An integrated analysis of structural safety, embodied carbon, and construction cost in a prefabricated Chinese timber house within a BIM-based environment

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Abstract

The timber building has received increasing attention in building industry due to its benefits to environmental resilience. This study presents a BIM-based integrated analysis in a new prefabricated timber house in northern China, considering seismic performance, construction material use/cost, and embodied carbon emission. Three new structure solutions were analysed in comparison with the conventional model. It can be found from the cost analysis that the shortest stud spacing achieves an increase of 23.67% and the longest stud spacing has a decrease of 21.92%. For the embodied carbon, the shortest stud spacing sees a decrease of 29.21%, while an increase of 12.52% is found in the longest stud spacing.

Key Innovations

- A BIM-based integrated analysis in a prefabricated timber house.
- The analysis including seismic performance, material use/cost, and embodied carbon.
- A necessity to integrate embodied carbon into the design of timber structure safety.

Practical Implications

During the detailed design of a perfricated timber house, it is necessary to balance material use and embodied carbon emission when the structural safety is achieved.

Introduction

The construction industry is responsible, predominately through the construction and operation of buildings, approximately for around 40% of global energy use, 25% of global water consumption, and around 30% of global greenhouse gas emissions (UNEP-SBCI, 2009). It is also recognized as one of the most significant contributors to human-induced environmental impact (Crawford and Cadorel, 2017). Studies can show that the use of timber for building construction is more beneficial in mitigating this effect (Lippke et al., 2011; Sathre & O'Connor, 2010), as a timber-based building can achieve a significantly lower lifecycle carbon balance than a comparable concrete-based building (Dodoo et al., 2009). In addition, the light timber structure applied in buildings has been proved with an excellent performance in seismic resilience (Buchanan et al., 2011; Ceccotti, 2008). Recently, the timber structure has received increasing attention in building industry across the world.

However, there are still many challenges found in the current application and development of timber structure, especially in the sector of residential building (Lehmann, 2013). It has been noted that the construction cost (Tykkä et al., 2010) or the total life cycle cost (Riala & Illola, 2014) tends to be a key issue determining the choice of timber material and relevant construction technology. Lehmann (2013) found that the uncertainty and lack of in-depth knowledge of regulations relevant to timber construction is still regarded as the critical barrier to limit the application of timber houses in Europe and Australia. An Australian survey identified the most significant barriers in houses to be a perceived increase in maintenance costs and fire risk, together with a limited awareness of the emerging timber technologies available (Xia et al., 2014).

The timber house has been investigated in terms of different aspects. The seismic performance was studied as the first topic. Foschi (1977) developed a finite element model to simulate the earthquake resistance of shear wall module, which was calibrated through the experimental data. Johnn (2005) proposed a new user-defined unit which can use a variety of nonlinear nail connection restoring force models and take full account of the hysteretic characteristics of the nail connection to improve the whole seismic performance of timber house. Later, the performance of carbon emission through the construction of timber house has attracted more attentions. An early study systemically (Börjesson & Gustavsson, 2000) analysed carbon emissions across the construction period of typical multi-storey residential buildings, through a comparison of frame material between wood and concrete. Clearly, a significant reduction of carbon emission can be found in the wood frame. The low-carbon benefit of timber structures has been proved in many later studies (Lehmann, 2013). Recently, studies tended to focus on the construction cost and material saving. Riala and Ilola (2014) explored several approaches to improve cost-effectiveness of timber construction by semi-structured interviews. Based on a life cycle period of 20 years, Kaziolas et al. (2015) proposed an innovative model to optimize the whole-life cost of a timber building, taking account of its mechanical, structural and energy subsystems. In addition, a hybrid optimization algorithm for timber material cutting was developed with an aim to minimize sheathing material waste in a timber building (Liu et al., 2019).

Given studies mentioned above, it can be found that a new trend for investigating applications of timber house is how to enhance the low-carbon benefit of timber material and at the same time reduce its cost. In addition, it seems that the design and construction of a timber house may need to be processed using an integrated approach (Kaziolas et al., 2015). As BIM-based building simulation techniques can provide practitioners and researchers with an opportunity to assess building performance from a mixed perspective (Drejeris & Kavolynas, 2014), it would be useful to apply an integrated analysis of timber house performance within a BIM environment.

This article presents a BIM-based analysis in a prefabricated Chinese timber house, in terms of seismic performance, material use/cost, and embodied carbon. In addition to the original structure design, three new structure solutions were introduced and analysed. A parametric study was conducted through the integrated approach taking into consideration the three factors.

Methods

Location and seismic building code

This house is located in Tianjin city in northern China (Latitude: 39.12° N, Longitude: 117.19° E). Tianjin has a humidity continental climate (MOHURD, 2019). July has the highest average temperature of 26°C (79°F), while the coldest month is found in January with the average temperature of -3.3°C (26°F).

According to one Chinese building regulation (MOHURD, 2019), the design of structural safety in buildings must be in compliance with the seismic intensity of the location. Tianjin has the seismic intensity of level 8 (calculated acceleration 0.20g), which means a high requirement for the earthquake-resistant structure. Thus, this study adopted the seismic performance as a baseline issue according to the parametric analysis in this timber house.

The timber house studied

The K-house in Figure 1 is the timber house studied in this article. It is a new timber terrace house with two floors and a total floor area of 43.56m^2. This house adopted a platform timber structure, which is currently the most common type of light-frame timber housing construction in China. In this house, small-sized timber components are densely installed with a centre distance of 406mm.

Figure 1: The timber house studied in this article.

Figure 2 shows the plan of K-House with an independent structure. The outline of K-House plan is a rectangle, with a width of 5640 mm and a depth of 12700 mm on the ground floor. The width and the depth of the first floor are 7275 mm and 12700 mm, respectively. K-House is composed of 16 timber shear walls to form the indoor spaces, and resist the lateral load caused by earthquake or wind. Names, positions, and dimensions of these shear walls are displayed in Figure 2.

Position	Name	Position	Name	Position	Name	Position	Name
	Wall A (WA)		Wall E (WE)		Wall I (WI)		Wall M (WM)
	Wall B (WB)		Wall F (WF)		Wall J (WJ)		Wall N (WN)
	Wall C (WC)		Wall G (WG)		Wall K (WK)		Wall O (WO)
	Wall D (WD)		Wall H (WH)		Wall L (WL)		Wall P (WP)

Figure 2: Plan of K-house, and positions and names of 16 shear walls.

According to Figure 3, construction procedures of K-House are as follows: 1) Dimension lumbers were produced using wood logs in the factory, and then transported to the construction site. 2) Dimension lumbers were arranged at a pitch of 406mm as the joist, which was assembled using the upper and lower timber beams to form the floorboard. 3) Each floorboard was used as an operating platform. The timber wall structures were then installed on the platform. 4) Finally, roof timber trusses were installed around external walls of the top floor.

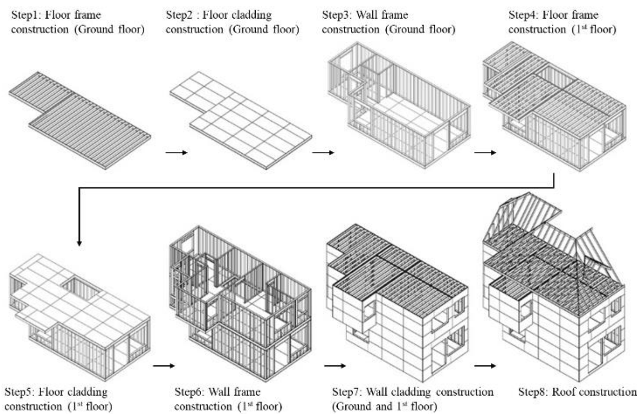

Figure 3: Construction procedures of K-house.

In Figure 4, key components of shear wall can be divided into two parts: structure and cladding panel. The structure includes top beam, top plate, sill beam and sill plate (horizontal), and studs (vertical). Arranged with a specific spacing, the studs are connected to the beam and plate using nails. The stud spacing refers to the centre distance between two adjacent studs. The cladding panel is mainly composed of drywall (internal) and sheathing wall (external). The cladding sheets of timber structure wall (prefabricated) are available in a standard size with nominal dimensions (1220mm×2440mm) and thickness (12mm). During the process of construction, only standard cladding sheets can be applied to fit the designed dimensions through cutting or connection, and then fastened to timber studs and plates. In addition, cladding butt joints should always be spliced on the stud and be staggered. The cavity between shear wall and drywall is filled with the insulation materials (rock wool).

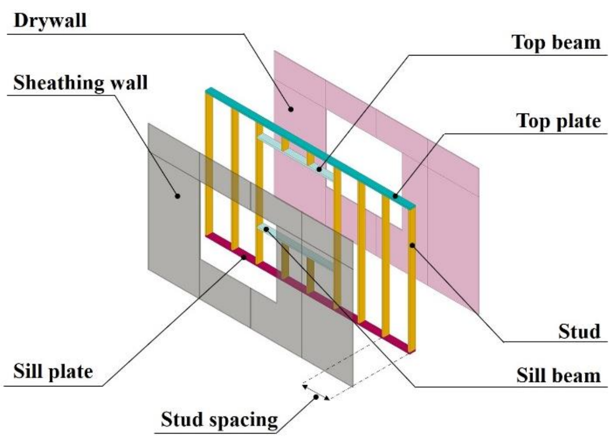

Figure 4: Components of shear wall structure and cladding panel.

Table 1 and 2 present key materials and dimensions of shear wall structures and cladding panels. The material of five wall structure components is Spruce-Pine-Fir (SPF), which is a typical commercial softwood product made in Canada and is widely used as a structural material in current Chinese timber houses. The section dimension of each structure component has the same values of 38×140 mm. For the cladding panels, the sheathing wall is constructed using Oriented Strand Board (OSB), while the drywall is made of gypsum board (GB). Both cladding panels have the nominal dimension of 1220×2440×15 mm.

Table 1: Materials and dimensions of shear wall: structure.

Name	Material	Section Dimension(mm)
Stud	Spruce-Pine-Fir (SPF)	38×140
Sill plate		
Top plate		
Sill beam		
Top beam		

Table 2: Materials and dimensions of shear wall: cladding panel.

Name	Material	Dimension per Sheet (mm)
Sheathing wall	Oriented Strand Board (OSB)	1220×2440×15
Drywall	Gypsum board (GB)	1220×2440×15

Structure simulation

This study used the Revit-Dynamo (for modelling) and Abaqus Unified FEA (Finite Element Analysis) to assess the seismic performance in this timber house according to various structure solutions.

The original structure of K-House was designed using a conventional model, with a typical characteristic: the stud spacing of shear wall was set as 406 mm. This setting was developed from practices and can well comply with the building regulations (MOHURD, 2017; MOHURD, 2019). In China, the stud spacing of shear wall can be allowed to conduct some adjustment according to different needs (MOHURD 2017). Thus, within the allowed range of structural safety (MOHURD, 2017), this study tested three new structure solutions in terms of stud spacing of shear wall: 305 mm (24.9% decrease), 490 mm (20.7% increase) and 610 mm (50.2% increase). Based on the practical experience, the largest stud spacing (610 mm) can be well fitted with many common types of sheathing wall, drywall, insulation layer and finish material.

In this light frame timber house, the shear wall was the main anti-lateral load component (see the 16 walls in Figure 2). For the seismic simulation using Abaqus, the applied lateral load was set on the top of each shear wall and the ultimate lateral load of each wall in each solution was then calculated to justify its performance.

Table 3: Settings of seismic performance simulation using Abaqus (Cheng, 2007; Johnn, 2005; Folz and Filiatrault, 2001)

Structure component	Element	Element Parameter
Stud	B21	E = 9650MPa; B×H = 38 mm×140 mm
Sheathing wall	CPS4R	E_1 = 1840MPa; E_2 = 1840MPa; G12 = 620MPa; t = 15 mm
Nail (sheathing wall and stud)	User-defined Element: U_1	K_1=700N/mm; K_2=24 N/mm; K_3=20 N/mm; K_4=785 N/mm; K_5=28 N/mm; F_0=1000N; F_1=142N; δ_{yield}=1.2 mm; δ_u=9.0 mm; δ_{fail}=40.0 mm; α =0.8; β =1.1
Nail (stud and stud)	User-defined Element: U_1	K_1=700N/mm; K_2=24.0; K_3=20.0; K_4=785; F_0=3300N; F_1=142N; δ_u=10.0 mm; δ_{fail}=40.0 mm; α =0.8; β =1.1

As the shear wall is a plane bearing component, it can be defined as a two-dimensional model in Abaqus simulation. When the shear wall receives the lateral load, the stud and top and bottom beams are simultaneously subjected to the axial force. The bending moment was simulated by the beam element B21, whilst the cladding panels were simulated by shell element CPS4R (Hibbitt, 2003). The nail connection was analysed through two-node element (Johnn, 2005). Table 3 presents settings for each structure component of shear wall and its corresponding finite element and material parameters in Abaqus. In this table, E represents elastic modulus of material; B represents section height of stud; H represents section width of stud; G represents shear modulus; t represents thickness of sheathing wall; K_1 represents initial stiffness of a sheathing–to–framing connection; K_2 represents secondary stiffness of a sheathing–to–framing connection; K_3 represents softening stiffness of a sheathing–to–framing connection; K_4 represents unloading stiffness of a sheathing–to–framing connection; K_5 represents slipping stiffness of a sheathing–to–framing connection; δ_{yield} represents apparent yield displacement of a sheathing–to–framing connection; δ_u represents unloading displacement of a sheathing–to–framing connection ; δ_{fail} represents softening displacement corresponding to the failure load of a sheathing–to–framing connection; α represents sheathing-to-framing connection degradation hysteresis model parameter; β represents sheathing-to-framing connection degradation hysteresis model parameter.

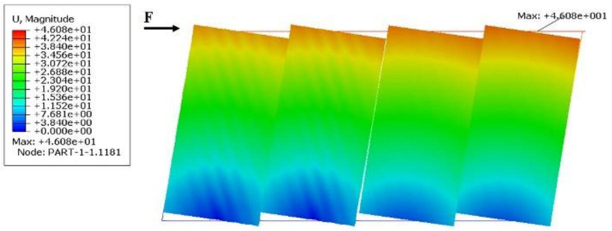

Figure 5. The deformation cloud picture of timber frame shear wall (Abaqus).

Figure 5 shows one simulated result of the deformation cloud picture of timber frame shear wall. It can be found that under the lateral load, the deformation of the cladding is mainly torsion, while the stud has been changed from a rectangle to a parallelogram with a slight bending.

Use and cost of main construction materials

Given various structural solutions, the material usage of this timber house was assessed using Revit-Dynamo (BIM tool) and relevant construction costs were calculated according to material characteristics and prices (Table 4 & 5) recommended in a reference (MOHURD 2013). As mentioned above, cladding butt joints should always be spliced on the stud and be staggered. Therefore, different stud spacing will lead to different standard cladding layouts, and various amounts of cladding material use in each case. In this paper, the total cladding use includes the cladding applied on the house and the cladding wasted during the construction.

Table 4: Price of construction material: structure.

Name	Level	Unit price (RMB)
SPF	Ⅱc	2600/m^3

Table 5: Prices of construction material: cladding panel.

Name	Dimension per sheet (mm)	Unit price (RMB)
OSB	2440×1220×15	105/sheet
GB	2440×1220×15	12/sheet

Embodied carbon

Given various structural solutions, the material usage of this timber house was assessed using Revit-Dynamo (BIM tool) and relevant construction costs were calculated according to material characteristics and prices (Table 4 & 5) recommended in a reference (MOHURD 2013).

According to the life of cycle assessment for building materials, the "cradle-through-construction" include main processes of production, distribution, and installation (BSI, 2011). Since applications of various waste treatment models will lead to huge differences in embodied carbon calculation in the end of life, this study only focuses on the embodied carbon of timber material using the way of 'from cradle to construction'. The main algorithms of embodied carbon for three materials (SPF, OSB, Gypsum Board) used in this study can be found in Table 6.

Table 6: Algorithms of embodied carbon (cradle-through-construction). (WFG, 2017)

Name	Parameters describing environmental impacts	Units	Cradle stage (kg/m^3)	Distribution and Construction (kg/m^3)
SPF	Global Warming Potential (kg)	CO2eq	-712	49.26
OSB			-8.99	0.74
Gypsum Board			1.85	1.11

BIM workflow

Revit-Dynamo (BIM tool) was applied to complete the integrated analysis in this study. The workflow is shown in Figure 6.

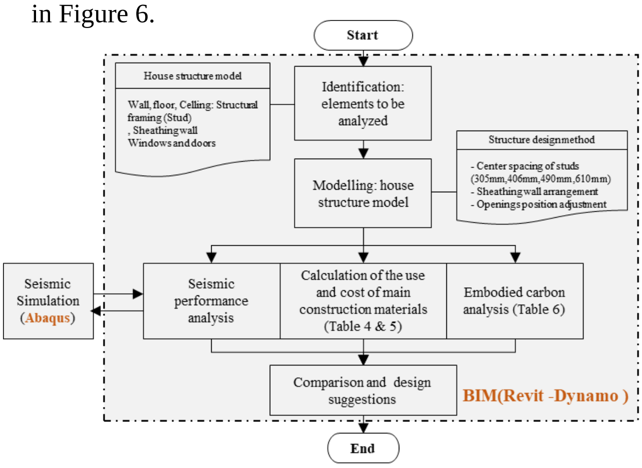

Figure 6: Workflow in a BIM environment.

First, key elements to be analysed were identified from different structures including floor, celling, shear wall (structure and cladding), windows and doors. Second, alternative solutions were designed and set for the structure with the highest potential (i.e. shear wall): (1) defining stud spacing (305 mm, 490 mm, 610 mm); (2) fitting cladding panels with the wall structure; (3) adjusting positions of openings (window and door). Following this, three parallel processes were conducted at the same time to provide with results of seismic performance, materials use and cost, and embodied carbon, respectively. The seismic analysis was conducted in Abaqus. The structure models were transferred from Revit and calculated data were sent back through the connection with Revit. Finally, a parametric analysis was achieved based on the three types of data.

Results

Analysis of seismic performance

Table 7 gives ultimate lateral loads on each shear wall (Figure 2) in K-House with the stud spacing of 406mm (conventional model). WF can bear the highest load among walls of ground floor (72.3KN), whilst at the first floor WP has similar load (72.5KN). The lowest ultimate load can be found at WL, which is approximately 1/6 of the load of WF or WP. It can be found that the increasing wall length can increase the ultimate load.

Table 7: Ultimate lateral loads on the shear wall with the conventional structure (stud spacing: 406 mm).

Level	Position	Dimension(mm)	Ultimate lateral load (KN)
Ground Floor	WA	5640×3200×170	36.4
	WB	8600×3200×170	54.2
	WC	2100×3200×170	14.7
	WD	4100×3200×170	27.6
	WE	3540×3200×170	22.6
	WF	12700×3200×170	72.3
First floor	WG	5640×3100×170	36.9
	WH	5300×3100×170	34.8
	WI	7275×3100×170	46.7
	WJ	3300×3100×170	20.1
	WK	7275×3100×170	46.5
	WL	1900×3100×170	12.2
	WM	2100×3100×170	14.1
	WN	4100×3100×170	28.8
	WO	3540×3100×170	23.9
	WP	12700×3100×170	72.5

To compare the seimesic performance between new and conventional structure solutons, the relative difference of ultimate lateral load R_{load} is defined using the following equation:

$$R_{load} = \frac{F_i - F_c}{F_C} \times 100\% \qquad (1)$$

where, F_i represents the ultimate lateral load when the stud spacing is 305 mm, 490 mm, and 610 mm, respectively; F_c is the ultimate lateral load for a conventional stud spacing (406 mm).

Table 8: Relative differences of ultimate loads on the shear walls with alternative structural solutions (stud spacing: 305mm, 490mm, 610mm); ground floor.

Position	Dimension(mm)	Stud Spacing(mm)	R_{load} (%)
WA	5640×3200×170	305	3.30
		490	-1.92
		610	-6.04
WB	8600×3200×170	305	3.14
		490	-1.11
		610	-6.64
WC	2100×3200×170	305	4.71
		490	-1.60
		610	-7.49
WD	4100×3200×170	305	2.67
		490	-1.81
		610	-7.25
WE	3540×3200×170	305	2.21
		490	-1.77
		610	-6.19
WF	12700×3200×170	305	3.04
		490	-0.97
		610	-6.22

Table 9: Relative differences of ultimate loads on the shear walls with alternative structural solutions (stud spacing: 305mm, 490mm, 610mm); first floor.

Position	Dimension(mm)	Stud Spacing(mm)	R_{load} (%)
WG	5640×3100×170	305	2.71
		490	-1.63
		610	-6.50
WH	5300×3100×170	305	4.89
		490	-2.59
		610	-7.76
WI	7275×3100×170	305	3.00
		490	-2.36
		610	-5.14
WJ	3300×3100×170	305	4.48
		490	-2.49
		610	-10.45
WK	7275×3100×170	305	2.37
		490	-1.29
		610	-7.10
WL	1900×3100×170	305	2.33
		490	-1.74
		610	-7.56
WM	2100×3100×170	305	2.21
		490	-1.66
		610	-6.63
WN	4100×3100×170	305	2.78
		490	-2.43
		610	-4.86
WO	3540×3100×170	305	2.93
		490	-4.60
		610	-8.37
WP	12700×3100×170	305	1.52
		490	-2.62
		610	-6.34

Table 8 & 9 show R_{load} values of 16 shear walls at the ground and first floors, respectively. The largest load reduction is found at WJ, which is around 10% (610 mm), while WH can see the biggest load increase of 4.89% (305 mm). In addition, when the stud spacing decreases to 305 mm (24.9% decrease), the average value of R_{load} raises to around 3.17%. On the other hand, when the stud spacing increases to 490 mm (20.7% increase) and 610 mm (50.2% increase), the average values of R_{load} drop to -1.53 % and -6.64, respectively. These trends indicate that the new structural solutions cannot significantly change the seismic performance of wall structures when compared with the conventional design.

Analysis of materials use and cost

Table 10 & 11 give the material use and relevant cost for the construction of conventional shear wall. The SPF use for the structure is 15.7 m^3 and costs 40,820 RMB. As for the cladding panel, the material use and cost tend to be lower (29,400 RMB for OSB; 1,488 RMB for gypsum board).

Table 10: Material use and relevant cost of conventional wall structure (stud spacing: 406mm).

Name	Use (m^3)	Total cost (RMB)
SPF	15.70	40,820

Table 11: Material use and relevant cost of conventional wall cladding (stud spacing: 406mm).

Name	Use (Sheet)	Cost (RMB)
OSB	280	29,400
Gypsum Board	124	1,488

Table 12 shows that the material use and cost of three new structural solutions (A, B, and C). Taking the conventional solution as a reference (Table 10 & 11), the use of SPF increases by 29% for A, and decrease by 4.5% for B and 12.7% for C. Similarly, for OBS use, three new solutions see relative differences as 16% (A), -6.1% (B), -35% (C). With the gypsum board, the three values are 19.4% (A), -6.5% (B), and -25.8% (C). It can be found that decreasing the stud spacing can significantly increase the material use for both structure and cladding panels, while a clear reduction of material use can be particularly found at the cladding panel with an increasing stud spacing. Moreover, relative differences of total material cost are 24% (A), -4.8% (B), and -22% (C).

Table 12: Materials use and cost with alternative structural solutions (stud spacing: 305mm, 490mm, 610mm).

Name	Material use (SPF: m^3; OSB & GB: sheet)			Material cost (RMB)		
	A	B	C	A	B	C
SPF	20.3	15.0	13.7	52,780	39,260	35,770
OSB	325	263	182	34,125	27,615	19,110
GB	148	116	92	1,776	1,392	1,104
Total				88,681	68,267	55,984
Note: A - Stud spacing is 305mm; B - Stud spacing is 490mm; C - Stud spacing is 610mm;						

Analysis of embodied carbon

Table 13 indicates the calculated emission of embodied carbon of conventional design in this timber house (stud spacing: 406 mm). The embodied carbon in product stage is -11260.12 kg while this value can reach at 785.72 kg in the construction process stage. Due to the carbon sequestration characteristics of timber, the overall embodied carbon emission can be changed into -10747.4 kg with a whole process of cradle-through-construction.

Table 13: Emission of embodied carbon of conventional design (cradle-through-construction).

Name	Cradle stage (kg)	Construction process stage (kg)	Total (kg)
SPF	-11178	773.38	-10405.02
OSB	-89.92	7.42	-82.5
Gypsum Board	8.19	4.92	13.11
Total	-11260.12	785.72	-10474.4

Table 14 expresses the calculated emission of embodied carbon of three optimized structural solutions (A, B, and C). For the process of cradle-through-construction, solution A can achieve the lowest embodied carbon emission (-13533.8 kg) while the highest embodied carbon emission is found for solution C (-9163.2 kg). Similar trend is presented at the cradle stage, with the highest and lowest values for solution A (-14548.18 kg) and solution C (-9849.48), respectively. At the construction process stage, positive embodied carbon emissions are 1014.43 kg (A), 755.37 kg (B), 686.27 kg (C). Compared with the embodied carbon of conventional structure (Table 13), solution A can see a carbon reduction by 30% according to the total process, while solution B and C have the increased total carbon emission by 3.2% and 11.9%, respectively.

Table 14: Emission of embodied carbon of alternative structural solutions (cradle-through-construction).

Name	Cradle stage (kg)			Construction process stage (kg)			Total
	SPF	OSB	GB	SPF	OSB	GB	
A	-14453	-104.36	9.78	999.97	8.59	5.86	-13533.8
B	-10751	-84.45	7.66	743.82	7.04	4.59	-10072.6
C	-9797	-58.44	6.07	677.82	4.81	3.64	-9163.2
Note: A - Stud spacing is 305mm; B - Stud spacing is 490mm; C - Stud spacing is 610mm;							

According to Table 13 and 14, the use of SPF (for wall structure) can make significant contributions to the reduction of embodied carbon emissions. The embodied carbon emission at the construction stage of this house can be sequestered by the production of SPF at the cradle stage. Thus, the structure design of a timbe house would be critical in terms of embodied carbon emission.

Discussions and suggestions

Taking the conventional structure solution (stud spacing 406 mm) as the reference, Figure 7 gives relative differences of ultimate lateral load, material cost, and embodied carbon emission of three alternative structure solutions (stud spacing: 305mm, 490mm, 610mm).

Generally, increasing the stud spacing will reduce material costs while increasing embodied carbon from cradle-through-construction. The opposite varying trends of cost and embodied carbon can be achieved through reducing the stud spacing. Absolute relative differences of ultimate lateral load of three solutions are lower than 7%, indicating that no significant impact of stud spacing can be found on the seismic performance. For the structure with a stud spacing of 490 mm, all absolute relative differences (lateral load, cost, and embodied carbon) are less than 5%. This might be due to a fact that a small increase in stud spacing (lower than 25%) cannot lead to big impact on the three aspects.

There are big relative differences of cost and embodied carbon, which can be found in structures with stud spacing of 305 mm and 610 mm. Compared with the conventional solution, the short stud spacing can achieve an increase in cost by 23.67%, while a decrease in cost by 21.92% is found for the long stud spacing. As for the embodied carbon, an opposite trend occurs as: short stud spacing sees a decrease by 29.21% and long stud spacing has an increase by 12.52%. Thus, it seems that to balance cost and embodied carbon emission could be an important analysis target when a proper level of seismic performance has been achieved in a series of structural solutions. Given the alternative solutions, increasing the stud spacing is a good measure to reduce material costs and embodied carbon in the construction process stage. Narrowing stud spacing will deliver a positive impact on the seismic performance, and more importantly on the embodied carbon reduction from cradle to construction. If taking the 20% difference as a threshold, the short spacing sees significant embodied carbon reduction and cost increase. However, the long spacing can bring in the significant cost decrease and an insignificant increase in embodied carbon (< 15%).

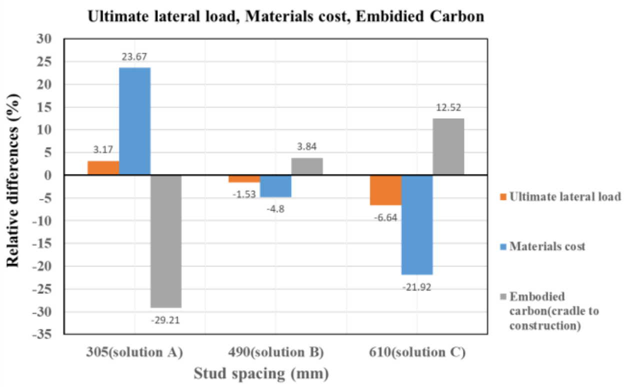

Figure 7: Relative differences of alternative structural solutions: ultimate lateral load, material cost, and embodied carbon (taking conventional solution as the reference).

Conclusion

This article has presented a BIM-based simulation analysis of seismic performance, embodied carbon, and construction cost in a prefabricated Chinese timber house. Some conclusions that can be drawn from this study include:

1) It is necessary to implement an integrated analysis at the design stage of a prefabricated timber house to achieve a substantially sustainable design. In addition to the basic analysis of structural safety (seismic performance), it would be required to include material use/cost and embodied carbon, which have been proved as core issues relating to the achievement of sustainable construction of contemporary buildings.

2) A BIM-based simulation environment can help achieve the integrated analysis in an efficient way. Using one typical BIM tool, this study investigated variations of material use/cost and embodied carbon emission based on several alternative structural solutions in this timber house.

3) In a prefabricated timber house, it is possible to conduct effective structural change through the adjustment of key structure components (e.g. wall structure in this study). Some design solutions can lead to significant reduction of material use and relevant cost while keeping the seismic performance of structure at a proper level.

4) When conducting structural change in a prefabricated timber house, there is a need to balance material use/cost and embodied carbon emission. The alternative solution with higher levels of structure material use and cost (23.67%) can significantly benefit the reduction of embodied carbon emission (29.21%) according to a process of 'from-cradle-through-construction'. However, the decreasing material use (21.92%) can reduce the embodied carbon emission at the construction stage but will deliver a detrimental impact on the embodied carbon reduction (12.52%) in the process of 'from-cradle-through-construction'.

Limitations and future work: These conclusions are obviously limited to a simple structure model (e.g. the same stud spacing). It would be necessary to investigate various stud spacing configurations at wall, roof, and floors. In addition, the structural safety simulation did not include some factors (e.g. wind, water, etc.). The process of timber product lifespan ignores de-construction and disposal, which might over-estimates the benefit of carbon sequestration. These issues will be studied in future work.

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