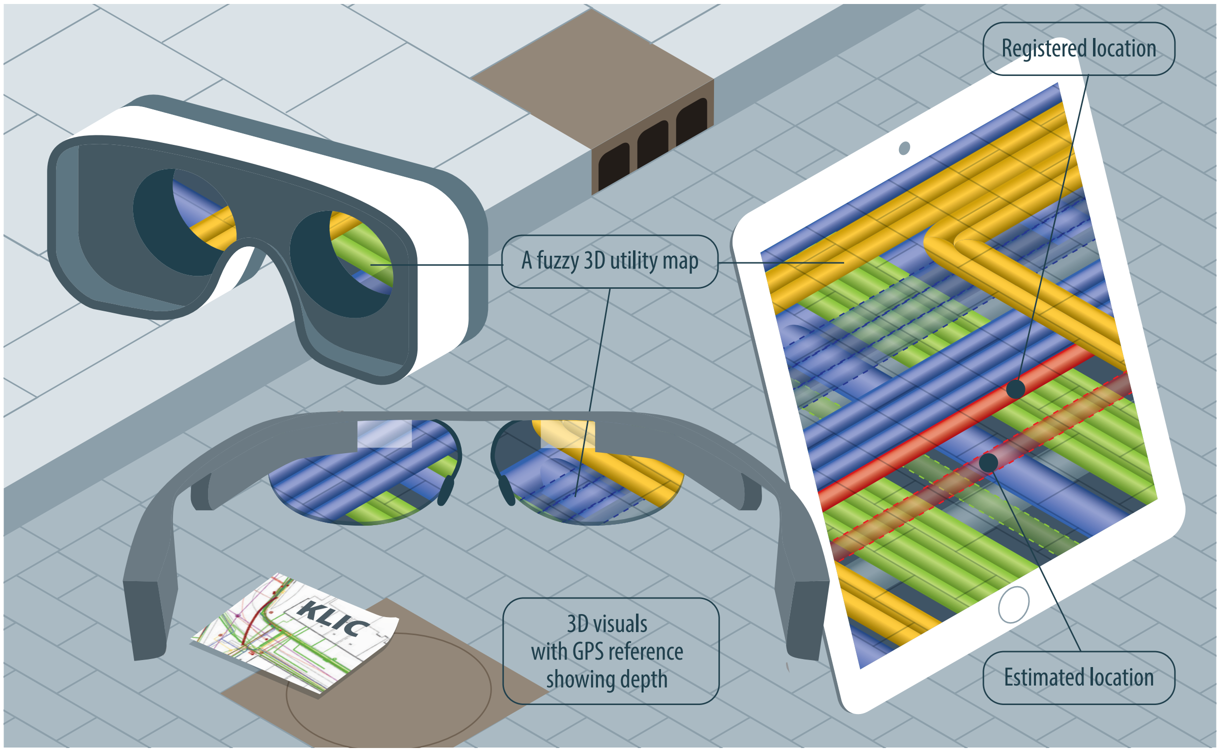


FIGURE 1 Graphical abstract

olde Scholtenhuis, L., Zlatanova, S., den Duijn, X., Ntarladima, A., Theocharous, E. (2017). Spying the underground: Visualizing subsurface utilities' location with uncertainties with fuzzy 3D. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

The developed model describes a utility network by using concepts such as network features and elements. The features describe, for example, information about the quality of location data. In turn, quality can capture location data by using attributes such as standard, estimated, and measured location. The values and reliability of the location attributes differ since 3D object locations are dynamic; i.e. they change over time when soil settles and cables move. Experts indicated that the registered location has a 5cm accuracy if a utility line is installed recently. Nevertheless, in some parts of Rotterdam, the ground may sink up to 1 cm annually. Such movement patterns are hard to generalize since soil conditions differ spatially. Experts judged that estimated locations can deviate from the real locations around 50 cm to 100 cm in all directions.

In the prototype, we visualized these uncertainties by using a minimum, medium and maximum sized cylinder shape that enclosed the standard pipe geometry.

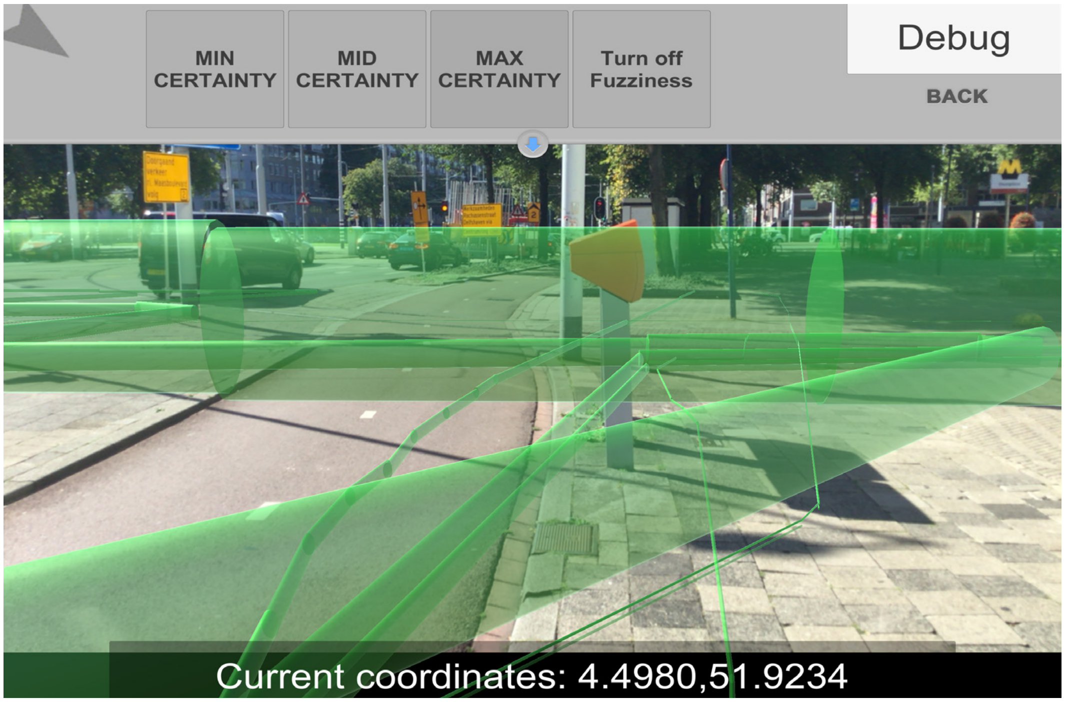
The existing version of the AR-application shows that fuzzy 3D models can be used to convey uncertainty information in utility maps. Three main technical hiccups need to be addressed in future research to further extend this application. First, the actual positioning of the AR-device is important to properly visualize the utility locations. Future research can explore how alternatives to GPS (e.g. LIDAR) can help to position the device more accurately in urban canyons where GPS signal is weak. Regarding the visualization of depth in AR, we also found that it most difficult to show the depth of a virtual object compared to a real-life image on the screen. Our current solution, using a scale symbol to indicate distances between pipes and the surface level, seemed not to be visible and clear. The third important step for future research concerns the visualization of the fuzzy shapes around pipe geometries. Currently, this shape is based on a fixed value for each pipe (having either a minimum, medium of maximum size). In future developments, it would be more realistic to let the size of the uncertainty shape be dependent on the reliability and overlap between existing location information about a pipe section.

FIGURE 2

All in all, this lighthouse project demonstrated a proof of concept for fuzzy 3D utility modeling in AR. The developed algorithm and UML model enabled the fuzzy visualization of three types of depth information (standard, registered, estimated). The first tests on the Oostplein revealed the first use cases and provided fruitful insights into the future development of the tool. Meanwhile, the product generated spin-off since Recognize was able to use the deliverable in projects for two new clients.

Support

- Municipality of Rotterdam
- Recognize B.V.



Current coordinates: 4.4980,51.9234

FIGURE 3

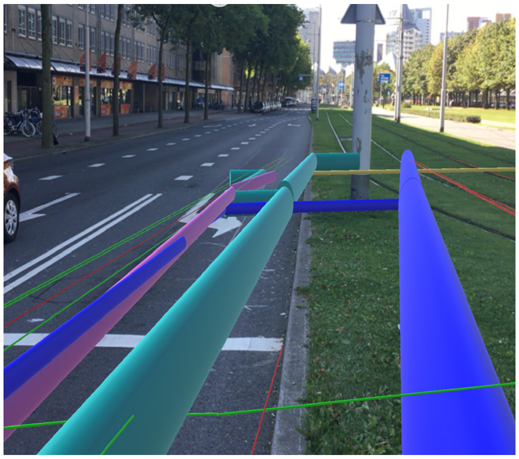


FIGURE 4

FIGURE 5

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olde Scholtenhuis, L., Zlatanova, S., den Duijn, X., Ntarladima, A., Theocharous, E. (2017). Spying the underground: Visualizing subsurface utilities' location with uncertainties with fuzzy 3D. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Unleash the building bots

3d printing structures with an autonomous robot swarm

Aant van der Zee [1], **Paul de Ruiter** [2] , **Hayo Meijs** [3]

[1] *Delft University of Technology*
[2] *Eindhoven University of Technology*
[3] *TBI Kennislab*

Abstract

3D printing techniques for the building industry are developing fast. Concepts like Contour printing, concrete printing concepts of the TU/E and D Shape are examples. Despite the range of techniques is broad (and vary from a large gantry system, to a supersized Delta printer for example), many of the developed 3D printing machines are constraint in their movement. Mobile 3D printers however show advantages in flexibility, as they can move outside the constraint of a large 3D printer and they can move in the highly unstructured and hazardous environment of the building site, which can be dangerous for people to work in. The Institute for advanced architecture of Catalonia developed vehicles, which they call minibuilders, each designed for a special task in the building process, printing the foundation, printing a wall, smoothing the outer-wall etc. The minibuilders are used in succession according the building process. However they are still limited in their autonomy and capability. The minibuilders are tethered with a hose to a vehicle, which carries the concrete supply.

Keywords

3D printing structures; mobile 3D printing machine; minibuilders; building robot

van der Zee, A., de Ruiter P., Meijs, H. (2017). Unleash the building bots: 3d printing structures with an autonomous robot swarm. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

To develop autonomous agent-based robots, which are not constraint in their reach and which have the capability to work together.

In this research we will look for the possibility to develop autonomous agent-based robots, which are not constraint in their reach and which have the capability to work together. The robots will decide how and with how many other robots they will do the job. Autonomous robots are robots that can perform desired tasks in unstructured environments without continuous human guidance. Each robot has a list of components, which it can print with the basic material. Together the robots calculate how to solve a 3D print task and how many must/can help. If one robot needs to refuel or needs to get additional printing material, the others distribute the tasks between them so the job will continue. When returning to the building site the robot can choose to join in or perform another task. The robots need to know when to "refuel" and to refill the basic extrusion-material from a centralized point. In summary each robot must have at least the following capabilities:

1. Know its location on site;
2. Know its exact geo-locate location of the building;
3. Know its state;
4. Know where its fellow robots are;
5. Avoiding obstacles (fellow robots, material and fuel, erected building components)
6. Communicate with fellow robots;
7. Extrude simple components (columns, walls).

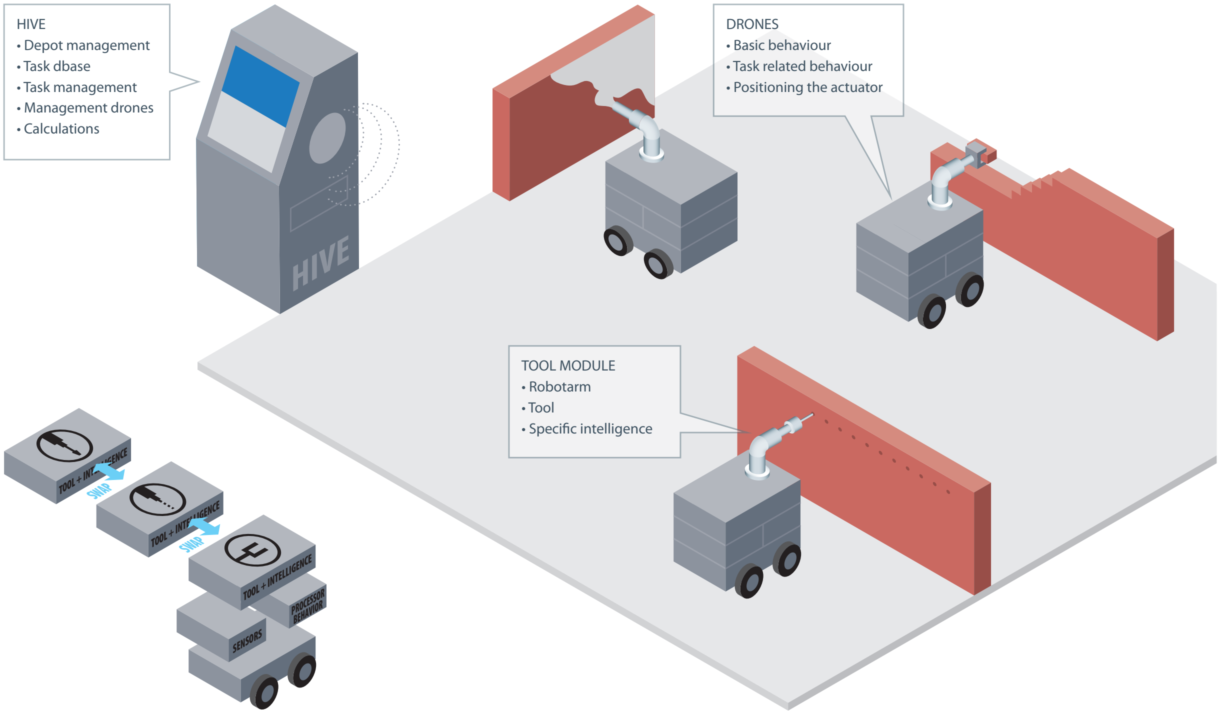

FIGURE 1 Graphical abstract

> Each building bot has a microprocessor as it’s mind and is connected to the hive by Bluetooth.

In order to keep the weight of each robot low, it can only carry a limit amount of concrete. So the extruded walls must be light weighted. For the project a new type of nozzle was developed, which can print the two side plates and the wall infill in one step. This type of wall has also a higher thermal isolation than solid walls.
A problem that still has to be solved is the “climbing”. The building bots must be capable of climbing a wall in order to reach the location where it has to print, or climb down a wall in order to go to the hive for refilling its concrete supply.

Each building bot has a microprocessor as it’s mind and is connected to the hive by Bluetooth. The microprocessor can be programmed to round obstacles which the building bot will encounter on its path to the hive or work location. It knows its location on the site by calculating its orientation by means of the difference in speed between left and right wheel and by comparing its location to the line between starting point (= hive) and endpoint (= work location).
The building bots can, besides printing, also be programmed to perform other tasks. Therefor a small industrial robotic arm or other tools can replace the printing nozzle. When other tools are mounted on the builderbot, it can perform some simple tasks at, for people, hazardous locations.

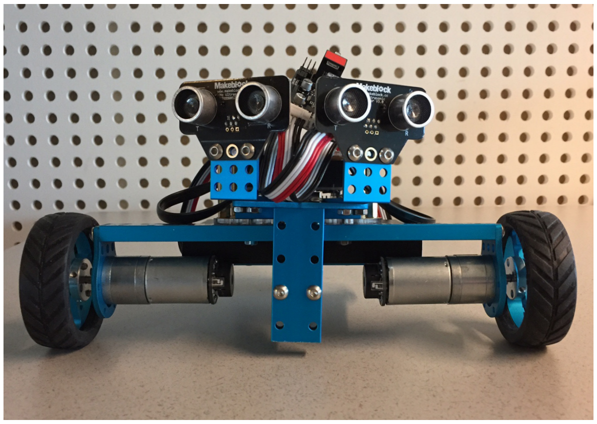

FIGURE 2

FIGURE 3

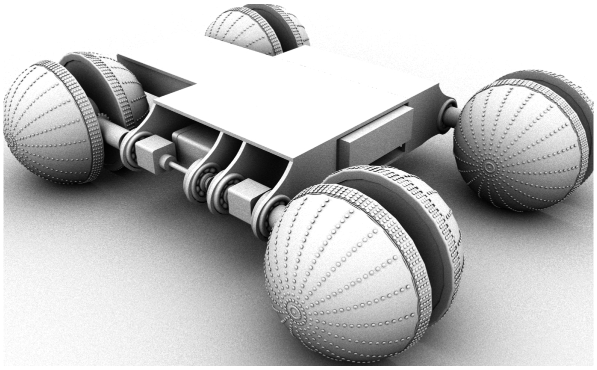

FIGURE 4

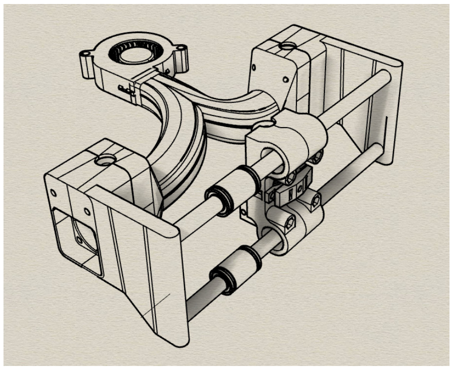

FIGURE 5

De Reus van Schimmert

from water tower to data center

Konstantinos Tzanakakis [1], **Madeleine Gibescu** [1] , **Ed Nijssen** [1], **Nico Eurelings** [2]

[1] *Eindhoven University of Technology*
[2] *De Reus van Schimmert*

Abstract

The water tower of Schimmert was built in 1926 to cover the needs of water of Schimmert and the surrounding areas as well. This imposing 38 meters high tower dwarfs any nearby buildings, providing a 360° view of the surrounding area and deserves its pseudonym de Reus van Schimmert (the Giant of Schimmert). In the attempt to find a sustainable business model for the iconic building the concept of installing a data center in its core is investigated. The waste heat from the servers will be transferred to the reservoir on the top and from there used to power a district heating system in Schimmert.

Keywords

Schimmert; Reus van Schimmert; data center; waste heat; district heating system

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Tzanakakis, K., Gibescu, M., Nijssen, E., Eurelings, N. (2017). De Reus van Schimmert: From water tower to data center. SPOOL, 4(2).
doi:10.7480/spool.2013.1.624

100% of the electricity fed to a server is transformed into heat.

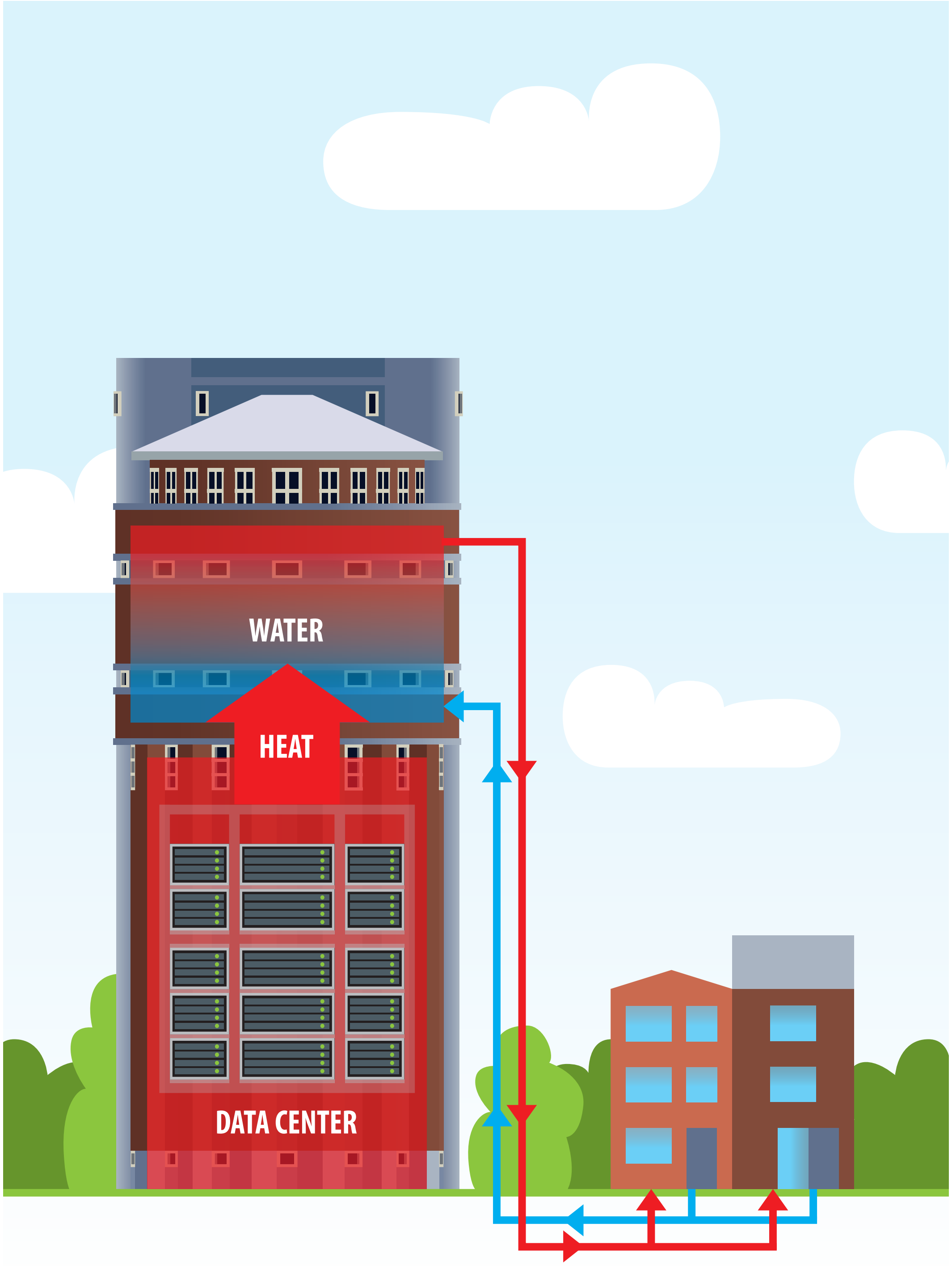


FIGURE 1 raphical abstract

The waste heat from the servers will be transferred to the reservoir on the top and from there used to power a district heating system in Schimmert.

The cloud, mobile services, Big Data, Internet of Things and social media have become important services in today's digitalized society. And data centers are what enables them. The need for IT infrastructure is ever increasing and their operation is critical. Although the data center business is booming, the growing demand of these services not only directly translates to higher energy demand and operating costs but also leads to a more severe impact on the environment.

However, within these very same data centers lies the potential to address such environmental, economic and societal concerns. Data centers are uniquely positioned at the crossroads of both energy and data networks and will have the opportunity to become key players within their local sustainable energy systems.

The IT equipment generates heat throughout its operation. Actually, 100% of the electricity fed to a server is transformed into heat and this heat needs to be removed from the server rooms. For this reason, data centers need cooling in order to maintain environmental conditions suitable for the operation of the information technology equipment.

Heat disposal is of paramount concern in the design of data centers. Typically the heat is dissipated away from the IT equipment and practically wasted into the atmosphere. However this waste heat can be re-used for many applications, providing an extra source of revenue to the data center operator while at the same time improving the energy efficiency of the facilities. This has as a result a smaller CO2 footprint and a reduced cost of ownership.

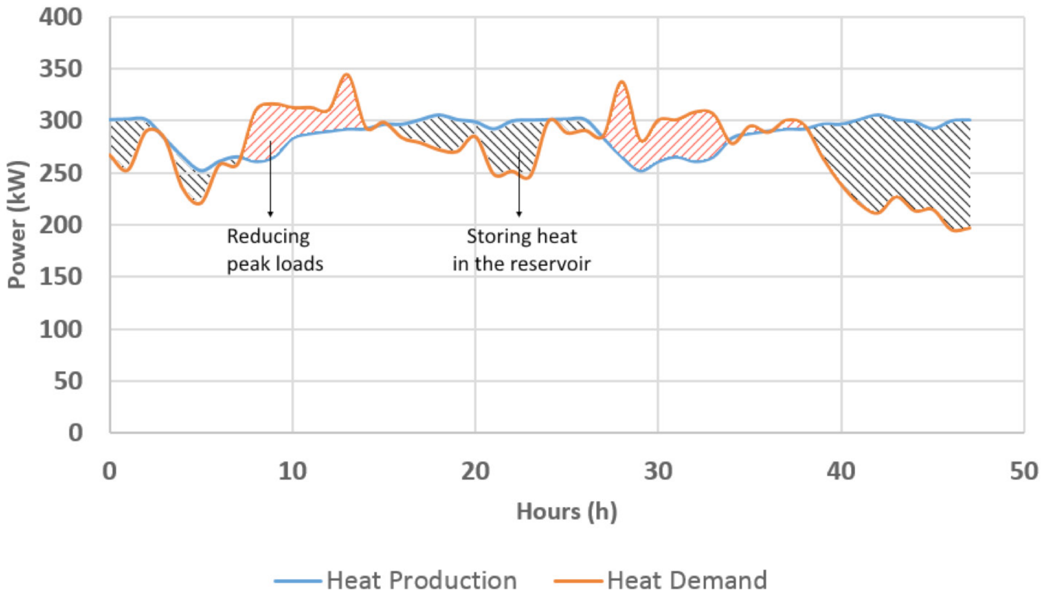


FIGURE 2

Tzanakakis, K., Gibescu, M., Nijssen, E., Eurelings, N. (2017). De Reus van Schimmert: From water tower to data center. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

De Reus van Schimmert has the potential to be transformed into a data center that smartly utilizes the waste heat that is generated by the IT operation. The proposed design, consisting of the data center and the corresponding district heating system fueled by the data center's waste heat, is a venture that can position itself strategically in the local growing ICT market. In addition to that, selling the waste heat provides an additional income source while providing once more a service to the citizens of Schimmert.

Sixty five houses can be heated using the waste heat. However, a difference exists between the time the waste heat is available from the IT operation and the actual demand in the houses. Storage technology has the potential to give a solution to the challenge of this mismatch, providing security of supply without the need of oversizing the system in order to guarantee a continuous energy flow. For this reason, the reservoir on the top of the tower will be used as a buffer, a heat storage system. During times of low demand the excess heat is stored in the tank while when the demand surpasses the supply, the difference is covered by the stored energy.

Data centers are likely to remain an important part of the global economy for many years to come.
At present the demand for such facilities is increasing and, as users find more ways to enjoy and exploit access to vast amounts of data, the demand will increase even further. De Reus van Schimmert can be once again a lighting beacon of the area, this time because of its sustainable paradigm. It can showcase that although data centers demand massive amounts of electricity and as a consequence are responsible for CO2 emissions, they can put this energy in good use by providing sustainable heating to the local area.

Industrial symbiosis software

software and method to facilitate industrial symbiosis

Immanuel Geesing [1], **Bauke de Vries** [1], **Frits Rutten** [3]

[1] *Eindhoven University of Technology*
[2] *Delft University of Technology*
[3] *Stichting Bedrijventerrein Helmond*

Abstract

Bedrijven gaan tegenwoordig vooral lineair om met hun materialen. Grondstoffen komen binnen, worden verwerkt tot producten en hun afval wordt afgevoerd. Binnen één bedrijf ziet dit er logisch uit, maar in een systeem van meerdere bedrijven is te zien dat dit efficiënter kan. Als het afval van een bedrijf gebruikt zou worden als grondstof door een ander bedrijf, ontstaat er industriële symbiose. Daardoor worden er minder grondstoffen verbruikt en worden bruikbare restmaterialen niet verspild.
Om bedrijven te helpen bij het zoeken naar partners voor zulke uitwisselingen, is de software InduSym ontwikkeld. Met de software kunnen bedrijven hun grondstoffen en restmateriaal invoeren in een database. Een algoritme doorzoekt deze database en presenteert in een rapport de kansen om te komen tot een symbiotische uitwisseling van reststromen.

Keywords

InduSym; industrial symbiosis; online software; companies

Geesing, I., de Vries, B., Rutten, F. (2017). Industrial symbiosis software: Software and method to facilitate industrial symbiosis. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

De software bespaart geld, maakt ze socialer en duurzamer en verbetert daarmee hun imago.

InduSym is een online software die ontworpen is om de vraag naar grondstoffen en het overschot aan restmateriaal van bedrijven bij elkaar te brengen. De software maakt het voor bedrijven zo eenvoudig mogelijk om de grondstoffen die ze gebruiken en de materialen die ze overhouden in te voeren in een database. Indien gewenst kunnen bedrijven meer informatie over de materialen geven, wat het eenvoudiger maakt voor andere bedrijven om in te schatten of ze een goede partner zijn voor industriële symbiose. Dit kan door middel van een nummer uit de Europese afvalstoffenlijst (Euralcode), omschrijvingen en tags. Ze kunnen bovendien alvast een indicatie geven over de financiële overeenkomst die ze willen sluiten, bijvoorbeeld of de reststroom gratis aangeboden wordt, of dat ze er een betaling voor verwachten.

Met de ingevulde informatie zoekt een algoritme in de database naar overeenkomsten met andere bedrijven. Als er een match tussen reststroom en grondstof gevonden wordt, kunnen de bedrijven met elkaar in contact treden om te onderzoeken of deze in de praktijk kan worden gebracht als symbiotische uitwisseling. Om de software eenvoudig, laagdrempelig en efficiënt te houden, zijn de matches betrekkelijk algemeen. Materiaaleigenschappen zoals temperatuur en volume, of proceseigenschappen zoals continu en batchgewijs kunnen in de omschrijving vermeld worden indien ze naar verwachting relevant zijn, maar dit is niet verplicht. Deze meer gedetailleerde informatie kan altijd nog aangevuld worden wanneer er match geïdentificeerd is en de intentie er is om deze in de praktijk te brengen. Dit voorkomt dat er veel tijd en moeite wordt gestopt in het omschrijven van materialen waar geen match op gevonden wordt.

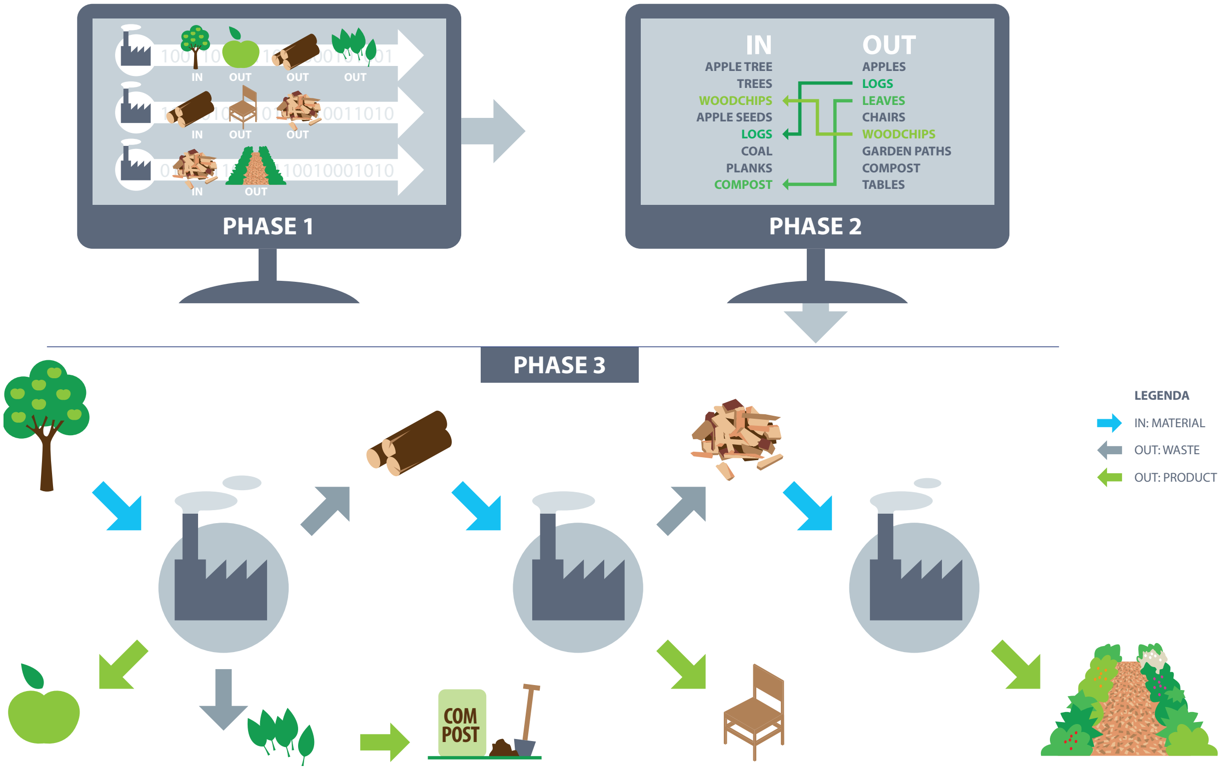


FIGURE 1 Graphical abstract

Geesing, I., de Vries, B., Rutten, F. (2017). Industrial symbiosis software: Software and method to facilitate industrial symbiosis. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Met InduSym kunnen bedrijven komen tot een symbiotische uitwisseling van reststromen.

De software kijkt naar matches tussen de bestaande bedrijfsprocessen, maar het is voor bedrijven ook mogelijk om zelf in de database te zoeken naar materiaalstromen waar nog geen match voor gevonden is. Dit is bijvoorbeeld handig bij het zich oriënteren op het aanbod aan lokale reststromen en het zoeken naar nieuwe mogelijkheden om de bedrijfsprocessen te veranderen of uit te breiden.

De software is tevens inzetbaar voor het analyseren van bedrijventerreinen omdat ermee in kaart wordt gebracht welke reststromen er beschikbaar zijn en naar welke materialen veel vraag is. Hier kunnen vervolgens ook projecten uit voortkomen. Als er bijv. veel biomassa beschikbaar is, kan overwogen worden een biomassacentrale te bouwen. Als er juist een grote vraag blijkt te bestaan naar een bepaald type grondstof, kan een bedrijf met zulke reststromen aangetrokken worden om zich op het bedrijventerrein te vestigen.

Om te komen tot een ontwerp dat zo veel mogelijk is toegespitst op de wensen van bedrijven, zijn interviews gehouden met bedrijven die zich aangesloten hebben bij de Helmonds Energie Community. Er werd met name gevraagd welke functionaliteiten voor hen belangrijk zijn en welke aspecten hen zouden kunnen belemmeren bij het komen tot industriële symbiose.

Bij bedrijven is winst vrijwel altijd de hoogste prioriteit. Ze beseffen echter wel dat als ze niet duurzaam handelen, ze op den duur klanten verliezen en buiten de markt komen te staan. De belangrijkste voordelen die de software hen dus biedt zijn de mogelijkheid om goedkopere grondstoffen te vinden en goedkoper van hun restmateriaal af te komen. Bovendien helpt het hun na te denken over hoe ze omgaan met hun afval en verwachten ze dat uit de verhoogde samenwerking op het bedrijventerrein ook andere voordelen voortkomen. De software bespaart hen dus geld, maakt ze socialer en duurzamer en verbetert daarmee hun imago.

De drie belangrijkste voorwaarden voor bedrijven om gebruik te maken van de InduSym-software waren dat de matches wel financiële kansen moeten bieden, er vertrouwelijk met gevoelige informatie omgegaan moet worden en het gebruik ervan niet te tijdrovend moet zijn.

Bij de vraag naar welke randaspecten het belangrijkst zijn voor de bedrijven, bleek dat vertrouwelijkheid en anonimiteit van de informatie aanzienlijk minder belangrijk zijn dan een eenvoudige, effectieve software die hen mogelijkheden biedt om geld te verdienen en te besparen. De bedrijven zijn dus bereid informatie over hun processen te delen en optimistisch over de kansen die de InduSym-software biedt.

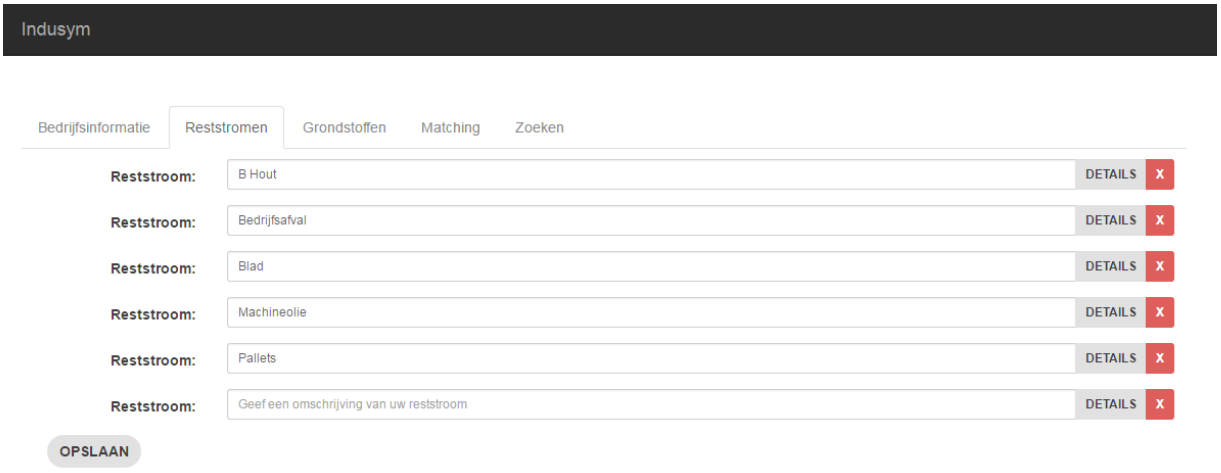
Industriële symbiose is dan ook goed voor zowel het milieu, mensen en de portemonnee, in lijn met het duurzaamheidsprincipe People, Planet, Profit. Door de symbiotische uitwisselingen verbruiken de bedrijven minder grondstoffen en wordt de waarde die nog in restmateriaal zit niet verspild door het bijvoorbeeld meteen te verbranden of te gebruiken als landvulling. Ook wordt het transport van deze materialen lokaler, wat eveneens goed is voor het milieu. Op termijn zou een bedrijventerrein zelfs zelfvoorzienend kunnen worden door de bedrijven op elkaar af te stemmen en bedrijven aan te trekken die de industriële symbiose bevorderen.

Geesing, I., de Vries, B., Rutten, F. (2017). Industrial symbiosis software: Software and method to facilitate industrial symbiosis. SPOOL, 4(2). doi:10.7480/spool.2013.1.624

Uiteraard is dat ook goed voor de werkgelegenheid. Door het aangaan van samenwerking tussen de bedrijven, wordt hun verbondenheid met hun bedrijventerrein bovendien groter en zullen bedrijven zich er langer vestigen. Dit leidt tot een stabielere situatie. Als bedrijven met elkaar in gesprek gaan over materiaaluitwisselingen, kan dit ook leiden tot samenwerking en initiatieven op andere vlakken.

Bedrijven die nu nog veel moeten betalen voor het afvoeren en verwerken van hun reststromen, kunnen er straks veel goedkoper of gratis van af komen, en in sommige gevallen zelfs geld aan verdienen. De bedrijven die deze reststromen afnemen hebben op hun beurt een duurzame en goedkopere bron van grondstoffen.

Na een jaar onderzoek, ontwerp en ontwikkeling, is de software InduSym nu voltooid. Als eerste stap naar een duurzamere situatie en meer circulaire economie zal deze software gebruikt en doorontwikkeld worden op de bedrijventerreinen die aangesloten zijn bij de Stichting Bedrijventerreinen Helmond.



Reststroom: B Hout

Reststroom: Bedrijfsafval

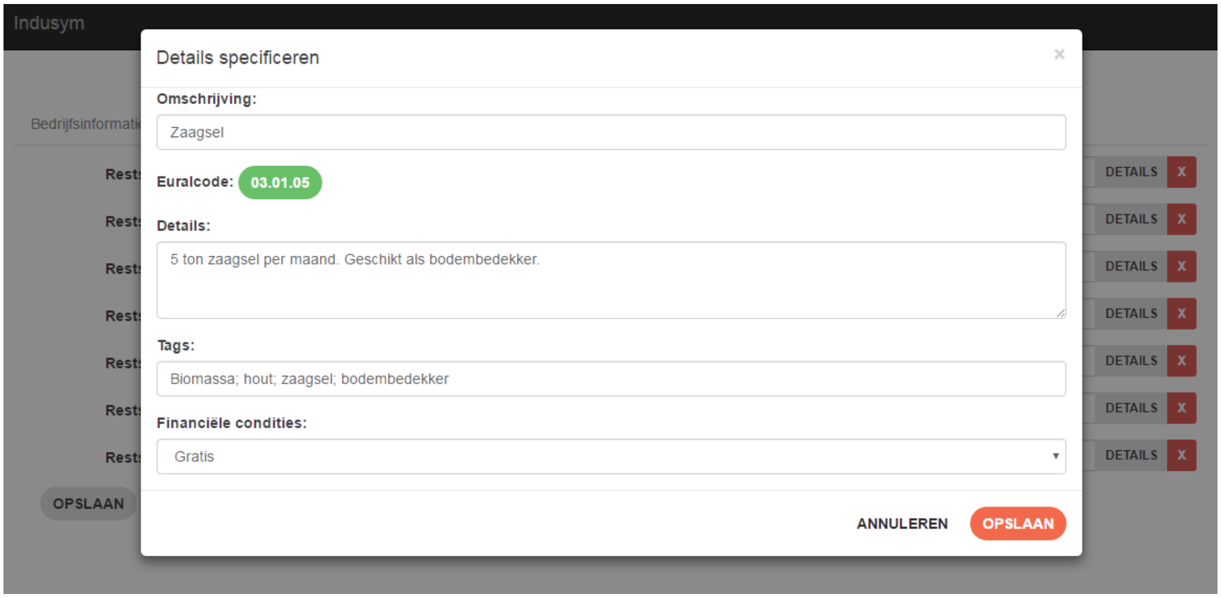
Reststroom: Blad

Reststroom: Machineolie

Reststroom: Pallets

Reststroom: Geef een omschrijving van uw reststroom

FIGURE 2 Indusym software: Invoer van reststromen.



Omschrijving: Zaagsel

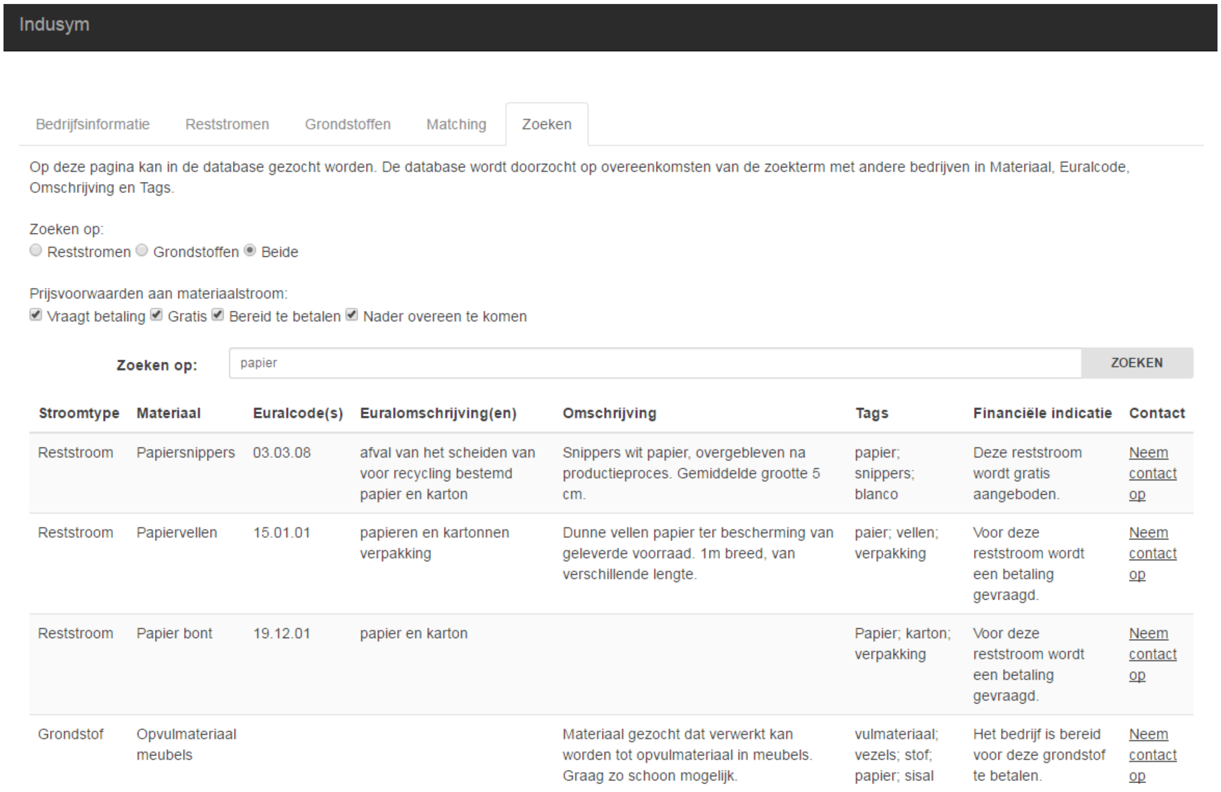
Euralcode: 03.01.05

Details: 5 ton zaagsel per maand. Geschikt als bodembedekker.

Tags: Biomassa; hout; zaagsel; bodembedekker

Financiële condities: Gratis

FIGURE 3 Indusym software: Specificatie van de reststroom.



Op deze pagina kan in de database gezocht worden. De database wordt doorzocht op overeenkomsten van de zoekterm met andere bedrijven in Materiaal, Euralcode, Omschrijving en Tags.

Zoeken op:
○ Reststromen ○ Grondstoffen ● Beide

Prijsvoorwaarden aan materiaalstroom:
☑ Vraagt betaling ☑ Gratis ☑ Bereid te betalen ☑ Nader overeen te komen

Zoeken op: papier

Stroomtype	Materiaal	Euralcode(s)	Euralomschrijving(en)	Omschrijving	Tags	Financiële indicatie	Contact
Reststroom	Papiersnippers	03.03.08	afval van het scheiden van voor recycling bestemd papier en karton	Snippers wit papier, overgebleven na productieproces. Gemiddelde grootte 5 cm.	papier; snippers; blanco	Deze reststroom wordt gratis aangeboden.	Neem contact op
Reststroom	Papiervellen	15.01.01	papieren en kartonnen verpakking	Dunne vellen papier ter bescherming van geleverde voorraad. 1m breed, van verschillende lengte.	paier; vellen; verpakking	Voor deze reststroom wordt een betaling gevraagd.	Neem contact op
Reststroom	Papier bont	19.12.01	papier en karton		Papier; karton; verpakking	Voor deze reststroom wordt een betaling gevraagd.	Neem contact op
Grondstof	Opvulmateriaal meubels			Materiaal gezocht dat verwerkt kan worden tot opvulmateriaal in meubels. Graag zo schoon mogelijk.	vulmateriaal; vezels; stof; papier; sisal	Het bedrijf is bereid voor deze grondstof te betalen.	Neem contact op

FIGURE 4 Indusym software: Specificatie van de reststroom.

Transition towards DC micro grids

From an AC to a hybrid AC and DC energy infrastructure

Evi Ploumpidou [1], **Sjoerd Romme** [1], **Madeleine Gibescu** [1], **Arno Bronswijk** [2], **Harry Stokman** [3], **Pepijn van Wiligenburg** [3], **Wil Paulus** [3]

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Abstract

Our electricity is predominantly powered by alternating current (AC), ever since the War of Currents ended in the favor of Nicola Tesla at the end of the 19th century. However, lots of the appliances we use, such as electronics and lights with light-emitting diode (LED) technology, work internally on direct current (DC) and it is projected that the number of these appliances will increase in the near future. Another contributor to the increase in DC consumption is the ongoing electrification of mobility (Electric Vehicles (EVs)). At the same time, photovoltaics (PV) generate DC voltages, while the most common storage technologies also use DC. In order to integrate all these appliances and technologies to the existing AC grid, there is a need for converters which introduce power losses. By distributing DC power to DC devices instead of converting it to AC first, it is possible to avoid substantial energy losses that occur every time electricity is converted.
This situation initiated the concept for the implementation of the DC-Flexhouse project. A prototype DC installation will be developed and tested in one of the buildings of the developing living lab area called the District of Tomorrow (De Wijk van Morgen) which is located in Heerlen, the Netherlands. A neighborhood cooperative (Vrieheide cooperatie) is also part of the consortium in order to address the aspect of social acceptance. Although DC seems to be a promising solution for a more sustainable energy system, the business case is still debatable due to both technology- and market-related challenges. The current energy infrastructure is predominantly based on AC, manufacturers produce devices based on AC standards and people are using many AC products across a long life span. This Smart Energy Buildings & Cities (SEB&C) PDEng project is a contribution to the DC-Flexhouse project. The aim is to analyze the challenges in the transition to DC micro grids, assess the market potential of DC applications in the built environment and develop a framework that leads to a commercial success.

Keywords

DC micro grids; Smart Energy Buildgins & Cities; DC-Flexhouse; De Wijk van Morgen; Vrieheide cooperatie

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By distributing DC power to DC devices instead of converting it to AC first, it is possible to avoid substantial energy losses which occur every time electricity is converted.

Project scope and objectives

This project targets to support the transition to DC micro grids in the built environment by investigating enabling strategies for successful market introduction, while taking into account both technology and market aspects. More specifically, the following objectives are identified:

- Assessing the market potential: The market opportunities that arise within the DC innovation are investigated based on trends in the energy sector and relevant industries.
- Proposing a strategy for the transition to DC micro grids: Companies and organizations involved in the DC-Flexhouse project can use this proposition to steer activities towards the commercial realization of DC micro grids. The proposed strategy is intended to be applied not only to DC-Flexhouse project but also to future projects for the development of DC technology.

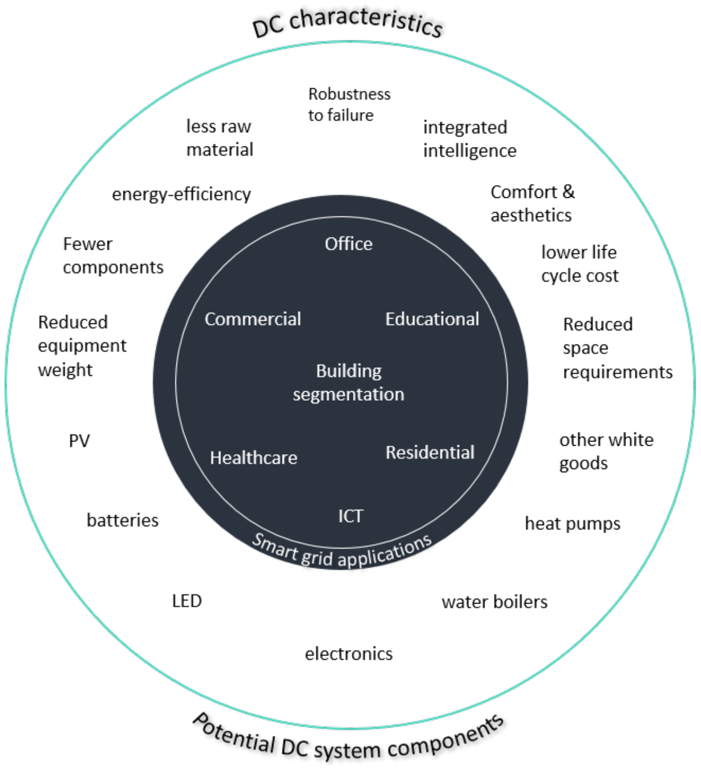

FIGURE 1 Graphical abstract

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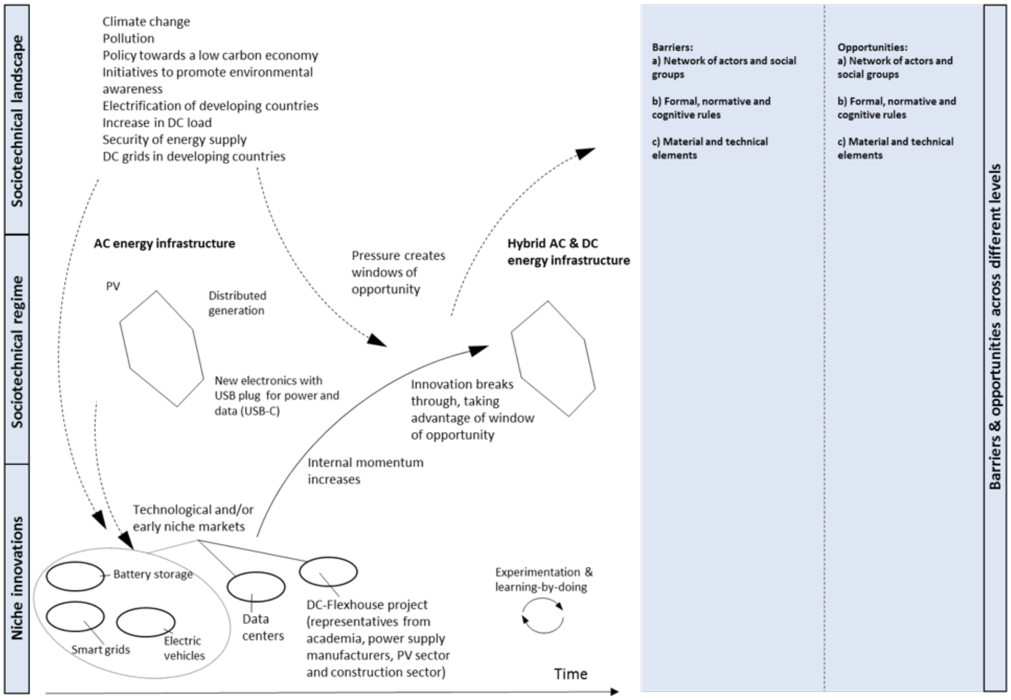

FIGURE 2 Graphical abstract

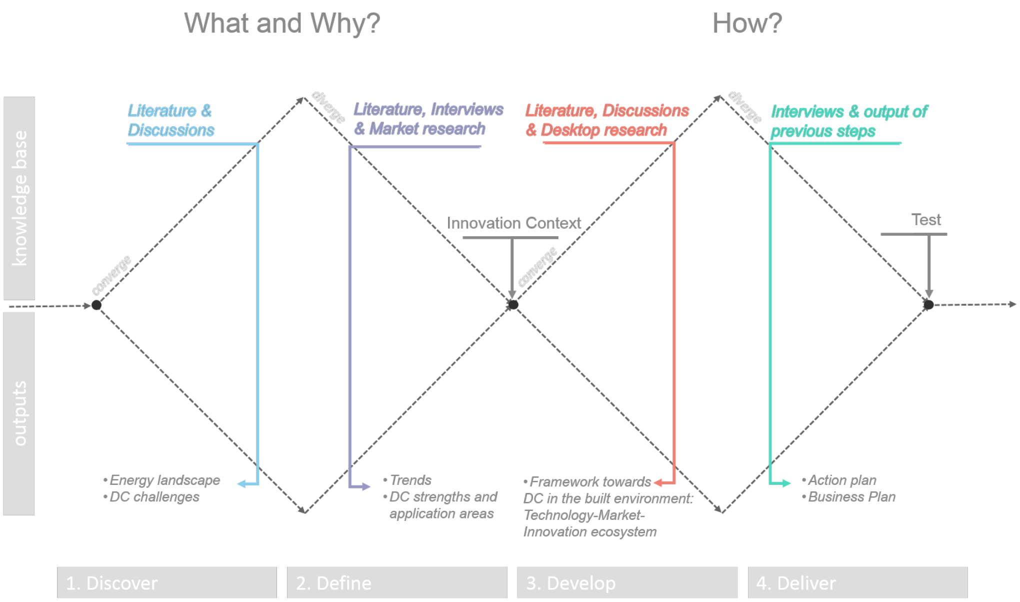

FIGURE 3 Graphical abstract

Methodology

The methodology of this project combines principles grounded in research on innovation and transition management with guidelines from a more practical structured design process. More specifically, the implementation of this project was based on the combination of transition theories, the Multi-level Perspective (MLP) and Transition Management (TM) with the Design Thinking (DT) method. The MLP is used to analyze how transitions towards sustainable energy systems take place and identify how DC innovation can potentially challenge the current energy system, while TM provides guidelines aimed at facilitating and directing processes towards the commercialization of DC. DT offers a step-by-step guideline for developing innovative solutions for complex problems by deliberately incorporating the concerns, interests and values of stakeholders into the design process.

Background information

The prototype in-building DC micro grid that is being designed in the framework of the DC-Flexhouse project will integrate PVs, battery storage and DC loads. The goal is to provide direct DC power to DC loads, thus avoiding the otherwise necessary conversion steps. The key feature of the DC micro grid, however, is that it is a smart grid in itself, meaning that it comes equipped with an energy management system to monitor and manage energy use.

In addition to the benefits of energy savings and potential lower capital costs due to fewer components (elimination of converters), DC offers the advantage of high penetration rate of intelligent hardware thanks to electronic transducer technology. This feature allows smart grid services to be offered to all electricity market players, including the end-users (building owners/users) themselves.

Brief discussion of results

DC technology is a radical innovation that requires the transformation of the well-established AC energy system. At the time this PDEng project is conducted, there is no explicit market need for DC applications. Therefore, it appears to be difficult to gauge the market potential at this moment. However, building upon the MLP framework, the trends and drivers that can lead to the breakthrough of the DC innovation were identified.

The wider developments in the energy and building sectors, such as the increasing use of DC loads, growing penetration of PV, expected falling prices of battery storage technologies, potential change in net-metering policy for PV, and regulations for improved energy efficiency of buildings, point at the future market potential. In other words, it can be argued that DC innovation fits within the overall energy transition and can have a big impact if managed properly.

Based on my personal observations during my involvement in the DC-Flexhouse project and principles inferred from the innovation and transition management literature, a set of recommendations towards the commercialization of DC was developed. Following these recommendations increases the likelihood of commercial success in the future.

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Parties that want to promote DC technology should first target to build strategic alliances with co-innovators and then find frontrunners that are willing to invest and adopt the innovation. A key co-innovator is grid operators. A financial analysis for residential buildings indicates that an in-building DC installation is an attractive business case for the building owner when the power supply is provided by a DC distribution grid. Therefore, the involvement of grid operators is crucial for the successful commercialization of DC applications. The frontrunners create the niche markets that facilitate the diffusion of the innovation into the mainstream markets. According to the transition management literature, the transformation of regimes starts from technological niches and/or early niche markets. In the DC case, potential niche markets or early adopters were identified by combining the value proposition of DC with needs and perceived values in different market segments. Potential groups of early adopters are office buildings with high lighting and computing demand, educational buildings and new neighborhoods. Niche markets might initially not generate a substantial level of profit for the actors in the value chain, but entering these niche markets will facilitate broader market development at a later stage.

Deliverables

In line with the project objectives, the key deliverables are:

- An assessment of the market potential of the DC innovation that is grounded on transition management literature
- A case study for residential buildings with a photovoltaic installation based on a cost-benefit analysis
- An action plan for companies and organizations involved in the DC-Flexhouse project towards the commercialization of DC technology
- A business plan for the development and market introduction of DC applications based on future trends and financial projections (pro-forma financial statements)

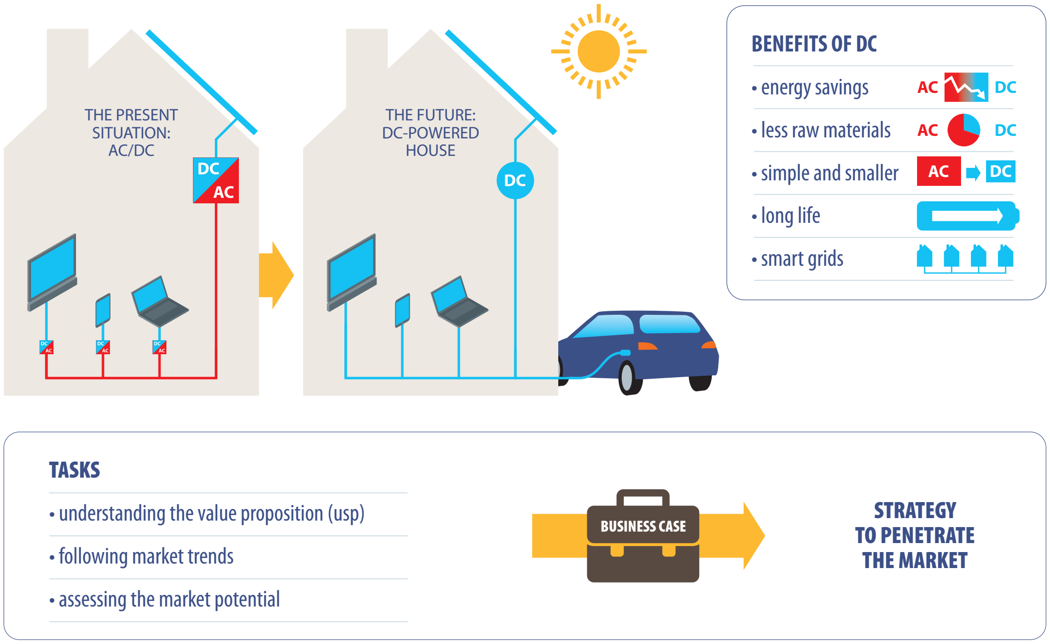

FIGURE 4 Graphical abstract

Conclusions

Overall, this PDEng project demonstrates the future market potential of DC and provides a strategy that paves the way towards a commercial success based on examples of successful breakthrough of other sustainable innovations. Early involvement of actors within the value chain at this stage will help them capitalize on this market potential in the future and generate new revenues from the production of DC products. If the findings of the DC-Flexhouse project validate in practice the current theoretically validated findings for improved energy efficiency, reduced capital costs and robustness to failure, we can expect to see DC installations in the built environment in the near future.

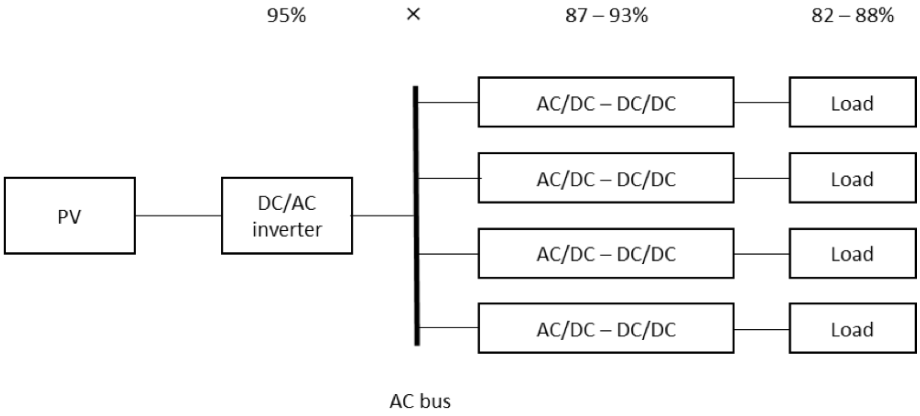

FIGURE 5 Conventional AC architecture with PV system

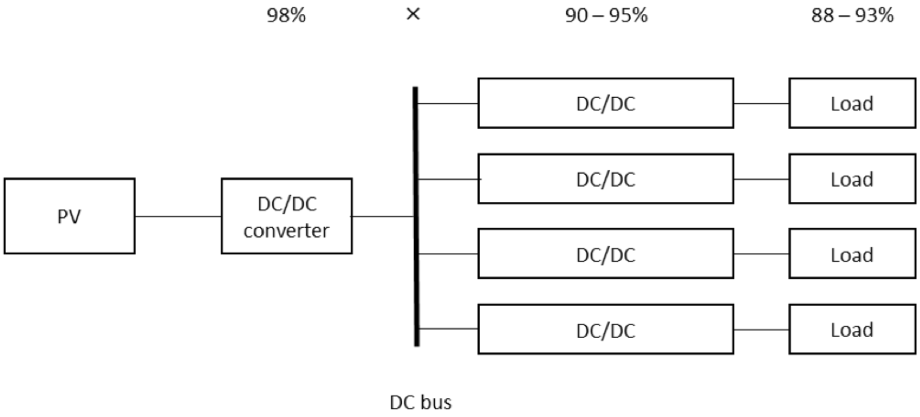

FIGURE 6 DC architecture with PV system

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