Comparative study on carbon emission of steel and aluminum alloy structure greenhouse building in whole life cycle

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ABSTRACT

Based on case study on a greenhouse building, this paper systematically quantifies and analyzes the difference of carbon emission intensity between steel structure and aluminum alloy structure building in the whole life cycle. This paper traces carbon emission intensity of steel and aluminum alloy, and puts forward a calculation method to achieve a reasonable and localized carbon emission intensity value. At the same time, considering recycling characteristics of metal building materials, different methodologies for metal recycling in carbon accounting are studied and compared. Sensitivity analysis is conducted on 3 variables, which are aluminum to steel mass ratio (v), recycled content (R) and recyclability (r) using 2 methods for metal recycling, and different comparative results of carbon emissions in the whole life cycle of steel and aluminum structure greenhouse buildings in different scenarios are obtained. This study analyzed the impact of structural type (material) selection on carbon emissions in the whole life cycle of buildings. In addition to its findings on low-carbon advantages of steel structure greenhouses under current conditions, it also extends to dynamic research results under different scenarios in the future, which can provide reference for architects and engineers in building industry to further explore the potential of carbon reduction in the follow-up building design practice.

Keywords: Carbon emission, whole life cycle of building, steel structure, aluminum alloy structure, sensitivity analysis, low-carbon building design

1. INTRODUCTION

According to the International Green Building Association, 39% of the global carbon emissions from energy sources are caused by the construction industry, of which 28% are from purchased energy from buildings in operation and 11% are from the production of building materials and construction activities[1]. Under the trend of climate warming, building industry pays more and more attention to the whole life cycle carbon emissions, including the embodied carbon of buildings. Taking “IStructE World Structure Award 2022” as an example, four of the top 10 winning cases used glued laminated timber structure or bamboo structure[2]. Low-carbon design of buildings is gradually being concerned by the building industry worldwide.

In 2021, China announced the dual carbon goal to the world, including carbon neutrality in 2030 and carbon peak in 2060[3]. Taking China’s 2020 statistics as an example, emissions related to building industry accounted for more than 50% of the annual carbon emissions, which come from production activities of building materials such as steel and cement, the operation of existing buildings, construction sites and other activities. Therefore, carbon reduction in the building industry is the key to the realization of China’s dual carbon and climate goals. In recent years, the evolution of China’s national design standards shows that its building industry has been carrying out energy saving and carbon reduction actions from top to bottom. China first issued a calculation standard specifically for building carbon emissions in 2019 as a guidance book only, rather than mandatory requirements for carbon emissions calculation in the stage of building design[4]. In 2022, a national standard, “General Code for energy efficiency and renewable energy application in buildings” (GB55015-2021) made carbon emission calculation a mandatory requirement for the first time, focusing on energy saving and carbon reduction in building’s operation stage[5]. Another latest national standard “Zero Carbon Building Technical Standard” (draft for comments), for the first time, encourage professionals in building industry to carry out embodied carbon and life cycle carbon reduction design[6].

Low-carbon building design is of great importance for carbon reduction in building industry. On one hand, building energy-saving design affects the intensity of energy consumption and carbon emissions in the building operation stage,

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on the other hand, choices made on building and structural design schemes affect the selection of building materials, amount of building materials consumed, construction activities, which means that it affects carbon emissions in the production and construction of building materials.

However, difficulties have been met in the practice of low-carbon building design:

(1) Low carbon performance is difficult to quantify. At present, due to the lack of publicly released baseline of building carbon emission intensity in China, low-carbon performance is at the qualitative level, impression level, and lack of quantitative data endorsement.

(2) Source of carbon emission is not clear. For official database, the construction of carbon emission factor database in China has just started and the amount of official database data is small. As for folk database, difficulties include unclear data source and unclear carbon accounting boundary.

(3) The emission reduction path is not clear. When facing specific engineering cases, designers and engineers are overwhelmed about how to plan emission reduction paths and what emission reduction measures to adopt. This makes it difficult for professionals to provide low-carbon building design solutions effectively.

(4) Timeliness of emission data is poor. At present, the official database of carbon calculation in China's building industry was published in 2019[4], and most of the data were accounted in 2013, which is 10 years ago. Material production progress and breakdown of electricity mix in the last decade are not same as current status in China.

In order to ensure the goal of low-carbon building design achieved, it is necessary to focus on whole life cycle of building and compare carbon emission intensity of different building schemes from an early stage of design. Wang et al. (2015) compared carbon emission intensity of residential buildings with different but similar architectural design among 4 different structural types, and found steel structure scheme emitted less amount of carbon than concrete structure but higher amount of carbon than timber concrete in the context of whole life cycle of building[7]. Zhang et al. (2024) compared the whole life cycle carbon emission of a hotel building between 2 different steel structural types under the same architectural design scheme[8]. Both studies mentioned above adopted a constant carbon emission factor for steel without taking into account of different methods for metal recycling in carbon accounting and recycled materials such as scrap steel used for metal production.

In this comparative study on carbon emissions of building between different structural types, a greenhouse building is chosen as research object to explore the method for the selection of low-carbon structural schemes at design stage for 2 reasons. One is that selection of different building types would not affect greenhouse building layout so that it is comparatively easy to control variables in life-cycle carbon emission. The other reason is that China's greenhouse buildings such as Taiyuan Botanical Garden Domes and Tianfu Architectural Expo Main Hall are attracting more and more attention worldwide because of its outstanding structural design and low-carbon performance[2,9]. In addition, this study compared different methods for metal recycling and analyze the impact of sensitivity factors (aluminum to steel mass ratio, recycled contents and recyclability) on carbon emission intensity of metal structural building to avoid limitation of adopting constant emission factor of metal materials in carbon accounting.

2. METHODS

2.1 Accounting boundary of carbon emission in the whole life cycle of building

According to China's "Standard for building carbon emission calculation", the whole life cycle of buildings is generally divided into building materials production stage, building materials transportation stage, building construction stage, building operation stage and building demolition stage[4] (Figure 1).

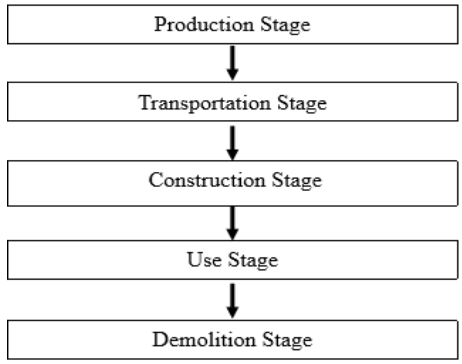

Figure 1. Accounting boundary of the whole life cycle of building.

2.2 Accounting boundary of steel and aluminum building materials production stage

The accounting boundary of carbon emission in the production stage of building materials is "from cradle to gate", which includes ore mining, raw material production, material processing and transportation before leaving production plant[10].

There are two types of production lines for steel and aluminum profiles[11-14] (see Figures 2 and 3). One is primary material production line, in which primary steel and primary aluminum ingots are manufactured by taking iron ore and bauxite as raw materials. The other is recycled material production line, in which scrap steel and scrap aluminum are used as raw materials to produce recycled steel and recycled aluminum ingots. Compared with the original material production line, the recycled material production line can greatly save carbon. Taking aluminum as an example, the emission of producing 1 t recycled aluminum ingot is only 4.45% of the primary aluminum ingot[11]. For steel, the emission of producing 1 t of recycled steel is about 25%-33% of the primary steel[14].

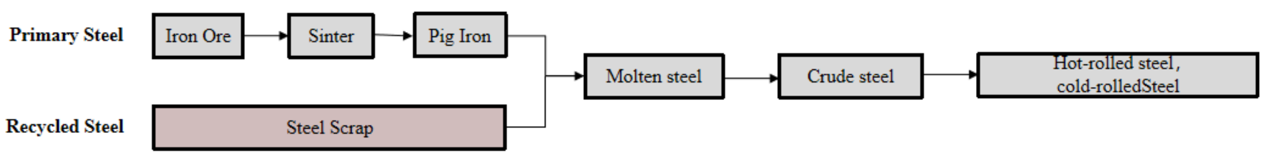

Figure 2. Production process of primary and recycled steel.

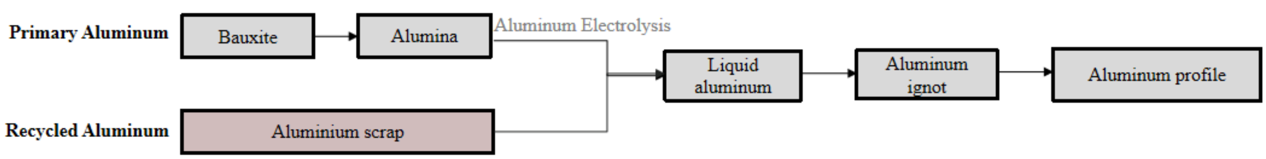

Figure 3. Production process of primary and recycled aluminum.

2.3 Analysis on carbon emission factors of steel and aluminum profiles

Extensive research has been conducted among worldwide databases on carbon emission intensity values per ton of steel and aluminum. Globally, the carbon emission intensity per ton of steel varies from country to country (Table 1), ranging from 1736 to 2630 $kgCO_2$ eq, whilst the carbon emission intensity per ton of aluminum ingot varies greatly (Table 2), ranging from 5000 to 25000 $kgCO_2$ eq. accounting boundary, the proportion of recycled components and the difference of production process may be the factors affecting the emission intensity of tons of steel and tons of aluminum. In China, over the whole processes of primary aluminum ingot production, the emission intensity of aluminum electrolysis accounts for more than 70%[11]. Therefore, the difference in the proportion of clean energy in the State Grid in different regions may be the reason why the emission intensity per ton of aluminum fluctuates significantly larger than that per ton of steel.

In principle, domestic database data is preferred as reference for material carbon emission factor. However, in Chinese database, the proportion of recycled components in steel and aluminum accounting is unknown. Besides, only aluminum ingot production data is provided with emission data of aluminum profile production missing. Considering main purpose of this study, it is not appropriate to quote database data of China and other countries for identifying the carbon emission factors of steel and aluminum profiles. Instead, referring to the inventory data taken from the domestic production process data[11-13] and conducting LCA modeling autonomously (using database Ecoinvent 3.0) is adopted to gain reasonable and localized emission factors for steel and aluminum. For LCA modeling for aluminum, Tian et al. (2019) and Gao (2012) provide reference for inventory data of aluminum ingot production[11] and aluminum ingot processing and extrusion to aluminum profiles[12], respectively. For LCA modeling for steel, the research results of Wei et al. (2022) are referred as inventory data of steel production stage[13].

Tables 1 and 2 show the comparison results of emissions per ton of steel and per ton of aluminum between the Chinese and foreign databases and the LCA modeling method.

Table 1. Comparison between research and modeling results of carbon emission intensity per ton of steel.

Data source	**Accounting boundary**	**Emission density (kg CO_2 eq/t)**	**Proportion of recycled contents**
American Reference[15]	Crude steel	1736	Unknown
UK Database[16]	Steel	2630	0
	Steel	2360	16.28%
	Steel	2260	21.85%
Chinese Standard[4]	Steel	2350	Unknown
LCA Modeling	Steel	2437	16.28%

Table 2. Comparison between research and modeling results of carbon emission intensity per ton of steel.

Data source	**Accounting boundary**	**Emission density (kg CO_2 eq/t)**	**Proportion of recycled contents**
UK Database[15]	Aluminum Ingot	5000~22078	0
	Aluminum profile	14600 (China)	31%
	Aluminum profile	13100 (World)	0
Chinese Standard	Aluminum Ingot	20300	Unknown
International Aluminium Association (IAI)[17]	Aluminum Ingot	5000-25000	0
LCA Modeling	Aluminum Ingot	21497	0
	Aluminum Ingot	26357	0

Considering that the data of carbon emission factors of steel and aluminum profiles vary greatly from country to country; in order to facilitate the subsequent sensitivity analysis, the carbon emission factors of steel and aluminum profiles are calculated by LCA modeling method. Carbon emission intensity of primary materials and recycled materials are modeled in line with China's production process, and results are shown in Table 3. The values of the proportion of recycled contents (R) and the recyclability (r) of the steel and aluminum profiles used in the case study calculation are shown in Table 4.

Table 3. Carbon emission intensity values of primary and recycled steel and aluminum profiles adopted in case study.

Building materials	**Primary material ($kgCO_2$ eq/t)**	**Recycled material ($kgCO_2$ eq/t)**	**Notes**
Aluminum profile	26357	3763	
Steel	2734	911	Based on 33% of carbon emissions from recycled materials as primary materials[14].

Table 4. Values of the proportion of recycled contents (R) and recyclability (r) of steel and aluminum profiles adopted in case study.

Building materials	Recycled content (R)	Recyclability (r)	Notes
Aluminum profile	31%[16]	95%[16]	World data (no Chinese data available)
Steel	16.28%[13]	81%[16]	Chinese data

2.4 Carbon emission accounting method for metal recycling

The accounting method of carbon emission intensity of building materials considering metal recycling has not been unified around the world[4,16]. Four methods have been investigated in the study, which are shown in Table 5. Methods 1-3 are from the UK Database: ICE V3.0[16]. Method 4 is from China's "Standard for building carbon emission calculation"[4].

(1) Method 1 "Recycling content approach": it only focuses on the proportion of waste input in the material production stage, such as scrap steel, which is the proportion of recycled materials produced.

(2) Method 2 "Substitution method": it only focuses on the recyclability of material after the demolition of the building and the end of the use of the material.

(3) Method 3 "50:50 method": it not only pays attention to the proportion of recycled materials produced from waste materials in the material production stage, but also pays attention to the recyclability of materials after use. It provides equal weights for recycled materials used to material recyclability at its end of life.

(4) Method 4 "Recycling method": Similar to method 3, it not only pays attention to the proportion of recycled materials produced from waste materials in the material production stage, but also pays attention to the recovery rate of materials after use. When recycled materials are used, they shall be calculated as 50% of the carbon emissions of the primary materials they replace. Recyclable building waste generated in the building construction and demolition stages may be calculated as 50% of the carbon emissions of the primary materials, and shall be deducted from the building carbon emissions.

Table 5. Introduction to four carbon emission accounting methods for metal recycling.

No.	Method	Calculation formulation
1	Recycled content approach (100:0)	$E = (1-R)E_V + R * E_R \quad (1)$
2	Substitution method (0:100)	$E = \mathrm{r}E_R + (1-\mathrm{r}) * E_V \quad (2)$
3	50:50 method	$E = \frac{1}{2}(1-\mathrm{R})E_V + \frac{1}{2}R * E_R + \frac{1}{2}r * E_R + \frac{1}{2}(1-\mathrm{r}) * E_V \quad (3)$
4	Recycling approach	$E = (1-\mathrm{R})E_V + \frac{1}{2}R * E_V - \frac{1}{2}r * E_V \quad (4)$

The comparison of carbon emission intensity per unit mass of steel and aluminum profiles under different recycling methodologies is shown in Figure 4. Generally, design life of Chinese buildings is 50 years. The proportion of waste input and the proportion of recycled materials (R) in the production stage will be defined in the bidding and procurement process within 1 to 2 years, while material recyclability (r) after the end of material use will be defined in the demolition stage after 50 years. Therefore, recycled content of materials is more predictable than the recyclability of material, over time span of building's life cycle, especially in the context of approaching dual carbon goal towards 2030 and 2060. In this case, method 1 is more acceptable under the context of building life-cycle emission accounting because front-end procurement activities are relatively more controllable than the back-end demolition activities. In terms of building carbon emission accounting. For methods 3 and 4, the calculation methods and results are similar. Therefore, only method 1 and method 4 are used in the followed-up case study analysis.

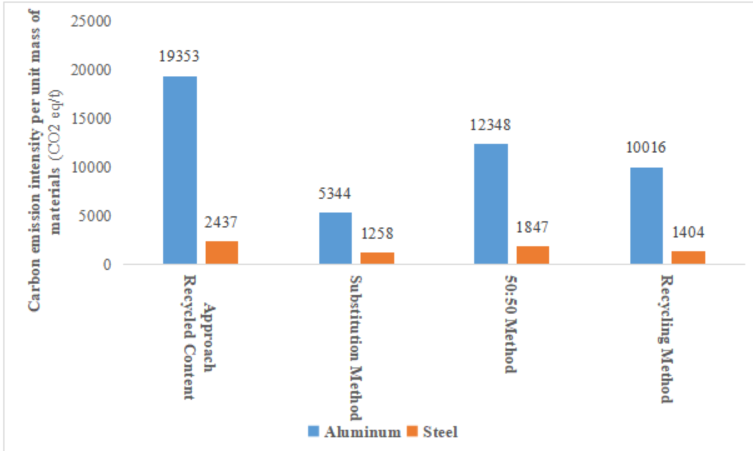

Figure 4. Comparison chart of carbon emission intensity per unit mass of building materials under different recycling methodologies.

3. CASE STUDY ON CARBON EMISSIONS OF STEEL AND ALUMINUM ALLOY STRUCTURE GREENHOUSE BUILDING IN WHOLE LIFE CYCLE

3.1 Case introduction

The project is located in Suzhou City, Jiangsu Province. With a building area of 11403 m^2, it is a single-layer reticulated shell structure and is functioned as a greenhouse building.

In order to compare the whole life cycle carbon emission intensity of steel and aluminum alloy structures, control variable method is adopted in the comparative study and two structural schemes are designed for the same building architectural plan and building physical performance. It means that building scale of steel structure and aluminum alloy structure greenhouse building are the same, with same gross building area, building height, and building volume. Besides, thermal performance and structural performance of two schemes are designed according to the same goal, which means the only difference of two schemes are the structure types and materials used related to building structures. Calculation and analysis are carried out according to the bill of quantities of steel and aluminum alloy structures.

3.2 Building carbon emission calculation list

The calculation scope of embodied carbon in the case includes the production and transportation stage of main building materials such as steel, aluminum profiles, glass, glass sub-frame and fireproof paint, the construction stage of building, the maintenance of main materials in the operation stage, and the carbon emission in the demolition stage of buildings. Quantities of main building materials are obtained from design drawings and models, as shown in Table 6. The purpose of this study is to compare the impact of steel and aluminum structural scheme selection on the carbon emission intensity of the whole life cycle of the building, so the quantities of non-major building materials that are not affected by the structural scheme selection are not counted, and the non-major building materials are not involved in the subsequent carbon emission calculation of building materials.

In the stage of building materials transportation, the transportation distance of steel and aluminum profiles is based on the survey results of factories around the project site. Transportation distance of other building materials refers to domestic literature data (see Table 6)[18]. Truck is selected as the transportation mode.

The carbon emission in the construction stage comes from the energy consumption of construction machinery and labor, and corresponding data is taken from profiles provided by construction unit (See Table 7).

In order to maintain the consistency of emission factors, building materials and energy emission accounting refer to the database Ecoinvent 3.0, and the evaluation method is IPCC2013 GWP 100 wa. Carbon emission of construction workers in the construction stage is calculated according to 19.76 $kgCO_2$/man-day[19].

Carbon emission of building operation stage is calculated according to the design operating life of the building of 50 years. Considering that the service life of steel anti-corrosion and fireproof coating is about 15 years, two rounds of maintenance over building's life span (50 years) are considered in the building operation stage. The energy consumption intensity values of the two schemes in the operation stage are estimated and shown in Table 8.

Table 6. List of main building materials of the case.

Structural type	Main building materials	Overall weight (t)	Transportation distance (km)[18]
Aluminum	Steel (Q345)	2.87	25.00
	Aluminum profile (6061T6)	191.64	30.00
	Glass	264	98.84
	Fireproof paint (fire resistance: 2.5 h)	1.03	103.81
	Anti-corrosive paint (epoxy zinc-rich + epoxy micaceous iron oxide + fluorocarbon)	0.02	103.81
	Glass sub-frame: integrated sub-frame + pressing block (material: aluminum)	23.6	30.00
Steel	Steel (Q3 45)	464	25.00
	Fireproof paint (fire resistance: 2.5 h)	121.27	103.81
	Anti-corrosive paint (epoxy zinc-rich + epoxy micaceous iron oxide + fluorocarbon)	2.34	103.81
	Glass	264	98.84

Table 7. Inventory data during the construction stage.

Structure type	Diesel		Labour	
	Energy consumption (kg/machine-team)	Machine-team	No. of workers	Working days (8 hour/day)
Aluminum	30.75	24.16	30	10
Steel	30.75	47.85	30	10

Table 8. Annual energy consumption of building in operation stage.

Energy type	Energy consumption	Unit
Natural gas	47.6	$m^3/m^{2}\cdot a$
Electricity	79.3	$kWh/m^2\cdot a$

3.3 Calculation and comparison of carbon emissions in whole life cycle

The comparison of the whole life cycle carbon emission intensity of the two schemes is based on two accounting methods for metal recycling, namely recycled content approach from ICE 3.0 and recycling approach from China's national standard.

It can be seen from Figures 5 and 6 that the carbon emission intensity of aluminum alloy structure greenhouse building is higher than that of steel structure greenhouse building in the whole life cycle and building production stage under both methods. Since steel structure scheme needs requires two rounds of maintenance of steel fireproof and anti-corrosive coatings in the life cycle, the carbon emission intensity of the aluminum alloy structure greenhouse in the building operation stage is lower than that of the steel structure scheme (see Figure 7).

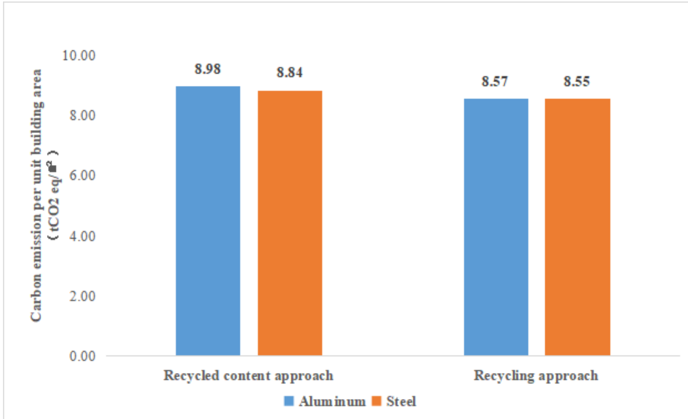

Figure 5. Comparison of carbon emission intensity of aluminum structure and steel structure building in the whole life cycle.

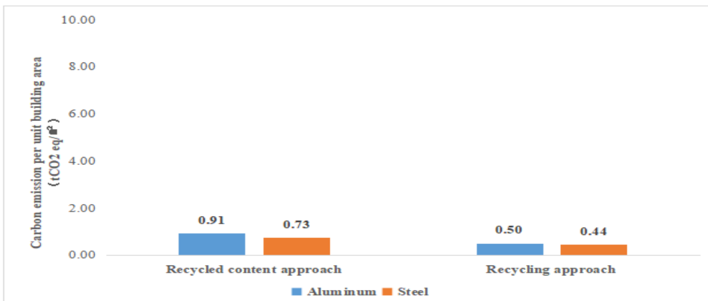

Figure 6. Comparison of carbon emission intensity of aluminum structure and steel structure building in the production stage of building materials.

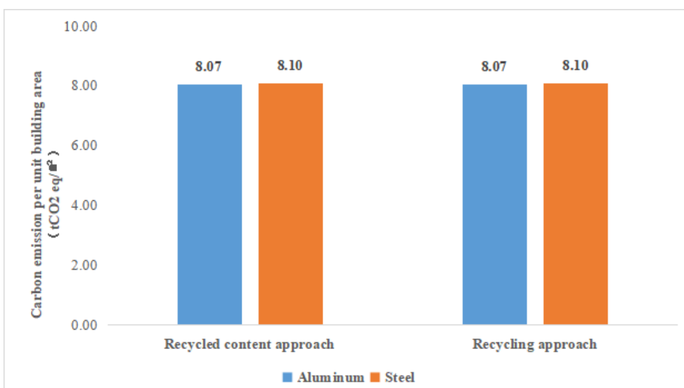

Figure 7. Comparison of carbon emission intensity of aluminum structure and steel structure building in operation stage.

3.4 Sensitivity analysis

Considering the limitation of fixed emission factors input in case study and in order to further explore the carbon reduction potential of steel and aluminum alloy structures, sensitivity analysis is conducted on 3 key variables to test how they affect the output results so that the research results can be used for reference by other projects. Variables include aluminum to steel mass ratio (v), recycled content (R) and recyclability (r). The dots in Figures 8-12 refer to the input and output value of case study. Sensitivity analysis is conducted to test how target variables affect output results of case study, which are comparison results between steel and aluminum alloy structure on building life cycle carbon emission intensity.

(1) Aluminum to steel mass ratio (v)

As shown in Figures 8 and 9, the critical points of v values affecting the comparison results are similar under the listed two methods for metal recycling. According to the recycled content approach, when v is equal to 33.6%, the carbon emission intensity of the whole life cycle of aluminum alloy structure building is equal to that of steel structure. When v is less than 33.6%, the life cycle carbon emission intensity of aluminum alloy structure is lower than that of steel structure. According to the national recycling approach, the critical point of v value of the comparison result is changed from 33.6% to 39.1%.

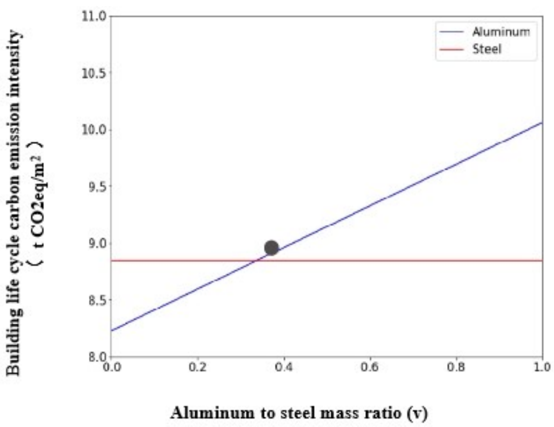

Figure 8. Sensitivity analysis result of aluminum to steel mass ratio (v) using recycled content approach.

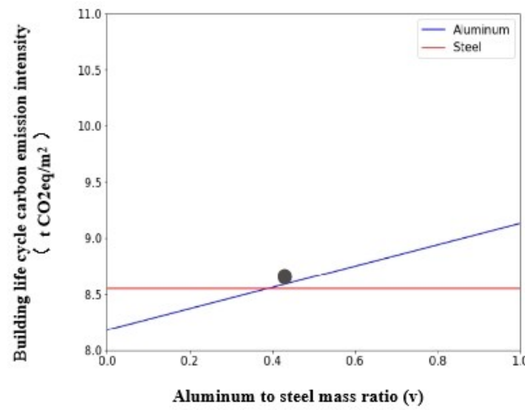

Figure 9. Sensitivity analysis result of aluminum to steel mass ratio (v) using recycling approach.

The comparison results show that the amount of building materials affects the comparison results of carbon emission intensity of different schemes. When the proportion of aluminum consumption is reduced to less than 33.6% of steel consumption, building life cycle emission intensity of the aluminum alloy structure scheme is lower than the steel structure scheme.

(2) Recycled content (R)

As shown in Figures 10 and 11, when the value of $R_{Aluminum}$ is within a certain range, the comparison results are not affected by R_{Steel}. There are obvious differences in the critical point of $R_{Aluminum}$ value behind the similar conclusions of two methods.

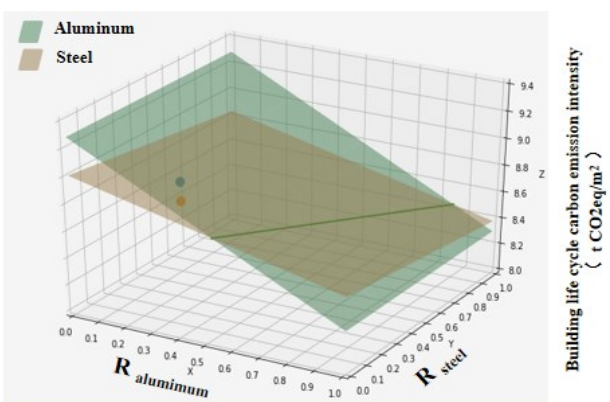

Figure 10. Sensitivity analysis result of recycled content of aluminum and steel (R) using recycled content approach.

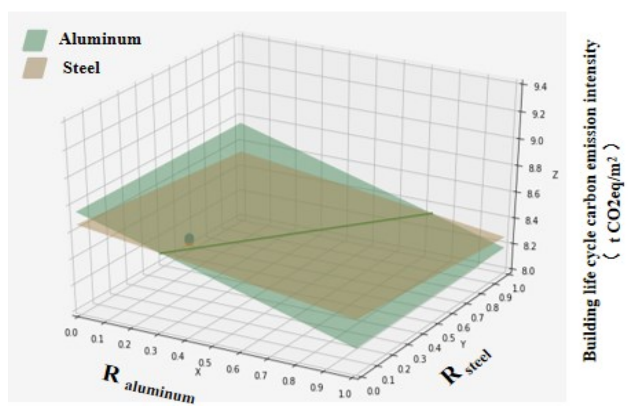

Figure 11. Sensitivity analysis result of recycled content of aluminum and steel (R) using recycling approach.

According to the recycled content approach, when $R_{Aluminum}$≤85. 1%, the comparison results of the two schemes are related to the value of R_{Steel}, and when $R_{Aluminum}$<52. 3%, the aluminum structure scheme is always higher regardless of the value of R_{Steel}. When $R_{Aluminum}$>85. 1%, the aluminum structure scheme always emits lower carbon regardless of the value of R_{Steel}.

According to the recycling approach, when $R_{Aluminum}$ is less than 30.8%, emissions of aluminum structure scheme is always higher regardless of the value of R_{Steel}. When $R_{Aluminum}>73.0\%$, the aluminum structure scheme is always lower regardless of the value of R_{Steel}.

The comparison results show that if the recycled content (R) of aluminum products is greatly increased to 73.0% (recycling approach) and 85.1% (recycling content approach), the comparison results of the scheme will be opposite to original case study results, regardless of recycled contents (R) of steel components.

(3) Recyclability (r)

Regardless of input variables fluctuation (see Figures 12 and 13), carbon emission intensity of aluminum structure scheme stays higher using recycled content approach. when $R_{Aluminum}$ is less than 65.5% in the national standard recycling method, the aluminum structure scheme is always higher regardless of the value of R_{Steel}.

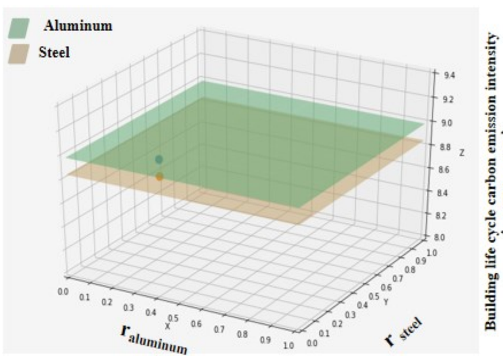

Figure 12. Sensitivity analysis result of recyclability of aluminum and steel (r) using recycled content approach.

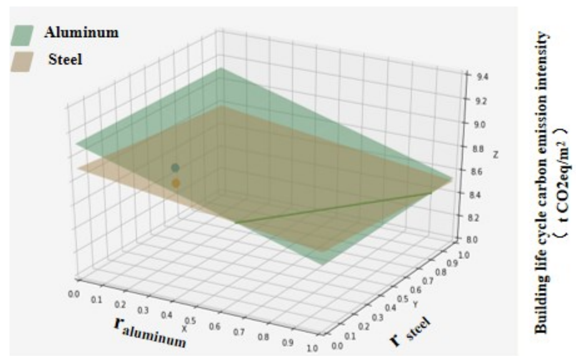

Figure 13. Sensitivity analysis result of recyclability of aluminum and steel (r) using recycling approach.

When recycling method is used for analysis, improving the recyclability of aluminum profiles to some extent will change the comparison results of carbon emissions between the two schemes.

4. CONCLUSION

This study researches the implementation path of quantifying and comparing the carbon emission intensity of different structural schemes in the whole life cycle of buildings in the design stage. Taking a greenhouse building as the research object, the whole life cycle carbon emission intensity of steel structure and aluminum alloy structure is calculated and compared. In order to further-explore the carbon reduction potential of greenhouse buildings with steel and aluminum alloy structures, the sensitivity analysis on the main influencing variables (aluminum to steel mass ratio, recycled content (R) and the recyclability (r)) was carried out. The main results are as follows:

(1) There are some differences in carbon emission factors of metal materials in different databases, and the difference of aluminum is greater than that of steel. In the production process of metal materials, the proportion of recycled materials and the proportion of power grid energy structure are one of the reasons for the difference.

(2) Metal materials have the characteristics of recycling, and the calculation method of carbon emission intensity of building materials considering the characteristics of metal recycling has not been unified abroad. Relatively speaking, the recycled content approach and recycling approach are more acceptable.

(3) Under different recycling methods, the life cycle carbon emission intensity of steel structure is lower than that of aluminum alloy structure.

(4) The relative consumption ratio of steel and aluminum building materials, the proportion of recycled contents and the recyclability of materials are three key variables. The sensitivity analysis is conducted on 3 key variables, and the different comparison results of carbon emission intensity of steel and aluminum greenhouse buildings in the whole life cycle are obtained.

To sum up, this paper studies the impact of structural material type selection on carbon emissions in the whole life cycle of a greenhouse building. It traces source of carbon emissions of major building materials and derived a localized solution to major building materials by LCA modeling. At the same time, in view of the characteristics of metal recycling, this paper studies the impact of different metal structure schemes on the comparison results using 2 different recycling methodologies and conducts sensitivity analysis on key impact factors, in order to assist in identifying low-carbon structural design scheme in a wide range of scenarios by avoiding using constant emission factors of metal materials. Although research object of this study is greenhouse building, the research method is transferable to low-carbon building study and design practice for other building functions. Research results of sensitivity analysis can provide a reference for designers in the building industry to explore potential of steel and aluminum alloy building in carbon reduction.

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