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A High Performance Controlled Temperature Building Shell for the Sustainable Upgrading of Buildings

Angeliki Kylili[a], Paris A. Fokaides[a,*]

[a] *Frederick University, Cyprus, School of Engineering and Applied Sciences, 7, Frederickou Str., 1036, Nicosia, Cyprous*

Abstract

The energy and environmental upgrading of the built sector is a burning topic that has urged scientific communities worldwide to keep searching for innovative high performance sustainable building products, systems, designs, and practices. The synergy among several approaches and methodologies has been widely accepted and established as the key in achieving the most sustainable constructions. The aim of this paper is to present a novel high performance building element that establishes a building's thermal comfort and effective cooling, while at the same time it has negligible energy requirements. The operation of this innovative solution is based on an active controlled temperature building shell that employs airflow patterns for the stabilization of the building's temperatures. This work investigates the energy performance of the controlled temperature building shell through the employment of numerical simulation tools, while life cycle methodology is also implemented for the assessment of the environmental impact of the novel element. The results and conclusions of the analysis will establish the overall level of performance of the proposed solution, and demonstrate the significance of integrating several methodologies for the promotion of the sustainable upgrading of the building sector.

Keywords: Building element; thermal comfort; numerical simulation; Life Cycle Assessment; double skin facade

1. Introduction

The European Union is aiming for a 20% cut in Europe's annual primary energy consumption by 2020. Several measures have been proposed to increase efficiency at all stages of the energy chain [0]. The measures focus mainly on the building and transport sectors, where the potential for savings is greatest. Building operation causes many forms

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* Corresponding author. Tel.: +35722394394; fax: +35722438234.
E-mail address: eng.fp@frederick.ac.cy

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of environmental degradation that place an increasing burden on Europe's resources and jeopardize the future of the building industry and societal health and welfare [0]. It is expected that cutting-edge building materials and elements will play a major role in the fulfillment of the European energy targets. Accordingly, the improvement of the thermal properties of the building envelope represents one major strategy towards promotion of energy efficiency and energy conservation in the building sector. Among the established solutions, double skin facades (DSF) have been proven to have added advantages in improving thermal insulation performance of the building envelope [0]. For that reason the employment of DSF has gained significant popularity within the building sector, while the fundamentals of their operation could potentially form the basis for the development of new innovative building elements.

The key objective of this study is to introduce and validate the performance of a novel concept, the Controlled Temperature Building Shell. The operation principle of the Controlled Temperature Building Shell is based on the continuous induction of controlled-temperature air within the building envelope, conditioned with the use of a heat pump, resulting to a steady building shell temperature. The introduced concept is validated both with the use of finite element analysis (Comsol Multiphysics) [0], as well as with the implementation of a comprehensive life cycle assessment, (EcoHestia Database) [0] . In this study a brief review of the current DSF technologies is implemented. The methodology of the study and information regarding the parameters and conditions of the numerical simulation tools is also provided. This study constitutes a "proof-of-concept" validation of the Controlled Temperature Building Shell. The basic principles of this concept are reported, the technology concept is formulated and its numerical critical functions are described. The Controlled Temperature Building Shell is set into an appropriate context and a numerically-based study to validate its analytical prediction is implemented. The results of the analysis and the lessons learnt are presented in Section 4.

2. Theoretical Background

2.1. Double- skin ventilated facades

DSFs are multiple layer skins constructions, which are typically comprised of an external skin, an intermediate space and an internal skin, such as a cavity is formed where air is flowing [0] [0]. Within this context, DSFs can collect or discard heat, and can also be operated under different ventilation modes, depending on the building energy requirements and the climatic conditions. The Trombe wall concept can also be considered as a DSF application [0]. According to Zhou and Chen [0] and Wong et al. [0] most of the studies about DSFs performance have been carried out in colder and temperate climate conditions, including Europe, North America, and Japan, while recently DSF have also appeared in the hot-summer and cold-winter zones. With regard to their design features, DSFs offer a number of benefits. The air channel can significantly reduce the heating and cooling energy demands [0] [0] [0] and also improve the building's thermal comfort [0]. Additionally, the external layer provides protection against the weather and improved acoustic insulation [0]. Despite the reduction of the heating and cooling demands during their operational phase, DSFs are building elements that require additional building and insulation materials that suggests higher energy consumption and additional environmental burden during their manufacturing and installation phase [0]. Life Cycle Assessment (LCA) studies of DSF take into consideration the material and energy consumption throughout their life cycle, including the raw materials extraction, production, maintaining and waste management phases. DSF LCA studies consider the embodied energy versus the energy savings achieved during their operational stage, extracting relevant KPIs. Documented LCA results indicate that the use of a ventilated façade with PCM in its air chamber reduces by 7.7% the overall environmental impact of the building, by considering a 50- year lifetime [0]. Additionally, the parametric analysis of 128 DSF configurations, undertaken in the work of [0] revealed that DSFs are more energy-efficient than single-skin in 98% of the cases, and more carbon-efficient in 85% of the cases.

2.2. Controlled Temperature Building Shell description

The operation principle of the Controlled Temperature Building Shell is based on the continuous induction of controlled-temperature air within the building envelope resulting to a steady building shell temperature. The Controlled Temperature Building Shell element shares similar structural characteristics with DSFs, incorporating an external façade, an intermediate space and an internal façade, such as air can flow within the intermediate space, and thus creating an air cavity in between the two facades. The single active cavity inside the building shell is 5cm thick, in which air of controlled temperature is circulated. The air circulating into the cavity comes from an air storage of steady temperature, the temperature control of which is achieved automatically through the employment of a heat pump. The operation of the novel building element also enables the induction of air at the inlet of the cavity, such as different airflow paths within the air cavity can be controlled, also establishing mechanical ventilation conditions. Accordingly, the flow rate of the air circuit can be adjusted depending to the changes of the external environmental temperature. Through the tuning of the air flow within the active cavity, the insulating ability of the cavity is improved and minimization of the overall building energy consumption is achieved. The structural design and operational performance of the Controlled Temperature Building Shell contribute to the fulfillment of the current building codes' requirements for achieving significant reductions of buildings' heating, and cooling demands. The Controlled Temperature Building Shell is an innovative, reliable and environmental- friendly building solution that will ensure the control of the building's shell temperature through a combination of energy management mechanisms and technologies.

2.3. Previous numerical studies of double- skin ventilated facades

Double – skin ventilated facades have been a topic of research over the last years, with comprehensive review works in literature [0] [0] [0]. The literature on this field is mainly focused in studying numerically their thermal performance under different climate zones and different ways of implementation. Some of the studies are identifying parameters that significantly impact the model results and aim towards the improvement of the thermal performance of ventilated facades. Parameters found to be given particular attention in modelling were solar radiation (Giancola et al. [0]; Hazem et al. [0]; Diarce et al. [0]), and wind and flow behavior (Diarce et al. [0]; Nore et al. [0]; Aparicio-Fernández et al. [22]), as well as the accuracy of the employed coefficients (Suárez et al. [0]).

The focus of additional studies found in literature was also the development of models that were able to reduce significantly the computation time. In particular, Zeng et al. [0] and Xue and Li [25] proposed methodologies that were not only practical, but also achieved significant time savings. Moreover, Pasut and De Carli [26] demonstrated that the time and effort for developing a 3D model for the investigation of ventilated DSFs is not justified by a substantial improvement of the results.

3. Methodology

3.1. Finite Element Method (FEM)

Under the context of this work, a 2D numerical analysis was conducted to simulate the thermal performance of the Controlled Temperature Building Shell using the heat transfer module of a Finite Element Method (FEM) computational tool (Comsol Multiphysics). FEM is an effective numerical approach for finding solutions to boundary value problems, especially transient heat transfer problems, for partial differential equations. The mesh consisted of 57558 domain elements and 10 boundary elements and the number of degrees of freedom for which the domain was solved was 84417 (plus 4330 internal).

The transient heat transfer node employed uses the following equation (Equation 1), to model heat transfer in solids [0]:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p U \nabla T + \nabla(-\lambda \nabla T) = \Phi \tag{1}$$

Conjugated heat transfer between the gaseous air and the solid building wall was assumed. Accordingly, the Congugate Heat Transfer module of Comsol Multiphysics was employed, which refers to the combination of heat transfer in solids and fluids [0]. In the building wall, conduction heat transfer mechanisms dominate whereas in the enclosed air, convection mechanisms dominate the heat transfer. The problem modelled in the simulation considered that the building envelope is made up of two opaque building walls with a 5cm wide cavity in- between, where air is circulated. External boundary conditions simulated the external temperature over the course of a day and were subjected to the exterior façade of the exterior building wall. The external boundary conditions, ranging between 10˚C and 50 ˚C throughout the day, are defined by the following sinusoidal function (Equation 2):

$$30 + 20 \times [sin(2\pi \times {}^{t}/_{24})] \tag{2}$$

Furthermore, to simulate the operation of the Controlled Temperature Building Shell, an inlet condition was assumed for the lower boundary of the fluid domain, and an outlet condition to the upper boundary. The employed inlet boundary conditions simulated the introduction of controlled- temperature air (22˚C) within the building envelope, while the outlet boundary conditions ensured that the air in the cavity was exiting the building system at temperatures and velocities that allow the establishment of indoor thermal comfort. Accordingly, the definition of the energy requirements for achieving this can be established.

3.2. Life Cycle Assessment

For the investigation of the environmental performance of the Controlled Temperature Building Shell, whole-building LCA has been conducted through the employment of the building environmental assessment tool EcoHestia [0]. The building under investigation was assumed to have a total useful area of 100 m^2 [10m × 10m]. EcoHestia is a comprehensive environmental impact LCA tool, incorporating the most commonly- used building elements for the case of Cyprus. The EcoHestia analysis performs 'cradle- to- site' LCA, and is based on the characteristics of the local construction industry and on primary data provided by local product manufacturers. The materials quantities used for the construction of the investigated building are evaluated against the Key Performance Indicators (KPIs) of the tool, which represent the environmental impact of each construction material per kilogram (kg) of material, considering all the raw materials and energy requirement for its manufacturing at the plant and its transportation to the construction site. To enable the objective evaluation between the energy savings achieved during the operational phase of the building and its environmental burden for its construction, the LCA results are expressed in terms of the embodied energy of the building per unit area.

4. Results and Discussion

4.1. Numerical analysis

The analysis has been conducted for two cases, where the one considers for a building which has a conventional 25 cm thick wall envelope, while the second case considers for a building with super- insulator 7,5 cm thick walls. The building materials thermal conductivities chosen for the implementation of the numerical simulation represent U-Values of commonly- met building types —based on the assumption of a 7,5 cm thick building wall, as defined in Table 1. It is also worth mentioning that also the time lag between peak external temperature and interior heat was taken into consideration for the numerical simulations.

Table 1. Selected building U- Values and building types (based on the assumption of a 7,5 cm thick building walls)

Selected U-Value [W/m^{2}K]	Building material thermal conductivity, k [W/(mK]	Building type
2,13	0,2100	Building with plasterboard
1,4	0,0680	Building with 10cm×10cm brick
0,5	0,0150	Building with 10cm×10cm brick and 5cm polystyrene
0,2	0,0054	Building with 10cm×10cm brick and 10cm polystyrene

indicates the minimum velocities at which the air flow of the Controlled Temperature Building Shell should operate in order to establish a steady building shell temperature. The findings of the analysis indicate that lowering the U- Value of the building, results to the operation of the Controlled Temperature Building Shell in lower air velocities to maintain a steady building shell temperature. This is evident in both cases, conventional and super-insulator building envelopes. Furthermore,

shows that the application of the Controlled Temperature Building Shell in conventional buildings is more efficient, requiring lower air flow velocities than the corresponding application in super- insulating buildings. This is directly related to the wall thickness and the relevant time lag between the exterior and internal temperatures [0]. Provided as an example, the conventional building wall study case, incorporating a building material with thermal conductivity of 0,21 W/(mK) has a time lag of 4 hours, while in the case of the super- insulator building wall, the interior temperature change is immediate (Figure 1).

Table 2. Minimum required inlet air flow velocities [m/s] to establish steady building shell temperatures for selected building U- Values

Building material thermal conductivity, k [W/(mK]	Air inlet velocity for establishing a steady building shell temperature, V_{in} [m/s]	
	Conventional building envelope	Super- insulator building envelope
0,2100	0,19	0,46
0,0680	0,13	0,30
0,0150	0,04	0,12
0,0054	0,05	0,07

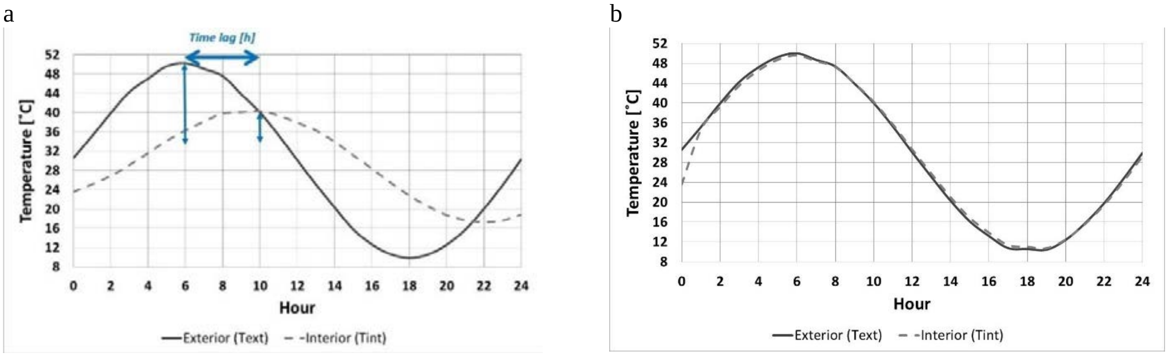
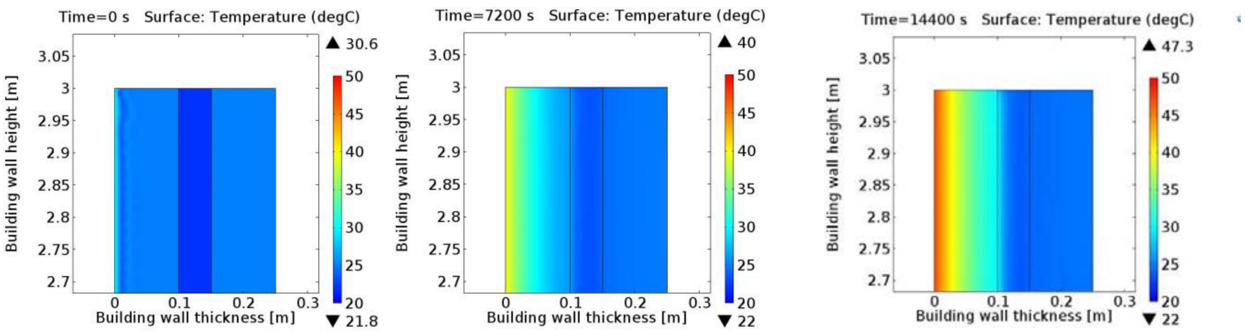


Fig. 1. Time lag between peak external temperature and interior temperature in (a) the conventional thick building envelope and (b) the super-insulator building envelope

Fig. illustrates the thermal performance of the Controlled Temperature Building Shell at the heights 0- 0.3m, 1.35- 1.65m, and 2.7- 3 m in a conventional building incorporating a building material with thermal conductivity of 0,21 W/(mK). In this case, the simulation was conducted with the assumption that the Controlled Temperature Building Shell was operating at inlet velocities of 0.19 m/s in order to maintain a steady building shell temperature. Another point that is worth noticing is the case of the Controlled Temperature Building Shell in a conventional building incorporating a very low thermal conductivity building material (0,0054 W/(mK)). From the velocity graphs of the specific numerical simulation, it is indicated that the very low air velocities required for the establishment of a steady building shell temperature allow the development of vortex along the first meter height of the air cavity of the Controlled Temperature Building Shell, as indicated in Fig. . Although in Table 1, it is indicated that the minimum air inlet velocity for establishing a steady building shell temperature, Vin, is 0.05 m/s, this is highly affected by the vortex created at the entrance part of the air cavity. Accordingly, it is more accurate to state that the minimum air outlet velocity for establishing a steady building shell temperature for this case is 0.01 m/s.



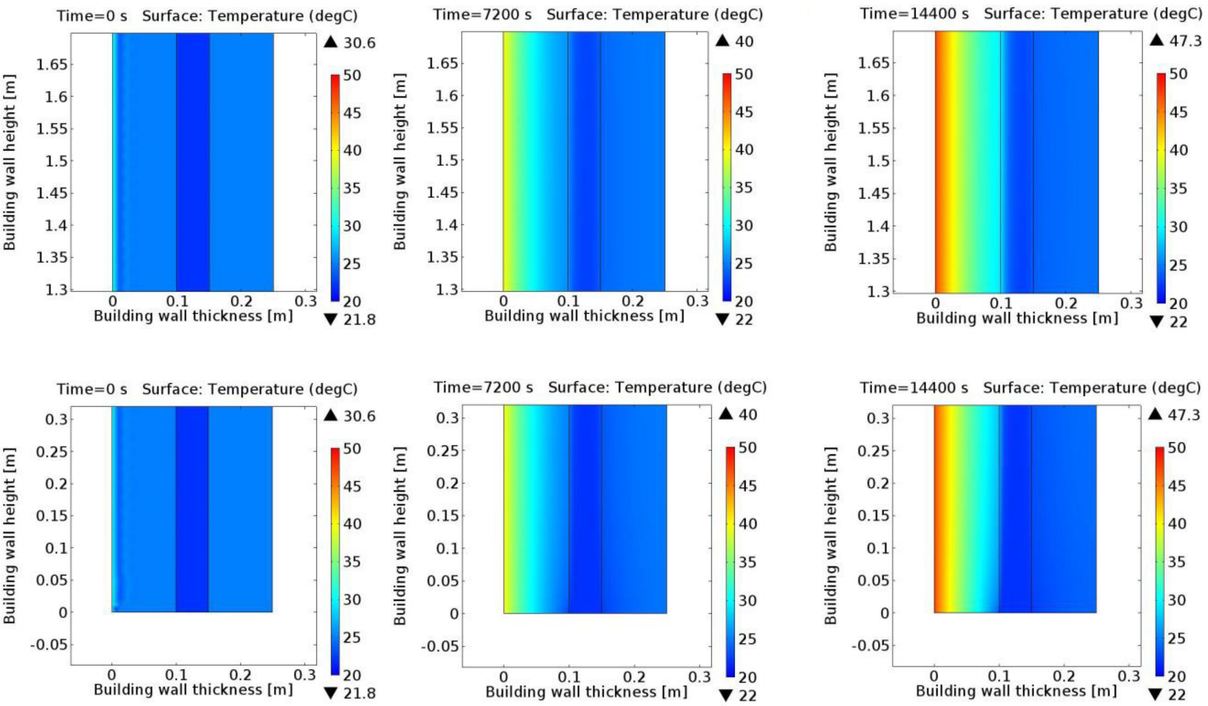


Fig. 2. Thermal performance of the Controlled Temperature Building Shell (at the heights 0- 0.3m, 1.35- 1.65m, and 2.7- 3m) in a conventional building incorporating a building material with thermal conductivity of 0,21 W/(mK), operating at inlet velocities of 0.17 m/s.

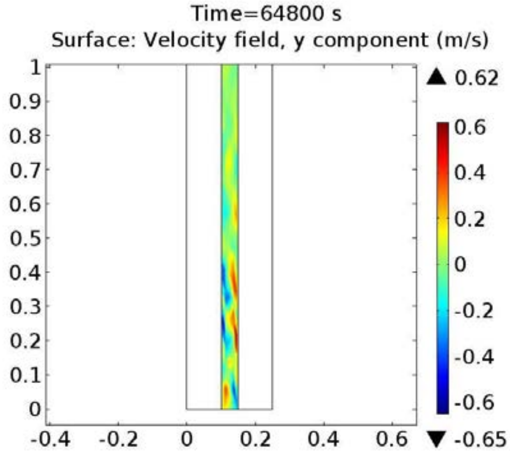


Fig. 3. Velocity graph of the Controlled Temperature Building Shell in a conventional building incorporating a building material with thermal conductivity of 0,0054 W/(mK), operating at inlet velocities of 0.05 m/s.

To cover the needs for operating the Controlled Temperature Building Shell, the employment of a heat pump is assumed. Table 3 shows a comparison between the energy requirements of the heat pump (E1) against the amount of heat transferred through the masonry of the building under examination, ie. the buiding's heat flux (E2). The results suggest a linear relationship between the two, where the energy requirements of the Controlled Temperature Building Shell operation are significantly lower than the heat flux of the building.

Table 3. Minimum required inlet air flow velocities [m/s] for steady building shell temperatures for selected building U- Values

Building material thermal conductivity, k [W/(mK]	Conventional building envelope		Super- insulator building envelope	
	E1	E2	E1	E2
0,21	134,2	5291,0	81,2	4616,3
0,068	206,6	3445,5	53	1414,7
0,015	120,1	1350,9	21,2	211,7
0,0054	31,8	794,5	24,7	70,3

4.2. Life Cycle Impact

In order to establish the energy- efficiency and environmental- friendliness of the novel building element, the findings of the previous section regarding the energy requirements of the Controlled Temperature Building Shell for providing heating and cooling to the building under investigation are weighted against its embodied energy. For the life cycle analysis, the pre-utilization phase of the building under investigation from raw materials extraction to the construction of the building was considered. Through the employment of the environmental building assessment tool EcoHestia, a cradle- to- site LCA was conducted. Accordingly, the system boundaries of this LCA comprise only the manufacturing of the novel building element, whereas its operational and end- of- life management phases are found outside the system boundaries, and thus are not included in this analysis. The functional unit of the analysis, referring to residential buildings is one square meter (1 m^2) of useful floor area, such as the results of the LCA enable the evaluation against the energy requirements of the building for heating and cooling purposes during its operational phase. [0]

The detailed Life Cycle Impact Assessment (LCIA), as well as the embodied energy of each type of building under examination per 1 m^2 of useful floor area, generated by EcoHestia, is presented in Table 4. Evidently, in terms of environmental performance, the Controlled Temperature Building Shell building element incorporating plasterboard is superior to the brick masonry building types with its embodied energy only amounting to 2,4 kWh per m^2 of useful floor area. However, at the same time its operation has the highest energy demands, as indicated in Table 3. As expected the highest environmental burdens and embodied energy are presented by the building envelope that incorporates the best insulation, although it offers the lowest U- Value to the building and thus significant reductions to its operational energy requirements. As a general comment regarding the LCA of the buildings under examination, an inverse relationship is observed between the embodied energy of the building and the energy required for the operation of the Controlled Temperature Building Shell for establishing a steady building shell temperature.

Table 5 compares the lifetime energy demand of the Controlled Temperature Building Shell against its embodied energy. The results of the analysis indicate that the ratio of the energy requirements for operating the Controlled Temperature Building Shell with the aid of the heat pump and the embodied energy of the building element itself drops significantly, as the thermal insulation of the building envelope increases.

Table 4. Embodied energy per one square meter (1 m^2) of useful floor area of buildings under examination

	Building type	Total Embodied Energy (MJ)
1	Building with plasterboard	8,7
2	Building with 10cm×10cm brick	4190,4
3	Building with 10cm×10cm brick and 5cm polystyrene	4342,0
4	Building with 10cm×10cm brick and 10cm polystyrene	4493,5

Table 5. Comparison of the lifetime energy demand of the Controlled Temperature Building Shell against its embodied energy

Building type		Energy requirements of heat pump (kWh)	Total Embodied Energy (kWh)	Energy Demand: Embodied Energy (%)
1	Building with plasterboard	587,8	2,4	244,9
2	Building with 10cm×10cm brick	904,9	1164,0	0,8
3	Building with 10cm×10cm brick and 5cm polystyrene	526,0	1206,1	0,4
4	Building with 10cm×10cm brick and 10cm polystyrene	139,3	1248,2	0,1

5. Conclusions

A novel concept, the Controlled Temperature Building Shell, whose operation is based on the continuous induction of controlled-temperature air within the building envelope to establish a steady building shell temperature, is introduced in this study. The energy performance of this innovative building element is validated through the implementation of two assessments; finite element analysis and LCA. The finite element analysis has been conducted using two cases, where the one considers for the Controlled Temperature Building Shell application in a conventional thick building envelope, and the other for its application to a super- insulator envelope. The results of the numerical simulation analysis revealed the interdependence of the building materials that make up the Controlled Temperature Building Shell and the velocities at which the Controlled Temperature Building Shell should operate in order to maintain a steady building shell temperature. Accordingly, it has been concluded lowering the U-Value of the building could result in significant reductions in the energy requirements of the Controlled Temperature Building Shell. The LCA findings revealed that the better insulated is the building envelope, the higher its embodied energy, although the lower U- Value to the building also means substantial decreases to the operational energy requirements of the Controlled Temperature Building Shell. The proposed concept is anticipated to provide justified solutions to the building industry, especially in view of the Zero Energy Building challenge. [0 0].

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