Climate Change, Energy Performance and Carbon Emission in a Prefabricated Timber House in Northern China: A Dynamic Analysis

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ABSTRACT: Climate change can bring a big challenge to energy efficiency and carbon emission in cities. Timber houses have been recognized as an effective solution to mitigate climate change. This paper presents a dynamic simulation analysis of the energy performance and operational carbon emission in a prefabricated timber house in northern China (cold climate), considering climate change scenarios for 2020, 2050, and 2080, and various architectural characteristics. Several key findings were achieved as follows: 1) Climate change would deliver significant negative effects on cooling demand and relevant carbon emissions for this timber house, but would benefit the heating energy performance. 2) House layout and shape factor could affect energy demand and carbon emissions for this house. A terrace house may yield around 83% carbon emissions of a similar detached house base model, while a 12% reduction in shape factor can lead to an 18% reduction in carbon emissions. 3) In addition, energy demand and carbon emissions of the house could receive substantial effect from the correct choice of orientation and window-to-wall ratio WWR. A south-facing solution can deliver a reduction in carbon emissions of up to 18%, while a reduction of 0.2 in WWR would lead to a reduction of 12% in carbon emissions.
KEYWORDS: Climate Change, Prefabricated Timber House, Primary Energy Performance, Operational Carbon Emission, Dynamic Simulation

1. INTRODUCTION

Increased human activities have been recognized as the main cause of climate change [1]. Combined with the rapidly growing urbanization, climate change will deliver a significant negative impact on the building energy consumption in cities [1]. In China currently, around 45% of primary energy consumption is found in commercial and residential buildings and this number might rise with the increasing risk of global warming [2]. In addition, studies show that the construction industry is responsible, predominately through the construction and operation of buildings, for around 51.3 % of national greenhouse gas emissions in China [2]. Consequently, the Chinese government has produced numerous strategies to strongly promote low-carbon solutions to improve energy efficiency in residential buildings and achieve climate targets of carbon peak emissions [2, 3, 4].

In recent decades, the potential of timber material to mitigate climate change by reducing greenhouse gas emissions has been widely recognized in building construction [5]. Important investigations into energy and environmental performance in timber houses were mainly based in Europe. One Slovenian study first developed a simple algorithm for architects to estimate energy demand in a prefabricated timber-frame building [6]. In Sweden, a multi-story apartment building of timber construction was analysed using simulation [7]. Results indicated that there was a strong possibility to achieve a low energy target in such a timber house in a cold climate. Another Swedish study [8] compared lifecycle carbon emissions between two multi-storey timber buildings, with conventional and innovative constructions, and identified the key passive solution to reduce carbon emission in a timber structure. Moreover, under various European climates, the links between passive solutions (e.g. shape factor, window-wall ratio) and energy performance in timber-frame houses were comprehensively tested [9, 10]. In addition, a British investigation [11] found evidence to mitigate overheating in a well-insulated timber house using thermal mass. It can be found that prefabricated timber houses have been widely studied in Europe over the past 10 years.

Currently, China has embarked on the promotion of prefabricated building construction as an ambitious governmental initiative [3], because it can significantly contribute to climate change mitigation, and help to reduce carbon emissions and energy and material use [12]. In line with this purpose, there is an increasing trend to encourage the prefabricated timber buildings, especially for the dwelling [13]. However, in Chinese building industry, there is a clear lack of knowledge in terms of prefabricated timber house design and construction, particularly for energy and carbon performances under various Chinese climates.

This study presents a dynamic thermal simulation analysis of primary energy performance and operational carbon emissions in a prefabricated timber house in northern China, considering climate change and key architectural characteristics. These results can be further developed into guidelines to support the design of low carbon timber houses under current and future climate scenarios in China.

2. METHODS

2.1 Location and climate

The house studied is located in Tianjin city in northern China (Latitude: 39.12° N, Longitude: 117.19° E). Tianjin has a humid continental climate. July has the highest average temperature of 26°C, while the coldest month is found in January with an average temperature of -3.3°C [4].

2.2 Timber house models

As shown in Fig.1, the timber house studied has two floors and an attic space, with a total area of 143.56 m^2. The Base Model in this study was a detached house - it has a rectangle plan, with one living room (ground floor) and two bedrooms (first floor) – see Fig. 2. This house was built using a prefabricated timber-frame structure system. Its key components (including walls, floors, roof) were composed of a wood structure and cladding panels. The structure included a top beam, top plate, sill beam and sill plate (horizontal), and studs (vertical). Arranged with a specific spacing, the studs were connected to the beam and plate using nails. The cladding panel was mainly composed of drywall (internal) and sheathing wall (external). The cladding sheets of timber structure wall were available in a standard size with nominal dimensions (1220×2440mm) and thickness (12mm). The cavity between the studs was filled with insulation materials (Rockwool) [13].

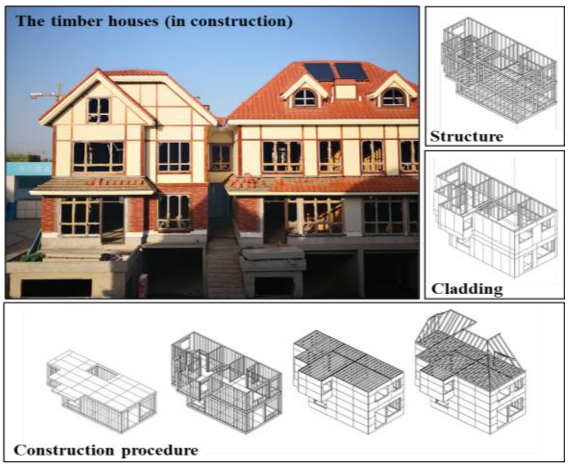

Figure 1: *The timber house and its construction procedure.*

All components of this house were assembled in a factory. In addition, doors and windows were fitted and even electrics and plumbing were installed within the wall sections. These prefabricated components were installed into rooms on site in line with the defined house plan. Finally, all connections of components were fixed by metal fastener. In this study, several key architectural parameters were studied: 1) Three layouts - the Base Model (single unit), semi-detached houses (two units), and terrace houses (four units). The Base Model was the basic house unit used to make up the other two layouts. 2) House size: three sizes of the Base Model were studied in terms of width (W) and length (L) (see Fig. 2), including M1, M2, and M3 (Table. 1). These dimensions were defined in accordance with the prefabricated requirement, i.e. to fit the standard cladding dimensions (1220×2440mm) to reduce material waste [13]. Given a fixed volume of this house model (451m^3), thus, M1, M2 and M3 have various values of Shape Factor (SF) (M1>M2>M3). 3) Orientation: three orientations were studied - South (S), Southeast (SE), Southwest (SW) [14]. 4) WWR (window-to-wall ratio): three ratios were used - 0.45 (large), 0.35 (medium), and 0.25 (small). In addition, the window positions were set according to the requirement of energy efficiency and daylighting in a regulation [4].

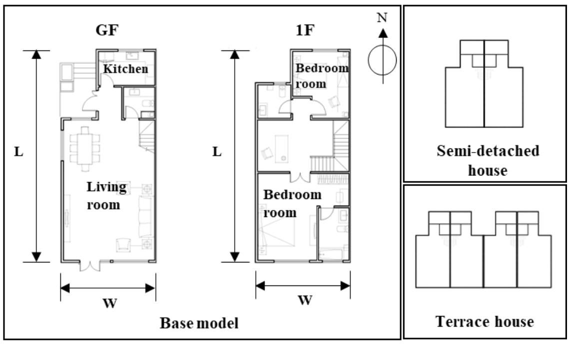

Figure 2: *Plans of base model and various layouts studied.*

Table 1: *Various dimensions of Base Model.*

Model	M1	M2	M3
W (m)	6.10	7.32	8.54
L (m)	13.42	10.98	8.54
Shape Factor	0.57	0.53	0.50

A total of 81 model combinations were finally analysed in terms of the four aspects of architectural characteristics mentioned (Fig.3).

2.3 Future climate change

The impact of climate change was tested through the comparison between three scenarios:

current year (2020), future year (2050), and future year (2080). The future weather data was achieved through the MORPHING method and the weather data generator software Meteonorm [15].

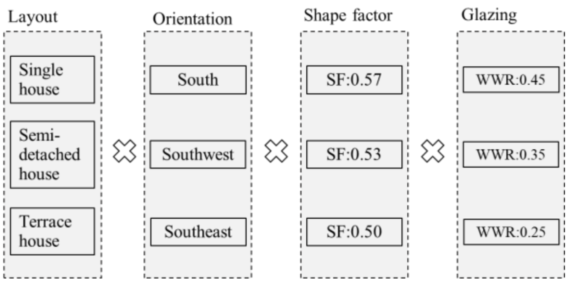

Figure 3: *Building parameters studied.*

According to Fig.4, the annual average temperature will increase by 2.25 °C over the period from 2020 to 2080 due to the increasing trend of global warming. The average winter temperature will grow from -2.65°C in 2020 to 0.36 °C in 2080, whilst a rise can be found in average summer temperature from 26.81°C to 28.87°C during the same period.

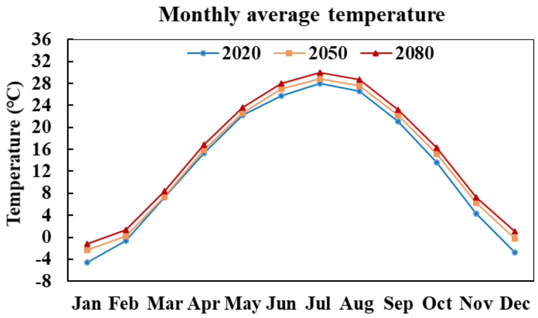

Figure 4: *Variation of monthly average temperature in current and future climate scenarios (2020, 2050, 2080).*

2.4 Dynamic energy performance simulation

DesignBuilder(+EnergyPlus) software was adopted to conduct a dynamic simulation of annual primary energy demands (heating and cooling) in all timber house models (https://designbuilder.co.uk), taking into account three climate scenarios.

In this study, the thermal transmittances (U-value) of the external wall, roof and floor of each house were set as: U(wall)=0.37 W/m^{2}K, U(roof)=0.3W/m^{2}K and U (ground floor) =0.25W/m^{2}K. A constant construction infiltration rate of 0.5 ac/h was used. A low emissivity LoE double glazing system (Clear, 3mm/6mm air) was applied for all windows, with a solar gain g-value of 0.6 and U-value of 2.4 W/m^{2}K. The U-value of the window frame (painted wooden frame) was 3.6 W/m^{2}K. All settings were defined based on the constructions of the real timber house (Fig.1).

In addition, the setpoints of heating and cooling were 18°C and 26°C, respectively [4]. Each house was assumed to be occupied by a family of two adults and one pre-school age child [4, 9, 10]. In these models, natural gas was used for providing heating while the electricity was used for cooling and lighting systems. In China, the CO_2 emission factors of natural gas and electricity are 0.202kg /kWh and 0.878 kg /kWh respectively [16], which were applied in the analysis of carbon emission in this study.

3. RESULTS

3.1 Effects of climate change and house layout

Fig. 5 indicates the impact of the climate change and house layout on primary energy demand and operational carbon emission in the house models (south-facing, M1 and WWR=0.45).

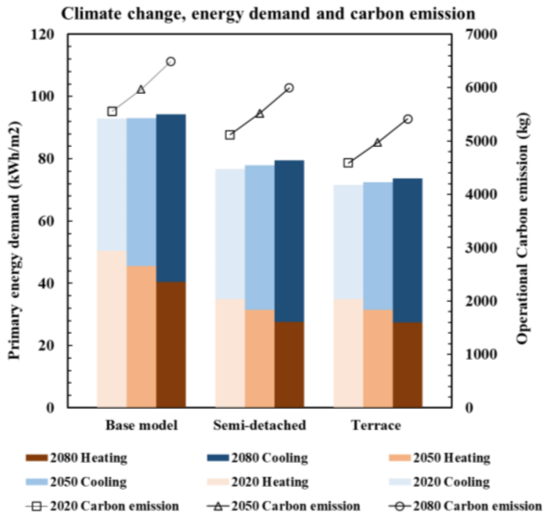

Figure 5: *Energy demand and operational carbon emission with various house layouts and climate scenarios (South-facing, M1, WWR: 0.45).*

Generally, there was an increase in primary energy demand over the period from 2020 to 2080. For the cooling demand, a significant increase can be found during this period in each model. The base model had the largest growth: from 42.42 kWh/m^2 in 2020 to 53.76 kWh/m^2 in 2080. For the heating demand, however, there was a clear drop in heating demand in this period. The largest decrease was found in the terrace house, where the heating demand dropped from 34.97 kWh/m^2 to 27.42 kWh/m^2. In addition, there were big differences in primary energy demand in the various house models. The terrace house achieved the lowest energy demand with any climate scenario, while the highest demand was found in the base model. In 2080, the terrace house and semi-detached house energy demands were around 78% and 84% respectively of the value in the base model.

Similarly, the operational carbon emissions in all models increased from 2020 to 2080 (Fig.5). Taking the current year (2020) as reference, three models showed an increase in carbon emissions as: 7.3% (2050, base model), 7.8% (2050, semi-detached model), 8.3% (2050, terrace), 16.7% (2080, base model), 17.1% (2080, semi-detached model), 18% (2080, terrace).

In Table 2, from 2020 to 2080, there was an increase in peak cooling demand while the peak heating demand decreased in all models. The largest peak energy demand can be found in the base model. Compared with the base model, the terrace house produced lower peak energy demand, especially in cooling (40% reduction).

Table 2: *Peak energy demand (hourly) varying in house layout and climate scenario.*

		Peak energy demand (kW)		
		Base model	Semi-detached	Terrace
Heating	2020	6.02	5.08	4.68
	2050	5.94	4.95	4.50
	2080	5.28	4.87	4.49
Cooling	2020	7.47	6.74	5.37
	2050	8.16	7.41	5.68
	2080	8.17	7.67	5.87

3.2 Effects of climate change and shape factor

Fig.6 shows the impact of the climate change and house shape factor (SF) on primary energy demand and operational carbon emissions in the house models (south-facing, terrace house, and WWR=0.45).

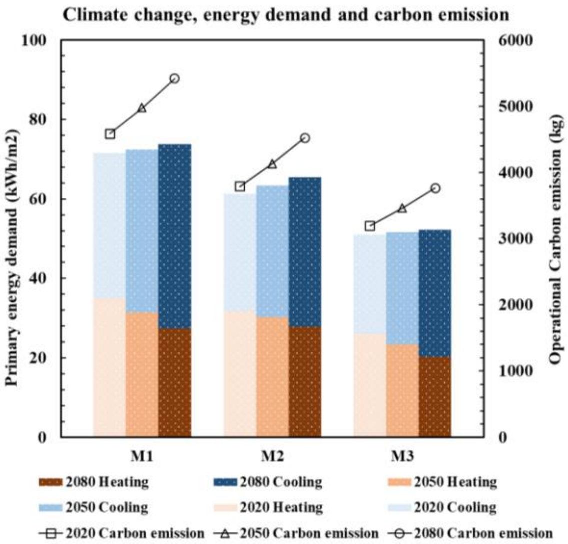

Figure 6: *Energy demand and operational carbon emission with various house shape factors (South-facing, Terrace house, WWR: 0.45).*

For each SF, both primary energy demand and cooling demand increased from 2020 to 2080, while there was a decrease in heating demand. For the three models, M1 (SF=0.57) showed the largest increase in cooling demand from 2020 to 2080 (31%). The highest reduction of heating demand over this period was found in M3 (SF=0.50) at 26%. In addition, decreasing the SF significantly reduced all energy demands. Compared with M1, average energy demands (three years) of the other models had reductions of 11% (M2) and 28% (M3). Fig.6 also shows that the operational carbon emissions of the three models increased from 2020 to 2080. Taking the current year (2020) as reference, three models showed increased carbon emission of: 8% (2050, M1), 9% (2050, M2), 9% (2050, M3), 18% (2080, M1), 19% (2080, M2), 18% (2080, M3).

Table 3: *Peak energy demand (hourly) varying in shape factor and climate scenario.*

		Peak energy demand (kW)		
		M1	M2	M3
Heating	2020	4.68	3.92	3.26
	2050	4.50	3.81	3.15
	2080	4.49	3.77	3.06
Cooling	2020	5.37	4.82	4.06
	2050	5.68	4.91	4.51
	2080	5.87	4.98	4.60

For Table 3, similarly, an increasing peak cooling demand and a decreasing peak heating demand was found from 2020 to 2080. M1 showed the largest peak energy demand, while the lowest peak energy demand was for M3.

3.3 Effects of climate change and orientation

Fig.7 shows the impact of the climate change and orientation on primary energy demand and operational carbon emission in the house models (M1, terrace house, and WWR=0.45).

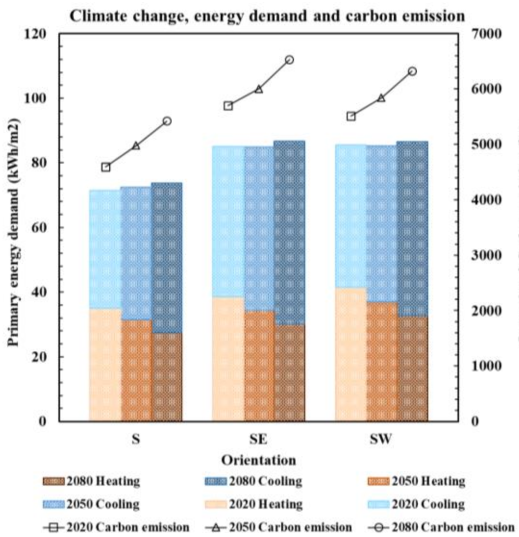

Figure 7: *Energy demand and operational carbon emission with various orientations (M1, Terrace house, WWR: 0.45).*

With each orientation, similarly, the cooling demand significantly increased from 2020 to 2080, while the heating demand tended to decrease.

However, there was a slight increase in the total energy demand for each orientation. Orientations SE and SW created similar energy demands under current and future climate scenarios, while a lower energy demand was found for the south orientation S. Energy demands with orientation S were 71.53 kWh/m^2 (2020), 72.51 kWh/m^2 (2050), 73.76 kWh/m^2 (2080). The three orientations showed an increase in cooling demand from 2020 to 2080 as 26% (S), 22% (SE), 21% (SW), while there were no big differences found between the decreases in their heating demands.

Fig.7 also shows that there was an increase in operational carbon emission from 2020 to 2080 with each orientation. Taking the current year (2020) as reference, the three orientations saw increases of carbon emissions as: 8% (2050, S), 5% (2050, SE), 6% (2050, SW), 18% (2080, S), 14% (2080, SE), 14% (2080, SW).

Table 4: *Peak energy demand varying in orientation and climate scenario*

		Peak energy demand (kW)		
		S	SE	SW
Heating	2020	4.68	5.24	5.34
	2050	4.5	4.83	5.01
	2080	4.49	4.80	4.94
Cooling	2020	5.37	6.55	7.60
	2050	5.68	7.50	8.13
	2080	5.87	7.85	8.29

In Table 4, from 2020 to 2080, there was an increase in peak cooling demand while the peak heating demand decreased for all orientations. The orientation SW led to the highest peak heating demand (5.34kW) in 2020 and the largest cooling demand (8.29kW) in 2080.

3.4 Effects of Climate change and WWR

Fig. 8 indicates the impact of the climate change and WWR on primary energy demand and operational carbon emission in the house models (south-facing, terrace house and M1).

In general, there was an increase in primary energy demand and cooling demand from 2020 to 2080 for each WWR. Similar to the results in section 3.1, 3.2 and 3.3, the heating demand tended to decrease in this period. In addition, there were big differences of primary energy demand found in various WWRs. Compared with the largest WWR (0.45), the other two WWR values delivered a reduction in primary energy demand of 7% (WWR=0.35) and 10% (WWR=0.25).

A similar trend in operational carbon variation was found in Fig.8: there was a significant rise from 2020 to 2080. Taking the current year (2020) as reference, three WWR values produced increases of carbon emissions as: 8% (2050, WWR=0.45), 8% (2050, WWR=0.35), 8% (2050, WWR=0.25), 18% (2080, WWR=0.45), 18% (2080, WWR=0.35), 18% (2080, WWR=0.25).

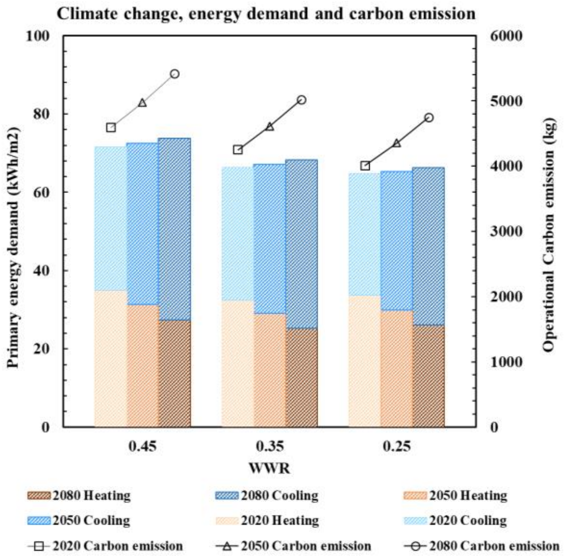

Figure 8 : *Energy demand and operational carbon emission with various WWR values (South-facing, M1, Terrace house).*

From 2020 to 2080 (Table 5), models with various WWR showed a clear increase in peak cooling demand, but a reduction in peak heating demand. The decrease of WWR reduced both peak heating and cooling demands. For example, a WWR reduction of 0.2 led to reductions in peak heating and cooling demands of 6% and 20%, respectively.

Table 5: *Peak energy demand varying in WWR and climate scenario.*

		Peak energy demand (kW)		
		WWR 0.45	WWR 0.35	WWR 0.25
Heating	2020	5.01	4.68	4.60
	2050	4.81	4.44	4.38
	2080	4.39	4.42	4.34
Cooling	2020	5.96	5.14	4.93
	2050	6.49	5.44	5.23
	2080	6.95	5.62	5.37

4. CONCLUSIONS

This study has presented a simulation analysis in terms of climate change, building layout, shape factor, orientation and WWR in a prefabricated timber house in Northern China (cold climate). Some findings that can be drawn from this study include:

1). In general, the climate change (period: 2020 to 2080) delivered significant negative effects on the primary energy demand and operational carbon emission in the timber houses, especially for the energy and carbon performances relevant to the cooling systems. However, the heating energy performance and relevant carbon emission received a positive impact from the global warming.

2). There is a clear effect of house layout on the primary energy demand and operational carbon emission in this prefabricated timber house under current and future climate scenarios. Compared with other layouts, the terrace house has been proved with the lowest primary energy demand and the smallest operational carbon emission.

3). Reducing the shape factor of the house can significantly reduce the primary energy demand and operational carbon emissions. A 12% reduction in shape factor could reduce primary energy demand by 30% and carbon emissions by 18%.

4). For this prefabricated timber house, the building orientation played a significant role in energy demand and carbon emissions under current and future climate scenarios. In comparison to south-east and south-west, the south-facing orientation reduced energy demand and operational carbon emission by around 17% and 18%, respectively.

5). Lowering the WWR could give rise to lower primary energy demand and operational carbon emissions in this timber house under current and future climate scenarios. A reduction of 0.2 in WWR led to reductions of energy demand and carbon emission of 10% and 12%, respectively. However, it could be necessary to balance the daylighting requirement and energy saving with the application of such solutions.

Limitations and future work: These conclusions are obviously limited to a simple house model. More architectural characteristics will be considered in future research. In addition, other issues relating to timber structure lifecycle assessment would be included in the calculation of carbon emission (e.g., construction, de-construction and disposal). These aspects will be studied in the future work.

REFERENCES

1. IPCC, (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
2. China Association of Building Energy Efficiency. (2020). China Building Energy Research Report [Online], Available: http://www.cabee.org/site/content/24021 [20 January 2022].
3. SCC (The State Council of the People's Republic of China) (2016). Some Opinions of the CPC Central Committee and the State Council on Further Strengthening the Management of Urban Planning and Construction, [online], Available: http://www.gov.cn/gongbao/content/2016/content_5051277 [20 January 2022].
4. MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China), (2018). Design standard for energy efficiency of residential buildings in severe cold and cold zones (JGJ 26-2018). Beijing, China.
5. Sathre, R. & Gustavsson, L., (2009). Using wood products to mitigate climate change: External costs and structural change. *Applied Energy*, 86(2), 251-257.
6. Premrov, M., Leskovar, V. Ž., (2011). An approach in architectural design of energy-efficient timber buildings with a focus on the optimal glazing size in the south-oriented facade. *Energy and Buildings,* 43, 3410-3418.
7. Kildsgaard I, Jarnehammar A, Widheden A, Wall M., (2013). Energy and Environmental Performance of Multi-Story Apartment Buildings Built in Timber Construction Using Passive House Principles. *Buildings,* 3(1), 258-277.
8. Dodoo, A., Gustavsson, L., Sathre, R., (2014). Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems. *Energy and Buildings,* 82, 194-210.
9. Premrov, M., Leskovar, V. Ž., & Mihalič, K., (2016). Influence of the building shape on the energy performance of timber-glass buildings in different climatic conditions. *Energy*, 108, 201-211.
10. Premrov, M., Žigart, M., & Leskovar, V. Ž., (2018). Influence of the building shape on the energy performance of timber-glass buildings located in warm climatic regions. *Energy*, 149, 496-504.
11. Rodrigues, L., Sougkakis, V., Gillott, M., (2016). Investigating the potential of adding thermal mass to mitigate overheating in a super-insulated low-energy timber house. *Journal of Low-Carbon Technologies,* 11, 305-316.
12. Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P., (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and buildings*, 47, 159-168.
13. MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China) (2017). *Standard for design of timber structures*. (GB: 50005-2017)
14. MOHURD (Ministry of Housing and Urban-Rural Development of the People's Republic of China) (2019). *Uniform standard for design of civil buildings.* Beijing, China. (GB: 50352-2019).
15. Remund, J., Müller, S., Kunz, S., Huguenin-Landl, B., Studer, C., & Cattin, R., (2017). Global Meteorological Database, Version 7 Software and Data for Engineers Planers and Education. METEOTEST Fabrik strasse 14 CH-3012 Bern Switzerland, 1-17.
16. Hou, G., Xu, Y., Jia, J., Lu, J., (2013). Research on the relationship between energy structure and carbon dioxide emissions. Chinese Society for Environmental Sciences, (CSES). In *China Environmental Science Society Academic Annual Conference*. Kunming, China, 1-2 August.