LINKING CONSTRUCTIVE AND ENERGY INNOVATIONS FOR A NET ZERO-ENERGY BUILDING

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INTRODUCTION
This article explains the design, construction and energy strategies of LINQ, a net-zero energy building that was successfully entered into the Solar Decathlon Middle East 2018 held in Dubai. Students of engineering, building physics, architecture and urban planning designed, built and operated LINQ. It is mainly powered by solar energy and made of bio-materials. Some of LINQ's innovations are the ventilated façade with customizable bio-based tiles, the indirect evaporative water cooling system, and the light building integrated photovoltaic-thermal system. LINQ sent more energy to the grid than it drew throughout the competition. However, energy production could have been improved according to simulations and technical specifications. LINQ is a good example of current and future building expectations—combining multiple criteria, strategies, and solutions—to contribute to environmental, social and economic sustainability.

KEYWORDS
indirect evaporative cooling system, bio-based materials, building integrated photovoltaic-thermal system, solar-powered building, thermal mass, energy-efficient building, Solar Decathlon.

1. BACKGROUND
The building sector represents 36% of the world's energy consumption and it accounts for nearly 40% of global greenhouse gas (GHG) emissions (GABC 2018). It is expected that the growth of both population (UN 2019) and the purchasing power of emerging economies and developing companies will increase energy demand by 50% by 2060 (IEA 2017). In addition, traditional energy sources (fossil fuels) are expected to become scarce in the coming decades (Kjärstad and Johnsson 2009). Therefore, there is a need to reduce energy consumption and to implement renewable energies in buildings to diminish their environmental impact (EC 2018).

A sustainable building is energy efficient and is designed in accordance with the local climate. It also provides a healthy environment for its inhabitants and reduces the consumption

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of resources (Serra Soriano et al. 2014). Most of the energy strategies used in such buildings can be broadly classified as passive or active strategies. Passive strategies consist of optimizing the natural resources when designing the building (e.g. solar orientation, glazing and shading systems and insulation), while active strategies are efficient mechanical systems that are incorporated into the building (e.g. HVAC system, efficient lighting and appliances and photovoltaic systems).

Materials are increasingly important in the life cycle of a building, although the focus is still on reducing their operational energy consumption (de Klijn-Chevalerias and Javed 2017; van Loon et al. 2019). Bio-based materials are considered promising resources for twenty-first-century buildings (Sandak et al. 2019). They can efficiently sequester CO_2, giving them a smaller carbon footprint compared to other materials such as steel, glass, or concrete. Nevertheless, they might require a treatment to ensure their properties and functionality, thereby elongating their service life (Sandak et al. 2019).

One initiative that promotes energy-efficient buildings is the collegial competition Solar Decathlon, which has been organized by the U.S. State Energy Department (DOE) since 2002 (SD 2019). This competition focusses on creating public awareness of the benefits of using solar energy and efficient energy management. The main goals of Solar Decathlon are:

- Provide participating students training in clean energies.
- Educate students and the public about the latest technologies and materials on energy-efficiency, clean energies, smart home solutions, electric vehicles, and high-performance buildings.
- Demonstrate to the public that such buildings which incorporate these technologies and principles are comfortable and provide savings.

Solar Decathlon 2018 (SDME) edition took place in Dubai. Students were challenged to design and operate houses for the Middle East climate. These houses should be full-scale, innovative, sustainable and powered mainly by the energy of the sun. In addition, houses should comply with competition objectives organized into 10 categories: architecture, engineering and construction, energy management, energy efficiency, comfort conditions, apartment functioning, sustainable transportation, sustainability, communication and innovation.

Team VIRTUe, from the Eindhoven University of Technology (TU/e), successfully entered the LINQ project in SDME. This building was principally made of bio-materials. Some bio-materials and energy strategies used in LINQ had also been used in previous competitions of Solar Decathlon (Brambilla et al. 2017; Cronemberger et al. 2014; Ma et al. 2019; Montero et al. 2014; Pataky et al. 2014; Serra Soriano et al. 2014; Yu et al. 2019). However, due to several innovations, LINQ won in the category of "*Innovation in Energy Efficiency*." These innovations will be explained along with its concept, design, construction and energy strategies, which are related to each other, to contribute to a more sustainable building practice.

2. THE CONCEPT OF "LINQ"

Prior to the design process, Team VIRTUe conducted an extensive analysis of the history and current situation of Dubai, which consisted of a literature review and interviews with expats. It was observed that the disconnection between citizens was growing, which is a common phenomenon in fast-growing cities all over the world. In this particular case, some of the main factors are

FIGURE 1. Section of the apartment complex in the neighborhood in Dubai (Team VIRTUe 2018a).

the infill of former public spaces (Alawadi 2017) and the increase of the distance that inhabitants have to travel every day due to the fast growth of the city (Ogaily 2015). Additionally, there is large segregation between people from different income classes (Alawadi 2017).

In response, Team VIRTUe designed a concept that promoted improving connection. First, LINQ was committed to creating a social environment in which people could interact and share experiences. Second, LINQ wanted to connect people to environmentally sustainable technologies, encouraging people to understand, use and personalize them. Finally, these technologies should complement and strengthen each other in order to be more efficient. Hence, the concept of LINQ aimed to finally connect people and technologies to each other to improve collaboration, efficiency, and quality of life of current and future generations.

LINQ consisted of a small, human-scale apartment complex with eleven apartments and many shared spaces for their inhabitants and the neighborhood (Figure 1). In addition, all floors of the building were connected by a curved green atrium, which served as a meeting place and vertical garden for their inhabitants. It was expected that the inhabitants of LINQ were diverse in age, household composition (single, couple, family) and income (middle to high income) with different daily routines throughout the day.

3. LINQ APARTMENT

LINQ built at SDME is one of the apartments of the LINQ apartment complex (Figures 2 and 3). Nevertheless, it was modulated as a detached house for the competition. The LINQ apartment had around 65 m^2, and the architectural program consisted of a dining room, living room, a bedroom, entrance and a central service area (kitchen, toilet and shower) (Figure 4).

4. BUILDING DESIGN PRINCIPLES

The apartment was designed with the close collaboration of diverse disciplines (architecture, urban planning, building physics, and mechanic, structural, industrial and electric engineering) together with the advice and support of innovative technology companies. In addition, it was designed following the '*SDME rules and building code*' (SDME 2018) and the European building codes (EC 2019). First, several simulations were conducted during the design process to obtain the most optimized model. Then, LINQ was built and checked in TU/e (The Netherlands). And finally, it was transported and installed in Dubai for the competition.

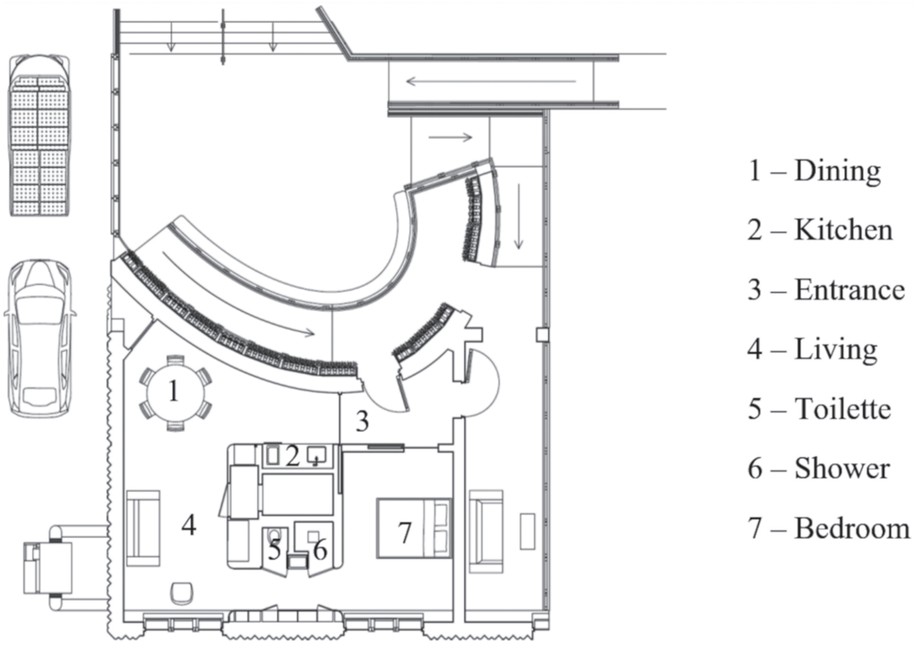
Several requirements conditioned significantly the design of LINQ. First, energy consumption should be as low as possible; for this purpose, several energy passive and active strategies

FIGURE 2. LINQ was part of LINQ the apartment complex (Team VIRTUe 2018a).

were used. Second, the selection of materials should consider the environmental impact from a life cycle perspective; to do this, most of the materials were made of bio-based materials. Third, apartment components should be light enough for easy handling and transport, and they also should fit into standard shipping containers (Figures 5 and 6); containers were first transported by boat, and then, driven by truck to the location. Finally, the apartment should be assembled

FIGURE 3. LINQ in TU/e (source: Bart van Overbeeke) (Team VIRTUe 2019).

FIGURE 4. Floor plan of LINQ.

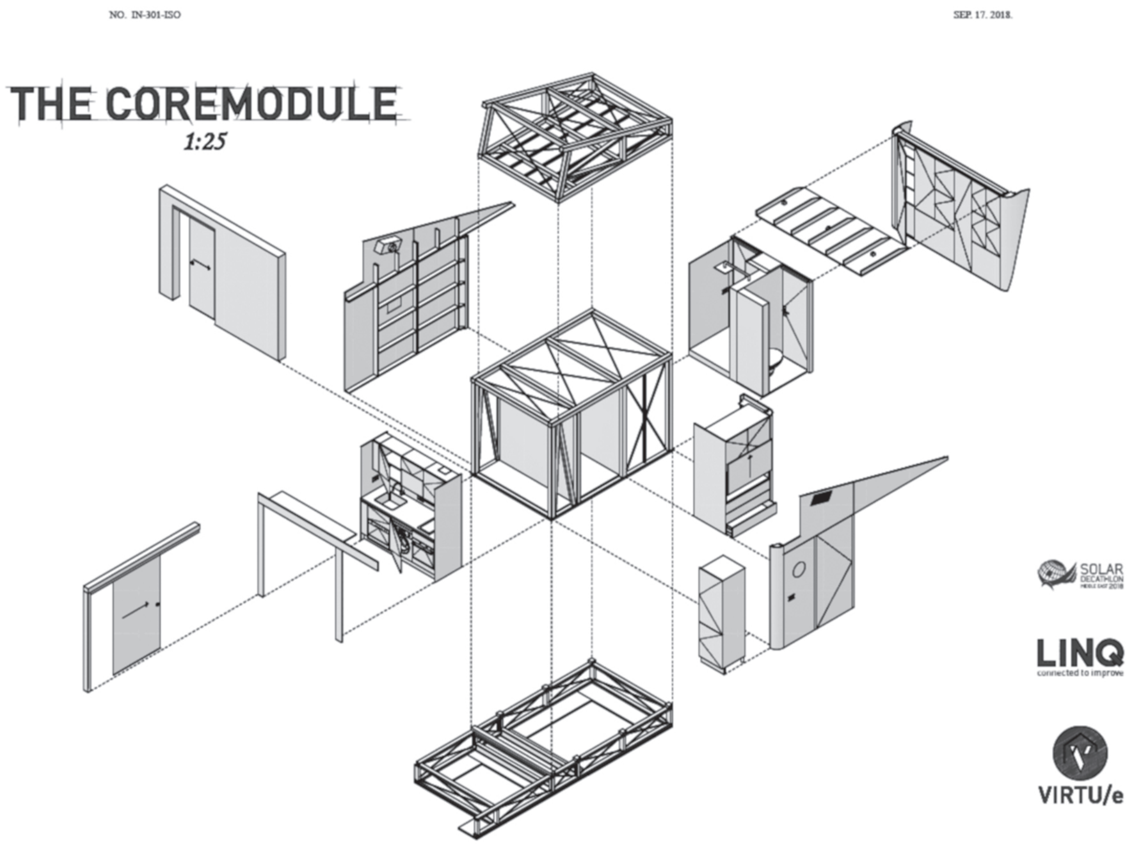


quickly (15 days); to enable this, a central structural core was designed, where most loads of the apartment were transferred, simplifying in this way the foundation and, as a result, the rest of the structure. This structural core was composed of a foundation, technical and roof modules which were placed one on top of the other (Figure 7). The structure of this core was made of steel because it had to withstand large loads and facilitate the ease of transport and assembly.

FIGURE 5. The technical module was placed inside a shipping container to be transported to Dubai (Team VIRTUe 2019).

FIGURE 6. Shipping containers were transported to Dubai by boat (Team VIRTUe 2019).

FIGURE 7. The structural core consisted of foundation, technical and roof modules (Team VIRTUe 2018b).



5. CONSTRUCTION OF THE APARTMENT

Foundation

The foundation of the apartment consisted of the foundation module, footings, foundation beams and ground anchors. Footings could be adjusted in height, in order to adapt the apartment to the surface of the ground. Footings were not designed at the edges of the apartment giving the impression that LINQ was an apartment instead of a house (Figures 8 and 9). For

FIGURE 8. Footings were not disposed at the edges of the apartment (Team VIRTUe 2018b).

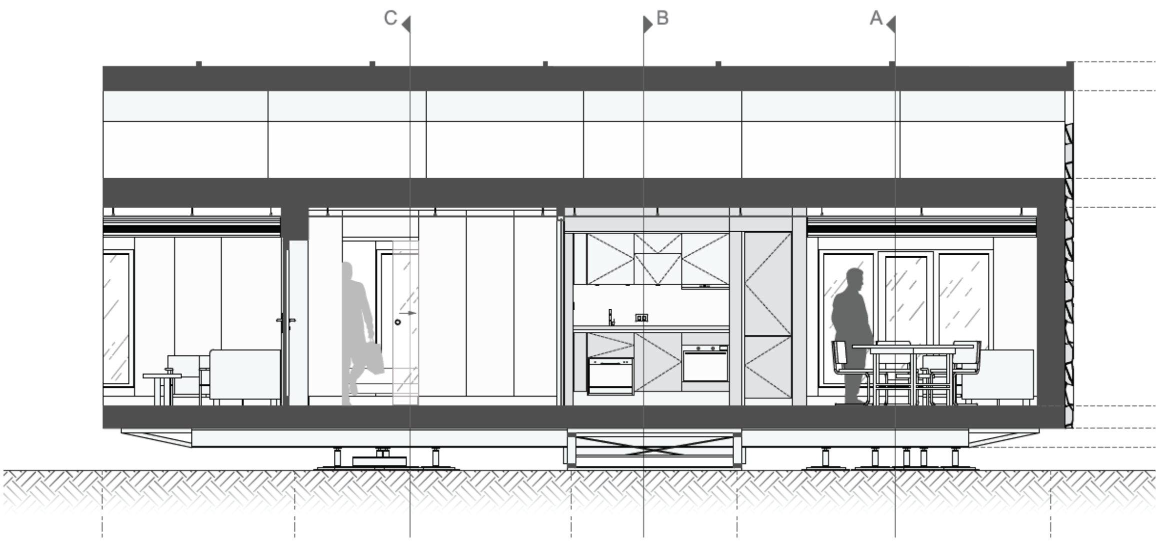


FIGURE 9. Steel footings in the TU/e. They were placed on the ground in Dubai.

the same reason, foundation beams, which were disposed over the footings, decreased in height towards the edges of the apartment. Furthermore, ground anchors were installed to prevent the uplifting and overturning of the structure. The anchors had to be installed in the footings, but they were finally connected directly to the foundation beams during the latest drawings so as not to depend on specific locations and to not have problems with the mesh size of the grid, through which the anchor should have been placed.

Technical and Roof Modules

The technical module contains most of the installations, the kitchen, toilette and shower, which were pre-installed in The Netherlands. This reduced assembly times, facilitated the transport and reduced human error. The technical module was also situated centrally in the apartment providing free movement (Figure 10). Moreover, it was placed over the floor (Figure 11), although

FIGURE 10. Technical and roof modules were finished as closets and provided free movement around (Team VIRTUe 2019).

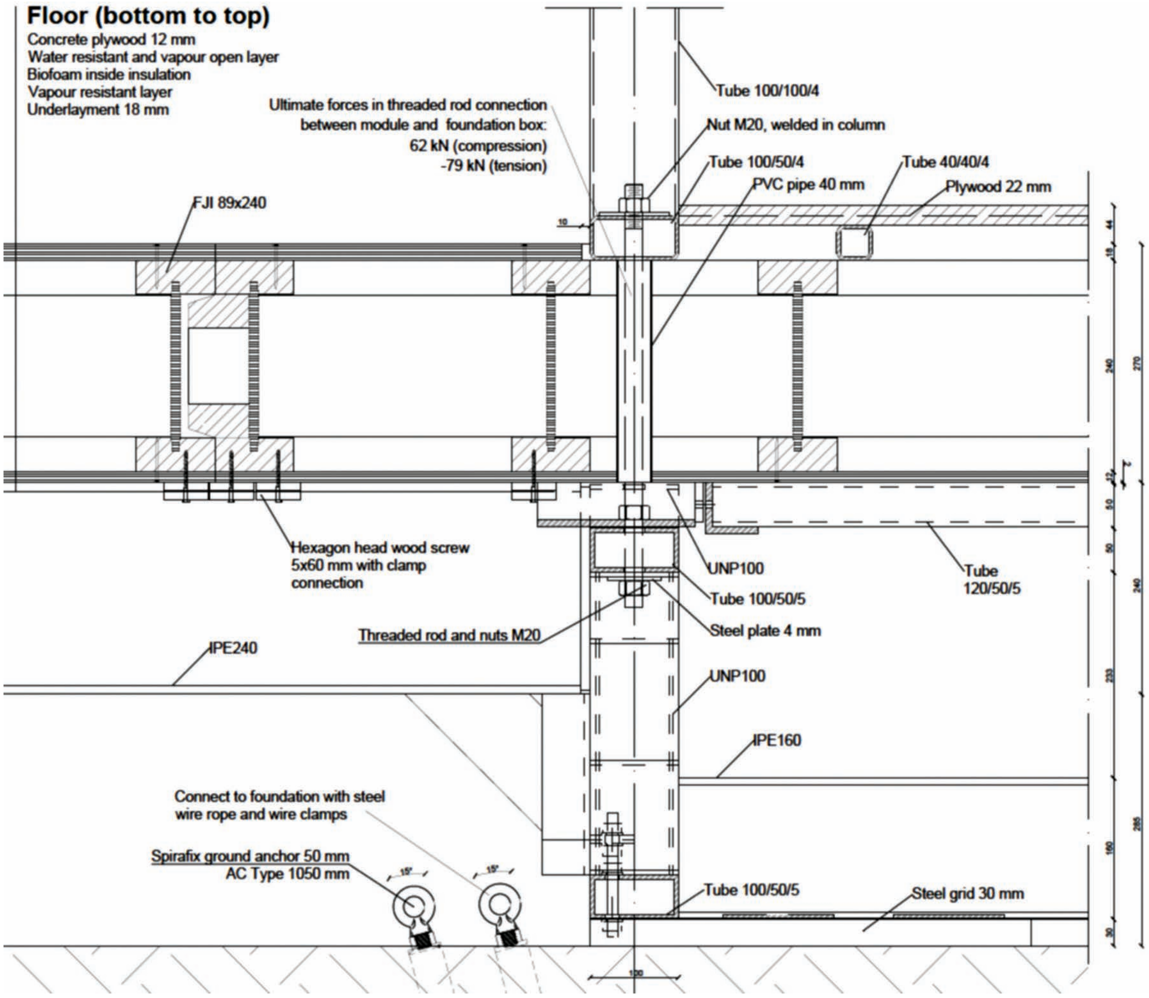
FIGURE 11. The roof module laid over the technical module (source: Bart van Overbeeke). The North beam laid over the roof module and exterior walls (Team VIRTUe 2019).

loads were transferred to the foundation beams and foundation module with steel threaded rods (Figures 12 and 13). This is because the floor could not be able to resist the loads of the module. Additionally, the roof module was laid over the technical module, which withstood the loads from the roof and the North beam.

The Envelope

One of the main objectives of Team VIRTUe was to build the apartment with bio-based materials. The envelope was composed of panels which consisted of I-profiled Finnjoist timber beams, which are 40% lighter than traditional timber beams, and Biofoam® Inside insulation. The I-section of the beams was selected over other sections because it allows allocating insulation inside. In addition, beam webs were made of timber which reduces thermal bridges. The insulation material was made of recycled expanded polystyrene and a percentage of the innovative Biofoam® which is made of biopolymers from raw vegetable materials. In addition, Biofoam® is pressure-resistant, moisture insensitive, resistant to pests, fungus and bacteria, sustainable and cradle-to-cradle. In addition, plywood plates were applied on top of the Finnjoist beams to close the panels enabling them to work as plane elements and providing stability to the apartment. This box principle was also used to achieve the big cantilever of the canopy roof. Figures 14–16 show the significant constructive sections of the bio-based walls.

FIGURES 12 AND 13. Joining between the technical module and foundation module by means of threaded rods (Team VIRTUe 2018b).



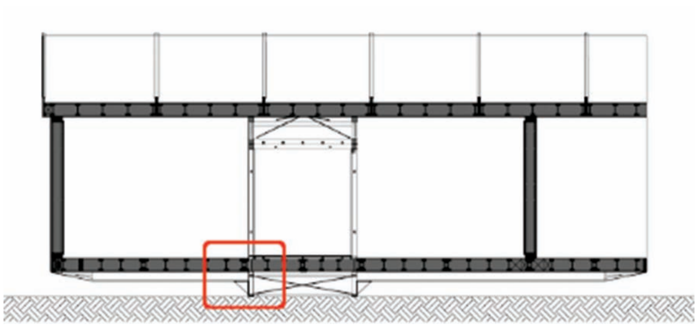
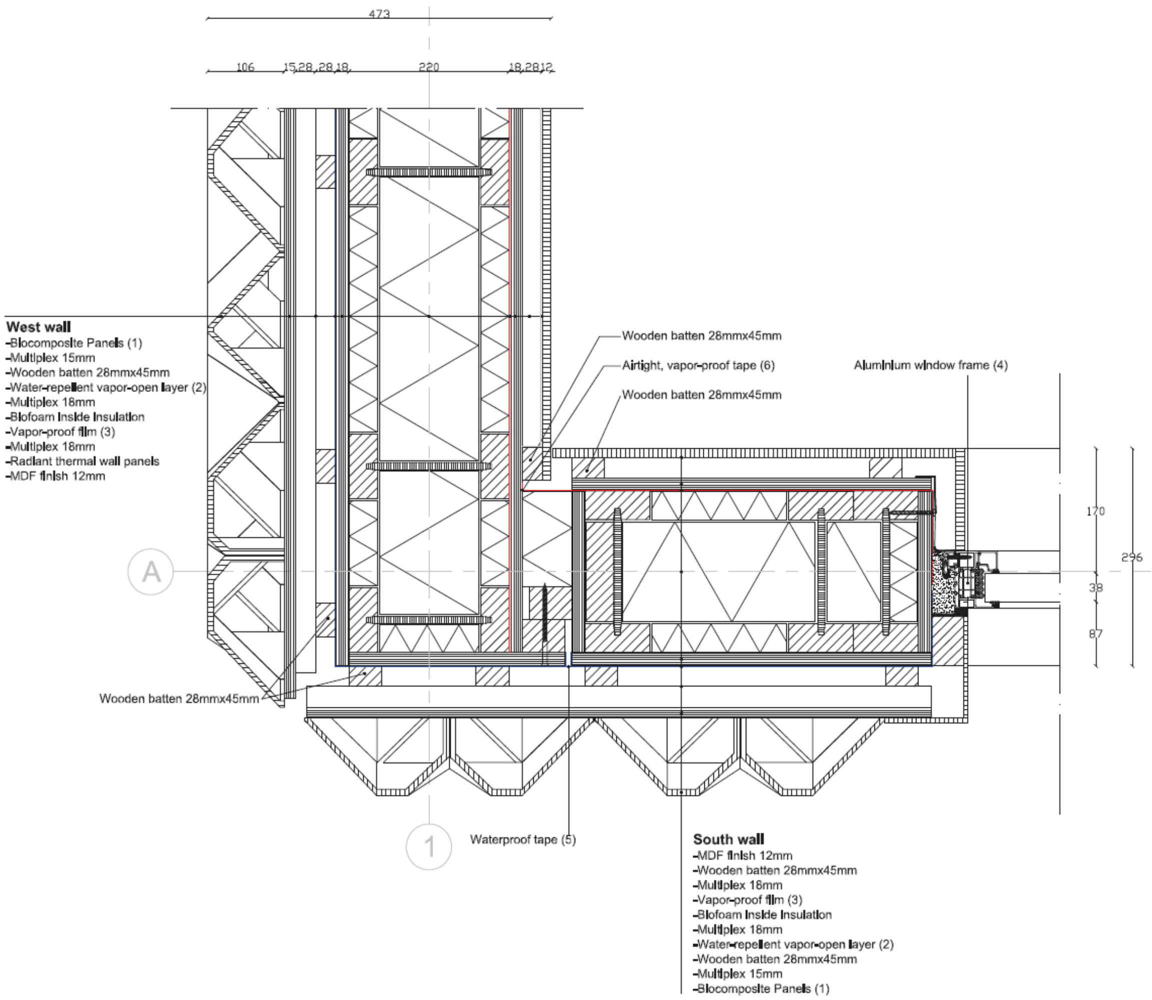


FIGURE 14. Detail of the West and South walls (Team VIRTUe 2018b).

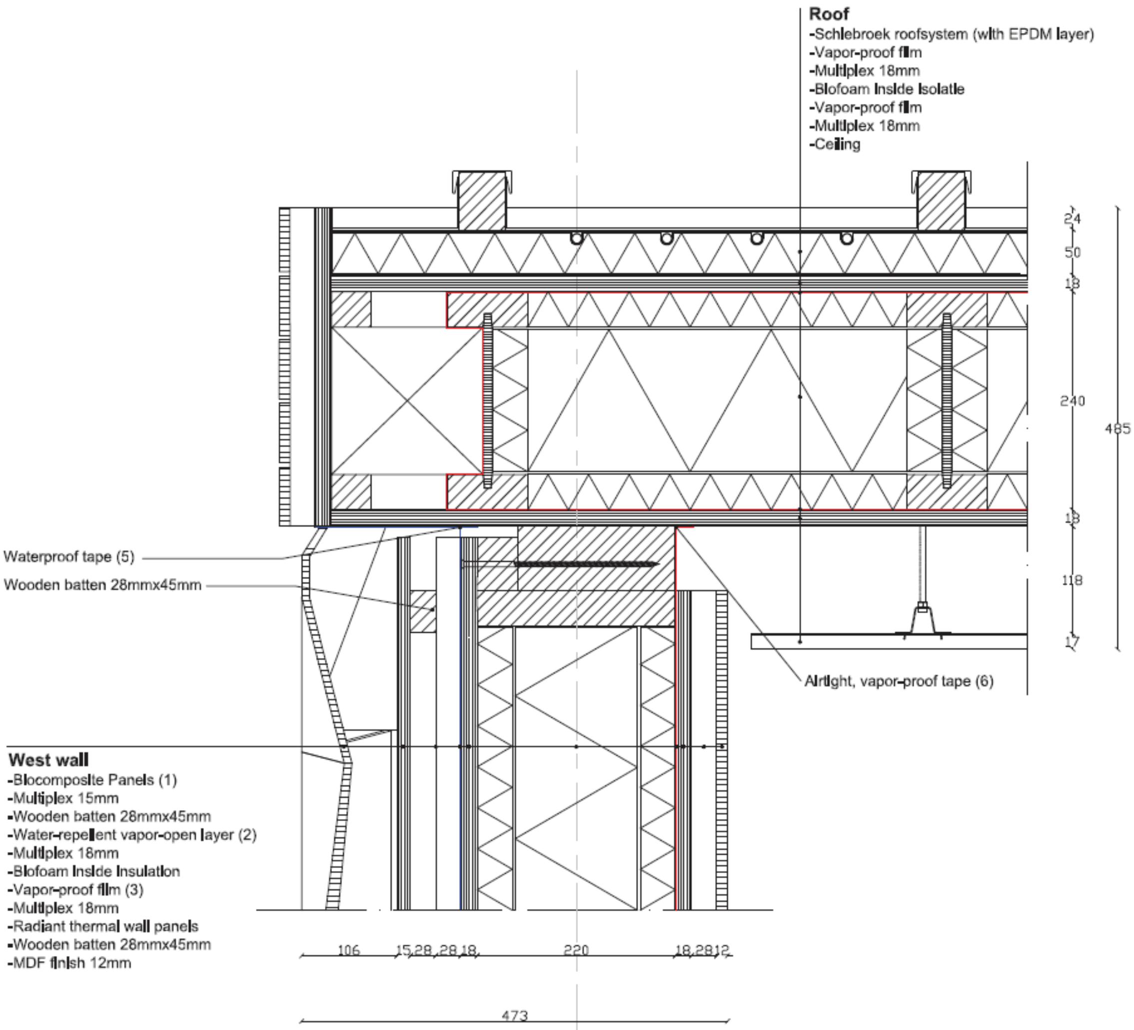


Furthermore, all panels were designed with the same structure and connections between panels, to facilitate their prefabrication and construction. The connections of the panels were made by screws not requiring glue. Panels were fully reusable and demountable thereby enlarging their useful life. Panels were assembled and joints were sealed with special tape to ensure a water, damp proof and airtight envelope (Figure 17).

The cladding of the apartment was also made of biomaterials, which were mostly made from waste fibers like toilet paper and roadside grass, calcium carbonate ($CaCO3$), waste material from drinking water companies and bio-based polyester resin (NPSP 2018; Willem Bottger 2019). These materials were mixed into a dough and pressed under high pressure (10 MPa) and temperature (140°C) into rigid tiles (Figures 18 and 19). Afterwards, these were mounted on the outer walls of the building.

Some of the requirements of the tile design was that they should allow upward airflows within to dissipate the heat and cool down the apartment (Figures 20 and 21). In addition,

FIGURE 15. Detail of the West wall and the roof (Team VIRTUe 2018b).



they should be cradle-to-cradle, impermeable, resistant and light. Therefore, bio-based materials were considered one of the best options to build this façade.

Tilted Roof, Canopy Roof and North Beam

The tilted roof was supported by the North beam. This beam balanced the forces between the tilted roof and the canopy roof, and transferred them to the structural core (Figure 22). When the roof exercised a compressive force on the North beam, the canopy gave a compressive force in the other direction. In addition, several steel threaded rods were placed at the edge of the canopy roof connecting it with the tilted roof to deal with tension forces (e.g. wind) (Figures 23 and 24).

The North beam was a box girder made of Kerto®-Q panels, which is a strong, dimensionally stable and laminated wood. The girder was filled with Thermoflex®, which is durable

FIGURE 16. Detail of the West wall and the floor (Team VIRTUe 2018b).

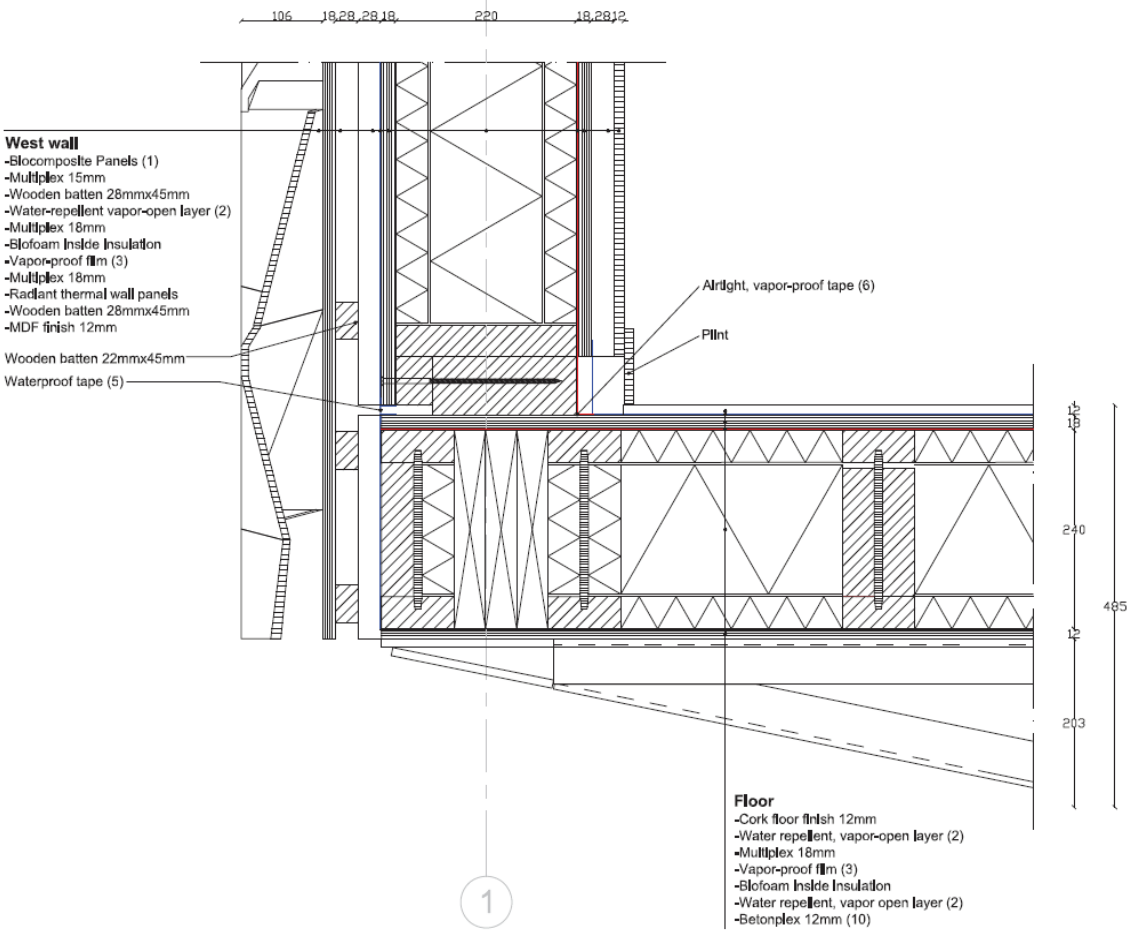


FIGURE 17. (Orange) foils stick out from the panels to seal them afterward (Team VIRTUe 2019).

FIGURE 18. The bio-based dought was placed inside the mould.

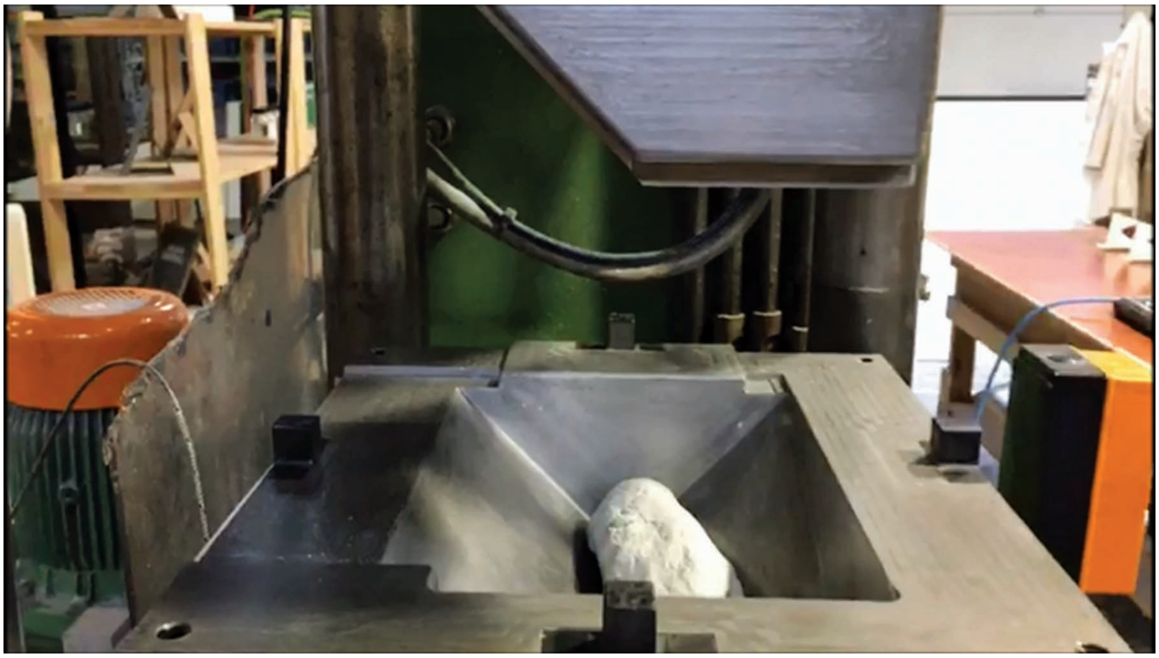


FIGURE 19. The bio-based dought was pressed under high pressure and temperature.

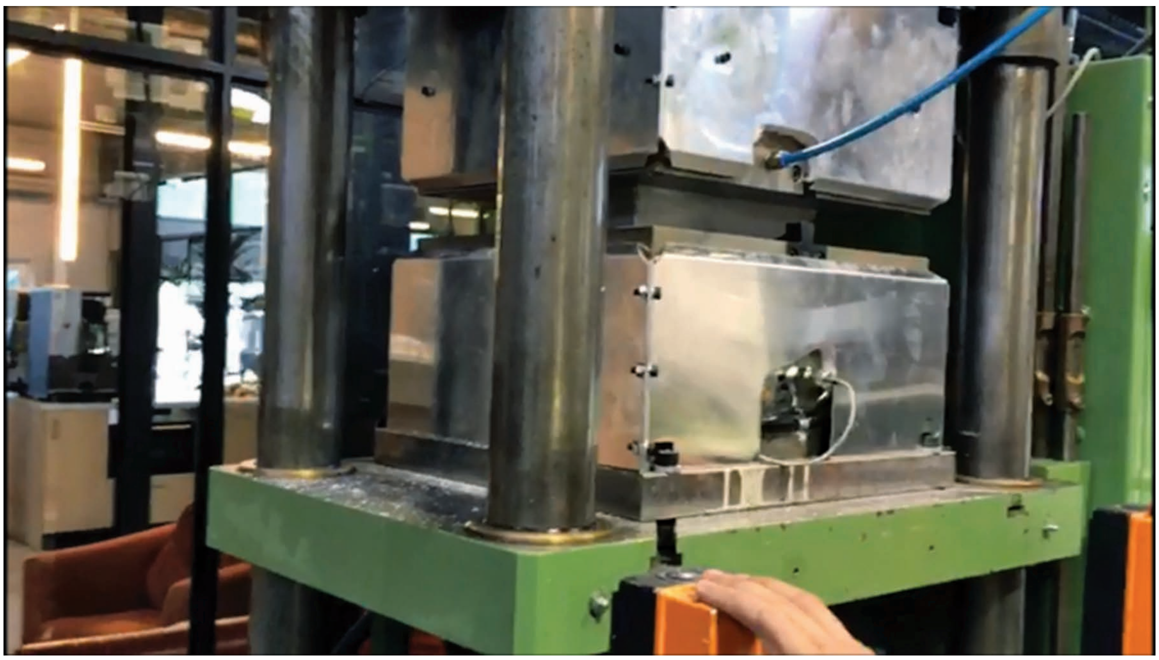


FIGURE 20. Façade tiles should allow upward airflows (Team VIRTUe 2018b).

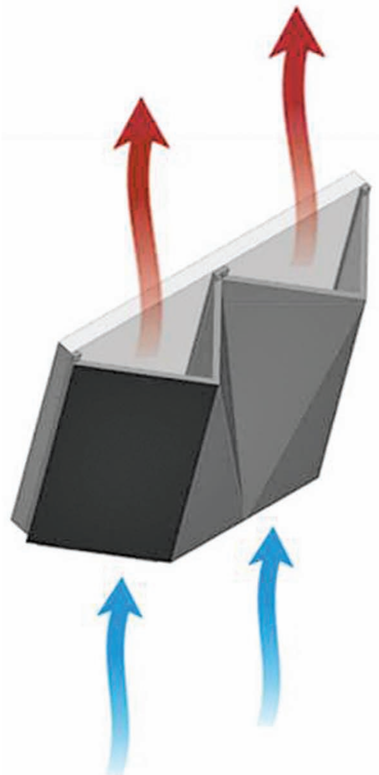


FIGURE 21. The form of the tiles was repeated as a pattern all over the façade (Team VIRTUe 2019).

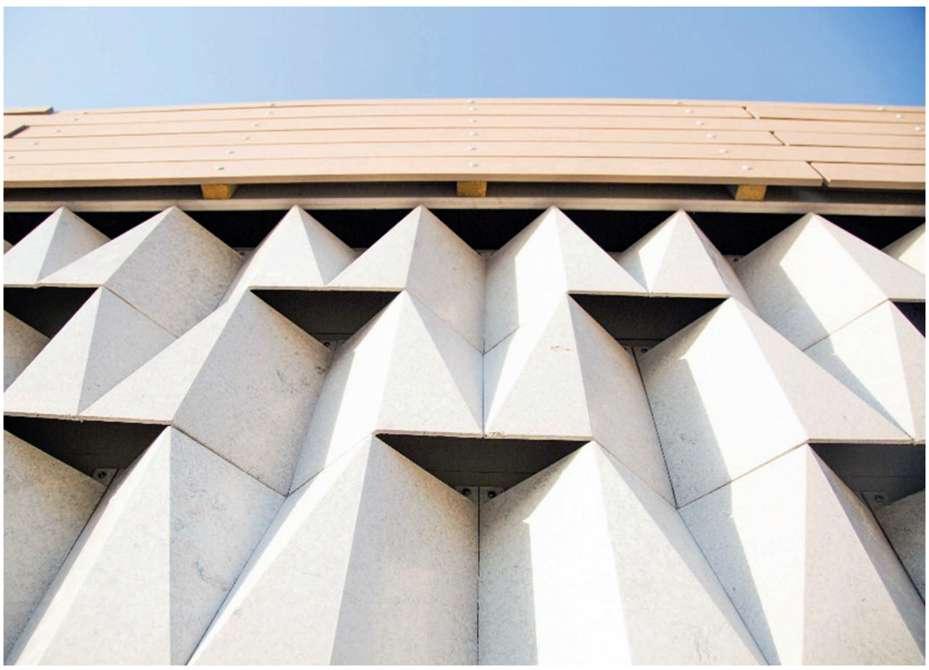


FIGURE 22. The tilted roof, the North beam and the canopy roof. (Team VIRTUe 2019).

insulation made of wood wool. The North beam had a very high strength and moment capacity and transferred the compressive forces to the structural core, East and West walls. Additionally, the tensile forces were directly transferred to the module supports by bending moments in the North beam.

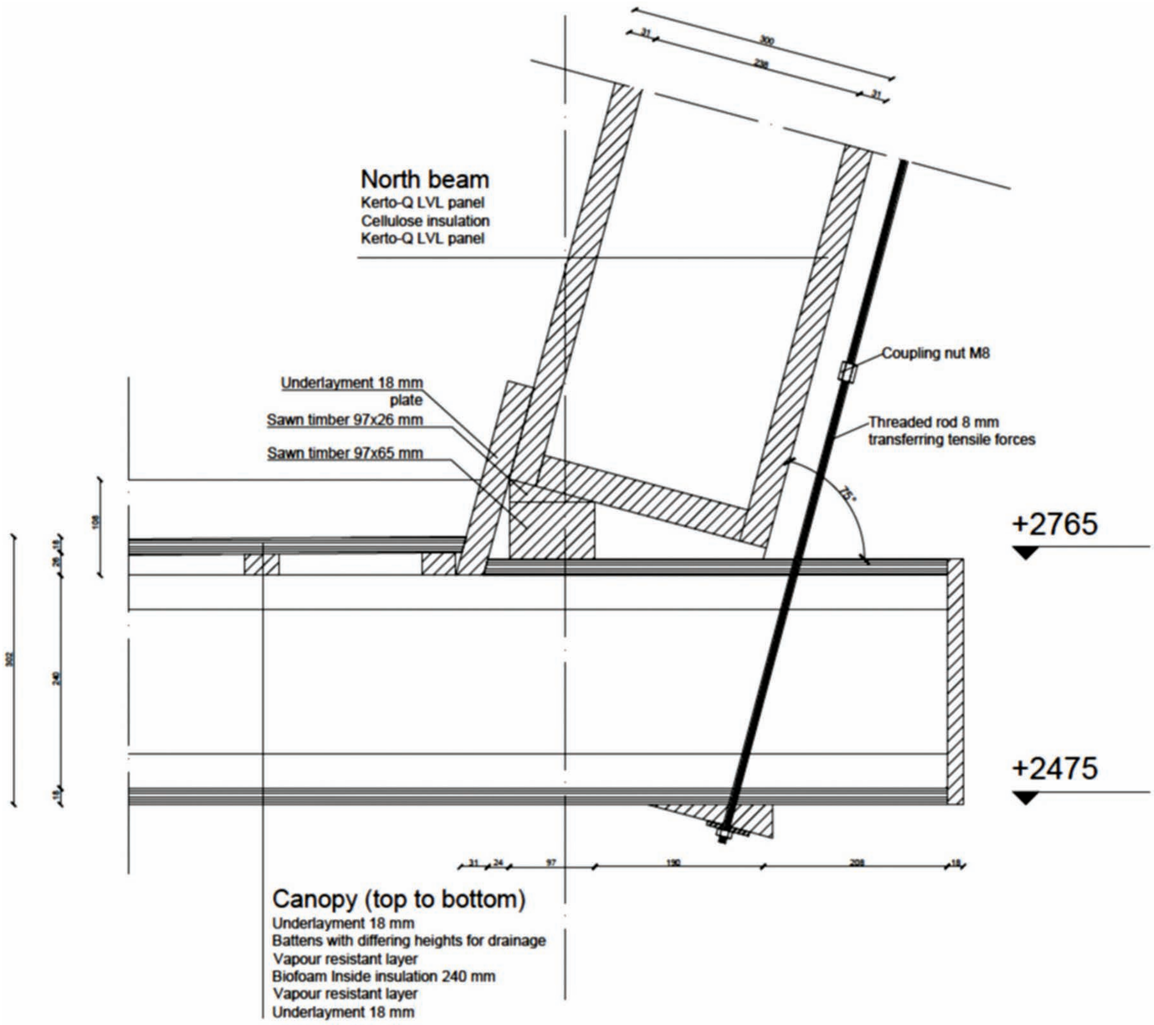
The South Wall

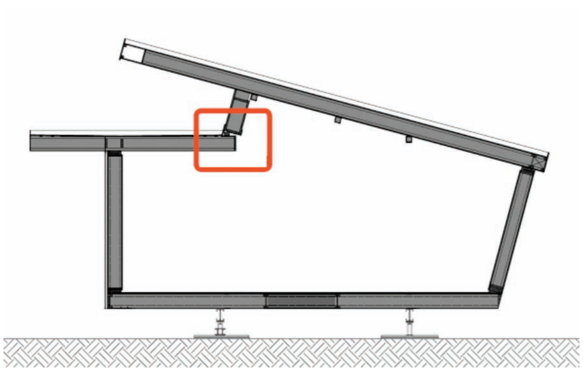
The South wall supported part of the loads of the tilted roof and laid over the apartment floor (Figures 25 and 26). If the South wall had transferred all loads to the floor, the latter would have failed. Therefore, a part of these loads was transferred also to the West and East walls, which were used as supporting truss beams.

Steel Threaded Rods and Plates

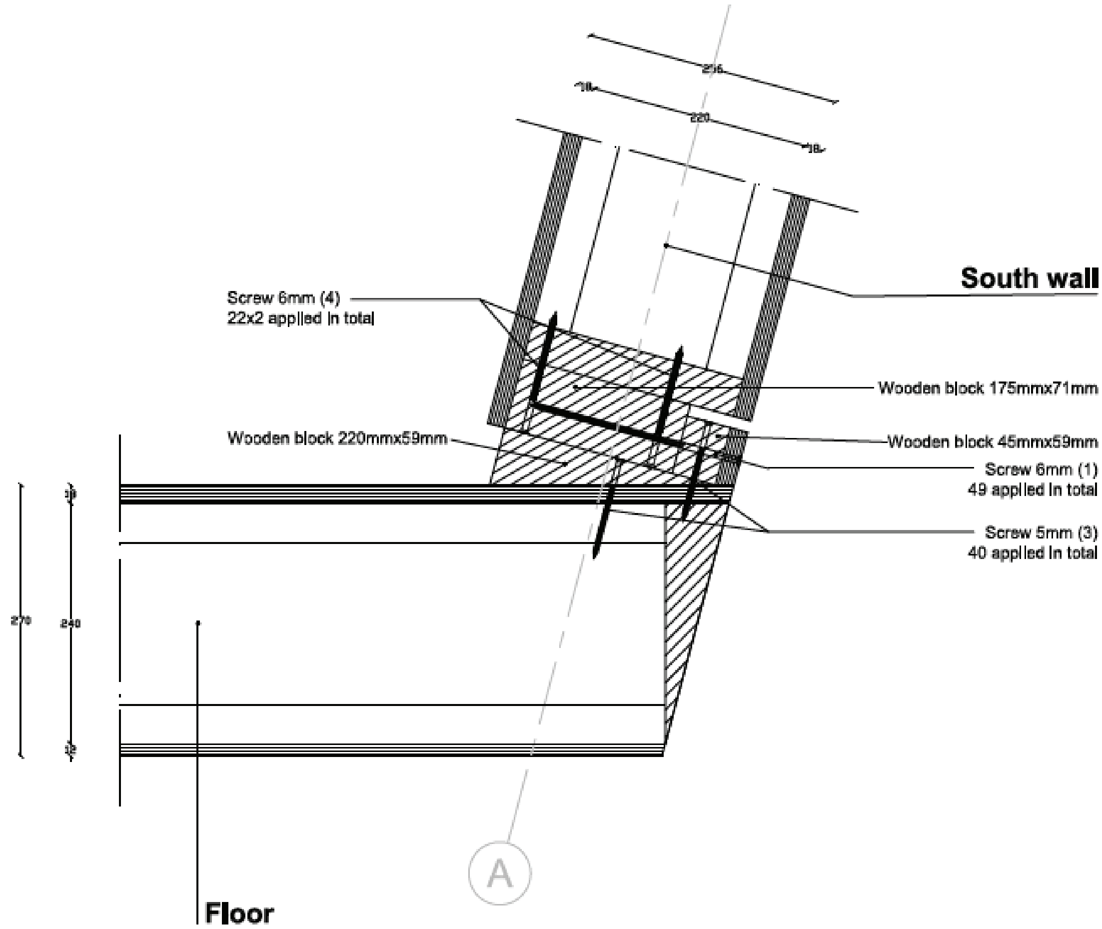
Lastly, due to the combination of many overhangs and high wind forces, tensile forces occurred in the structure. The tensile resistance of timber is not high compared to the compressive resistance. For this reason, steel threaded rods and plates were used in connections to transform tensile forces in timber into compression forces (Figure 27). If these connections had been made with screws, larger timber elements would have been required in order to prevent the timber from splitting.

FIGURES 23 AND 24. Steel threaded rods connected the tilted roof with the canopy roof (Team VIRTUe 2018b).





FIGURES 25 AND 26. The screwed connection between the South wall and the apartment floor (Team VIRTUe 2018b).



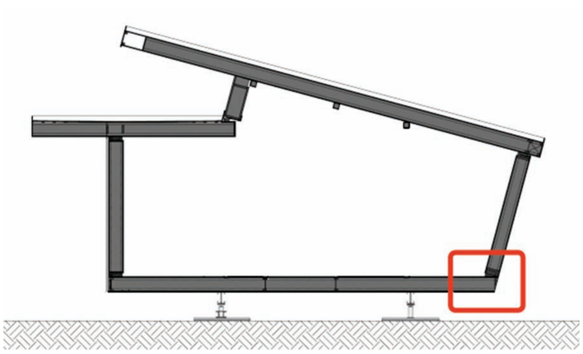
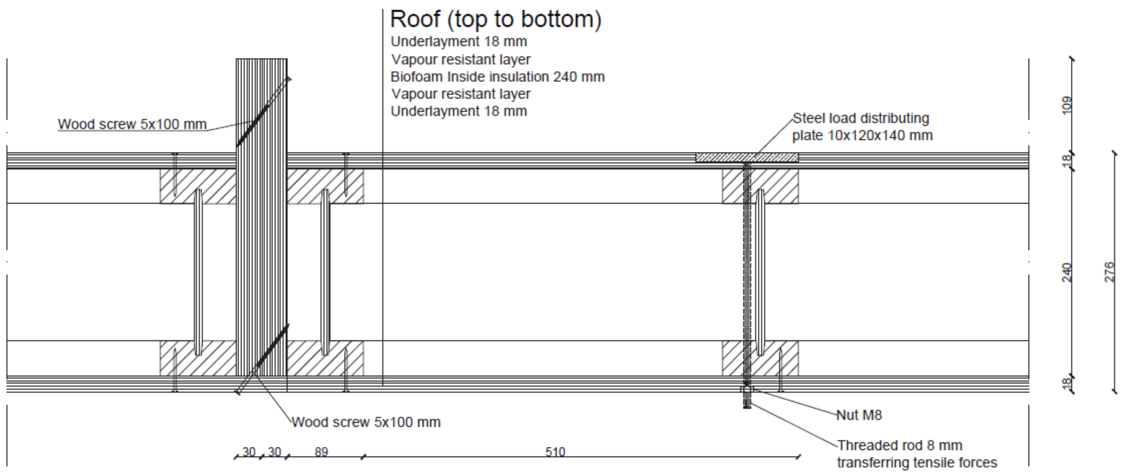


FIGURE 27. Steel threaded rod and plate mounted in a roof panel. The steel plate distributed the compression exerted by the threaded rod to the panel (Team VIRTUe 2018b).



6. PASSIVE ENERGY STRATEGIES INTEGRATED INTO THE APARTMENT

Several passive energy strategies were integrated into LINQ. For instance, the South façade was tilted outwards at 15° to the vertical to reduce solar exposure during the summer (Figure 28), while the roof was tilted towards the South at 15° to the horizontal to increase the harvesting of energy. In addition, there were two large windows to improve daylight and outside views. These windows were double-glazed with a metallic coating to reflect radiation. In addition, the South and West façades were ventilated. The outdoor cladding was made of tiles. These absorbed the heat of direct sunlight, avoiding the overheating of the walls (Figure 29). Another strategy was

FIGURE 28. The South façade was tilted to reduce solar exposure during summer (Team VIRTUe 2018b).

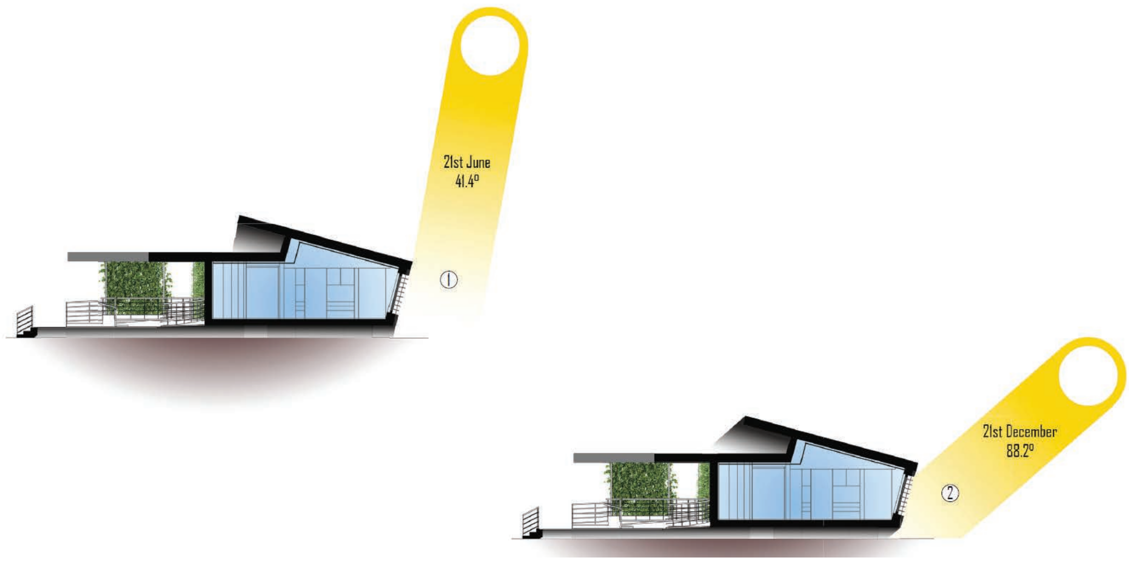


FIGURE 29. The South façade was ventilated and had several windows (Team VIRTUe 2019).

the thick insulation of the panels which contributed to reducing the heat transfer. Moreover, the North wall was covered with plants to provide natural cooling and improve air quality (Figures 30 and 31) (Othman and Sahidin 2016).

FIGURE 30. The cladding tiles absorbed the heat of direct sunlight, avoiding the overheating of the walls (Team VIRTUe 2018b).

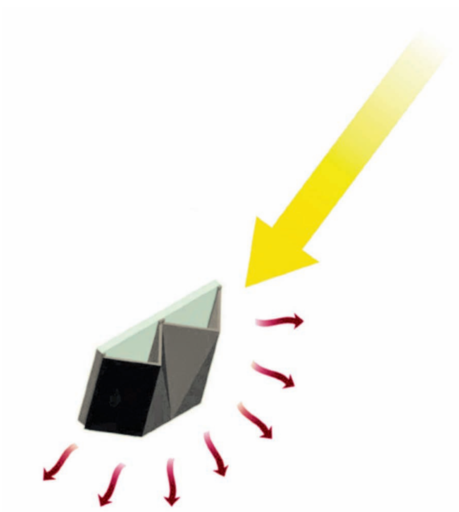


FIGURE 31. The North façade was covered with plants (Team VIRTUe 2019).

7. SEMI-PASSIVE ENERGY STRATEGY INTEGRATED INTO THE APARTMENT

Most of the required energy in buildings in the United Arab Emirates (UAE) is required to cool the indoor environment (Radhi 2009). One of the mechanical systems employed in LINQ was the radiant cooling system, which is a semi-passive strategy, also used in previous Solar Decathlon competitions (Azarbayjani et al. 2014; Ma et al. 2019). Chilled water, stored in a 500-liter buffer tank, was pumped into the radiant panels in the East, West, and part of the North external walls, which absorbed heat through radiation and convection from the indoor space (Figure 32). The return water flowed back to the buffer tank throughout the entire day before being cooled overnight using the existing PV/T system (Figure 33). The principle

FIGURE 32. Day operation of the PV/T cooling system.

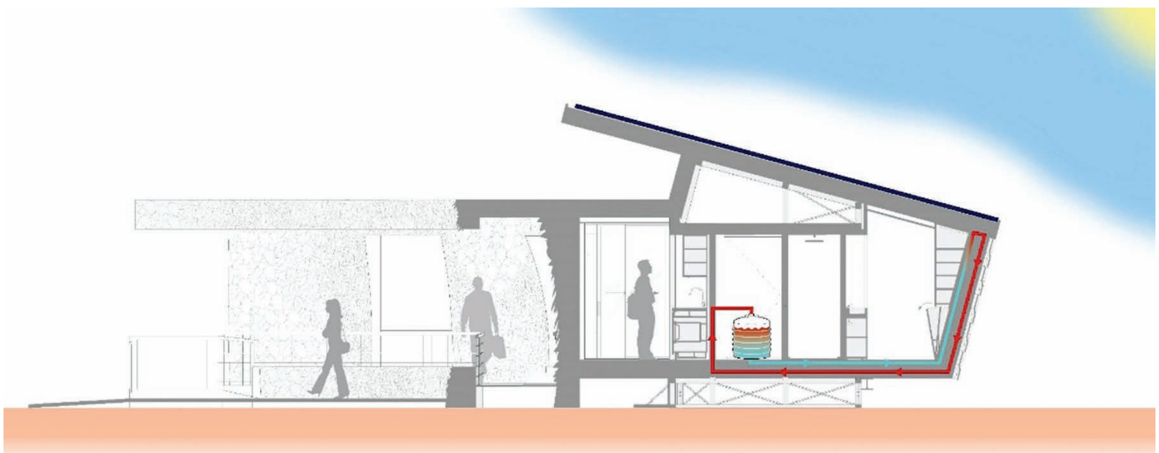
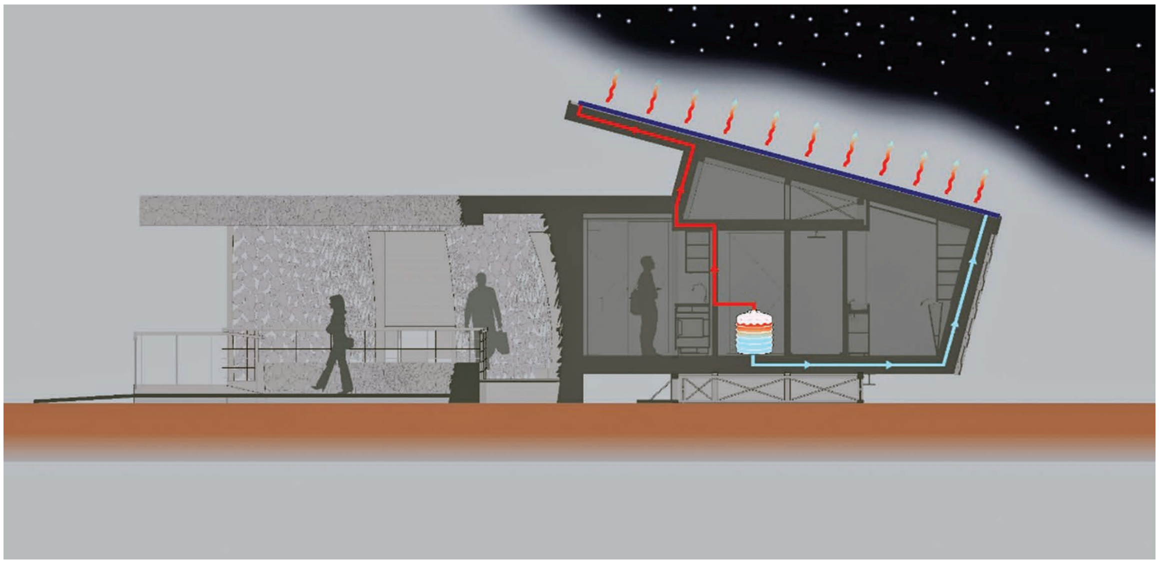


FIGURE 33. Night operation of the PV/T cooling system.



by which the water was cooled is called *"nocturnal sky radiant cooling"* (Gürlich et al. 2017). The heat from the *"warm"* water in the buffer tank was rejected to the night sky using long-wave radiation.

8. ACTIVE ENERGY STRATEGY INTEGRATED INTO THE APARTMENT

The main active system in LINQ to generate energy was the building integrated photovoltaic-thermal (BIPV/T) system (Figure 34). It consisted of 6 panels mounted in parallel with an area of 7.65 m^2 each. The final circuit was wired to two inverters: a primary inverter that only output energy from PV array to the AC-loads and Solar Hai grid, and a second inverter that interfaced both PV array and energy storage system (ESS) with the AC-loads in the building (Team VIRTUe 2018b). Together they could generate 7700 watt-peak (W_p) of electricity.

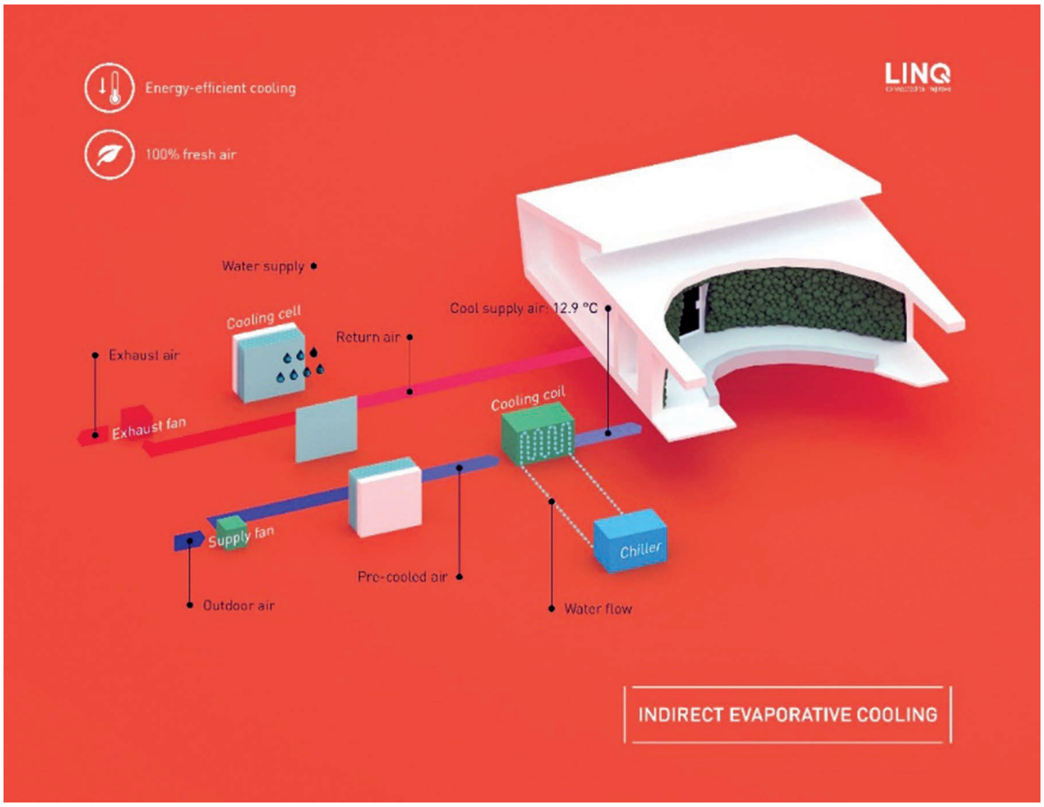
The BIPV/T system, broadly speaking, consisted of a PV system disposed over a solar thermal system. The covering layer of the BIPV/T system was black colored and highly absorbent. Under this layer, there was a system of pipes with a liquid mixture that extracted the solar heat from the roof covering and transport it to a heat-cold storage system, where it was stored for a short period of time until it was needed.

Some of the main advantages of this BIPV/T system respect to conventional ones are that PV panels are thinner, thus it reduces significantly the weight of the roof. In addition, PV panels incorporated amorphous photovoltaic cells which capture the indirect light of the sun. Moreover, this system absorbs and drains the excess of the heat of the roof that can occur in hot days, which enhances the power yield from the PV cells. Finally, there is no coupling under the top layer of the roof, which prevents the risk of leakage and enables to walk on the PV panels.

Another strategy was to use evaporative cooling and heat recovery to cool down indoor spaces (Figure 35). This system did not reuse or recirculate the foul air from the rooms and thus provided 100% fresh air into the conditioned space. The counter-flow heat exchanger employed water to wet a mesh which cooled down outside hot air to the desired temperature. Since the air was being indirectly cooled, better efficiency in temperature drop was achieved.

FIGURE 34. The building integrated photovoltaic-thermal system was integrated into the roof (Team VIRTUe 2019).

FIGURE 35. Indirect evaporative cooling was used to conditioning the indoor spaces (Team VIRTUe 2018b).



Moreover, diffusers employed underfloor air distribution (UFAD) with displacement ventilation. The walls of the central module had return vents at the highest point, which exhausted out the return air. The advantage of the UFAD system is two-fold. Firstly, the thermal stratification reduces the cooling energy since only the breathing zone is cooled whereas in the upper zone there is relatively hotter and exhausted air. Secondly, displacement ventilation avoids the mixing of air using low velocities, which as a result effectively removes indoor contaminants. It must be noted, however, that this is the case when humans are only the source of contaminants. The return air was channeled through the air handling unit to recover *"coolness"* by absorbing heat only from incoming outdoor air before being exhausted, meaning there was only sensible heat that was transferred.

9. ACHIEVEMENT OF NET ZERO-ENERGY PERFORMANCE

Simulations tools are usually used during the design and construction phases of buildings. Some energy analysis (Alsailani 2018) were conducted on LINQ to improve its performance. Electrical balance simulations were calculated with TRNSYS (TRNSYS 2019) and using the weather file from the AL-Maktoum International Airport (White Box Technologies 2019). TRNSYS provides a wide variety of transient models with different modeling complexity in a flexible graphical interface. Moreover, the software provides all the sub-models and simulation outputs needed to fulfill the goals of the study. The complexity of each sub-models was assessed to minimize simulation errors. A simple model provides errors due to approximation, while a complex model introduces uncertainty due to estimation. Therefore, a compromise solution minimizes simulation errors (Gaetani et al. 2016). To minimize simulation errors, the modeling complexity of each sub-model was determined based on its objective. The influence of some modeling uncertainties was evaluated later in a sensitivity analysis study that has not been incorporated herein because it was not relevant for the results. In addition, TRNSYS component Type 56 (SEL 2007) was used for modeling the thermal zones of the apartment. This model uses a heat balance method which is suitable for solving room indoor conditions and suits the case study (Pedersen, C.O., D.E. Fisher 1997; SEL 2007).

The envelope was calculated accordingly several data sources and assumptions. The envelope is made of lightweight construction materials and has a very high thermal resistance insulation. Biofoam® insulation with a thickness of 240 mm (R-Value of 7.2 m^2 k/W) was used in the floor and the roof; and with a thickness of 220 mm (R-Value of 6.6 m^2 k/W) in the exterior walls. Thermal properties of the envelope are summarized in Table 1. In addition, fixed heat

TABLE 1. Calculated building envelope thickness, R-Value, U-value, and capacitance.

	Total Thickness (mm)	R-value (m^2 k/W)	U-value (W/m^{2}k)	Capacitance (J/m^{2}k)
Floor	286	7.48	0.131	65.04
Roof	296	7.99	0.127	61.24
East, West and South Walls	368	7.66	0.127	104.31
North Wall	518	7.3	0.133	506.61

TABLE 2. Estimated U- and G- values for windows and doors.

Openings	U-Value (W/m²k)	G-Value (%100)
Windows	1.34	0.63
Doors	0.70	0.14

transfer coefficients of 7.7 W/m^2K and 25 W/m^2K were used for the interior and the exterior surfaces, respectively. It was considered an absorbance coefficient of 0.6 for all interior surfaces; 0.3 for the East, West and South walls; and 0.6 for the roof and the North wall. Besides, no detailed data of windows was found, therefore approximate common values were used as shown in Table 2. Finally, a default interior shading (e.g. curtains) was assumed for the windows.

To calculate the simulations, a simplified geometry for the building envelope was created (Figure 36) which contains similar wall dimension, slopes, and shading to the actual apartment design (Figure 37). In addition, the model was divided into different thermal zones which have different thermal conditions (Figures 38 and 39). Characteristics of these zones are summarized in Table 3. In addition, airflow between adjacent zones was modeled, and 0.1 air changes per hour for infiltration was assumed as the apartment construction is airtight.

The loads for modeling the apartment are explained below. First, two occupants were assumed to live in the apartment. Internal heat gain for the occupants was approximated according to the 2013 ASHRAE Handbook Fundamentals (ASHRAE 2013) (Table 4). Second, electrical loads and heat gains of the apartment lighting and appliances were approximated according to studies shown by 2014 Building America Simulation Protocol loads for new

FIGURE 36. The geometry of LINQ with TRNSYS.

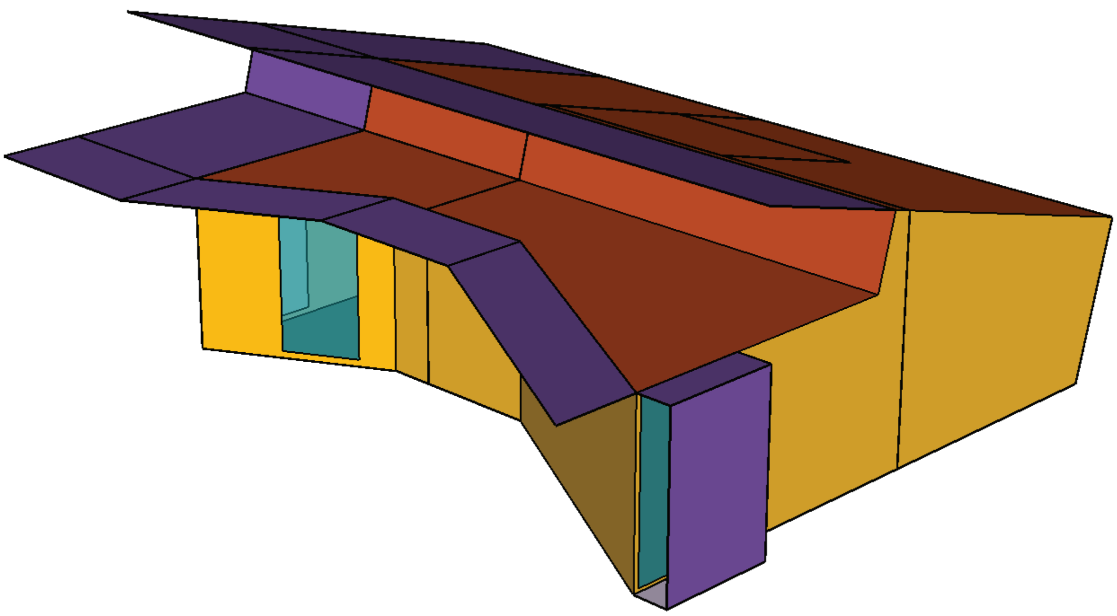


FIGURE 37. The geometry of LINQ with a drawing software.

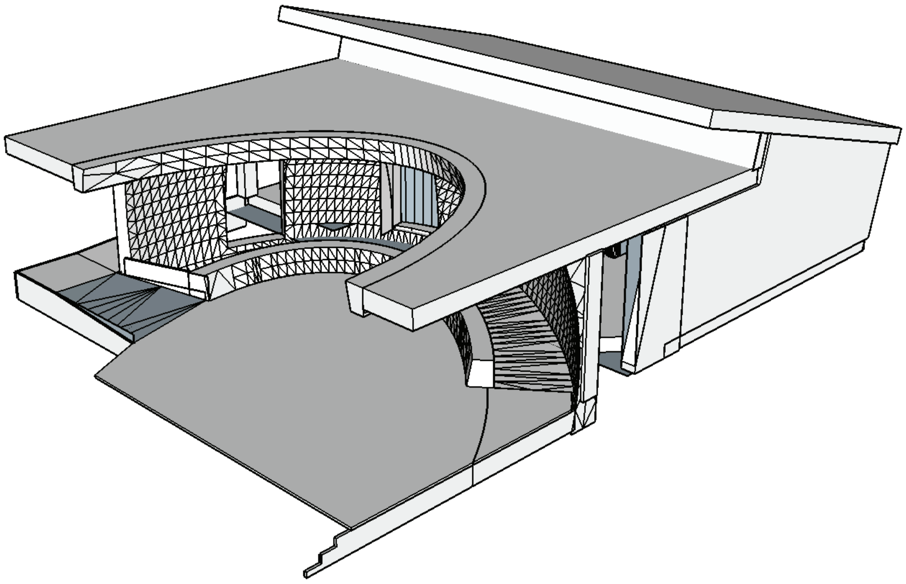


FIGURE 38. Floor plan with different thermal zones. The air supply and exhaust terminals are included with their flow rate.

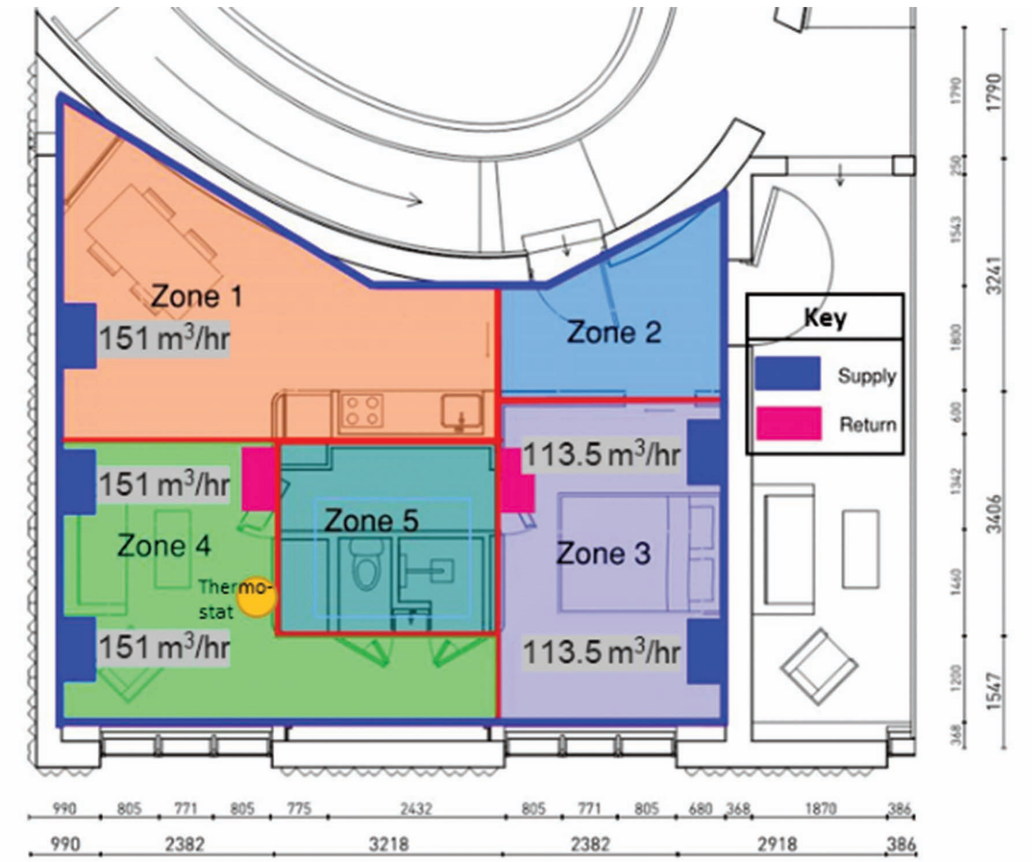
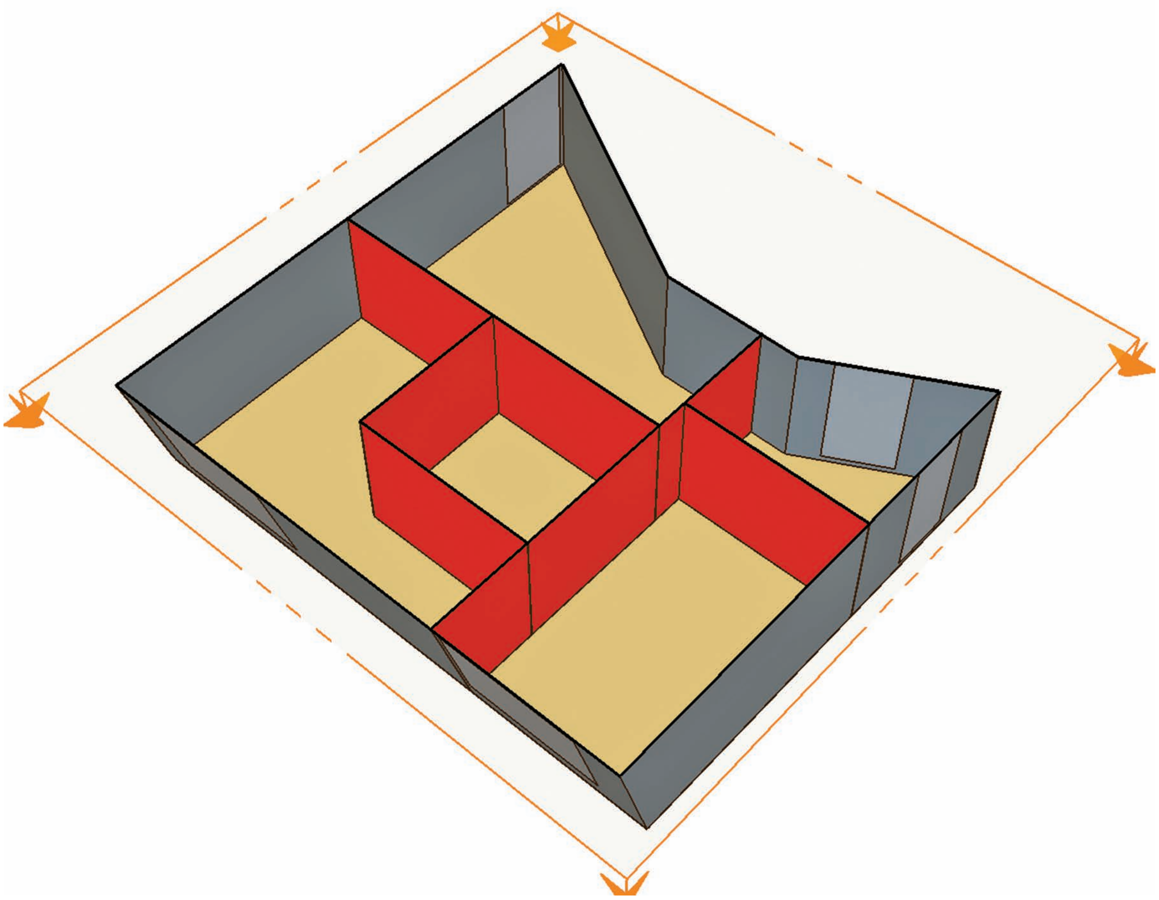


FIGURE 39. Top section view for the TRNSYS model.



construction (Wilson Jiang et al. 2014; EPDF 2010; KEMA 2009). Table 5 summarizes daily end-use electric consumption for appliance and lighting. It is noted that the lighting loads are very low compared to appliances since the apartment is using LEDs lighting only. It was assumed that all the loads have only convective gains. The total equipment and lighting hourly schedules were modeled according to R. G. Pratt et al. (1989) shown by the protocol.

TABLE 3. Zone occupancy category, floor area, and conditioning status.

Zone	Occupancy Category	Area (m^2)	Conditioned
1	Dining	19.01	Yes
2	Entrance	6.13	No
3	Bedroom	14.2	Yes
4	Living Room	15.5	Yes
5	Service	8.12	No

TABLE 4. The internal gain for one person. The degree of activity is III (seated, very light work) with 24°C room dry bulb temperature (115W per/person).

Sensible Internal Load (W/person)		Latent Load (W/person)
Radiant	Convective	Moisture
28	42	45

TABLE 5. Daily electric end-use for appliance and lighting. Partial sensible and latent gains are included.

Devices	Daily Electricity Use (kWh)	Sensible Load Fraction	Latent Load Fraction
Appliance	8.88	0.70	0.057
Lighting	1.53	1	0

Estimations of the monthly energy consumption and production of LINQ are shown in Figure 40. As can be seen, the energy production of the BIPV/T system counteracts completely the energy consumption of the HVAC system, appliances, hot water and lighting in all months. In five months, the production of energy is higher than the consumption (February, March, April, June and August). The HVAC system and appliances have the highest energy consumptions during the year. Nevertheless, the energy consumption of the HVAC system is greater during summer months because of the use of air conditioning.

FIGURE 40. Monthly energy production and consumption. *Terminology: HVAC system—Heating, ventilating and air conditioning. BIPV/T—Building-integrated photovoltaic-thermal system.*

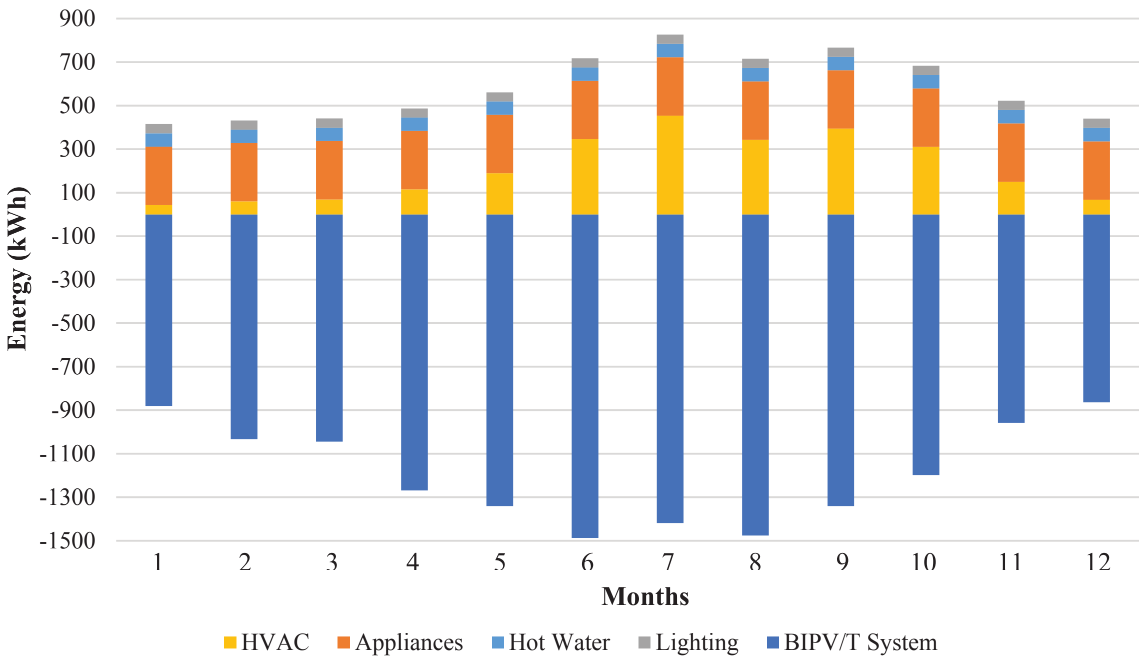
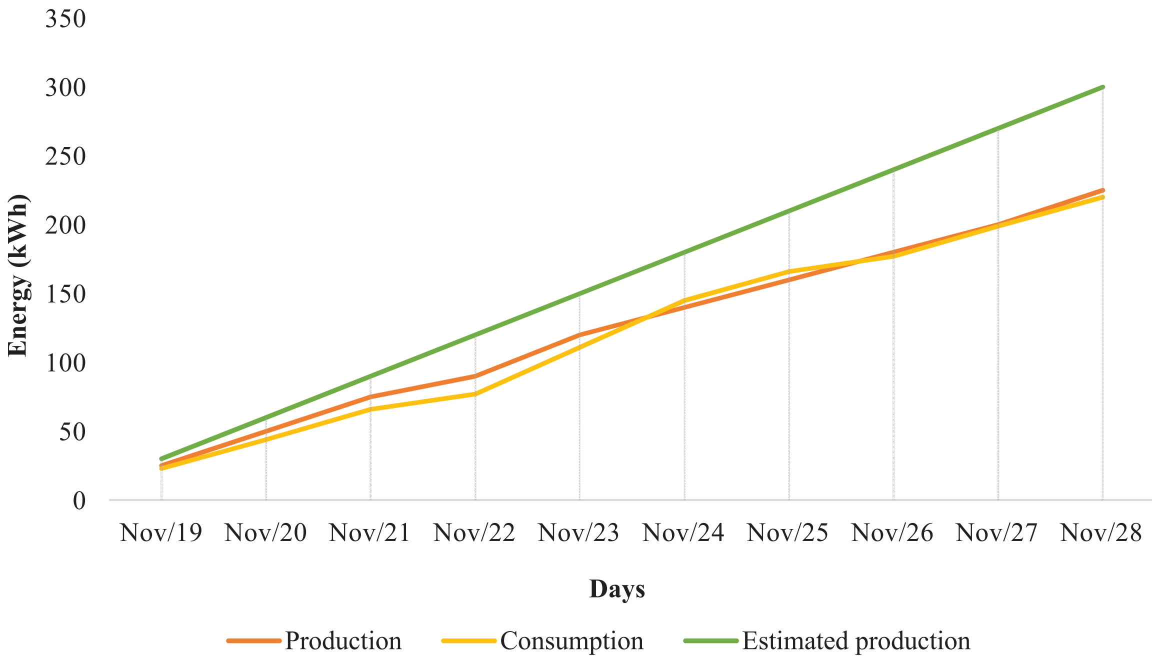


FIGURE 41. Energy production, consumption, and estimated production during the competition in Dubai.



As a result of the good net electrical energy balance, LINQ earned all points from this competition category. This means that the amount of energy sent to the grid was equal or higher than the energy drawn from the grid during SDME. Nonetheless, the energy production was around 29% (i.e. 2200 W_p) lower as expected in the simulations because one of the inverters was damaged during transport to Dubai. Consequently, some panels of the BIPV/T did not work. Had the inverter functioned properly, the energy production would exceed the energy consumption resulting LINQ in an energy-plus building (Voss et al. 2011). Figure 41 shows the energy production and consumption according to LINQ sensors during the days of the competition, and the estimation of the energy production if the inverted had worked properly.

One the other hand, LINQ was designed as an apartment of LINQ the apartment complex. Some buildings (such high-rise buildings) require more energy despite the same floor area. Thus, Team VIRTUe proposed to use the East façade of LINQ the apartment complex to install BIPV/T panels in order to compensate this possible increase in energy consumption.

10. CONCLUSIONS

This article explains the design, construction and energy strategies of LINQ, a net-zero energy building that was successfully entered into the Solar Decathlon Middle East 2018 held in Dubai. The building is mainly made of bio-materials, mostly powered by solar energy, transportable by container, and easy and fast to install (15 days). Some of the main innovations are the bio-based ventilated façade with customizable tiles, the indirect evaporative water-cooling system, and the BIPV/T system. Main conclusions are summarized below:

- The centralization of building forces in a structural core minimizes the installation of the structure and consequently reduces the time to assemble the building.

- This structural core was equipped with installations, kitchen, toilette and shower, which were installed in The Netherlands; thus facilitating the transport, diminishing assembly times in Dubai, and reducing human error.
- The repetition of the constructive details and solutions eases the design and construction of the building. It also facilitates that the envelope is water, damp proof and airtight.
- According to simulations, the energy production of LINQ, located in Dubai, is greater than its consumption in all months, which makes LINQ an energy-plus building. In addition, the energy production doubles the consumption in five months. Besides, the use of HVAC and applications should be controlled, especially in summer, since they showed the highest energy consumptions.
- During the competition (November), the amount of energy sent to the grid was slightly greater than the energy drawn from the grid, which makes LINQ at least a net zero-energy building. Had the inverter functioned properly, it would have provided a better electrical balance for the building, which goes in line with the simulations. It follows that it is possible to construct a building mainly made of bio-based materials to achieve these energy yields, thereby reducing both emboddied and operational energy of the building.

These constructive and energy innovations could be applied to buildings from other locations, and also temporal buildings. Nonetheless, the selection of them should always take into account the specifications of each location. LINQ will be installed in the Netherlands shortly, which will provide a great opportunity to take data and draw conclusions of its energy performance in another climate.

ACKNOWLEDGMENTS

We would like to thank: VIRTUe who designed, built, managed and dismantled LINQ; R.C.G.M. Loonen, M.Z. Tantawi and Hèrm Hofmeyer for their valuable advice; and TU/e, Oxycom, EPC, NPSP, VolkerWessels and Stam+DeKoning for their support.

This research was supported by the Stimuleringsfonds Metropool Regio Eindhoven (MRE); Europees Innovatieprogramma Zuid Nederland (OPZuid); and Impulsregeling SER Brabant voor innovatie en bedrijvigheid in energie in de gebouwde omgeving voor bedrijven in de provincie Noord-Brabant (SER).

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