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Designing of the module envelope of a hybrid modular building to meet the passive house standards in Luxembourg

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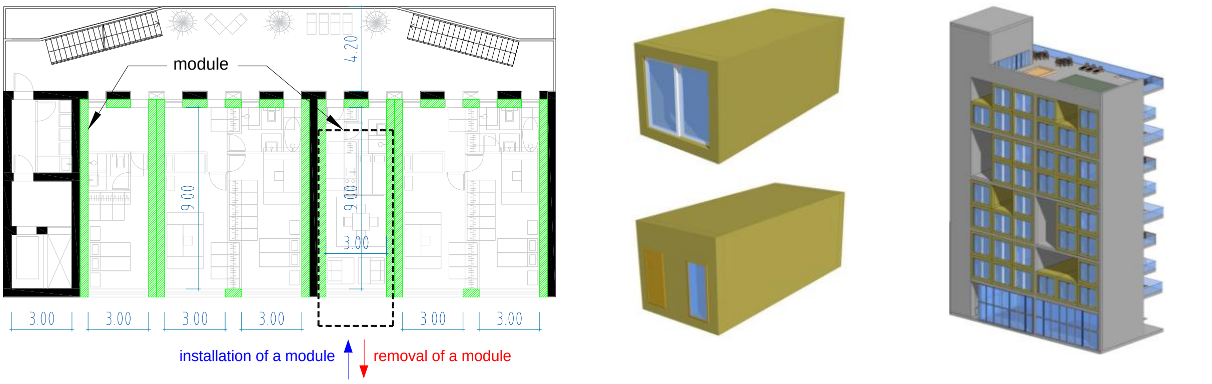
Abstract. To face the challenges of climate change, new buildings need to be further greener while being able to ensure a minimum comfort to the tenants. Nonetheless, extensibility and flexibility could be added to buildings. In this context, the architect jointly with the team of this research project have designed a hybrid modular construction called "slab building" which is composed of a permanent concrete structure and several removable wooden modules. A module offers 27 m² of living space but larger housings can be realized by combining two up to four modules. The aim of this paper is to design the walls of the modules to meet the criteria of nZEB. The thicknesses of the studied thermal insulations, namely rock wool, wood wool, polyurethane and aerogel, have been determined in accordance with the passive house requirements in Luxembourg. The embodied energy of the building materials has also been considered in the designing of the modules. Steady state calculations revealed that a wall thickness of 40 cm, comprising 31 cm of insulation is sufficient but according to the LCA outcomes, there is no environmental benefit in having the modules comply with the AAA energy class requirements at reasonable wall thicknesses.

1. Introduction

Compared to conventional constructions, modular buildings have remarkable advantages. Firstly, they offer faster construction process [1][2][3]. Secondly, they provide an improved construction quality [3][4][5][6]. Thirdly, they offer a great layout flexibility over time as the modules can be refitted, relocated and refurbished. Lastly, they allow reducing construction waste, construction interruptions and nuisances generated on site [3]. Frames of modules can be made of metal, timber, concrete or mixed materials but lightweight structure modules do not always allow the erection of high-rise buildings and generally present a higher risk of overheating. Considering these pros and cons, the architect jointly with the team of this research project have designed a hybrid modular construction called "slab building" which is composed of a permanent concrete structure and several removable wooden modules (**Fig. 1**). The permanent concrete structure is expected to have a life span of at least 75 years whereas the modules 20 to 25 years. The building will be used for housings, eventually also for home offices. The "slab building" has four open floors on the modules side, and nine floors on the shafts side. The ground floor and the top floor will be used as common space and the four open floors will accommodate the 48 plug-in modules. Each open floor can receive up to twelve modules, which consist of a stack of six modules. A module offers 27 m² of living space but larger housings can be realized by combining two up to four units. The permanent concrete structure serves as docking infrastructure for the modules, ensures both vertical and horizontal circulation and hosts the common utility rooms. This architectural design has been adopted to provide a high flexibility and extensibility so that modules can be plugged-in, combined or unplugged from the docking infrastructure without affecting the neighbour modules. At the end-of-life stage, modules will be unplugged then refurbished or recycled.



(a) (b) (c)

Fig. 1. (a) Current floor plan of the "slab building", (b) 3D views of a module, (c) 3D view of the "slab building"

The purpose of this paper is to design the module envelope to fulfil two Luxembourgish regulatory requirements on energy performance of buildings. The first requirement is related to the current building permit application and the second one to the AAA energy class, corresponding to the passive house standards in Luxembourg and which is requisite for a nZEB. In the designing of the module envelope, the embodied energy of building materials is also to consider.

2. Methods

2.1. Basis of the Luxembourgish regulatory calculations

Luxembourgish regulatory calculations are based on energy balance at steady state conditions and rely on the "Règlement Grand-Ducal sur la performance énergétique des bâtiments d'habitation" [7][8]. This regulation defines the calculation principles to estimate the specific heat demand qH and the specific need for primary energy Qp for the certified building and for the reference building. The value of qH defines the "thermal insulation class" and the value of Qp defines the "energy performance class". The appraisal of qH takes into account the heat losses by transmission, the heat losses by ventilation, the

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solar gains and the internal gains. The calculation of Qp takes into consideration the heat production for the heating of space and domestic hot water including the electric need to run the auxiliaries and also the annual specific credit in primary energy obtained through the generation of electricity from PV panels. Therefore, the requirements for building permit application are fulfilled if the value of qH and Qp of the certified building are less than those of the reference building. The "A energy performance class" is reached when Qp of the certified building does not exceed 45 kWh/(m².y) and the "A thermal insulation class" is reached when Qp does not exceed 22 kWh/(m².y). In most countries, the maximum value of the specific need for primary energy to meet the passive house requirements is 15 kWh/(m².y).

2.2. *Calculation assumptions*

The module is assimilated to a single-family house implemented on a hosting site. Because of the plug-in system, all walls of the module are assumed to be against exterior. The interior dimensions of the module are fixed (3.0m*9.0m*2.7m) but the exterior dimensions are depending on the wall thicknesses. For the building permit application requirements, characteristics of ventilation system, windows and door are those found on typical low energy houses. For the AAA energy class requirements, characteristics of these components have been set to very high performance, and PV panels have been used. As the orientation of the module is undefined, the worst orientation (window facing north) has been considered. A ground-water heat pump with mix of electricity as fuel has been chosen as heat generator. The inlet and the outlet temperature of the heat emitters are 35°C and 28°C respectively. The heat generator heats domestic hot water. Regarding the air infiltration, the wind exposure and the airtightness are "mean" and "high" respectively for both requirements, whereas the air change rate n_{50} is 0.6 [1/h] for the AAA energy class and 1 [1/h] for the building permit application. Computation assumptions are given in **Table 1**.

Table 1. Calculation assumptions

	AAA energy class	Building permit application
Dual flow ventilation system:		
- Heat recovery efficiency	η = 90 %	η = 85 %
- Specific fan power	0.25 W/(m³/h)	0.30 W/(m³/h)
Door (on the rear façade)		
- Gross dimensions (width x height)	0.90 m x 2.10 m	0.90 m x 2.10 m
- $U_{installed}$	0.5 W/(m².K)	1 W/(m².K)
Glazing and frame:		
- $U_{glazing}$	0.55 W/(m².K)	1.10 W/(m².K)
- g-value	60 %	60 %
- U_{frame}	0.70 W/(m².K)	1.10 W/(m².K)
Non-opening window (on the rear façade)		
- Gross dimensions (width x height)	0.90 m x 2.10 m	0.90 m x 2.10 m
- Surface ratio glazing/window	80 %	70 %
- $U_{installed}$	0.65 W/(m².K)	1.21 W/(m².K)
Window (on the front façade)		
- Gross dimensions (width x height)	3.00 m x 2.70 m	3.00 m x 2.70 m
- Surface ratio glazing/window	80 %	75 %
- $U_{installed}$	0.64 W/(m².K)	1.20 W/(m².K)

3. Results

3.1. *Structure of the module wall*

As much as possible, module envelope will be built with wood-based materials which are known for having a low embodied energy. The walls, roof and floor of the module will have the same structure and thickness but supplementary elements could be added. For mechanical stability reasons, the minimum thickness of the roof/floor is 31 cm, which corresponds to an insulation thickness of 22 cm. **Fig. 2** illustrates the structure of the module walls. Thermal conductivity of materials are extracted from Lesosai software database or from datasheets of product for the thermal insulations [9][10][11][12].

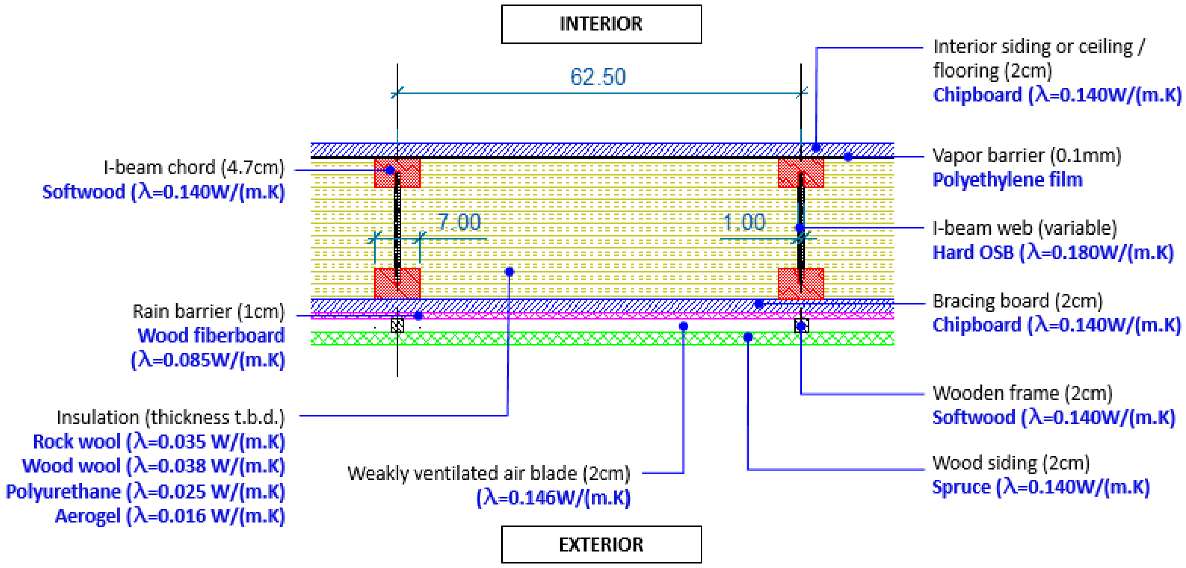

Fig. 2. Structure of the module wall

3.2. Insulation thickness of the module wall

Required thicknesses have been obtained by iteration. Results are presented on the following tables.

Table 2. Values of qH and Qp for the module - AAA energy class requirements

		Aerogel 31 cm	Polyurethane 51 cm	Rock wool 71 cm	Wood wool 91 cm
Thermal insulat. perform.	Wall thickness [cm]	40	60	80	100
	Shape factor Ai/Ve [m²/m³]	1.30	1.19	1.05	1.01
	U_{wall} [W/(m².K)]	0.062	0.054	0.046	0.044
	Thermal bridges* [W/(m².K)]	-0.017	-0.018	-0.019	-0.019
	qH [kWh/(m².y)] – north orientation	20.67	19.41	17.84	17.54
	qH [kWh/(m².y)] – south orientation	8.98	7.97	6.80	6.59
Energy perform.	Qp [kWh/(m².y)] – north orientation	43.11	42.34	41.38	41.20
	PV panels [kW_{peak}]	0.10	0.10	0.10	0.10

* Based on detailed calculation

Table 3. Values of qH and Qp for the module - Building permit application requirements

		Aerogel 15 cm	Polyurethane 17 cm	Rock wool 22 cm	Wood wool 22 cm	Wood wool 31 cm
Thermal insulat. perform.	Wall thickness [cm]	24	26	31	31	40
	Shape factor Ai/Ve [m²/m³]	1.41	1.40	1.36	1.36	1.30
	U_{wall} [W/(m².K)]	0.159	0.173	0.159	0.169	0.123
	Thermal bridges* [W/(m².K)]	-0.032	-0.031	-0.033	-0.035	-0.030
	qH [kWh/(m².y)] – north orient.	72.99 [D]	80.46 [D]	75.86 [D]	79.69 [D]	64.38 [C]
	qH_{ref} [kWh/(m².y)] – north orient.	79.71	80.92	86.21	83.98	89.68
	qH [kWh/(m².y)] – south orient.	53.01 [C]	59.76 [C]	55.34 [C]	58.85 [C]	44.66 [C]
	qH_{ref} [kWh/(m².y)] – south orient.	61.49	62.55	67.33	65.24	70.32
Energy perform.	Qp [kWh/(m².y)] – north orient.	83.45 (B)	88.02 (B)	85.21 (B)	87.55 (B)	78.18 (B)
	Qp_{ref} [kWh/(m².y)] – north orient.	118.75	120.12	126.11	123.58	130.03

* Based on detailed calculation
qH_{ref} is the value of qH for the reference building and Qp_{ref} is the value of Qp for the reference building
Letters in square brackets are the thermal insulation classes and letters in brackets, the energy performance classes

3.3. Embodied vs operational energy of the thermal insulation

In this paper, the embodied and the operational energy takes only into account the thermal insulation of the module. A life span of 25 years has been considered. The energy reference area of a module is constant (27 m²) but the total surface of thermal insulation depends on the insulation thickness. The total surfaces of the thermal insulation are 129, 131, 135, 141, 156, 172 and 189 m² respectively for the insulation thickness 15, 17, 22, 31, 51, 71 and 91 cm. The embodied energy of the thermal insulations have been extracted from ÖKOBAUDAT and from datasheet of product for the aerogel. After adjustment, the embodied energy of the aerogel [13], polyurethane [14], rock wool [15] and wood wool [16] are respectively 540, 123, 49 and 2 $kgCO_2eq/m^3$. **Fig. 3** presents the CO_2 footprint of the embodied and the operational energy by thermal insulation material and thickness.

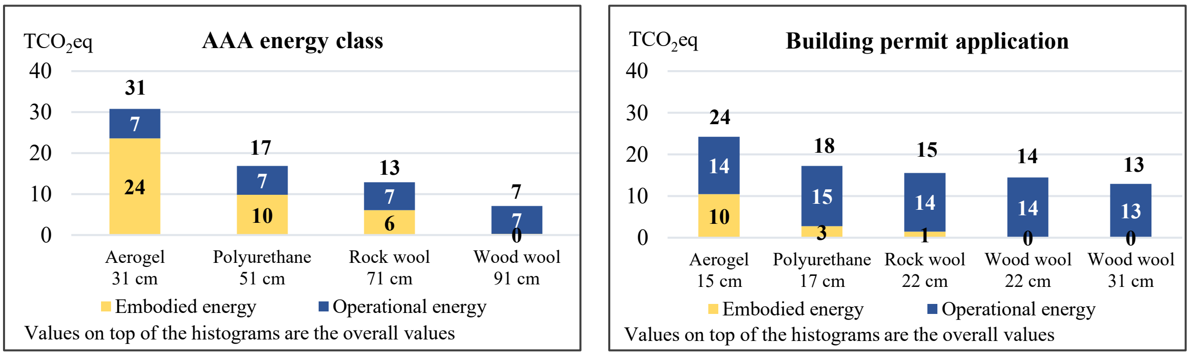

Fig. 3. CO_2 footprint of the embodied energy and the operational energy by thermal insulation thickness

4. Discussion

Wall U-values to reach A thermal insulation class varies from 0.062 to 0.044 W/(m².K) which are quite low compared to the typical wall U-values for passive houses which are between 0.10 and 15 W/(m².K) [17]. This is obviously due to the worst orientation but probably also to the shape factor whose typical values vary between 0.8 and 1 m²/m³ for low energy single-family houses [5]. The small size of net floor area (27 m²) in combination with the six outside envelope surfaces leads to relatively high transmission losses to be compensated by high insulation thicknesses which again increase the outer envelope surface. **Fig. 3** shows that the aerogel is the less environmentally friendly insulation material because of its high value of embodied energy. It allows reaching AAA energy class with an insulation thickness of 31 cm, but its overall CO_2 footprint (31 TCO_2eq) is bigger than those of the polyurethane 17 cm (18 TCO_2eq) the rock wool 22 cm (15 TCO_2eq) and the wood wool 22 cm (14 TCO_2eq) which are just fulfilling the requirements for the building permit application. The rock wool 71 cm (13 TCO_{2eq}) could be an alternative to reach the AAA energy class but it implies a wall thickness of 80 cm, which is not reasonable with respect to the net floor surface of the module.

5. Conclusion

A hybrid modular building with individual living modules of 27 m² each has been developed. In the worst case, an individual module is orientated north with all six envelope sides being exposed to outside conditions. In combination with the small size and so the unfavourable surface to volume ratio, this configuration requires rather high insulation thicknesses. The worst orientation of the module (window facing north) and the shape factor (between 1.26 and 1.41 for reasonable wall thicknesses) are penalizing parameters in designing the module envelope. For the AAA energy class requirements, a wall thickness of 40 cm comprising 31 cm of aerogel is sufficient. Moreover, according to the LCA outcomes, there is no environmental benefit in having the modules comply with the AAA energy class requirements at reasonable thicknesses. For the building permit application requirements, a wall thickness of 31 cm comprising 22 cm of wood wool is enough. The analysis shows also the necessity of a more holistic energy analyses of the whole concept of modular and flexible construction, going beyond the worst-case simulation of one single module. Other aspects like summer thermal comfort will also be analysed.

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