BALANCING OPERATIONAL AND EMBODIED EMISSIONS FOR THE ENERGY CONCEPT OF AN EXPERIMENTAL RESEARCH AND LIVING UNIT

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ABSTRACT

In a European context, energy standards in the built environment have made a valuable contribution to the sustainability of the industry over the past twenty years. The current cycle focuses predominantly on the thermal properties of the building envelope. As space heating and cooling with domestic water heating currently accounts for 60% of global energy consumption in buildings, this aspect will remain a key mechanism for building energy improvements. When considering 2050 energy targets, significant energy efficiency improvements will be required for new and renovated buildings in the next 5 – 10 years.

This research investigates the constraints placed on modern architecture by the influence of building energy regulation in the context of the HiLo module at NEST. Current building regulations are encouraging a convergence towards heavily insulated enclosures with minimised glazing, with the key design parameter being geometrical compactness. This assumes that the operational energy costs outweigh the costs of the embodied energy in the building materials and the construction process. As the building energy codes become increasingly severe for building designers, it is essential that innovation is central to architecture and regulatory assessment procedures become more sophisticated.

The goal of the HiLo module is to investigate if sustainable design related the total building lifecycle (BLC), rather than solely determined by an operational energy saving approach, will enhance architecturally and structurally challenging projects. This paper highlights the importance of the adaption of an early stage integrated design approach. In addition, it will demonstrate that considering the BLC will lead to more advanced sustainability focused outcomes for the built environment, without placing overbearing restrictions on architecture.

Keywords: Embodied Energy, Buildings, Integrated Design, Building Lifecycle.

1. INTRODUCTION

NEST (Next Evolution in Sustainable Building Technologies) is a district scale project by Empa and Eawag in partnership with the ETH Domain, to demonstrate innovation in the built environment [1]. NEST provides a basic infrastructure and access to an advanced ground source geothermal system, in the form of the backbone which, can accept up to fifteen modular buildings. This creates a unique setting for academic groups and innovative companies to implement research under real-world conditions. NEST serves as an interactive demonstration and research facility for the design of sustainable buildings and districts.

As one of the first NEST modules, HiLo utilises innovative design elements, specifications, materials, construction schemes and control systems which are informed by the principles of sustainable development [2]. The key objective of HiLo is to demonstrate that an integrated design process, which considers the lowering of both embodied and operational energy allows for sustainable design solutions without severe architectural compromises. Further, HiLo exhibits innovation in the domains of building energy efficiency and structural design while fostering a unique architectural expression.

Figure 1: Rendering of the exterior of the HiLo module.

HiLo is planned as an energy-plus module in operation phase and will be equipped with sensors providing a stream of thermal, lighting, energy consumption and external environment data. HiLo is currently at an advanced design phase, and is due to commence construction in early 2016.

The total building lifecycle energy consists of operational and embodied energy. Embodied energy considers the contribution during the construction, demolition and disposal phases (direct), which includes the production of materials (indirect). The operational energy is related to the use of the building, including heating, cooling, lighting and equipment [3].

Embodied energy has traditionally been neglected from the energy analysis of buildings. However, as recent improvements in the energy performance of buildings have been focused on operational energy (i.e. insulation, heat recovery ventilation), the proportion of embodied energy relative to operational energy has become more significant.

This paper introduces and discusses the energy concept of HiLo, in particular, the influence of the design of the thin concrete shell roof, as it offers the clearest example of balancing the operational performance with the embodied energy.

2. BACKGROUND

HiLo is headed jointly by the Chair of Architecture and Building Systems (A/S) and the BLOCK Research Group (BRG) at the Institute of Technology in Architecture at ETH Zurich. The academic leaders are supported by Supermanoeuvre Architects of Sydney, Australia and ZJA Zwarts & Jansma Architects of Amsterdam, Netherlands. This core team has developed the concept and building permit design phases for the project by respecting the dual brief of delivering a building, which confirms to current Swiss construction regulations and a project which will provide five years of operational phase research.

HiLo exhibits four core innovations:

- Integrated, thin shell roof [3,4]
- Funicular floor system [5]
- Adaptive solar facade [6]
- Occupant centred control [7].

The HiLo innovations are led by domain experts with involvement from associated disciplines. As buildings have a relatively long lifecycle, an integrated approach is seen a promising method of moving the construction industry towards 2050 energy targets [8].

Integrated design provides a platform to examine interdisciplinary early stage energy concepts and allows the full potential of energy savings to be realised over the building lifecycle (BLC). A simple example of the integrated approach is the adaption of a single CAD software system by the structural, energy and architecture core team members. The CAD platform is linked directly to the advanced analysis software used by each domain. This provided a method for the easy exchange of concepts and results, despite the complexity of the geometry. This integrated approach is used to develop outcomes, which are relevant in the context of the built environment and not limited to a laboratory setting.

3. INTEGRATED, THIN SHELL ROOF

The thin shell roof has been numerically optimised to deliver a highly efficient structural element [4]. This efficiency is translated into an architecturally elegant form through the use of the touchdown points (the connection locations from the roof to the main structure, see Figures 1 and 4). The improvement in structural performance reduces the overall volume of concrete by up to two-thirds compared to a typical concrete roof section (Figure 3). The shell roof is cast by a reusable and lightweight cable-net and fabric formwork system, which is expected to have less environmental impact compared to a standard method.

In order to visually highlight the structural efficiency of the shell roof, a key part of the design brief is to provide a highly glazed facade (Figure 1). The integrated approach considering all aspects in an early stage, allowed for the provision of the large glazed facade, while complying with the Swiss regulations.

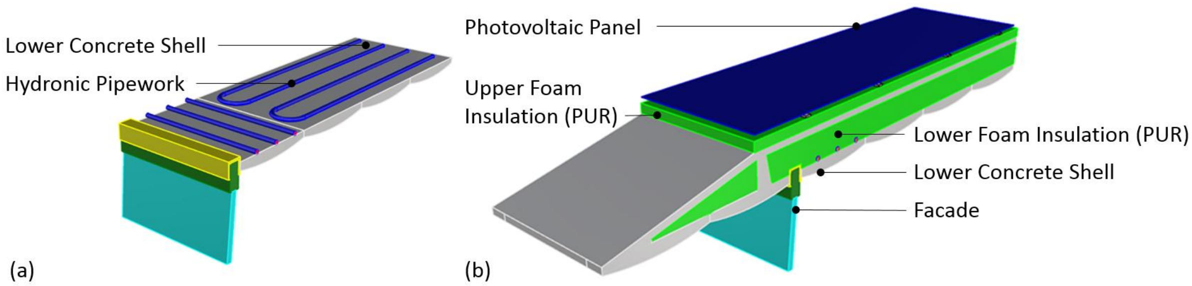

Figure 2: Integrated, thin composite shell roof, (a) Cutaway View (b) Isometric View.

The roof shell integrates multiple functions besides the structure. First, it is a thermally active element due to the integrated hydronic pipework (Figure 2a). This provides heating and cooling through the thin concrete radiant panel at ceiling level. Second, photovoltaic panels are integrated with the concrete shell (Figure 2b), on surfaces with complex geometry to utilise non-typical building envelopes as a resource for local renewable energy harvesting during the BLC.

Due to the shape and the materials, the roof offers further benefits, e.g. thermal mass. Thermal mass refers to the use of the internal materials of the building to absorb internal or solar heat gains, this process dampens internal air temperature fluctuations. As the exposed internal concrete shell constitutes a significant thermal mass resource, which is ideally distributed at ceiling level over the entire main space, it is engaged with a mixed ventilation strategy in the management of solar gains during the summer period. The natural component of the ventilation system is aided by the roof shape, which was optimised for a range of parameters during the current design phase. For example, the combination of a head height parameter and a glazing reduction parameter, resulted in a roof shape, which funnels air by buoyancy or cross ventilation to five boundary points at which facade openings are applied.

In terms of energy compliance, the negative features, such as the highly glazed facade are captured by the standards. However, the main beneficial features of the roof are not fully accounted for in the standards, when compared to a typical method of roof construction (see Figures 3a and 3b). These benefits include a reduction of the carbon emissions in the roof shell (see Figure 3c) and the application of the PV panels onto building elements with complex geometry. This is a limitation of the current regulations, which does not clearly encourage innovation and may need to be remedied if buildings are to be correctly assessed for energy performance over the BLC.

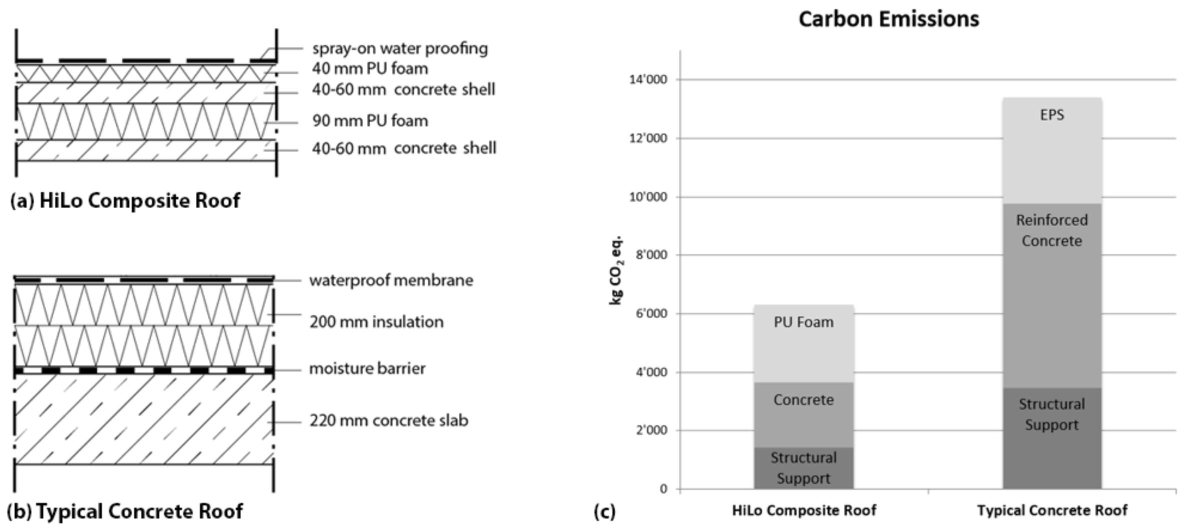

Figure 3: Carbon Emissions of the structural components of the HiLo Composite Roof and a Typical Concrete Roof.

The design of the integrated roof element has undergone many design iterations, driven by structural, thermal and aesthetic constraints. In terms of thermal performance, the key transition was the change from a single shell to the current composite shell. The energy related design constraints, which influenced this decision, are discussed in the next section.

4. ENERGY DESIGN OF THE SHELL ROOF

One of the main design strategies of the HiLo module is the extraction of the maximum potential from the building elements while considering the embodied energy contribution to the building lifecycle. The embodied energy analysis advises the design process, but this factor does not govern the final decisions. A balanced approach is employed by not just examining the material performance by volume, but also assessing the contribution of the material to a range of tasks. As a demonstration, this section discusses the integrated design process on the example of the roof shell.

As the roof shell is important in terms of the project research and forms a key component of the innovation strategy, it is preferred that the lower surface of the shell is not directly insulated (as shown in Figure 4). Therefore, at the roof/facade interface, the lower edge surface of the shell is exposed internally and externally. The concrete shell is an active heating element and the total external heat transfer coefficient can be up to 25 W/m^2 K. It was likely that relatively high thermal losses would occur at this location, as the roof was a single shell and was insulated with a roll applied aerogel insulation at an early design stage.

Figure 4: Rendering of the Interior of the HiLo Module.

A numerical study of the single shell roof showed that the edge losses were in excess of the amount recommend in SIA 380/1. Due to the concrete element thickness and the related structural issues, traditional methods such as thermal breaks or concrete mixes with insulation pearls (expended polystyrene) could not be readily employed to insulate the concrete shell. This is especially true in regions with large overhangs.

In order to resolve the thermal loss issue at the roof/facade interface, the structural engineers (BRG) proposed a composite roof shell, which provided thermally separate internal and external shells. As the design evolved, it was noted, based on numerical analysis of the shell, that temperature differences of the external and internal concrete shell volumes would cause stress at the composite interface layers. In order to counteract these forces, it would be typical to add steel shear connections between the shells. This approach would further complicate the construction of the formwork system and the process of placing the concrete. From the energy perspective, the improvements in the thermal performance of the roof/facade interface would be significantly reduced by the shear connection thermal losses.

The solution involved replacing the roll based aerogel insulation material with a spray-on polyurethane rigid foam (PUR), which can transfer stresses between the upper and the lower shells. As PUR is comparable to aerogel insulation in terms of embodied energy [9], the main concern related to the additional embodied energy related to an on-site spray-on application and at disposal phase. In addition, strong safety precautions must be employed during application due to respiratory hazards.

A CFD study of the single shell and the composite shell showed that the latter was superior in terms of thermal edge losses. In addition to the embodied energy contribution, the structural performance, simplification of the construction and the reduction the thermal losses (of the shell edge and the exclusion of the shear connection) during the operation phase were used to reach the final decision. These main three benefits outweighed the increase in embodied energy associated the composite shell with PUR insulation. Also, the preliminary embodied energy calculations show that the current composite shell roof design is superior to a typical concrete roof section in terms of carbon emissions [11]. Figure 3 shows a comparison of the structural and insulation elements of the HiLo composite roof and a typical concrete roof.

5. CONCLUSION

The concept and building permit design phases of HiLo have shown that as building design becomes more sophisticated, the inclusion of an early stage integrated design approach is vital to maximising the energy efficiency potential over the BLC.

In addition, the already advanced Swiss building energy assessment regulations need to evolve to deal with new methods of construction and building materials. While it is difficult to capture every permutation of a building design in the form of a building regulation, further improvements to the standards will help to achieve the ambitious 2050 energy targets. In particular, regulations which encourage designers to optimise the required volumes of building materials while improving element durability, form and performance are needed.

As HiLo develops during the next phases, high resolution numerical analysis will be carried out to quantify results at a research level. The research phase investigation will focus on the simulation of internal comfort parameters. These results will be calibrated over the initial operation phase of the building using an array of sensors. This analysis will be used to assess the quality of the standard design methods used at the concept and building permit phases.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Diederik Veenendaal of the BLOCK Research Group, Agnes Weilandt of Bollinger and Grohmann GmbH, the NEST team at Empa, the Kanton of Zurich, the Swiss Federal Office of Energy (BFE) and the various consultants involved in the project. Funding from Climate-KIC through the building accelerator (BTA) program is gratefully acknowledged.

7. REFERENCES

1. Empa: NEST project website, http://nest.empa.ch/, 2015.
2. ETH Zurich: HiLo project website, http://hilo.arch.ethz.ch/, 2015.
3. Pargana, N. et al.: Comparative environmental life cycle assessment of thermal insulation materials of buildings. Energy and Buildings, 82, pp.466–481, 2014.
4. Veenendaal, D. & Block, P.: Design process for prototype concrete shells using a hybrid cable-net and fabric formwork. Engineering Structures, 75(2014), pp.39–50, 2014.
5. López, D. et al.: Prototype of an ultra-thin, concrete vaulted floor system. Proceedings of the IASS-SLTE 2014 Symposium, 2014.
6. Rossi, D. et al.: Adaptive Distributed Robotics for Environmental Performance, Occupant Comfort and Architectural Expression. IJAC, 10(03), pp.341–360, 2011.
7. Nagy, Z. et al.: Occupant Centered Lighting Control for Comfort and Energy Efficient Building Operation. Energy and Buildings, 94, pp.100–108, 2015.
8. Sorrell, S.: Making the link: climate policy and the reform of the UK construction industry. Energy Policy, 31(9), pp.865–878, 2003.
9. Cuce, E. et al.: Toward aerogel based thermal superinsulation in buildings: A comprehensive review. Renewable & Sustainable Energy Reviews, 34, pp.273–299, 2014.
10. Swiss Society of Engineers and Architects (SIA): Swiss Standard SIA 2040: Effizienzpfad Energie (Path to Energy Efficiency), SIA, Zurich, 2011.