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Coupling energy systems with lightweight structures for a net plus energy building

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HIGHLIGHTS

- A case study of the design of multifunctional elements for a residential building.
- We introduce three novel multifunctional elements to a net plus energy building.
- We examine barriers to the design of low energy buildings during the early phase.
- We propose an integrated predesign phase for buildings with innovative systems.

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ABSTRACT

Future buildings will require significant performance improvements to adhere to greenhouse gas mitigation strategies. One method is to consider building components as multifunctional elements. These elements can perform several functions simultaneously, such as energy and structural aspects. As opposed to traditional sequential design in which each building element performs its own dedicated function. The former requires an integrated approach to prioritise the use of renewable energy sources and the reduction of materials. In this paper, we present three multifunctional elements: a lightweight shell roof, a funicular floor and an adaptive solar facade. We focus on the numerical simulation used to integrate thermally active building systems (TABS) and building integrated photovoltaics (BIPV) with lightweight structures. We outline a framework for the integration of the multifunctional element analysis with a dynamic building model and the performance factors of a district energy network. We exemplify the framework through the design of a real experimental building in Zurich, Switzerland. This delivered a net plus energy building (NPEB) with an annual weighted energy demand of 37.8 kW h/m^2 a and a weighted energy surplus of 45%. The results demonstrate the enhanced performance in terms of operational and embodied emissions.

1. Introduction

The European Union has set a 2050 target of an 80% reduction in greenhouse gas (GHG) emissions from 1990 levels [1]. To realise the transition from fossil fuels to renewable energy sources, extensive technical and economic feasibility studies have been completed on a national scale [2–4]. As part of this strategy, new approaches will be required to improve building energy efficiency and to incorporate energy generation from renewable sources. Further, it will be necessary to design and construct a high quantity of Net Zero Energy Buildings (NZEB) and Net Plus Energy Buildings (NPEB). Building energy targets have been defined in Article 9 of Directive 2010/31/EU, which specifies that all new construction should perform to a nearly NZEB metric after 2020 [5]. The building energy regulation is complimented by the 2009 Renewable Energy Sources Directive 2009/28/EC, which targets a 20% renewable energy share of gross final energy consumption by 2020 [6]. This implies that on-site energy generation will be a mandatory consideration for future buildings.

As a consequence of operational energy improvements, the embodied portion of building lifecycle (BLC) energy will become more relevant. A study of 60 European residential buildings found that the embodied energy portion for low energy buildings ranged from 9% to 46% [7,8]. Major factors for increases in embodied energy are the additional requirements for envelope insulation materials, advanced systems equipment and the associated maintenance work. Therefore with EU 2050 targets in mind, the delivery

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of lightweight structures and the selection of building materials will become key components of BLC energy design. One method is to consider building components as multifunctional elements. These elements can perform several functions simultaneously, such as energy and structural aspects. As opposed to traditional sequential design in which, each building element performs its own dedicated function. The former requires an integrated approach to prioritise the use of renewable energy sources and the reduction of materials. Advanced numerical methods are required to resolve performance issues, due to the reduction of conservative safety factors [9]. This delivers an enhanced element in terms of lifecycle emissions.

The contribution of this paper relates to three novel multifunctional elements: a lightweight shell roof, a funicular floor and an adaptive solar facade. We illustrate these elements as part of a real design of an experimental building. We report on the use of computational fluid dynamics (CFD) to develop thermally active building systems (TABS) with lightweight structural components. We outline methods for modelling the performance of on-site electricity generation using thin film PV modules on adaptive facade surfaces and a doubly curved roof surface. In addition, we outline a framework for the integration of the multifunctional element analysis with a dynamic building model and the performance factors of an electrical and thermal network at a district level. We quantify the results in terms of the modelled energy balance of the experimental building, which complies with current Swiss building regulations. As the innovation research team led the building project, insight is reported in terms of the design process for the development of multifunctional elements. This provides design guidance for the use of the method for real applications.

The paper is organised as follows: to emphasise the contribution of the paper, a review of existing research work is outlined in Section 2. In Section 3, the district systems and experimental building backgrounds are summarised. Section 4 discusses the numerical simulation of the multifunctional elements and the energy concept of the experimental building. Section 5 outlines a framework for integrating multifunctional analysis with a dynamic building simulation and district energy systems. Section 6 provides a discussion of the research outcomes and an outline of future work. Finally, in Section 7 the main conclusions are outlined.

2. Literature review

A high number of techniques [10,11] must be implemented in a coherent manner to achieve the operational energy performance level of NZEB. NZEB solutions vary strongly with climatic location [12,13]. For example, when the primary loading relates to cooling and dehumidification demands, a membrane liquid desiccant air conditioning system [14–17] could be central to the energy concept. This variability extends to the selection of renewable energy sources [18,19] and construction materials. Ascione et al. studied the use of passive strategies, including phase change materials, for NZEB design with a dynamic building simulation and a multi-objective optimisation algorithm [20]. The work focused on three cites with a Mediterranean climate. It highlighted the difficulty in converging to an optimum solution for winter and summer performance, while maintaining a high standard of thermal comfort [20]. A further challenge, as discussed by Yang et al., is the implementation of suitable control methods to achieve the required level of efficiency for low exergy systems [21]. The outlined level of complexity will increase the dependence of designers on numerical simulation at an early stage of a building project [9]. In previous research, there is a lack of NZEB or NPEB studies on the potential for improvements in lifecycle emissions by integrating energy systems and lightweight structures. This section highlights the need to improve TABS and BIPV analysis approaches to drive the considerable design changes necessary for the delivery of NZEB on a large scale.

TABS integrate a hydronic pipe network into the structure of a building. Internal building surfaces are transformed into radiant panels, which can be used for heating or cooling purposes [22]. In comparison to air-based space conditioning systems, TABS offer a number of advantages. These include less equipment noise, less draft and an improved vertical air temperature distribution [23]. Further, the utilisation of large surface areas allows a supply temperature of near room temperature for heating and cooling modes. The low temperature range is compatible with the use of efficient low temperature lift heat pumps and renewable energy sources, such as solar or ground source heat [21]. Extensive experimental and numerical studies on TABS have been completed at the Laboratory for Building Technologies at Empa [24,25]. This work highlights the importance of the hydronic circuit topology and the control strategy of TABS in intermittent operation. While previous studies focused on traditional implementations, this paper provides a reference for adapting TABS to complex geometry and lightweight structures.

Furthermore, it is important to identify synergies between various systems and to ensure compatibility with renewable energy sources [21]. The ability to utilise thermal inertia of a building structure is an important part of a TABS strategy. Aste et al. completed a calibrated sensible thermal energy simulation study of an office building, which was located in Milan, Italy [26]. The building was equipped with adaptive shading and it had the ability to schedule night ventilation. The cooling demand was reduced by 31% when the thermal inertia properties of the building were changed from light to medium-heavy components. The study also highlighted that thermal inertia was only effective when it was coupled with a suitable shading and a night ventilation strategy.

Adapting building facades to climate conditions has been identified as a key part of the technology roadmap for future buildings [27]. A number of research groups have developed working concepts [28] or the approach has been demonstrated on high profile bespoke building projects [29,30]. However to translate concepts into products, Loonen et al. have highlighted the importance of establishing simulation methods that capture the dynamic operational performance of facade systems [31].

Furthermore, dynamic control of facade elements is important to effectively regulate solar gains and daylight distribution, thereby improving building energy performance and indoor environmental quality [32]. Integrating photovoltaics with shading systems and lightweight structures opens new opportunities for building integrated photovoltaics (BIPV). However, the implementation of BIPV on non-ideal surfaces, such as a doubly curved roof surface is challenging. This stems from the wide range of associated constraints, which are not limited to PV electricity generation performance, such as structural integrity, weather protection and fire protection [33]. A major challenge from an energy point of view is non-uniform irradiance on PV modules due to partial shading and curvature [34,35]. This highlights the need for high-resolution analysis to improve energy efficiency of BIPV as well as to facilitate its structural integration. BIPV research will provide an insight into a key specialism that will be crucial in delivering EU 2020 [5] and Swiss MuKEn [36,37] building energy performance targets.

3. Project background

3.1. District systems

NEST (Next Evolution in Sustainable Building Technologies) is a district scale project by Empa (Swiss Federal Laboratories for