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Research Article

Design, construction, and thermal performance evaluation of an innovative bio-based ventilated façade

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Abstract The energy consumption of the construction sector and its overall environmental impact has greater potential for improvement than those of many other sectors. Most energy consumed throughout the lifecycle of a building is expended during its operation and maintenance, for which the building envelope plays an important role. This study reports on the design, construction, and thermal performance evaluation of a ventilated façade. The façade should be quickly assembled, disassembled, and stored in containers for easy onward transport. Such features comply with the Rules and Building Code of the Solar Decathlon Middle East 2018 and the relevant Eurocodes. The façade is constructed using bio-based materials in keeping with the principles of a circular economy. The exterior cladding consists of sanitary paper, grass, reeds, recycled textiles, drinking water treatment waste, bio-based polyester resin, and other materials. Temperature and the air velocity measurements recorded on the façade in Dubai showed that the façade had contributed to cool temperatures within the apartment, particularly during the hottest hours of the day. The façade is a promising option for climates with hot summers and mild winters as it contributes to reducing energy consumption and the environmental impact of building materials.

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1. Introduction

For a building and construction sector to meet the targets of the Paris Agreement (EC, 2018), it must reduce its greenhouse gas emissions by 2050 (IPCC, 2018). The sector accounts for nearly 40% of the total energy-related CO₂ emissions and 36% of the final energy use worldwide (GABC, 2018). In addition, population growth (UN, 2019) and great purchasing power in emerging economies and developing companies is expected to cause an increase in global energy demand by approximately 50% in 2060 (IEA, 2017). The reduction of energy consumption and the use of renewable energy sources in the construction industry constitute the necessary measures for the decrease of its overall environmental impact (EU, 2010).

Energy-saving strategies implemented in buildings can reduce energy consumption. These strategies can broadly be classified into active and passive approaches (Ali-Obaidi et al., 2014; Mitterer et al., 2012). Passive strategies depend on the optimization of natural resources (e.g., orientation, glazing, shading, and insulation), whereas active strategies are efficient mechanical systems that use and produce electricity (e.g., HVAC and photovoltaic systems) (Ma et al., 2019). The local climate must be considered when selecting the most appropriate active and passive energy strategies for a building to optimize resource consumption (Serra Soriano et al., 2014; Yu et al., 2019).

A ventilated façade is an effective energy strategy for climates with warm summers and mild winters (Gagliano et al., 2016; Maciel and Carvalho, 2019; Stazi et al., 2020). The use of ventilated façades for different types of buildings, climates, and design configurations has considerably increased in recent years (Maciel and Carvalho, 2019). A ventilated façade essentially consists of two opaque layers and a ventilated cavity (or cavities) between the two layers. The main benefit of a ventilated façade is heat dissipation. This feature arises from the exterior layer (i.e., the cladding) absorbing the incident direct solar radiation and the ventilation lead by natural convection in the ventilated cavity (Gagliano et al., 2016). Moreover, the inner layer of the façade works as building insulation or thermal mass. A driven-buoyancy phenomenon also arises in the ventilated cavity and pushes warm air out the façade, thereby allowing the entrance of colder air inside (Stefano Cammelli, 2016). Buoyancy forces occur because of the differences between indoor and outdoor air densities resulting from different temperatures and moisture levels. Furthermore, wind forces can help in removing the warm air out of the façade (Gagliano et al., 2016). A ventilated façade also provides insulation and controls humidity, thereby preventing the presence of moisture and condensations (Gagliano et al., 2016). The thermal performance of a ventilated façade is mainly affected by the design of its components, such as the distance between the two layers, the material of the exterior cladding, and the typology of the joints of the exterior cladding (open or closed) (Stazi et al., 2020). The evaluation of a ventilated façade is difficult given the lack of software and data to fully appraise its thermal performance. Nevertheless, for existing buildings, the performance of a ventilated façade can be assessed through on-site measurements (Naboni, 2007).

The selection of materials can also significantly reduce the environmental impact of buildings. Therefore, regulations are starting to consider their impact (de Klijn-Chevaleries and Javed, 2017; van Loon et al., 2019). In view of their sustainability and versatility, bio-based materials are considered promising resources for 21st century buildings (Sandak et al., 2019). Efficient sequestration of CO₂ endows such materials with a smaller carbon footprint than their counterparts, such as steel, glass, and concrete. Bio-based materials are renewable, reusable, and can be locally produced in an ecological manner with low transport costs. In particular, timber is a suitable material for the façade interface of the envelope (floors, walls, and roof) between the inside and the outside of the building, given its low thermal conductivity (Tapparo, 2017). On the contrary, certain drawbacks of bio-based materials include dimensional and thermal instability, low fire resistance, low resistance to biotic and abiotic degradation processes, and weak mechanical properties over time (Sandak et al., 2019). Nevertheless, several treatments available on the market can guarantee their expected properties and functionality, thereby prolonging their service life. Careful consideration of these materials is therefore of great importance for the design of a sustainable building.

Several initiatives actively promote energy-efficient buildings. The U.S. Department of Energy Solar Decathlon has been organizing the collegial Solar Decathlon competition since 2002 (SD, 2019). Its aims are focused on educating students and the public through examples of the latest energy-efficient design technologies and materials. The Solar Decathlon 2018 held in Dubai [Solar Decathlon Middle East (SDME, 2019)] challenged students to design zero-energy houses and construct them in a Middle-Eastern climate. The competition saw a range of buildings that were mainly powered by solar energy and were compliant with the objectives organized into the following 10 categories: architecture, engineering and construction, energy management, energy efficiency, comfort conditions, house functioning, sustainable transportation, sustainability, communication, and innovation.

The VIRTUE student team (VIRTUE, 2019a), from the Eindhoven University of Technology (TUe), successfully presented the LINQ apartment as a candidate in the 2018 SDME competition. The LINQ apartment is energy efficient with several innovative active and passive strategies, and it supplied more energy to the grid than it consumed throughout the competition (Pujadas-Gispert et al., 2020). Its ventilated façade was built with bio-based materials that respect the principles of the circular economy. The bio-based material was first used in a 3D-shaped façade in the Netherlands (Blok et al., 2019). Moreover, some examples of ventilated façades with bio-based materials were seen in previous Solar Decathlons, although their designs...
and some materials differ from those of the LINQ apartment (Brambilla et al., 2017; Pataky et al., 2014; Serra Soriano et al., 2014).

The main objective of this paper is to report on the design and construction of the innovative ventilated façade of the LINQ apartment and its thermal evaluation in Dubai. The specific objectives are to: (1) present the factors considered for the design of the façade; (2) describe and discuss the design and the construction of the façade; (3) present the temperature and the air velocity measurements recorded on the façade in Dubai; (4) evaluate the thermal performance of the façade; and (5) draw practical conclusions and recommendations for the future implementations of the façade, thereby contributing to sustainable construction practice.

2. The LINQ apartment

The LINQ apartment was included in "the LINQ apartment complex" (Fig. 1), which was part of a concept aiming to connect people with each other, people with technology, and technology with technology, to strengthen each other and improve environmental, social, and economic sustainability (VIRTUe, 2018a). The said apartment has a floor area of 65 m$^2$, comprising an entrance lobby, bedroom, dining room, living room, kitchen, and toilet and shower. Fig. 2 shows the plan of the LINQ apartment, whereas Fig. 3 illustrates an exterior view of the apartment at the TUe.

3. Passive energy strategies of the apartment

Temperatures tend to be very high during summertime in Dubai where the climate is generally hot and dry, although they can fall below 18°C for a few hours in winter when some heating may be required (NCM, 2019). Effective insulation was therefore recommended in the form of glazing with a very low solar gain coefficient and the use of shading systems and reflective exterior surfaces (Al-Obaidi et al., 2014; Mitterer et al., 2012). The strategies used in the LINQ apartment consisted of double-glazed windows with metallic coatings, a highly insulated envelope, a pale reflective grayish color on the exterior cladding, the south wall was inclined outwards at 15° from the vertical plane to reduce its solar exposure, south and west ventilated façades, and a north wall with a green façade (Fig. 4) (Pujadas-Gispert et al., 2020). Green façades provide natural cooling and insulation and improve air quality by removing toxins and other harmful substances and thus generate a positive effect on people’s health and well-being (Korjenic et al., 2016; Othman and Sahidin, 2016).

4. Ventilated façade

The concept behind the ventilated façade is that air will freely flow between the plywood boards and the exterior cladding. The following features are assumed to be among such façade’s functions: i) the exterior façade will absorb the incident direct solar radiation (Maciel and Carvalho, 2019); ii) the heat will be distributed through convection in the ventilated cavities (Gagliano et al., 2016); and iii) air buoyancies will be generated between the plywood boards and the exterior cladding, given the temperature difference, which will push warm air out and draw cooler air in, thereby providing a natural airstream in between (Stazi et al., 2020) (Fig. 5).

5. Materials and methods

5.1. Design and construction of the ventilated façade

Some initial requirements were set by the VIRTUe student team: i) the main materials of the apartment should be bio-based materials, ii) the parts should fit in containers for transport to Dubai, and iii) on-site assembly and disassembly should be quick (max. 15 days). These requirements guided several constructive decisions: lightweight and easy-to-handle components were selected, the dimensions of the components had to fit into a container, and the constructive solutions and details must be designed for easy assembly and disassembly. The design of the façade also had to comply with the rules of the competition; specifically, the façade had to be reflective and durable (SDME, 2018). The design was also compliant with European regulations (EC, 2019), thereby ensuring its stability and safety.

The selection of materials changed during the design. The VIRTUe student team considered several structures and materials (e.g., steel, ceramic, and stone) for the façade. A timber structure was finally selected because it was the most sustainable option from among those under consideration. A structure of panels rather than that of 3D modules was chosen as panels could be neatly packed in containers for transport to Dubai, and they occupied fewer

Fig. 1 Section of "the LINQ apartment complex" in a Dubai neighborhood (VIRTUe, 2018b).
containers than 3D modules. As regards the exterior cladding, the team initially considered stone, although stone slabs were too heavy for easy assembly and implied additional transport costs. A composite material resembling stone was then tested, but its excessive fragility meant that it could not be formed into the suitable shape for the cladding. Finally, a sustainable, lightweight, reflective, and durable bio-based material (Nabasco® 8010) was selected and met the design requirements. Further information on the development of the façade and its materials is provided in the following sections.

5.2. Thermal performance evaluation of the ventilated façade

The main aim was to study the reduction of the interior temperature of the apartment as a function of the exterior temperature, temperature dissipation in the façade layers, and airflows within the cavities of the façade. Accordingly, several sensors were placed between the layers and within the cavities of the façade. Sensor data were relayed to a data logger (October 11–28, 2018) during and after the competition to gather sufficient details for drawing conclusions. Measurements were recorded in two zones: the left and the right of the façade (in Fig. 6). In each zone, seven temperatures were recorded: three air temperatures (as T6, T7, and T8) and four surface temperatures (as T1, T2, T3, and T4). Note that T7 refers to the temperature of the upper part of the façade, whereas T8 refers to the temperature of the lower part. The temperature measurements were noted to investigate the variance in the temperatures between both parts. Air velocities at both points between the exterior cladding and the plywood boards were also documented to examine the airflows.
within the air cavities and the exterior temperatures (in Fig. 6, TOUT). The data records were taken with NTC air temperature thermistors ($\pm 0.05$ °C) (Sensordata, the Netherlands), surface temperature thermistors ($\pm 0.2$ °C) (GRANT Instruments, UK), air velocity transmitters ($\pm 0.2$ m/s) (CATEC, the Netherlands), and Squirrel 2040 data loggers (GRANT Instruments, UK). MATLAB software (v.R2019a) was utilized to process these data measurements.

6. Design and construction of the ventilated façade

6.1. Ventilated façade

The ventilated façade consisted of several components. The design and construction of these components are presented and discussed in the following sub-sections: exterior...
cladding (6.2), structural panels (6.3), and radiant thermal panels (6.4). The components were manufactured in the Netherlands, installed at the TUE for testing, and finally transported and installed at the SDME in Dubai. The installation of the components was performed in several steps. The panels (with the radiant panels previously attached to the interior side) were first mounted over the apartment floor with a crane and connected to each other. Orange water-repellent vapor-open foils were then sealed with air-tightening sealant tape. Subsequently, wooden battens secured at intervals to the panels served as supports for the plywood boards upon which the exterior cladding was firmly screwed. Finally, the piping from the radiant thermal panels was connected to the apartment facilities. Figs. 7 and 8 show the upper and lower parts of the west-facing ventilated façade.

6.2. Exterior cladding

The VIRTUe student team designed a ventilated façade for the south- and west-facing sides of the apartment for heat dissipation during the hottest hours of the day. The shape of the exterior cladding provided spaces through which air could flow between the exterior cladding and the plywood boards (Fig. 9(a)). The cladding consisted of triangular-shaped tiles (Fig. 9(b)), capable of withstanding winds from both sides and head-on (Fig. 9(c)). The shape also finished off a smooth transition to the corners of the apartment (Fig. 9(d)). The light grey reflective color of the tiles (Al-Obaidi et al., 2014) ensured that neither rain (common in the Netherlands) nor sand (in the UAE) remained inside.

Two symmetrical tiles that repeated a pattern over the façade were developed. The tile designs were first created through hand-drawn sketches and then modeled with 3D drawing software (Fig. 10(a)). The designs were modified following production-related feedback from the manufacturer. For instance, the tile corners were curved with smooth surfaces, so that none of the moldable material could stick to the corners of the mold. Moreover, the tile sizes could not be larger than 300 mm x 300 mm x 300 mm. In addition, the holes designed for the installation of the tiles were suppressed, as their small size could not be molded. The holes were drilled after the production process. Once the tile designs were prepared for production, a sample was printed on a 3D printer for final verification (Fig. 10(b)).

The tiles were made of a specific bio-based material (Nabasco® 8010) made of waste (sanitary paper, grass, reeds, recycled textiles, drinking-water treatment waste, and bio-based polyester resin); calcium carbonate (CaCO₃), a waste material from drinking water companies;
and a bio-based polyester resin (50% waste glycol from biodiesel production and 50% animal waste and cooking fats). A white pigment was also incorporated for a light gray tile color. These components were locally produced and thus reduced transport emissions. The tile is fire resistant and qualified as a class B–S1 d0 material in accordance with EN 13501-1 (Koninklijk Nederlands Normalisatie-instituut, 2019). Its mechanical properties and density are slightly lower than those of conventional glass. It requires low maintenance throughout its operational life and can be crushed and reused as a basic raw material in the same process at the end of its useful life (NPSP, 2018; Willem Bottger, 2019). Moreover, the tile is produced in accordance with the principles of a circular economy (Korhonen et al., 2018).

Forming the tiles involves an adaptation of the process used for glass-fiber-reinforced polyester products found in car headlight reflectors, interior coach panels, and washbasins (Willem Bottger, 2019). The production process consisted of pressing a dough-like mixture into a heated mold. Computer Numerical Control (CNC) milling was employed to machine the molds from two blocks of steel, measuring 600 mm × 600 mm × 400 mm each (Fig. 11). Students from the VIRTUe team produced the tiles at a factory specializing in composite materials with the assistance of skilled personnel.

The tile production can be summarized in several steps. The fiber materials were first shredded. They were then mixed with a binder to produce a malleable dough-like material (Fig. 12(a)(b)). The mixture was dosed in small portions sufficient for one tile, vacuum packed, and conserved in a fridge (Fig. 12(c)). The mold was subsequently installed in the press machine, the interior of which was previously greased and heated to 140 °C. A single dose of the mixture was placed in the mold and pressed at 10 MPa for approximately 3 min (Fig. 13). Afterwards, the tile was extracted from the mold at which point its strength had almost fully developed (Fig. 13). Finally, the excess material was wiped from the edges of the tile, thereby leaving a clean edge (Fig. 14).

Various adjustments were made to the tile production method. First, the tiles shrank inside the press when heated, so the dose had to be calibrated before the tiles were introduced into the machine. An insufficient dose risked the production of incomplete tiles (Fig. 15), and thus a surplus amount was provided in case covering the surface and the corners of the mold was unnecessary. Second, the composition of the bio-based material also had to be

Fig. 8 Detail of the lower part of the west-facing façade (VIRTUe, 2018c).
adjusted. The first tiles were brittle and easily broken (Fig. 15). This problem was solved by changing the percentage the fiber composition of the bio-based material. The temperature of the press was calibrated from 6 to 3 min. Finally, the fragility of the small flaps projecting out from the tile for mounting on the plywood boards was noted. This aspect could be improved by enlarging the tile on one side to strengthen those parts.

The tiles were installed by screwing them onto the plywood boards. One person can install a tile in place (Fig. 16), although the work was much quicker with three people: two holding the tile and one screwing it onto the plywood board.

6.3. Panels

The panels consisted of I-profiled beams, insulation, plywood boards, vapor-proof films, and orange water-repellent vapor-open foils. The I-profiled beams were selected because the Biofoam® insulation in the middle of the profile fitted that shape, thereby enlarging the insulated area of the panel. Biofoam® insulation, a biomimetic
cradle-to-cradle material, consists of raw vegetable matter that is resistant to moisture, pressure, pests, fungal growth, and bacteria. The vapor-proof films and the water-repellent vapor-open foils were installed to ensure a water-proof, damp-proof, and airtight envelope. The constructive details for the walls, the floors, and the roof were all designed for easy production and construction processes, and the glueless tongue-and-grooved panel system facilitated their disassembly and reuse.

The VIRTUE student team had the panels built at a factory. The frame with the I-profiled beams was assembled first. The stiffness of the insulation prevented its placement in a single process, so the insulation was initially packed inside the I-profiled beams (Fig. 17), and then additional insulation was placed between the I-profiled beams and in several other parts. The panels were then
wrapped with vapor-proof films (Fig. 18), and plywood boards were placed over them (Fig. 19). Finally, the panels were covered with orange water-repellent vapor-open foil (Fig. 20), and radiant thermal panels were installed on the inside face of the panels.

The panels were not completely airtight, as their dimensions had altered due to the hygrothermal conditions of Dubai. Dimensional tolerances had been considered during the design, although the climatic conditions proved excessive, thereby reducing their size. The problem was solved by filling the gaps with insulation and sealing the space between the panels with air-tightening sealant tape. Therefore, a careful analysis of the design tolerances of each climate is crucial whenever the apartment must be assembled and disassembled at a different location.
As mentioned, the design of the constructive details was intended to facilitate on-site assembly and disassembly of the apartment. However, the design specifications had different types of screws and nails for each constructive detail. Most of the students installing the panels had no prior knowledge of the design process and had to carefully check the fixture size, consequently slowing down the installation. If all details of the panel had been standardized fixtures, then the installation process could have been far quicker and with less chance of human error.

6.4. Radiant thermal panels

Several orientations of the apartment envelope had radiant thermal panels on the interior. The radiant thermal panels were connected to a water pipe system that was in turn connected to the Building Integrated Photovoltaic Thermal (BIPV/T) system on the roof and regulated with a pump. At daytime, stored chilled water was pumped into the radiant panels to absorb the heat from inside the LINQ apartment (Fig. 21). At night, this “warm” water was cooled using the PV/T system with the principle called “nocturnal sky radiant cooling” (Fig. 22) (Al-Obaidi et al., 2014; Gürlich et al., 2017). The dissipation of the heat of the water was conducted with long-wave radiation from the BIPV/T system (or roof) to the sky. This feature is employed because the temperature of the sky is usually lower than the temperature of most objects on earth, and therefore surfaces facing the sky experience long wave radiant loss. Nevertheless, this radiant loss is outweighed by the incoming solar radiation during daytime.

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7. Thermal performance evaluation of the ventilated façade

Representative results of the studied temperatures (outdoor, air, and surface) recorded in Dubai are shown in Fig. 23. Outdoor air temperatures ranged between 25 °C and 40 °C during the daytime, whereas they dropped to 15 °C at nighttime. Air temperatures within the cavities of the ventilated façade (T7 and T8) were higher than the outdoor air temperatures (TOUT) during the daytime. In addition, the air temperature in the upper part of the cavity (T7) was up to 10° higher than that in the lower part (T8). Although additional tests are needed, the rising airflow within the façade in all probability transported the heat upwards. The exterior cladding (T1) recorded the highest surface temperatures between 12 a.m. and 5 p.m. (up to 55 °C for November 15, 2018), given the exposure to sunlight. In addition, the inner layers, T2 and T3, recorded lower values than T1 (T2 ~5° less and T3 up to 15° less), probably because of the shading provided by the layers and the airflows rising up the ventilated façade that could have contributed to the cooling. Nevertheless, these layers (T2 and T3) were warmer than the exterior cladding.
(T1) during the nighttime because they still retained some of the daytime heat. On most days, surface temperatures inside the LINQ apartment remained stable (T4).

Results over two days (November 26–27, 2018) are shown below as representative examples. Fig. 24 shows the air velocities within the cavities of the ventilated façade and wind speeds. The air velocities within the façade bear some relation to the wind speeds, which in all likelihood was due to the wind entering the façade cavities. The overall results revealed that wind speeds were higher between 10:00 and 18:00, and this outcome coincided with the highest outdoor temperatures. These results suggested that airflows were also generated between the exterior cladding and the plywood boards due to temperature differences. In addition, air velocities varied between the lower (T8) and upper (T7) parts of the façade. Although further tests are required, a possible explanation for this result might be that airflows within the façade were disjointed, rather than continuous from the lower to the upper part, as the design of the exterior cladding was discontinuous.
8. Conclusions

In this study, the design and construction of a ventilated façade made of bio-based materials and its thermal performance evaluation were presented for a climate with warm summers and mild winters. This façade is from an energy-efficient apartment (the LINQ) that was successfully entered in the Solar Decathlon Middle East 2018 competition. The main conclusions of the study are summarized below.

- The façade made of bio-based materials, which are renewable and recyclable resources, contributed to the sustainability of the apartment: energy consumption for controlling indoor ambient temperatures was reduced, and the low environmental impact of the cradle-to-cradle materials is notable from a life-cycle perspective.
- The exterior cladding was made of a bio-based material (Nabasco® 8010) that included sanitary paper, grass, reeds, recycled textiles, drinking-water treatment waste, and bio-based polyester resin, among others. In line with the principles of the circular economy, the final product yielded a strong, lightweight tile, with similar properties to glass. The small flaps at the tile edges were excessively fragile and could break, thereby adversely affecting functionality. Thus, those small elements must be firmly embedded within the main body of tile. From the experience gained during tile production, the material can be clearly adapted to the needs of each design.
- The repetition of constructive solutions and elements in the design of the ventilated façade facilitated quality construction, performance, and speed of assembly. Additional improvements may be introduced by standardizing the types of screws and nails required for the constructive details.
- The design tolerances must be very carefully considered for each climate whenever the apartment is set to be assembled and disassembled at a new location.
- The temperature and air velocity measurements recorded in Dubai confirmed the presence of upward airflows within the cavities of the façade and between the exterior cladding and the plywood boards. These airflows were mainly due to wind flows through the façade cavities. In addition, temperature variations can also generate airflows within the cavities.
- The airflows (including wind), shading, and insulation provided by the layers of the ventilated façade contributed to the heat dissipation during daylight hours. In addition, the ventilated façade preserved the indoor temperature of the apartment at night. The façade therefore mitigated the effect of outdoor temperatures within the apartment. A detailed determination of its specific heat transfer mechanisms will be investigated in subsequent studies.

The LINQ apartment will soon be installed in the Netherlands, thereby providing the opportunity for an in-depth study of the façade and its heat-transfer
mechanisms. Conclusions may also be drawn on its performance in other climates. One objective is to include the facade and its bio-based materials in future construction and research projects, thereby softening the environmental impact of the building sector.

Declaration of Competing Interest

No conflict of interest.

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References