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NEST HiLo: Investigating lightweight construction and adaptive energy systems

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ABSTRACT

This paper presents research on lightweight construction and smart, integrated and adaptive building systems. The research is focused on addressing challenges related to the building industry at large, including most prominently the improvement of energy efficiency, onsite power generation, and the reduction of the quantity of materials required to build. We introduce four innovations in context of the design of an experimental building (NEST HiLo): a lightweight, unreinforced funicular floor system; a flexibly formed, concrete shell sandwich roof; a soft actuated, adaptive solar facade and an automated, occupant-centred control system. We demonstrate novel structural engineering approaches to compression-only concrete elements and shell design using multi-criteria shape optimisation. We explore a building facade concept, which employs robotic actuators for solar shading and on-site generation. In addition, the operational phase of the building will be used as a living laboratory where occupants' locations and needs for comfort are detected and used for the control of the energy innovations. The research provides insight into design topics that will become increasingly relevant for the evolution of improved lifecycle energy buildings.

1. Introduction

Buildings account for 40% of global energy consumption and up to 30% of global greenhouse gas (GHG) emissions [1]. Up to 46% [2] of this energy use is locked in for long periods due to the life span of buildings. Furthermore, this embodied energy and the related emissions may double or potentially even triple by mid-century due to several key trends, which includes population growth, additional building services requirements and increases to the size of households [3].

In the European Union (EU), advances in minimising energy usage have been largely focused on operational energy. Improvements in building envelope performance, energy systems efficiency and onsite power generation are delivering on 2020 targets for Net Zero Energy Buildings (NZEB) [4]. With a view to EU 2050 targets, that is an 80% reduction in GHG emissions from 1990 levels [5], further developments in GHG emissions reduction must also consider the impact of embodied energy.

Over the building lifecycle, the key energy related decisions are contained in the early design phase [6]. The decisions are made based on input of various domain experts. Enhancements in operational energy performance are related mainly to the energy systems domain. This is not the case for embodied energy, as other domains have a strong influence on embodied energy decisions. In fact, the structural system of buildings alone can account for up to 55% of embodied energy [7]. To improve lifecycle energy performance an integrated design approach can be used to manage the conflicting inter-domain constraints of a building design. Such an approach, proactively balances the requirements of the primary domain (e.g. structural design) with the impact on the energy domain. This is in contrast to the traditional sequential design approach, where each domain provides largely independent solutions.

This paper presents research on lightweight construction and

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adaptive energy systems, for an experimental building (HiLo). The objective of HiLo is to demonstrate that optimum lifecycle energy performance is possible on challenging buildings by balancing the constraints of architecture, structures and energy systems. HiLo is planned as a net plus energy building (NPEB) with an annual weighted energy demand of 37.8 kWh/m^2 and a weighted energy surplus of 45%. In previous work, we have presented the numerical simulation framework used to integrate thermally active building systems (TABS) and building integrated photovoltaics (BIPV) with lightweight structures [8]. Moreover, the numerical approaches used to optimise lightweight concrete structures were discussed in [9,10]. This paper provides an overview of the development of the four key HiLo innovations: a lightweight, unreinforced funicular floor system; a flexibly formed, concrete shell sandwich roof; a soft-actuated, adaptive solar facade; and an automated, occupant-centred control system.

The article is organised as follows. Section 2 summarises the key aspects of the project background. In Section 3, the architectural concept of HiLo is outlined. The four innovations are presented in Section 4. A discussion on future work is outlined in Section 5. The conclusions are provided in Section 6.

2. Background

As a future living and working laboratory, NEST (Next Evolution in Sustainable building Technologies) (Fig. 1) [11] consists of a central backbone building to accommodate exchangeable living and office buildings or units. This allows novel materials, components and innovative systems to be tested, demonstrated and optimised under real-world conditions. NEST is a modular, district scale research and demonstration platform for advanced and innovative building technologies in Switzerland. The NEST backbone building was completed in 2016.

As one of the first NEST modules, HiLo (Fig. 2) [12] is a research and innovation building in the domains of lightweight construction and adaptive building systems. HiLo (High performance, Low energy) is planned as a two bedroom apartment for visiting faculty of the Swiss federal research institutes Empa and Eawag and it is planned to start construction in early 2018.

3. Architectural concept

The architectural concept of HiLo involves the deployment of a doubly curved roof relative to an arrangement of cellular rooms, which yields a dual spatial condition. This supports the competing needs for privacy versus communality, and work versus living. The affordance of hybrid live/work scenarios is becoming increasingly relevant and desirable in response to the demands of our cities for quality urban housing. This concept attempts to minimise sprawl and dependence on transport infrastructures, while maintaining urban density, vibrancy and amenity. HiLo serves as an example of the exciting potentials such aspirations hold and the role that emerging technologies play in mediating these concerns against the broader performance frameworks of material and energy efficiencies.

Fig. 1. Early rendering of an intermediate state of NEST showing several research and innovation units (© Empa, Gramazio & Kohler).

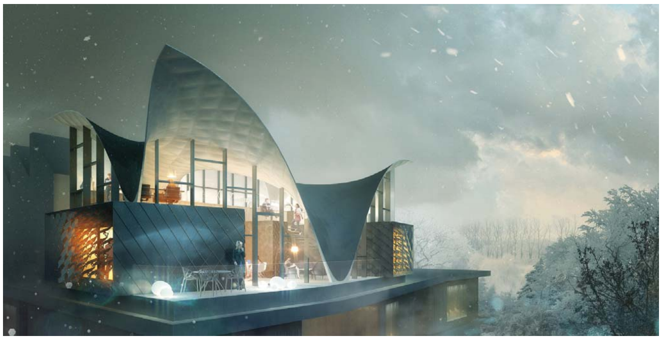

Fig. 2. Exterior of HiLo, initial design (© HiLo, Doug and Wolf).

The spatial organisation of HiLo serves to provide each innovation the best opportunity to be demonstrated and tested. Of most consequence is the decision to minimise contact with the roof; this allows its structural achievement to be fully appreciated (Fig. 3). To accomplish this, a primarily open plan approach has been adopted. Only sleeping and bathing activities have been allocated enclosed rooms. HiLo is 16 × 9 m in plan, has a floor area of 138 m^2, and an enclosed volume of 364 m^3. The heated floor area, i.e. the value used for energy calculations, is 175.1 m^2.

4. Innovations

The four innovations introduced through HiLo are (Fig. 4):

1. A lightweight funicular floor system (Section 4.1) that features,
    (a) a thin funicular concrete shell with stiffening fins, and
    (b) a hydronic radiant heating and cooling system;
2. An integrated, thin shell roof (Section 4.2) that features,
    (a) a mesh-reinforced concrete and PU foam sandwich structure,
    (b) flexible thin-film photovoltaics,
    (c) a hydronic radiant heating and cooling system, and
    (d) a lightweight flexible formwork for its construction;
3. An adaptive solar facade (Section 4.3), that features;
    (a) photovoltaic panels, driven by
    (b) soft robotic actuators; and,
4. An occupant-centred control system, that features (Section 4.4),

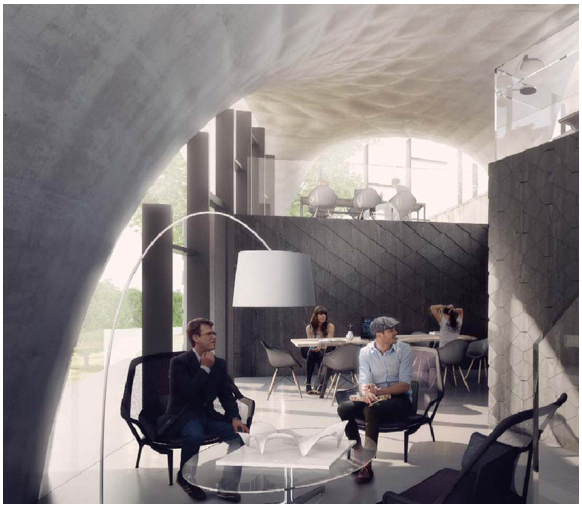

Fig. 3. Interior of HiLo, initial design (© HiLo, Doug and Wolf).

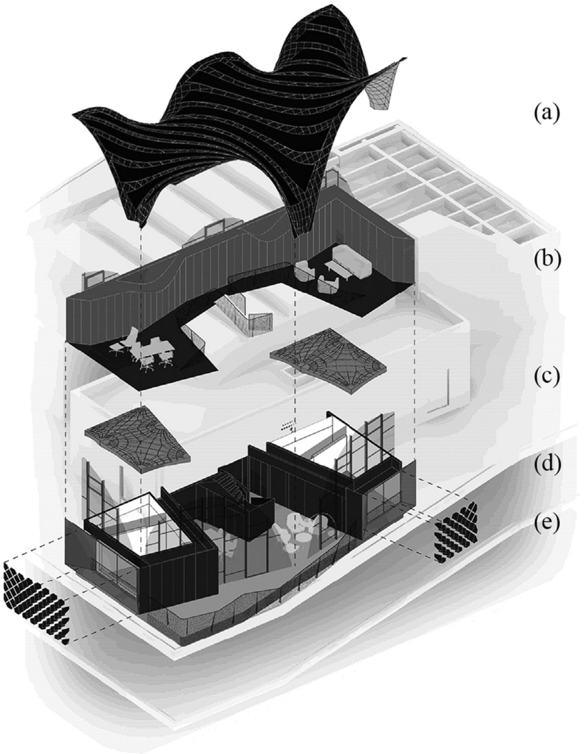

Fig. 4. Key innovations and components of HiLo: a) flexibly formed sandwich shell roof with photovoltaics; b) mezzanine level; c) funicular floor system; d) entry level with ribbon wall concealing utilities and services; and, e) soft-actuated adaptive solar facade.

(a) constant indoor/outdoor climate monitoring,
(b) adaptive set-points for the building systems, and
(c) learning of user preferences through interaction.

The following subsections will discuss the individual innovations.

4.1. Lightweight funicular floor system

A lightweight concrete floor system is being developed for HiLo (Fig. 5). The system features a prefabricated method that enables quick on-site installation as well as an integrated low exergy heating and cooling function. The overall system aims to reduce: the use of material; operational energy; the floor height; as well as construction cost and time, compared to traditional solutions. Each of the floor panels is geometrically unique and has its own set of specific interfaces with structure, space and infrastructure. Therefore, HiLo serves as the perfect test and proof of the system's flexibility.

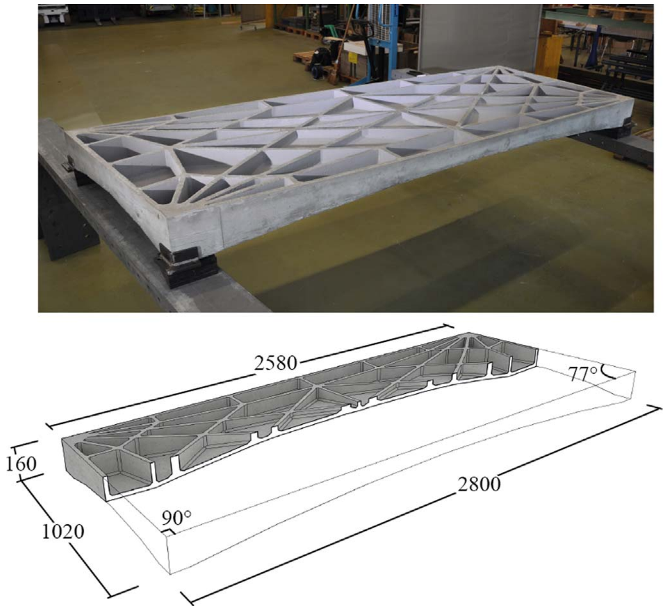

Fig. 5. Initial structural prototype of the floor system (dimensions in mm) [10].

4.1.1. Structural design

The floor system consists of a modular and thin concrete construction, made up of a vault, stiffening fins and a system of tension ties at the perimeter. The floor is shaped such that it works in compression only, while externalising any tension to the perimeter, thus avoiding the need for any traditional rebar. Each floor is supported at the four corners, which are connected by steel tension ties to absorb the horizontal thrusts of the funicular shell. This structural system is designed in concrete to achieve a thickness of only 20 mm for both vault and fins; while still being able to resist asymmetrical loading. As a result, this system would save more than 70% of concrete weight compared to an already efficient prestressed hollowcore floor slab.

The solution is inspired by built examples in tile vaulting in which thin, unreinforced masonry vaults are stiffened by vertical diaphragms, also called spandrel walls [14]. In traditional construction, spandrel walls had two main objectives: provide a horizontal level for the floor finishing and contribute to the structural behaviour, maintaining a minimum thickness of the vault while resisting asymmetrical loading. Contemporary projects, such as the Mapungubwe National Park Interpretive Centre, South Africa [15], and the Sustainable Urban Dwelling Unit (SUDU) prototype building, Ethiopia, (Fig. 6), have applied this technique successfully, combining a thin unreinforced masonry vault and spandrel walls, using low-strength, cement-stabilised earthen tiles [13].

All of the floors required for HiLo have different and irregular geometry. They are all quadrilateral in plan and are all supported at their corners, but their spans and shapes vary significantly. For this reason, a computational setup to generate the geometry for all floors was implemented [10].

Its objective is to obtain a compression-only shell under dead load, and an optimised density and arrangement of thin stiffeners for the live load combinations. This takes away the need for conventional rebar entirely by ensuring that the predominant stresses in the floors are compressive.

The design of the floors starts with the generation of a pattern that takes into account the expected force flow to the supports (Fig. 7). Using this pattern as a force diagram, the shape of the vault was

Fig. 6. Thin-tile floor with spandrell walls of the SUDU project in Addis Ababa, Ethiopia, 2010 [13].

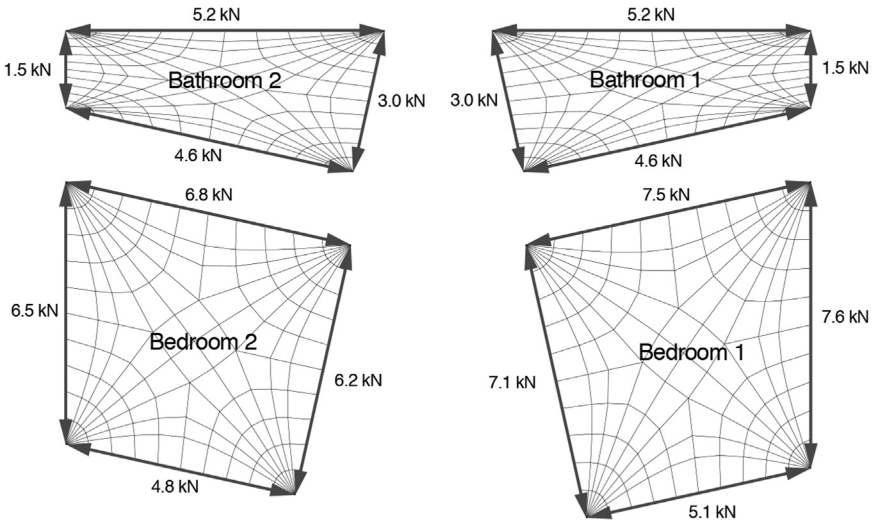

Fig. 7. Floor system fin patterns and post-tensioning forces.

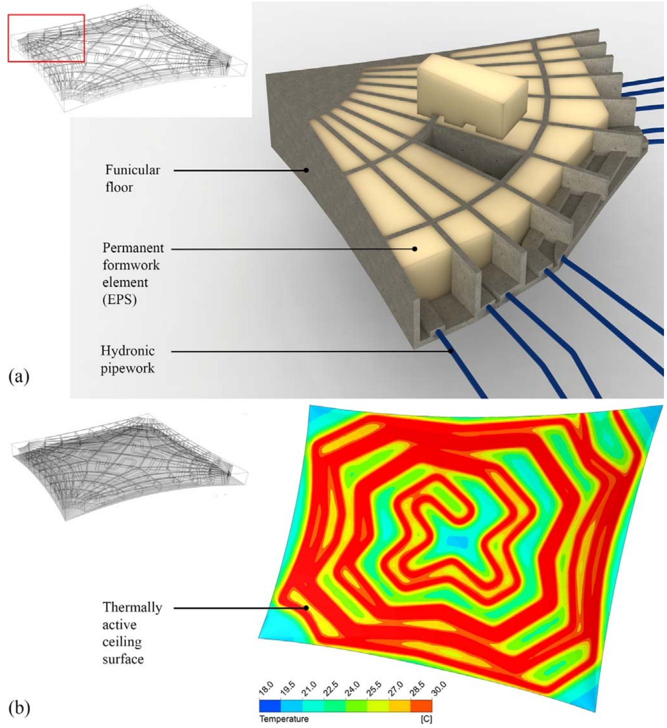

Fig. 8. (a) Cutaway view of the funicular floor, the hydronic pipework and the permanent formwork. (b) Heating case - ceiling surface temperature contour plot [20].

generated using Thrust Network Analysis (TNA). TNA is a form-finding method capable of generating funicular discrete networks under vertical loading conditions. It gives the designer a high degree of control over the shape by allowing different force flow assumptions in the network [16]. The pattern is translated into a compression-only network that is used as the shape of the vault. Two constraints are given to the TNA algorithm: the pattern is to stay fixed in plan, and the depth of the resulting vault is given. The floors are designed to have a total structural depth of 400 mm at the supports, this depth reduces to 30 mm at the centre of the floors.

To confirm the overall soundness of the shape, a best-fit TNA [17] is employed. It ensures that the resulting shape is capable of directing loads to the supports in an efficient manner, generating only compressive stresses, and that all forces are contained within the geometry of the structure. The resulting thrust network is used as the basis for the fin stiffeners. They are the result of extruding the edges of the network to their desired height.

The form-finding process assumes that the supports are completely fixed and that they can take both horizontal and vertical thrust from the floor system. However, in the HiLo unit only the vertical component of the thrust is transmitted to the NEST backbone structure, the horizontal component is taken by the tension ties that surround each floor.

Each tie is comprised of one round steel bar, connected to the concrete shell through a steel angle profile at the corners, and connected to each other by a tensioning sleeve, to allow for the bars to be post-tensioned. The diameter of each bar is different in each one of the floor systems, according to their spans. Larger floor spans result in shallower shells, and hence higher horizontal thrusts, this translates into higher diameters for the ties. The tension ties are dimensioned to take the horizontal thrusts generated by the floor under all of the loading conditions prescribed by SIA (Swiss Society of Engineers and Architects) code, and to ensure that the horizontal displacements of the supports are kept within what is allowable by the concrete shell. The ties are designed to have zero displacements in the shell under self-weight and dead loads (the standard load condition). This is achieved by calculating the horizontal thrust in each support under the standard loading condition, and using those forces to post-tension the ties. This means that under standard loading the tension on the ties is close to zero, and that there are no horizontal displacements of the supports. The forces used to post-tension the ties are shown in Fig. 7.

A 2.8 × 1 m prototype of the funicular floor system was built and tested for serviceability and ultimate loads [18]. The serviceability test showed that the floor was very stiff, with vertical deformations under span/25,000. The ultimate load was estimated using a very critical asymmetric load scenario, and showed that the floor carried 2.5 times the factored design load.

4.1.2. Building systems integration

The funicular floor above each bedroom will be a thermally active building system (TABS) [19]. This will be realised by integrating a hydronic pipe network within the concrete component (Fig. 8a), which will provide heating and cooling to the bedrooms through the thin (20 mm) concrete radiant panel at ceiling level.

The permanent formwork elements used to manufacture the floor will also serve as thermal insulation. The initial geometry of the expanded polystyrene (EPS) blocks (Fig. 8a) will be based on the structural design. This geometry will be updated to include a positioning channel for the hydronic pipework. Computational fluid dynamics (CFD) models of the full floor geometry (Fig. 8b) have been used to inform the loop layout strategy and estimate the thermal performance of the system. The numerical simulations were completed with the CFD code ANSYS Fluent 14. This provided steady state and transient thermal data for the geometrically complex systems. The results were also used to resolve building physics issues such as the connection between the funicular floor and the external building envelope. A full discussion of the modelling process is provided in [8,20,21].

4.2. *Integrated, thin shell roof*

The most attention grabbing of the innovations is the integrated, thin shell roof. It is envisioned as a lightweight, sandwich, thin shell roof structure, integrating both structure and building systems. This efficiency is translated into an architecturally elegant form through the use of the touchdown points to the main structure. The entire spatial strategy of HiLo is dedicated to allowing the roof's form to be fully comprehended (including from the street below).

The residential program places more diverse demands on the roof than large exhibition or sports hall programs, which are usually associated with shell structures. Thus, although relatively small, the roof is highly irregular and complete control is needed to successfully negotiate the diverse spatial, environmental (including balanced solar exposure) and structural interfaces. More specifically, the design aims to severely reduce material, and hence weight, both for the formwork and its resulting shell structure. To achieve all of this, the roof geometry is the specific result of a sequence of single- and subsequent multi-criteria evolutionary optimisation, evaluating various parameters related to structural and energy performance, as well as architectural, spatial and constructional constraints. Further engineering was carried out to incorporate additional nonlinearities necessary to assess the strength, stiffness and stability of the shell.

The improvement in structural performance targets a significant reduction in the concrete volume compared to a typical concrete roof section. This provides a low embodied energy building element, while retaining the beneficial characteristics of concrete in relation to operational energy. This reduces the structural requirements for building foundations and increases the potential for further embodied energy reductions. This integrated approach to design opens up sustainable district scale opportunities to address vertical densification of cities by, for example, providing very lightweight building extensions.

4.2.1. *Structural design*

Thin shell structures, if properly designed and constructed, are able to cover large spaces at minimal material cost through efficient membrane action. In our case, the shape of the roof is structurally optimised to push the limit of what is possible in concrete [22]. An evolutionary design process breeds possible solutions by continuously evaluating structural performance and functional constraints (Fig. 9). The most optimal geometry is chosen for further development.

The roof structure for HiLo is a thin mesh-reinforced sandwich shell, consisting of upper and lower concrete shells with a rigid polyurethane (PU) core. This provides a continuous surface in visible architectural concrete from the inside to the outside of the building, with minimal interruption by the glass facade. The sandwich design was primarily developed to minimise thermal bridging at the connection between the glass facade and the roof (Fig. 10). This increases the structural depth and reduces sensitivity to external loads.

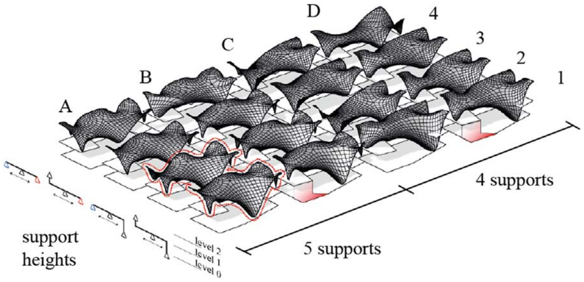

Fig. 9. Results from sixteen early optimisations (16 × 100 generations, 100 shells each), with A1 and A2 selected for further development based on overall structural and energy performance.

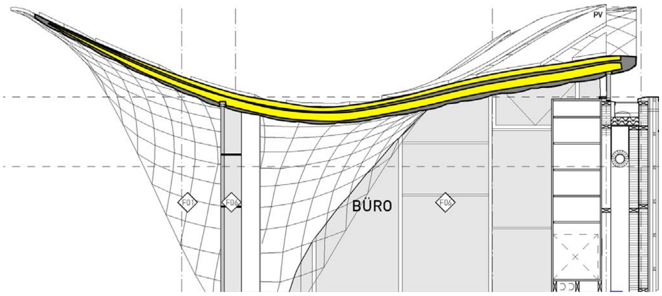

Fig. 10. The final sandwich shell roof evaluated during the final design phase.

The sandwich roof has a total concrete thickness (combined thickness of the upper and lower shells) varying between 3 and 30 cm, 8 cm on average, and spans in the range of 6–9 m. The total weight is 29 metric tons. The shell is supported on five 'touchdown' points and has free edges along its entire perimeter.

The shell is anticlastic (negative double curvature). This is a necessary construction constraint, as the shell will be constructed on a prestressed flexible formwork (Section 4.2.2) which is inherently anticlastic. As a result, the shell will locally act in bending and needs to be reinforced. An advantage of anticlastic shells is a lower sensitivity to imperfections. The differences in temperature and humidity on either side of the PU core lead to higher thermal loads and differential strains due to creep and shrinkage. The thermal actions have an immediate effect on the short-term behaviour of the shell, which acts restrained due to the shell's stiffness, leading to microcracking from the outset on the outer shell. However, this improves load thermal action factors, suggesting it acts as a form of prestress. In addition, a range of concrete strengths and the influence of using ferrocement or textile-reinforced concrete was evaluated, to inform the detailed design phase, and development of the actual concrete mix.

To fully realise the structural efficiency of a flexibly formed shell, it is crucial to both design an optimal shell within the project's constraints and to control the cable forces such that its form, despite the formwork's flexibility and the weight of the wet concrete, is in the end exactly as required. A computational approach to realise this goal was developed [22]. The first part of this procedure applies a multi-criteria optimisation to find the geometry of the roof, and consists of the following steps:

1. Generate the shell's boundary conditions and internal topology of the cable-net;
2. Generate an anticlastic surface based on a given force distribution, as the basis for the shell's geometry;
3. Generate governing load combinations in the serviceability limit state (to check for allowable deflections);
4. Optimise the thickness of the shell, subject to allowable deflections and yield strength of the material; and,
5. Evaluate, for each generated shape, the structural performance and several spatial criteria.

The roof was optimised in two rounds. Initially, a single-criterion optimisation (minimising mass subject to stress and deflection constraints), to study different boundary conditions (positions and number of supports as well as roof height) while evaluating various structural parameters. The amount of glazing and solar radiation was also measured. Based on this analysis, a multi-criteria optimisation was developed for the final design.

The four criteria optimised were internal elastic energy (proportional to mass), buckling load factor (lowest, positive value), deviation of the formwork to target shape, and surface area of glazing (Fig. 11). A fifth measure of the amount of head clearance below the roof was also calculated to compare results. Each optimisation consisted of about 100

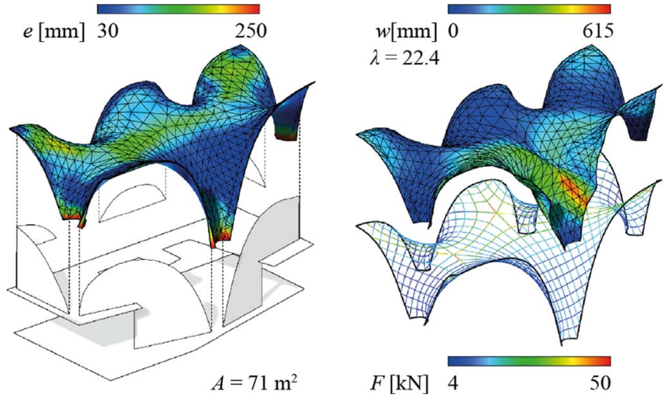

Fig. 11. Four criteria (clockwise from top left): elastic energy, buckling load factor λ for quasi-permanent load combination, cable-net deviations, and surface area A of clear glazing.

generations of 100 roof geometries (i.e. having evaluated 10,000 potential roof shapes).

The result from the optimisation phase was set as the target shape of the shell. This fed into a more advanced structural analysis, as a check on the optimised shape. The nonlinear finite element analysis included modelling the actual sandwich buildup, and some additional effects:

1. Geometric nonlinearity according to third order theory, accounting for snap through and post-buckling behaviour;
2. Material nonlinearity to introduce concrete cracking and plastic/ductile behaviour of both the concrete and its reinforcement;
3. Creep and shinkage that causes concrete deformations over time; and,
4. Limit load iterations, to evaluate the structure's capacity beyond the ultimate limit state.

The reinforced concrete was modelled as a C90/105 with B500A according to Swiss code SIA 262 [23] with corresponding yield strengths, but a parametric study was carried out as well for a range between C35 and C90 concrete, and for AR-glass and carbon fibre TRC, to inform the detailed engineering phase. Properties for TRC were taken from [24,25], with yield strengths calculated based on material factors for GFRP and CFRP [26]. The higher C90 concrete strength was mainly chosen based on the resulting creep and shrinkage behaviour according to code, and given previous experience with viscous and fine concrete mixes, which exhibit high strength [27]. The steel type was chosen based on its similarity to that mentioned in the American code for ferrocement, ACI 549.1R-93 [28]. The mesh layers are 1 mm diameter, with 13 mm spacing, so 60 mm^2/m per direction, with up to 12 layers per concrete face. The high density PU is modelled based on linear elastic properties from suppliers: $E = 300\,\mathrm{MPa}$, $f_y = 20\,\mathrm{MPa}$, $\rho = 600\,\mathrm{kg/m}^3$.

The shell was checked against the following requirements. In SLS, allowable deflections for occasional live loads are 1/500th of the span L, i.e. 18 mm for the shell, and 1/300th of twice a cantilever, i.e. 60 mm for the cantilevering slab supporting the shell at the front (according to Swiss code SIA 260 [29]). Deflections along the glass facade are chosen to be less than 10 mm. Crack width may not exceed 0.1 mm according to American code for ferrocement ACI 549R-97 [30]. In ULS, stresses should not exceed the material yield strengths and buckling with decreasing post-buckling capacity may not occur. In a load stepping calculation according to 1979 IASS recommendations [31] for concrete shells, a limit load of at least 1.75 the SLS load combinations should be reached.

4.2.2. *Construction system*

Shell structures have become rare as they are challenging to construct, traditionally requiring full and generally rigid formworks, which are both material and labour-intensive. The materials are often used only once, since they are customised for a specific doubly curved geometry. Due to the amount of work involved, these structures are generally not competitive in a contemporary building environment where labour is expensive such as Switzerland.

A highly efficient, reusable and lightweight flexible formwork system allows the reintroduction of efficient, doubly curved, thin shell roof structures without the typically associated high labour and resource investments. It has allowed us to reduce the amount of material, especially in relation to the falsework (scaffolding). In this case, the shuttering is replaced by a fabric and the falsework is replaced by cables which are supported by an external frame at its boundaries.

The formwork system offers a degree of control over the anticlastic shape, through non-uniform prestressing of the cable-net, such that it can be easily optimised for improved structural behaviour and other criteria compared to traditional geometries. In particular, an inverse optimisation was applied to determine the non-uniform prestresses in the final state, after deflection and under load of the wet concrete. From this, the initial prestressed state can be calculated, which represents the non-uniform pre-camber necessary beforehand, to obtain the optimised geometry after loading.

The first cable-net and fabric formwork prototype had dimensions of 1.8 × 1.8 × 1.2 m and was built to produce two prototype concrete shell structures [9]. The first shell had two main objectives. First, to establish, as a proof of concept, a complete workflow for the structural design of an anticlastic thin concrete shell taking into account the fabrication constraints of a hybrid cable-net and fabric formwork. Second, to construct a prototype shell based on this workflow in order to identify challenges in both computational and constructional aspects.

The second prototype was used to prove that the formwork system is able to control the final geometry within a tolerance of ± 5 mm. The main objective was to improve the control of the geometry through measurements of force and more accurate measurement of the geometry. By doing so, it was possible to demonstrate average tolerances as low as 1.3 mm for a 2.6 m span, so 1/2000th of the span (Figs. 12 and 13) [32].

4.2.3. *Building systems integration*

The roof shell integrates multiple functions besides the structure (Fig. 14). First, it is a thermally active system (TABS) due to the embedded hydronic pipework. This provides heating and cooling to the main living space through the concrete radiant surface at ceiling level. The large surface area of the shell is utilised to achieve low temperatures for heating and high temperatures for cooling, therefore reducing the amount of exergy required for heating purposes [33]. This is delivered efficiently by the district geothermal heat sources from the NEST backbone. Second, flexible thin-film CIGS (copper indium gallium

Fig. 12. The second prototype showing the timber frame and the prestressed cable net.

Fig. 13. This is the second prototype constructed at ETH Zurich for the HiLo project. It was used to demonstrate low construction tolerances.

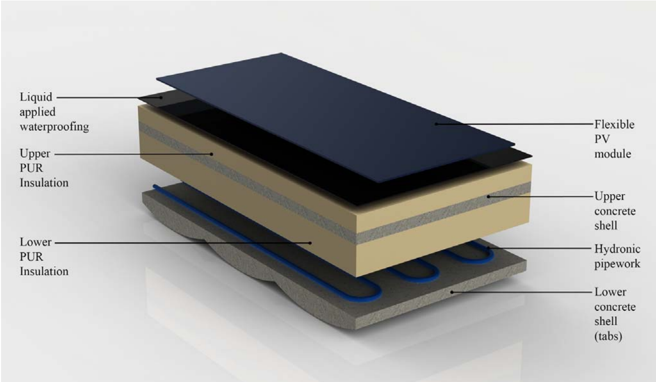

Fig. 14. Exploded view of the thin shell roof, the hydronic pipework, insulation layers and PV module.

selenide) photovoltaic panels are integrated with the concrete shell, a surface with complex geometry to demonstrate the utilisation of non-typical building envelopes as a resource for local renewable energy harvesting during the building lifecycle [34,35].

Thermal edge losses at the roof and the glass facade interface was one of the main drivers of the development of the sandwich shell. A CFD model was used to support the design and evaluate the impact on overall energy performance of HiLo. In addition, the TABS performance at ceiling level was also estimated using a CFD model. The model contained a parameter analysis, which included pipe spacing and the physical properties of the key materials. A discussion on the modelling process is provided in [8,34].

In relation to the roof PV panels, a parametric study has been performed analysing solar irradiation and other important design parameters (such as bending radius) as a function of panel orientation and PV module size [36,37]. The analysis showed that panel orientation has a significant impact on the effective PV surface area that can be installed on the roof, but a minor influence on the area specific insolation. As shown in Fig. 15, an orientation of 30° relative to the NEST building achieves the highest amount of active photovoltaic module area and provides an agreeable visual appearance.

4.3. Adaptive solar facade

A building facade is the boundary between two climatic conditions, the exterior and the interior. Thus, it acts as an interface and needs to respond to changing weather and occupant desires. For HiLo, an Adaptive Solar Facade (ASF) will be employed to provide a more flexible and responsive interface using a novel system currently under research and development [38]. As a result the facade will continually change, providing in a dynamic and temporal experience that animates a key urban corner of the NEST project throughout the day and night.

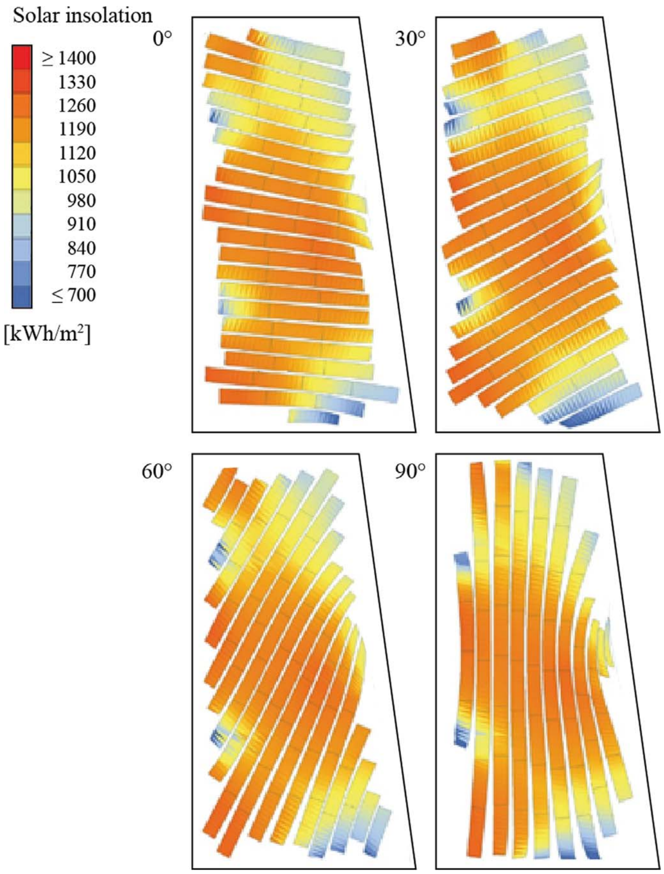

Fig. 15. PV module layout and annual solar irradiance on the HiLo roof for different strip orientations.

The two ASF's are located in front of the windows of the two bedrooms. This provides a strong interaction with the inhabitants, which allows testing between the four system imperatives: energy production, passive energy control (daylighting, solar ingress), occupant privacy and occupant views.

In addition, locating the two adaptive solar installations on facades with significantly different orientations, allows for a comprehensive assessment of the system capacity.

4.3.1. Solar shading and photovoltaic cells

Building shading systems have an important role in architecture, simultaneously influencing building appearance, building energy performance, and occupant comfort. Shading systems can control solar insolation, thereby offering reductions in heating/cooling loads, as well as modulate daylighting levels, hence offering reduction in artificial lighting energy. Architectural responses to this range from traditional shutters to automated shading systems.

In recent years, due to an increase in the availability of decentralised electricity generation technologies, such as photovoltaic (PV) cells, many architects have successfully integrated these systems into buildings to further improve energy performance. PV cells have been used in external building walls, as semi-transparent facades, or in skylight structures. Moreover, due to an increase in the use of large window openings and curtain walls in today's architecture, there is a growing need for integrating PV elements into shading systems [39,35].

The HiLo adaptive solar envelope consists of movable modular elements (Fig. 16), which provides solar energy generation, shading as well as controlling the opacity and transparency of the facade [37]. The

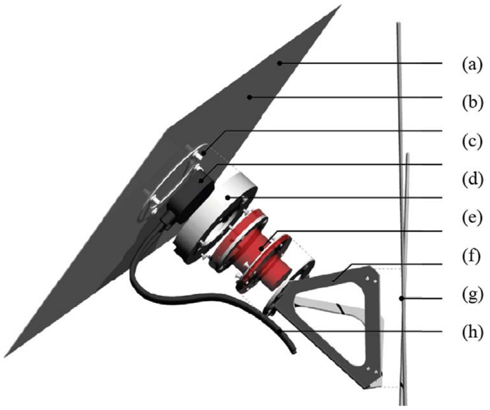

Fig. 16. Exploded view of the ASF element with (a) photovoltaic panel, (b) panel adapter, (c) junction box, (d) electronic shield, (e) soft pneumatic actuator, (f) cantilever, (g) cable-net structure, and (h) PV power cables.

different modes of the modules are controlled based on sensor as well as on occupant input.

A proof of concept prototype was constructed on the House of Natural Resources Building (HoNR) at the ETH Hönggerberg campus in Zurich (Fig. 17). This provided valuable feedback on system performance [35] and the construction detailing of the innovation.

The Adaptive Solar Facade employs soft pneumatic actuators [39,40,41–43] to individually rotate the facade modules (400 × 400 mm) according to the demand. The elements provide solar energy generation, shading as well as controlling the opacity (privacy) and transparency (views) of the facade. In correspondence to changes to the outside environment and demands of the interior and the occupants, the elements can rotate to provide the desired functionality. Fig. 18 presents a prototype of the soft pneumatic actuator developed for application within the adaptive solar facade. The actuators contain three inflatable chambers and are capable of orienting a PV cell in two degrees of freedom. Using an updated design of the actuator, it is possible to achieve fully open and closed facade states.

4.4. Occupant-centred control

Building automation considers the control of recurring equipment activities based on occupancy demand and weather conditions. Typical examples are maintaining the set points for HVAC systems, lighting, appliances, and security systems. The objectives of building automation are improved occupant comfort, a reduction in energy consumption, and a reduction in operation and maintenance costs. Well established for commercial buildings, currently there is a trend of moving these types of automation systems into the household, where traditionally the heating thermostat was the only automation element.

The reasons for this trend are the availability of affordable small scale computing power (e.g. Arduino & Raspberry Pi) and low power wireless sensor networks (e.g. Z-Wave & ZigBee), which has led to an explosion of do-it-yourself (DIY) home automation systems. The market for commercial building automation systems is rather saturated and this is encouraging suppliers (Siemens, ABB & Honeywell) to enter the new market of home automation. In addition, many novel companies emerge exclusively targeting the home automation market; examples are Aizo/digitalStrom, Adhoco, EnOcean and Insteon. Some of these companies have joined alliances, such as Z-Wave Alliance, ZigBee Alliance, and Qivicon, to collaborate on cross vendor home automation solutions.

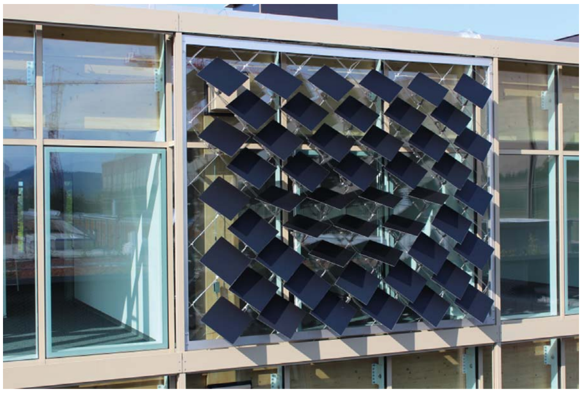

Fig. 17. Proof of concept prototype on the HoNR building.

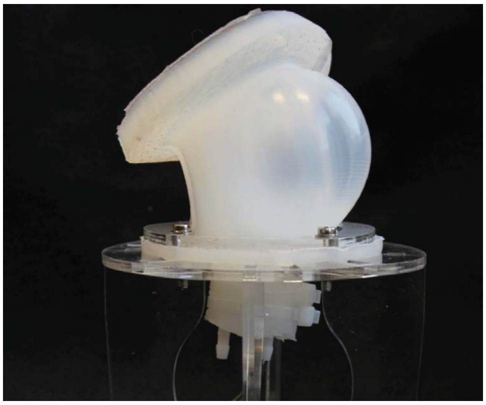

Fig. 18. Prototype of the soft pneumatic actuator.

Nonetheless, large-scale success of home automation has so far not been achieved, it remains merely in the realm of DIY systems. One possible reason is that currently available solutions in today's building automation industry have been designed with the aim to solve a conventional building control problem: minimisation of energy consumption, while keeping the occupant comfort within the standard range [44].

The occupant centred control (OCC) approach changes this focus to achieving comfort specifically tailored to individual occupants, while maximising the energy efficiency [45]. The OCC, therefore, can be defined as a learning-based building control that detects occupant-building interaction, learns the occupant's comfort needs, and automatically adapts building services to these requirements. This control strategy reduces the need for occupant's actions, achieves a level of comfort specifically tailored to the occupant, and further improves energy savings compared to conventional building control strategies.

This is illustrated by a lighting control study, where the control system was able to learn occupant specific illuminance levels in each office, based only on detection of the occupants using standard light switches. After the learning phase, the control system was able to automatically provide the desired illuminance levels, without further action from the occupant. During a 6-week study in 10 offices, energy savings of 37.9% and 73.2% compared to a standard setting control baseline and a worst-case scenario were achieved respectively [46,47].

In HiLo, a home automation system will be implemented to enable research in the domain of occupant centred control (Fig. 19). This home automation system will connect to all building services and will be capable of steering the functionality of each component. Therefore, it will allow researchers to manage experiments during the operation phase of HiLo.

The home automation system will permit the following tasks:

1. Actively monitor the indoor and outdoor climate parameters and occupant-building interaction;
2. Execute control algorithms on a central computer; and,
3. Send set point values to the building services.

In terms of the ASF, the home automation system will allow

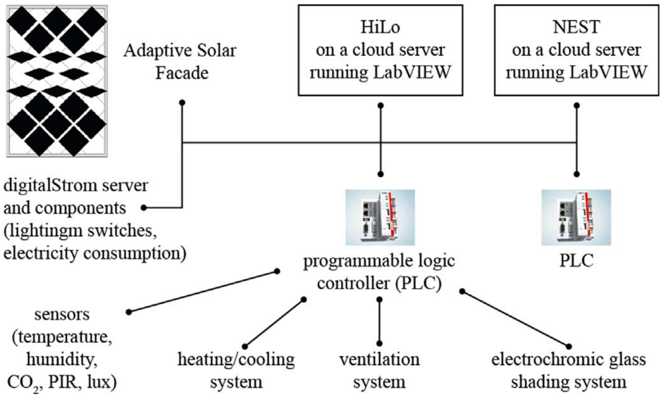

Fig. 19. A possible realisation of HiLo Home Automation system.

monitoring of the facade performance, e.g. its influence on the operation of other building services, on the overall building energy efficiency, as well as on the occupants' comfort, in real-world scenarios.

The HiLo apartment guests will be part of the experiments and their feedback will be taken into account in building control algorithms. The HiLo home automation system should be able to non-intrusively monitor the occupant's location and the occupant's interaction with building systems, such as adjustments of cooling/heating set points and lighting levels.

It will be possible to test, evaluate, and improve building control algorithms with different occupants in real-world scenarios, leading to results that are directly applicable to the building automation industry.

5. Discussion and future work

As the funicular floor system has a significantly lower mass when compared to traditional concrete floors, the sound insulation capabilities of the system are to be further studied. In this regard, the floor possesses an interesting advantage that can be exploited, it's stiffness. Numerical experiments have shown that the double curvature of the vault, as well as the fins, provide a significant amount of stiffness given sound insulation in the lower frequency range [48]. These results are in agreement with previous research [49–51]. The low frequencies are the most problematic for lightweight building components.

The fire safety of the funicular floor system used in HiLo is guaranteed by a set of emergency sprinklers. However, the thinness of the floor concrete elements leave it vulnerable to spalling. Further research on this issue should be conducted.

The fabrication method for the floor is a double sided mould, following the successful completion of the first full-scale prototype (Fig. 5). However, flexible and bespoke prefabrication solutions are being developed for the floor, which would allow mass-customisation.

The thin concrete shell and the funicular floor are integrated with TABS. At the concept stage, simulation was used to estimate thermal performance based on design data. Experimental verification and characterisation will be completed during the operational phase of HiLo. This will serve as a basis for operational optimisation as well as aiding future developments for highly efficient and integrated components.

HiLo will be used as a ‘living laboratory’ and a building space where occupants' locations and needs for comfort are detected and used for control of building services. Once the apartment receives its first residents, performance of the control system can be monitored, verified and improved. Besides the control of standard building services, we will explore the effects the adaptive solar facade has on occupants' comfort and the effects it has on the building energy balance.

6. Conclusions

HiLo seeks to address many challenges related to the building industry at large, including most prominently the issue of energy consumption and production, and the drastic reduction of materials required to build. The energy concept of HiLo targets zero GHG emissions and net-plus energy in operation, simultaneously exploring lightweight structural systems. This was achieved by employing an integrated design approach that identified and analysed the key parameters of each discipline at an early phase.

The floor system represents the most dramatic material savings within a project whose stated goal is the severe reduction of required materials. Through its funicular form, this structural system, cast in concrete, achieves a thickness of only 20 mm for both the vault and fins. This saves a significant volume of concrete material and weight compared to traditional concrete floor slabs used in the construction of frame buildings.

The roof goes beyond a shell with a singular function to simply span or cover, to create instead a shell that is at once a structure and a facade. Its shape is heavily optimised to push the limits of what is possible in concrete.

The structural optimisation that achieves very light concrete structures, presents an opportunity for low energy active cooling and heating system. This paper presents how this opportunity is being addressed in two integrated building components.

The adaptive solar facade consists of movable modular elements that are mounted curtain-like in front of the facade, employing novel soft pneumatic actuators. The elements provide solar energy generation, shading as well as controlling the opacity (privacy) and transparency (views) of the facade.

All of the systems for interior climatisation as well as energy harvesting are controlled by a building automation system to optimally balance between energy efficiency and user preferences, taking into account available renewable energy, both from the building and the district backbone. Adaptive learning algorithms facilitate the continuous improvement of the behaviour and thus the adaptation of the building systems to their users and environments.

The innovations of HiLo will be implemented within the NEST demonstration platform. This provides for the testing and development of these new ideas under real-life conditions and within a relatively short timeframe from inception. It is expected that the precise synergy of building systems, structure and high quality architectural design will show that HiLo delivers on its name and ambition: High performance, Low energy.

7. Core design team and acknowledgements

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References

[1] UNEP, Buildings and Climate Change, UNEP DTIE Sustainable Consumption and Production Branch, 15 Rue de Milan, 75009 Paris, France, 2013.

[2] I. Sartori, A. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: a review article, Energy Build. 39 (3) (2007) 249–257.

[3] L. Prez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (3) (2008) 394–398.

[4] D. D'Agostino, Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States, J. Build. Eng. 1 (2015) 20–32.

[5] M. Hübler, A. Löschel, The EU decarbonisation roadmap 2050 – what way to walk? Energy Policy 55 (2013) 190–207.

[6] S. Sorrell, Making the link climate policy and the reform of the UK construction industry, Energy Policy 31 (9) (2003) 865–878.

[7] S.C. Kaethner, J.A. Burridge, Embodied CO$_2$ of structural frames, Struct. Eng. 90 (5) (2012) 33–40.

[8] G. Lydon, J. Hofer, B. Svetozarevic, Z. Nagy, A. Schlueter, Coupling energy systems with lightweight structures for a net plus energy building, Appl. Energy 189 (2017) 310–326.

[9] D. Veenendaal, P. Block, Design process for a prototype concrete shells using a hybrid cable-net and fabric formwork, Eng. Struct. 75 (2014) 39–50.

[10] D. López López, D. Veenendaal, M. Akbarzadeh, P. Block, Prototype of an ultra-thin, concrete vaulted floor system, in: Proceedings of the IASS-SLTE 2014 Symposium, Brasilia, Brazil, 2014.

[11] NEST, The nest project website, 2015. ⟨http://nest.empa.ch/en/⟩ (Accessed 21 September 2015).

[12] HiLo, The hilo project website, 2015. ⟨http://hilo.arch.ethz.ch/⟩ (Accessed 21 September 2015).

[13] L. Davis, P. Block, Earthen masonry vaulting – mexican and catalan techniques, in: D. Hebel, M. Moges (Eds.), SUDU - the Sustainable Urban Dwelling Unit, Ruby Press, Berlin, 2015.

[14] J. Ochsendorf, Guastavino Vaulting, the Art of Structural Tile, Princeton Architectural Press, New York, 2010.

[15] M. Ramage, J. Ochsendorf, P. Rich, J. Bellamy, P. Block, Design and construction of the mapungubwe national park interpretive centre, south africa, J. Afr. Technol. Dev. Forum (ATDF) 7 (1) (2010) 14–23.

[16] P. Block, Thrust Network Analysis: Exploring Three-Dimensional Analysis (Ph.D. thesis), Massachusetts Institute of Technology, Cambridge, MA, USA, 2009.

[17] T. Van Mele, D. Panozzo, O. Sorkine-Hornung, P. Block, Best-fit thrust network analysis – rationalization of freeform meshes, in: S. Adriaenssens, P. Block, D. Veenendaal, C. Williams (Eds.), Shell Structures for Architecture: Form Finding and Optimization, Routledge, London, 2014.

[18] A. Liew, D. López López, T. Van Mele, P. Block, Design, fabrication and testing of a prototype, thin-vaulted, unreinforced concrete floor, Eng. Struct. 137 (2017) 323–335.

[19] K.-N. Rhee, B.W. Olesen, K.W. Kim, Ten questions about radiant heating and cooling systems, Build. Environ. 112 (2017) 367–381.

[20] G. Lydon, J. Hofer, Z. Nagy, A. Schlueter, High-resolution analysis for the development of tabs in lightweight structures, in: IBPSA Building Simulation 2017, San Francisco, USA, 2017.

[21] G. Lydon, J. Hofer, Z. Nagy, A. Schlueter, Thermal analysis of a multifunctional floor element, in: IBPSA Building Simulation and Optimization 2016, Newcastle, UK, 2016.

[22] D. Veenendaal, J. Bakker, P. Block, Structural design of the cable-net and fabric formed, ferrocement sandwich shell roof of nest hilo, in: Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, Amsterdam, Netherlands, 2015.

[23] SIA, SIA 262:2003 Concrete Structures., Swiss Society of Engineers and Architects, Zurich, 2004.

[24] J. Hegger, M. Horstmann, S. Voss, N. Will, Investigations on the bearing behaviour and application potential of textile reinforced concrete, Eng. Struct. 30 (2008) 2050–2056.

[25] J. Hegger, M. Horstmann, S. Voss, N. Will, Textilbewehrter beton - tragverhalten, bemessung und anwendung, Beton Stahlbetonbau 102 (6) (2007) 362–370.

[26] fib Bulletin No. 14. Externally bonded FRP reinforcement for RC structures, 2001.

[27] D. Veenendaal, P. Block, Design process for a prototype concrete shells using a hybrid cable-net and fabric formwork, Eng. Struct. 75 (2014) 39–50, http://dx.doi.org/10.1016/j.engstruct.2014.05.036.

[28] ACI, ACI 549.1R-93 [Reapproved 2009], Guide for the Design, Construction, and Repair of Ferrocement, American Concrete Institute, 1993.

[29] SIA, SIA 260:2003 Basis of Structural Design, Swiss Society of Engineers and Architects, Zurich, 2004.

[30] ACI, ACI 549R-97 [Reapproved 2009], Report on Ferrocement, American Concrete Institute, 1997.

[31] S.J. Medwadowski, H.A.M., G.K. Khaidukov, L. Kollár, K. Herbert, A. Paduart, E.P. Popov, F. del Pozo, H. Rühle, A. Sanmartin Q., A.C. Scordelis, IASS Recommendations for Reinforced Concrete Shells and Folded Plates, International Association for Shells and Spatial Structures, 1979.

[32] D. Veenendaal, M. Bezbradica, D. Novak, P. Block, Controlling the geometry and forces of hybrid cable-net and fabric formworks, in: Proceedings of the IASS-SLTE 2014 Symposium, Brasilia, Brazil, 2014.

[33] A. Schlueter, F. Thesseling, Building information model based energy/exergy performance assessment in early design stages, Autom. Constr. 18 (2) (2009) 153–163.

[34] G. Lydon, A. Willmann, J. Hofer, Z. Nagy, A. Schlueter, Balancing operational and embodied emissions for the energy concept of an experimental research and living unit, in: CISBAT – Future Buildings and Districts From Nano to Urban Scale, Lausanne, Switzerland, 2015.

[35] J. Hofer, A. Groenewolt, P. Jayathissa, Z. Nagy, A. Schlueter, Parametric analysis and systems design of dynamic photovoltaic shading modules, Energy Sci. Eng. 4 (2) (2016) 134–152.

[36] A. Groenewolt, J. Bakker, J. Hofer, Z. Nagy, A. Schlüter, Methods for modelling and analysis of bendable photovoltaic modules on irregularly curved surfaces, Int. J. Energy Environ. Eng. 7 (3) (2016) 261–271.

[37] P. Jayathissa, J. Schmidli, J. Hofer, A. Schlueter, Energy Performance of PVModules as Adaptive Building Shading Systems, in: EU PVSEC 2016: Proceedings, WIP Wirtschaft und Infrastruktur GmbH & Co Planungs KG, Munich, 2016, pp. 2513–2517.

[38] Z. Nagy, B. Svetozarevic, P. Jayathissa, M. Begle, J. Hofer, G. Lydon, A. Willmann, A. Schlueter, The adaptive solar facade: from concept to prototypes, Front. Archit. Res. 5 (2) (2016) 143–156.

[39] D. Rossi, Z. Nagy, A. Schlueter, Adaptive distributed robotics for environmental performance, occupant comfort and architectural expression, Int. J. Archit. Comput. 10 (3) (2012) 341–360.

[40] B. Svetozarevic, Z. Nagy, D. Rossi, A. Schlueter, Experimental Characterization of a 2-DOF Soft Robotic Platform for Architectural Applications, in: Robotics: Science and Systems, Workshop on Advances on Soft Robotics (RSS 2014), Berkeley, CA, USA, 2014.

[41] P. Jayathissa, Z. Nagy, N. Offedu, A. Schlueter, Numerical simulation of energy performance, and construction of the adaptive solar facade, in: Advanced Building Skins, Graz, Austria, 2015.

[42] B. Svetozarevic, Z. Nagy, J. Hofer, D. Jacob, M. Begle, E. Chatzi, A. Schlueter, Sorotrack: A two-axis soft robotic platform for solar tracking and building-integrated photovoltaic applications, in: Proceedings of IEEE International Conference on Robotics and Automation (ICRA), 2016.

[43] P. Jayathissa, M. Luzzatto, J. Schmidli, J. Hofer, Z. Nagy, A. Schlueter, Optimising building net energy demandBuilding Net Energy Demand with Dynamic bipv, Shading, Appl. Energy 202 (2017) 726–735.

[44] A. Dounis, C. Caraiscos, Advanced control systems engineering for energy and comfort management in a building environment?A review, Renew. Sustain. Energy Rev. 13 (6–7) (2009) 1246–1261.

[45] Z. Nagy, M. Hazas, M. Frei, D. Rossi, A. Schlueter, Illuminating adaptive comfort: Dynamic lighting for the active occupant, in: Proceedings of the 8th Windsor Conference: Counting the Cost of Comfort in a Changing World, London, UK, 2014.

[46] Z. Nagy, F.Y. Yong, M. Frei, A. Schlueter, Occupant centered lighting control for comfort and energy efficient building operation, Energy Build. 94 (2015) 100–108.

[47] Z. Nagy, F.Y. Yong, A. Schlueter, Occupant centered lighting control: a user study on balancing comfort, acceptance, and energy consumption, Energy Build. 126 (2016) 310–322.

[48] T. Méndez Echenagucia, N. Roozen, P. Block, Minimization of sound radiation in doubly curved shell structures by means of stiffness, in: Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2016, Tokyo, Japan, 2016.

[49] P. Joshi, S. Mulani, S. Gurav, R. Kapania, Design optimization for minimum sound radiation from point-excited curvilinearly stiffened panel, J. Aircr. (2010) 1100–1110.

[50] P. Joshi, S. Mulani, R. Kapania, Multi-objective vibro-acoustic optimization of stiffened panels, Struct. Multidiscip. Optim. 51 (2015) 835–848.

[51] C. Ng, C. Hui, Low-frequency sound insulation using stiffness control with honeycomb panels, Appl. Acoust. 69 (4) (2008) 293–301.