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An integrated energy performance-driven generative design methodology to foster modular lightweight steel framed dwellings in hot climates

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ABSTRACT

This paper presents a study on the application of lightweight steel framed (LSF) construction systems in hot climate. A generative design method created 6010 houses, with random geometry and random roof and exterior wall types with different insulation levels, and EnergyPlus was used to evaluate the energy consumption for air-conditioning of each building. The main goals were to determine which geometric variables correlate with the energy performance, and to provide some guidelines to foster efficient LSF buildings in hot climates. By correlating six geometry-based indexes with the energy consumption for each construction element type group, it was verified that roofs do not show significant correlation, while exterior walls presented weak to moderate positive correlation with the building volume, very weak to weak negative correlation with the relative compactness, no correlation with the shape coefficient, moderate to strong negative correlation with the window-to-floor, window-to-wall, and window-to-exterior surface ratios. The results also show that buildings with larger windows and greater level of insulation have better energy performance. No significant difference of energy performance was found between different LSF construction systems with equivalent thermal resistance.

Introduction

Lightweight steel framed (LSF) buildings have a widespread use in the USA, Australia and Japan and they are gaining market in Europe (Veljkovic & Johansson, 2006). Indeed, the popularity of LSF construction for use in residential buildings has been increasing in the recent years. This may be due to some advantages of LSF construction over heavyweight construction, pointed out by several authors (Gorgolewski, 2007; Martins, Santos, & Simões da Silva, 2016; Santos, Martins, & Simões da Silva, 2014; Santos, Simões da Silva, & Ungureanu, 2012; Soares, Gaspar, Santos, & Costa, 2014; Soares, Santos, Gervásio, Costa, & Simões da Silva, 2017c), such as small weight with high mechanical strength; high architectural flexibility; rapid construction and reduced disruption onsite; great potential for recycling and reuse; high potential for retrofitting; easy prefabrication, allowing modular construction suited to the economy of mass production; economy in handling and transportation; superior quality, precise tolerances and high standards achieved by offsite manufacturing control.

Generally speaking, LSF is a dry construction system (Burstrand, 1998) consisting of three main sorts of materials that are used in walls and slabs: cold-formed steel studs for load bearing, sheathing panels (e.g., oriented strand boards and gypsum wallboards), and insulation materials (e.g., mineral wool and expanded polystyrene) (Höglund & Burstrand, 1998). Waterproof and air tightness membranes are also used, as well as typical finishing layers. Further materials are needed for joining and fastening. For the ground floor, LSF buildings usually require a concrete slab, being the foundation work done with conventional methods (Veljkovic & Johansson, 2006). The foundation size is typically smaller given the lightness feature of LSF construction. Soares et al. (2017c) provides an extended review on this kind of construction, pointing out the main features related with the energy efficiency and thermal performance of LSF construction.

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Despite the advantages outlined above, the low thermal mass of LSF construction may be problematic for some functioning conditions and climates, leading to several comfort-related problems (e.g., overheating and larger temperature fluctuations). Kendrick, Ogden, Wang, and Baiche (2012) suggested that lightweight construction may lead to higher indoor temperatures during summer, particularly in the warmer future scenarios, due to the lack of thermal mass. Rodrigues, Gillott, and Tetlow (2013d) also pointed out the problem of summer overheating in a low-energy steel framed house regarding warmer scenarios. Overheating may also lead to higher cooling energy demand. Sage-Lauck and Sailor (2014) claimed that highly insulated and air-tight building envelopes tend to originate overheating during summer, which increases cooling energy demand or thermal discomfort in cases where no active cooling systems are installed. Phase change materials (PCMs) have been pointed out by several authors as a way to increase the thermal mass of lightweight construction (Sage-Lauck & Sailor, 2014; Evola & Marletta, 2014; Evola, Marletta, & Sicurella, 2013; Mandilaras, Stamatiadou, Katsourinis, Zannis, & Founti, 2013; Rodriguez-Ubinas, Arranz, Sánchez, & González, 2013). However, as referred by Soares, Costa, Gaspar, and Santos (2013), these materials are more promising in climates with high thermal load variation during the day, to allow for melting and solidification processes of the PCM to occur (considering the phase change temperature in the range of indoor thermal comfort temperatures). In hot climates, like Kuwait, which is the case under study in this paper, the discharging of PCMs may be somehow problematic, due to continuously operating cooling systems, typically employed to guarantee indoor thermal comfort. Therefore, PCMs will be out of the scope of this paper. On the other hand, other construction features, which may be related to overheating will be investigated, such as geometry-based indicators and the level of envelope insulation.

As suggested by Kaynakli (2012), thermal insulation is known to play a critical role in energy saving by reducing the rate of heat transfer through the building envelope. In the literature, it is referred that the level of insulation should be increased in colder climates to reduce the energy demand for heating. On the other hand, the insulation level can be reduced in warmer climates and the ventilation and free cooling strategies should be improved to reduce the energy needs for cooling. Despite these general rules, no performance-driven guidelines or standards are found in the literature to support practitioners in the design of more energy efficient LSF dwellings in hot climates. This is probably due to the unpopularity of this sort of constructions in these climates, or because the technology has not reached those markets yet. Therefore, what would be the best level of insulation for such climate conditions? Which geometric variables would better correlate with the energy consumption of the building? And finally, can LSF construction be used to promote an energy and carbon-efficient built environment in hot climate countries? To answer these questions, an integrated energy performance-driven generative design methodology is proposed in this paper, as several features have to be considered simultaneously when a high-performance building design is attempted.

Generative design methods are typically used to assist building designers to produce new and alternative design solutions in an automated procedure (Kalay, 2004), thus helping them in their divergent thinking and design exploration (Singh & Gu, 2012). These computer-based algorithms can produce large number of solutions and take over tedious tasks (Chakrabarti et al., 2011), which are otherwise costly and very time consuming. These algorithms have been applied to several aspects of building design, such as replication of architectural styles (Wonka, Wimmer, Sillion, & Ribarsky, 2003), mass housing (Duarte, 2005), facade design (Caldas, 2008), and furniture allocation in spaces (Merrell, Schkufza, Li, Agrawala, & Koltun, 2011).

With the rise of public concern about sustainability and energy efficiency, the design paradigm has drifted from the binomial form and function to the performance-based approach (Kalay, 1999; Oxman, 2008). To evaluate the building's design performance, several tools have been developed to assess energy consumption, visual comfort, construction cost, life-cycle cost, indoor air quality and thermal comfort, etc. One of those tools is the dynamic simulation of energy in buildings (DSEB). If the DSEB is coupled with generative design methods, it is possible to evaluate and compare the performance of a large number of alternative solutions (Rodrigues, Amaral, Gaspar, & Gomes, 2015) or even to improve those solutions with optimization techniques (Evins, 2013; Machairas, Tsangrassoulis, & Axarli, 2014; Rodrigues, Gaspar, & Gomes, 2014b; Wu, Ng, & Skitmore, 2016; Jalal & Bani, 2017).

As pointed out by Soares et al. (2017a), by producing a large set of building designs, with some sort of generative methods, and by evaluating their performance with DSEB tools, it is possible to carry out a statistical study of the influence of some particular parameter. This work presents such kind of approach by producing synthetic datasets of LSF residential buildings in hot climate conditions (in this case, in Kuwait), using a generative design method developed to create alternative building floor plans that have the same design program (Rodrigues, Gaspar, & Gomes, 2013a, 2013b; Rodrigues, Gaspar, & Gomes, 2013c) (i.e., the same rooms, spaces connectivity, openings, and other requirements and constraints). The buildings are then evaluated in a multi-zone fashion using the EnergyPlus software (version 8.7.0) to evaluate the influence of the climatic conditions, occupancy, lighting and equipment profiles, air-conditioning setpoints, and construction system on the energy demand for HVAC, in order to assess the energy consumption of each building. Finally, the dataset is statistically analyzed to determine which geometric variables correlate with the buildings' performance. The influence of the LSF construction system itself in the energy consumption of the building is also evaluated, mainly concerning the level of insulation, in order to provide some guidelines to foster efficient modular LSF residential buildings in hot climate conditions.

Methodology

This study follows a step-by-step methodology (Fig. 1): firstly, the climate region is chosen and the urban context is selected; secondly, the construction systems are defined and the geometric and topologic requirements and constraints are identified, considering the Kuwaiti cultural context and the local house design programs. Then, the building performance specifications are identified according to the 2010 building energy code of Kuwait (MEW, 2010). The next step is devoted to the generation of the synthetic dataset of buildings. It comprises three main parts: the production of random geometries using a generative design method; the DSEB study, and the evaluation of the energy demand of each generated geometry. Finally, the statistical analysis is carried out to correlate some geometry-based indexes and the energy consumption of each type of construction.

Hot climates – the case study of Kuwait

In this paper, the region of Kuwait is chosen to demonstrate how the proposed energy performance-driven generative design methodology can be used to foster modular LSF residential buildings in hot climates. The KISR Kuwait International Airport - KWT weather data file is used for the EnergyPlus runs. Moreover, the building construction activities in the country and the characteristic electricity demand in the residential sector are used as background context. It is believed that the assumptions made for the Kuwaiti reality can be somehow extrapolated and generalized to neighboring Gulf countries or even to the Middle East and North Africa (MENA) region countries with the similar weather conditions.