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Original Research

Benefit Allocation in the Construction Supply Chain Considering Carbon Emissions

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Abstract

The construction industry has played an important role in reducing carbon emissions. Various policies have been implemented to stimulate construction enterprises to reduce carbon emissions, but the effects of emission reduction are not obvious, for they do not directly benefit the enterprises. This paper employs a modified Shapley value method to study benefit allocation in a construction supply chain considering carbon emissions. Four correction factors are proposed for modifying the initial allocation, namely the contribution rate of inputs, the risk-sharing coefficient, the degree of cooperation and the contribution rate of carbon emissions. We analyze carbon emissions based on an illustrative example of a concrete supply chain consisting of a cement manufacturer, a concrete manufacturer and a construction enterprise, and present our findings. First, the enterprises intend to cooperate to achieve the greatest benefit, and second, the benefit allocation is greatly affected by carbon emissions. Participants that produce more carbon emissions have higher carbon tax costs, which reduce profits. Further suggestions are also presented, which may help enterprises reduce carbon emissions. And policy makers should arrive at a suitable level of carbon tax to promote the smooth progress of projects and to improve the emission reduction effect.

Keywords: modified Shapley value, construction supply chain, carbon emissions, benefit allocation

Introduction

Global warming has attracted increasing attention in recent decades. It is commonly believed that the accumulation of greenhouse gases, particularly carbon dioxide, has caused observed global warming. The construction industry, one of the primary contributors to global carbon emissions, is responsible for roughly 36% of total carbon emissions around the world [1-2]. Thus, as civil construction is responsible for significant carbon emissions, the construction industry should prioritize the efficient reduction of carbon emissions. Under this low-carbon background, a large number of studies conducted on the calculation of carbon emissions of construction projects, the emissions of different stages of those projects were demonstrated, which is helpful to control and mitigate carbon emissions precisely and effectively [3-5]. Many scholars have also studied the

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theoretical implications and applications of allocation schemes to accelerate emission reduction. Zhou and Wang [6] conducted a literature review that summarizes the extant literature and analyzed various allocation systems. In addition, some measures, including carbon taxes, subsidies for emissions and "cap-and-trade" systems, have helped enterprises reduce carbon emissions [7-9]. In the construction industry, enterprises within the supply chain are closely related to each other and are all impacted by carbon emissions regulations [10]. Therefore, it is important to research the carbon emission reduction of construction enterprises from the perspective of supply chains. As the demand for green activities in supply chains has increased and being environmentally responsible has become popular in recent years [11-12], many studies have indicated that construction enterprises in the supply chain should reconsider and readjust their operations strategies to improve environmental performance [13-15]. However, carbon restrictions may not directly benefit the enterprises; therefore, the stakeholders may not actively reduce their carbon emissions, which will affect the objective of emission reduction. To address this problem, this paper studies benefit allocation in a construction supply chain considering carbon emissions. We investigated the impact of carbon emissions on benefit allocation and thus enabled the enterprises to reduce carbon emissions.

To date, numerous studies have used cooperative game theory to research benefit allocation to determine that allocations are sufficiently accurate and fair [16]. Four allocation schemes, including the Shapley value, the DP equivalent method, the nucleolus method and the N-H solution, have been widely used to analyze benefit allocations [13, 17-20]. An evaluation of the capabilities of the four alternative allocation schemes highlights the advantages of the Shapley value [13]. Wu et al. [21] investigated the fairness and stability of the allocation schemes and concluded that the Shapley value is the most acceptable scheme for this type of study. And its calculation is simpler than other theoretical equitable methods. In addition, for a construction supply chain which is composed of several independent firms, each participant of the alliance is devoted to their core abilities to achieve information sharing, risk sharing and benefit sharing, etc. Then a reasonable and fair benefit allocation is of vital importance for the supply chain, and the Shapley value method exactly pays much attention to the fairness of benefit allocation. Based on the above reasons, the Shapley value method is applied in this paper to research the benefit allocation of construction supply chains. Regarding the complex environment of the construction industry and in order for stakeholders to be satisfied with the allocated benefit, this study proposes four correction factors to modify the initial benefit allocation, consisting of the contribution rate of inputs, the risk sharing coefficient, the degree of cooperation and the contribution rate of carbon emissions.

This study is unique for several reasons. Although much of the extant literature has studied benefit allocation [22-24], little attention has been paid to the construction industry. This paper investigates the benefit allocation of a construction supply chain using the Shapley value method. However, in order to consider the complexity of construction supply chains and to address the shortcomings of the Shapley value method, we modified the initial Shapley value to obtain a more reasonable and fairer benefit allocation scheme. Furthermore, some previous studies have considered correction factors when researching benefit allocation [25-26], but few also considered the effect of carbon emissions. This study considers carbon emissions as an influencing factor when analyzing benefit allocation. For this study, the data on carbon emissions are based on a practical project, which implies that the results more accurately reflect the impact of carbon emissions on the benefit allocation of a construction supply chain.

This study employs the modified Shapley value to research benefit allocation in a construction supply chain. The initial allocation is modified to ensure that a fair economic settlement is reached; this modification is based on changes in four factors that affect benefit allocation. Specifically, this study analyses the impact of carbon emissions on the benefit allocation, and the results will stimulate enterprises to reduce carbon emissions in the future.

Methods

In this section, we first describe the Shapley value model that will be used to calculate the initial benefit allocation. Then, considering the unique characteristics of the construction supply chain, we modify the initial Shapley value based on the influence factors and describe the method used to calculate the values for the correction factors.

Principle of the Shapley Value

The coalition game is a competitive and cooperative decision model in which the individual players collaborate to increase their benefits and achieve a win-win solution. The initial benefit allocation in a construction supply chain could be regarded as a coalition game among stakeholders. In a cooperative game, the marginal contribution of the responsible entities should maximize the total benefit; however, the fairness of the benefit allocation should be given close attention. The Shapley value is an appropriate method to measure the allocated benefit for a coalition and is widely used in the study of dynamic enterprise alliances.

The problem includes a finite set of players $N = \{1,2,3..., n\}$, and any subset S of N corresponds to a real-valued function $v(S)$. $v(S)$ represents the benefit that the coalition S can obtain in the game v and $\phi_i(v)$

represents the share of the total benefit that is allocated to player i by the Shapley value. The cooperative game is denoted as (N, v). The Shapley value $\phi_i(v)$ can be calculated as follows:

$$W(|S|) = (|S|-1)!(n-|S|)!/n \tag{1}$$

$$n(S) = v(S) - v(S \setminus i) \tag{2}$$

$$\varphi_i(v) = \sum_{i \in S} W(S) \times n(S) \tag{3}$$

…where $|S|$ is the number of players in coalition S, $W(|S|)$ is the weight coefficient of coalition S, $v(S/i)$ represents the overall benefit of the coalition, which is formed by all the members but i, and $n(S)$ is the marginal contribution of player i in coalition S.

This study analyzes a three-level construction supply chain composed of a cement manufacturer, a concrete manufacturer and a construction enterprise, which are also the subjects under study.

Modified Shapley Value

The traditional Shapley value method considers that the order in which the participants join the coalition has a great effect on evaluating the marginal contribution of each player. But it ignores other factors and assumes that the benefit is equally distributed among players ($1/n$). Therefore, the use of the Shapley value method to determine the distribution of the payoff needs further consideration. Due to the specific characteristics of a construction supply chain, to modify the initial allocation, this study considers the following factors.

This study considers factors that affect the benefit allocation of a construction supply chain and establishes the modified set of benefit allocation $J = \{1,2,3..., m\}$. a_{ij} ($i = 1,2,..., n; j = 1,2,..., m$) is the value of correction factor j of member i, as shown in Table 1. Therefore, the modified matrix $A = (a_{ij})_{n\times m}$ is:

$$A = (a_{ij})_{n\times m} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \end{bmatrix} \tag{4}$$

The modified factors have different dimensions, units and orders of magnitude; therefore, we need to normalize matrix A and obtain matrix $B = (b_{ij})_{n\times m}$. Then we need to determine the weight of each factor that is included in the benefit allocation $\lambda = [\lambda_1\ \lambda_2\ \lambda_3\ \lambda_4]^T$ and calculate the comprehensive coefficients of the factors included in the benefit allocation. The formula is as follows:

$$[D_1 \quad D_2 \quad D_3]^T = B \times \lambda \tag{5}$$

…where D_1, D_2, and D_3 respectively represent the influence of the cement manufacturer, the concrete manufacturer and the construction enterprise on the profit allocation. After corrections are made, the modified Shapley value can be calculated as follows:

$$\phi_i^{'}(v) = \phi_i(v) + (D_i - 1/n) \times v(N) \tag{6}$$

Method of Calculating the Correction Factors

This study considers four factors that have been modified in this analysis: the contribution rate of inputs, the coefficient of risk sharing, the degree of cooperation and the contribution rate of carbon emissions. With the exception of the last factor, the improved rough sets-analytic hierarchy process (RS-AHP) (which is a combination of AHP and rough set theory) is applied to determine the comprehensive weights of the stakeholders. For the contribution rate of carbon emissions, the weights of the stakeholders are determined based on the calculation of their carbon emissions.

Improved RS-AHP

AHP is a useful decision analysis tool that can cope with both qualitative and quantitative data in solving complicated decision-making problems. However, AHP is closely connected to human judgement, whose situation makes it inevitably encounter the problem of subjective arbitrariness during the decision-making process [27]. In order to solve the evaluation bias problem in AHP and improve the judgement consistency, rough set (RS) theory, which is used to address the uncertainty caused by the inadequacy and indiscernibility of information systems, is applied in this paper [28]. This method could simplify the raw data sets and handle with incomplete data. The researchers do not need to offer much knowledge of data collection

Table 1. Variables for the correction factors.

i \ j	Contribution rate of inputs	Risk sharing coefficient	Cooperation degree	Contribution rate of carbon emissions
Cement manufacturer	a_{11}	a_{12}	a_{13}	a_{14}
Concrete manufacturer	a_{21}	a_{22}	a_{23}	a_{24}
Construction enterprise	a_{31}	a_{32}	a_{33}	a_{34}

to deal with the problems, they just need to classify the measured data to discover the implicit knowledge. But this method cannot fully reveal the decision-makers' subjective cognitive value for each different indicator. To avoid problems that arise when applying these two kinds of evaluation methods independently, AHP and RS methods are combined to ensure that the evaluation results are more rational and scientific. The use of AHP is already mature and the calculation steps will not be repeated here for space reasons.

However, when using the original RS method, the weight coefficient cannot be 0. Therefore, the concept of conditional entropy is introduced to ensure that the weight coefficient of each condition attribute is not 0 [29]. It is helpful to reflect on the true importance of each condition attribute. The improved RS method involves the following steps.

Step 1: Calculate the conditional entropy. In this step, we denote $M = \langle U, R, V, f\rangle$ as a decision table, where U is the discussion field. $R = C \cup D$, $C = \{C_1, C_2,... C_m\}$ is the condition attribute set, and $D = \{D_1, D_2,... D_n\}$ represents the set of resulting objects. f is an information function that is defined as follows: $f{:}U\times R\rightarrow V$. The entropy of D relative to C, which describes the importance of condition attribute c_i in the system, is as follows:

$$I(D\,|\,C)=\sum_{i=1}^{m}\frac{|C_i|^2}{|U|^2}\sum_{j=1}^{n}\frac{|D_j\cap C_i|}{|C_i|}\left(1-\frac{|D_j\cap C_i|}{|C_i|}\right) \tag{8}$$

Step 2: Calculate the improved importance. In the decision table $M = \langle U, R, V, f\rangle\ \forall\ c \in C,\ a \in C$, the importance of c is expressed as follows:

$$sig(c)=I(D\,|\,C-\{c\})-I(D\,|\,C)+\frac{\sum_{a\in C}|a(x)|-\sum_{a\in C-\{c\}}|a(x)|}{\sum_{a\in C}|a(x)|} \tag{9}$$

…where $a(x) = U/\{a\}$.

Step 3: Calculate the improved weight coefficient. In the decision table $M = \langle U, R, V, f\rangle\ \forall\ c \in C$, the weight coefficient of c can be calculated as follows:

$$W_{(c)}=\frac{sig(c)+I(D\,|\,\{c\})}{\sum_{a\in C}\{sig(a)+I(D\,|\,\{a\})\}} \tag{10}$$

To fully reflect the advantages of both subjective and objective weighting, we combine the two methods and determine an optimal comprehensive weight. Therefore, we construct the optimization model and solve it.

For this analysis, $M = \langle U, R, V, f\rangle$ is a decision system, and w_{ai} is the subjective weight of a_i calculated by the AHP, while $w_{\sigma i}$ is the objective weight of a_i calculated by the RS method. w_i is the comprehensive weight, and $\Sigma w_{ai} = \Sigma w_{\sigma i} = \Sigma w_i = 1, 0\le w_{ai}, w_{\sigma i}, w_i\le 1$ (1,2,...m).

The optimization model can be described as follows:

$$\min\left\{\sum_{i=1}^{m}\left[\mu\left(\frac{1}{2}(w_i-w_{ai})^2\right)+(1-\mu)\left(\frac{1}{2}(w_i-w_{\sigma i})^2\right)\right]\right\} \tag{11}$$

… where

$$w_i\in\Omega=\left\{w_i\,|\,\sum_{i=1}^{m}w_i=1, 0\le w_i\le 1, (i=1,2,\cdots,m)\right\}; 0\le\mu\le 1$$

Theorem 1: The optimization model has a unique solution in the feasible domain, and its solution is as follows:

$$w_i=\mu w_{ai}+(1-\mu)w_{\sigma i}, i=1,2,\cdots,m \tag{12}$$

When the choice of weight tends to subjective experience, $\mu \in [0.5, 1]$, and when it tends to objective data, $\mu \in [0, 0.5]$. Through comprehensive analysis of the indicators and references to other literature [30-32], the golden ratio is used to decide the weights of linear combinations, that is, $\mu = 0.382$.

The Contribution Rate of Inputs

The uniqueness and importance of enterprises must be considered in the management of a construction supply chain. The amount of inputs is a main determinant of the distribution of benefit. Occasionally, companies reduce their investment as much as possible to pursue greater returns. However, the operating capacity of the entire supply chain is likely to decline due to the lack of investment when each member seeks to minimize their costs. Therefore, it is necessary to have sufficient resources to ensure the stable and efficient operation of a supply chain and to increase the benefits of all members. The inputs of the enterprises primarily include human resources, material resources and financial resources. The more inputs an enterprise brings to the supply chain, the more benefits that company deserves. In this study, the improved RS-AHP is applied to evaluate the contribution rate of inputs.

The Coefficient of Risk Sharing

For construction supply chains, risks exist during the whole process from raw material production to construction completion. The member companies undertake different tasks at different stages and are therefore subject to different levels of risk. To reflect on the principles of benefit sharing and risk sharing, the enterprises that bear greater risks should receive more benefits. According to prior research on risk in construction supply chains, the risks that cement manufacturers and concrete manufacturers face mainly include environmental risk, production risk, management risk and cooperative credit risk.

Construction enterprises mainly face environmental risk, management risk, cooperative credit risk, financial risk and technical risk.

The Degree of Cooperation

The degree of cooperation among the enterprises has a great effect on the construction supply chain, and it can be abstracted as a positive contribution to the stability of the supply chain. It is common for cooperative enterprises to be involved in multiple supply chains at the same time; they may have different levels of commitment in these chains, and if they leave a chain, it may cause great losses for the other members. Because the construction industry is complex and dynamic, cooperation in construction supply chains is relatively fragile. Therefore, when allocating benefits, it is appropriate to provide incentives to enterprises that are highly involved in the chain while allocating fewer benefits to enterprises that do not actively cooperate. Furthermore, trust and information sharing are considered to be the major determinant of the success of a strategic alliance [33-34], because it can enhance communication, reduce risks and help the chain optimize the benefits of the members. Thus, in this study, the degree of cooperation is evaluated by considering information disclosures, friendly trust, ability to trust and other positive measurements of cooperation. As in the previous analysis, the improved RS-AHP is used to evaluate cooperation.

The Contribution Rate of Carbon Emissions

Recently, there has been much interest in policies aimed at mitigating carbon emissions, and the carbon tax is regarded as an important policy instrument for curbing carbon emissions [35-36]. To analyse the impact of carbon emissions on benefit allocation, this study simplifies their relationship and only considers the influence of carbon tax policy.

In a construction supply chain, the major source of carbon dioxide is the burning of fossil fuels; therefore, it is common to impose a carbon tax on the use of fossil fuels. A carbon tax provides continuous incentives for emission reduction and is often unlimited. In addition, a carbon tax often encourages the development of technological innovation. For a member company in the supply chain, if market demand is fixed, higher carbon emissions would result in a higher carbon tax and fewer benefits.

This study proposes the concept of the contribution rate of carbon emissions. Let b_{14}, b_{24}, b_{34} denote the contribution rate of carbon emissions for three companies. In contrast to the three correction factors mentioned above, the contribution rate of carbon emissions is a negative indicator; therefore, a calculation is needed to transform this indicator into a positive value. The calculation formulas are expressed as follows:

$$b_{14} = w_1/w, b_{24} = w_2/w, b_{34} = w_3/w \tag{13}$$

$$a_{14} = 1/b_{14} = w/w_1, a_{24} = 1/b_{24} = w/w_2, a_{34} = 1/b_{34} = w/w_3 \tag{14}$$

$$w = w_1 + w_2 + w_3 \tag{15}$$

…where w_1, w_2, w_3 refer to the carbon emissions of the member companies in the construction supply chain. In addition, w is the total carbon emissions of the supply chain. To ensure consistency with the previous three positive indicators, a reciprocal transformation is applied to obtain a_{14}, a_{24}, a_{34}.

During the foundation construction process, material production is the major source of carbon emissions; however, the emissions from transportation and the use of equipment must also be considered [37]. Thus, in this paper the sources of carbon emissions are divided into three categories: material production, transportation and on-site construction.

For material production, carbon emissions can be calculated as follows:

$$E_p = \sum_{i=1}^{n} \left(m_i \times E_{p,i}\right) \tag{16}$$

…where E_p denotes the emissions from the production of materials, n represents the total number of material types, and m_i and $E_{p,i}$ are the quantity and carbon emission factors for type i material, respectively.

For material transportation, fuel combustion is the major source of carbon emissions; therefore, the carbon emissions for the transportation category can be estimated by:

$$E_t = \sum_{i=1}^{n} \left(\frac{m_i}{q} \times d_i \times E_{t,i}\right) \tag{17}$$

…where E_t denotes the emissions from transportation, m_i is the quantity of material i, q is the load on the vehicle, d_i represents the transport distance and $E_{t,i}$ is the emission factor for transferring material i.

For on-site construction, emissions are produced by various mechanical equipment and can be calculated as follows:

$$E_e = \sum_{i=1}^{n} \left(A \times p \times E_{e,i}\right) \tag{18}$$

…where E_e represents the total carbon emissions from on-site construction. A and p are the operation time and power of the machine, respectively, and $E_{e,i}$ is the carbon emission factor of electric power generation in China.

Table 2. Initial benefit allocation plan for the concrete supply chain.

Scenario	Characteristic function	Characteristic function value (in millions)
Act alone	$v(\{1\})$	3.46
	$v(\{2\})$	3.91
	$v(\{3\})$	11.00
Subset coalition	$v(\{1,2\})$	9.00
	$v(\{1,3\})$	15.50
	$v(\{2,3\})$	16.00
Entire coalition	$v(\{1,2,3\})$	22.00

Illustrative Example

Calculation of the Initial Shapley Value

Concrete is an important input used by the construction industry and cement is a critical input for concrete. It is important to use sustainable manufacturing processes and transportation modes for cement and concrete to reduce emissions [38]. Therefore, this study analyzes the benefit allocation in a concrete supply chain through a case that includes three companies that all play in the game. The set of players is denoted as $N = \{1,2,3\}$, in which 1, 2 and 3 represent a cement manufacturer, a concrete manufacturer and the construction enterprise, respectively. In theory, these companies partly cooperate in seven nonempty combinations as follows: {1}, {2}, {3}, {1,2}, {1,3}, {2,3}, {1,2,3}, with each subset forming a coalition in which different combinations of companies participate in a benefit allocation system. The three companies can expect a benefit of 3.46 million yuan, 3.91 million yuan and 11 million yuan, respectively, when they operate independently. To make the results of the case more convincing, the data were collected from the 2016 annual report of China Resources (Holdings) Co., Ltd. and on the Hanhua City Project in the city of Xi'an, China. In this paper, as mentioned above, $v(\{1\})$, $v(\{2\})$, $v(\{3\})$ are the individual production values, and $v(\{1,2\})$, $v(\{1,3\})$, $v(\{2,3\})$, $v(\{1,2,3\})$ are the cooperative production values for these companies. All three companies are of the consensus that cooperative production values will be higher than individual production values. Upon an investigation of the related companies, certain values have been estimated and are shown in Table 2. Based on the data in Table 2 and according to Equations (1), (2) and (3), the Shapley values for the three companies are calculated and are shown in Tables 3, 4 and 5.

Modified Shapley Value

This study uses the improved RS-AHP to determine the comprehensive weights of the contribution rate of the inputs, the coefficient of risk sharing and the degree of cooperation. Nine similar construction supply chains composed by material suppliers, manufacturers and construction enterprises are explored to obtain data needed for RS method calculations. The data of the qualitative indicators is evaluated by the experts from each construction supply chain and discretized to avoid data nonuniformity. The maximum eigenvalue method is used to calculate the weights of each factor by raising comparison matrices in AHP. Professionals above middle level of the companies in the construction supply chain with more than ten years working experience were asked as experts to give their opinions. At this level, the professionals are knowledgeable and capable of making

Table 3. Shapley value of the cement manufacturer.

S	1	$1\cup2$	$1\cup3$	$1\cup2\cup3$
$v(S)$	3.46	9.00	15.50	22.00
$v(S/1)$	0.00	3.91	11.00	16.00
$v(S) - v(S/1)$	3.46	5.09	4.50	6.00
$\|S\|$	1	2	2	3
$W(\|S\|) = [(\|S\| - 1)!(n - \|S\|)!]/n$	1/3	1/6	1/6	1/3
$W(\|S\|)\,[V(S) - V(S/1)]$	1.15	0.85	0.75	2.00
$\varphi(1)$	4.75			

Table 4. Shapley value of the concrete manufacturer.

S	2	$1\cup2$	$2\cup3$	$1\cup2\cup3$
$v(S)$	3.91	9.00	16.00	22.00
$v(S/2)$	0.00	3.46	11.00	15.50
$v(S) - v(S/2)$	3.91	5.54	5.00	6.50
$\|S\|$	1	2	2	3
$W(\|S\|) = [(\|S\| - 1)!(n - \|S\|)!]/n$	1/3	1/6	1/6	1/3
$W(\|S\|)\,[V(S) - V(S/2)]$	1.30	0.92	0.83	2.17
$\varphi(2)$	5.22			

Table 5. Shapley value of the construction enterprise.

S	3	$1\cup3$	$2\cup3$	$1\cup2\cup3$
$v(S)$	11.00	15.50	16.00	22.00
$v(S/3)$	0.00	3.46	3.91	9.00
$v(S) - v(S/3)$	11.00	12.04	12.09	13.00
$\|S\|$	1	2	2	3
$W(\|S\|) = [(\|S\| - 1)!(n - \|S\|)!]/n$	1/3	1/6	1/6	1/3
$W(\|S\|)\,[V(S) - V(S/3)]$	3.67	2.01	2.02	4.33
$\varphi(3)$	12.03			

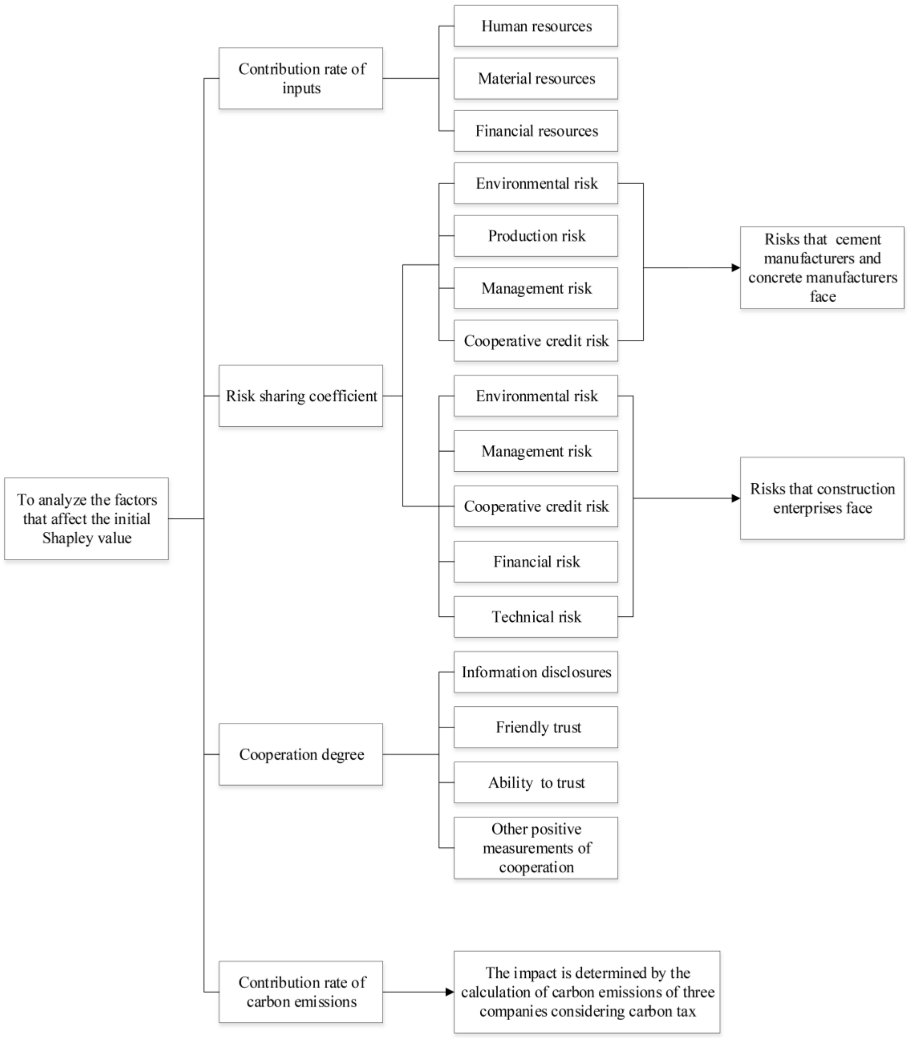

Fig. 1. AHP-based hierarchical structure of the factors that affect the initial Shapley value.

reliable and reasonable decisions. The objectives of this research were explained to the experts before starting the work, and these experts made their decisions personally for collecting the data needed in this paper. The process of consultation with the construction experts assisted in developing the hierarchical structure as shown in Fig. 1. According to the collected data and the improved RS-AHP method, the impact weights of each factor are calculated as follows:

$$P = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_2 & a_2 & a_3 \\ a_3 & a_3 & a_3 \end{bmatrix} = \begin{bmatrix} 0.284 & 0.261 & 0.346 \\ 0.319 & 0.416 & 0.316 \\ 0.397 & 0.323 & 0.338 \end{bmatrix}$$

To determine the impact weight of the contribution rate of carbon emissions, the carbon emissions for the three companies are estimated. To ensure the accuracy and reliability of the results, the data on the various

Table 6. Carbon emissions of raw materials.

Raw materials	Quantity (t)	Emission factor	The amount of carbon emissions (t)
Water	6096.08	0.194kg CO_2/t	1.18
Cement	16,058.82	700kg CO_2/t	11,241.17[a]
Sand	17,835.39	50kg CO_2/t	891.77
Gravel	43,613.11	50kg CO_2/m^3	1406.87
Total			13,540.99

[a] Note: The carbon emissions of the cement have been calculated in the previous section; thus, they have been excluded from the total carbon emissions of the concrete manufacturer.

Table 7. Shapley value and carbon emissions.

Companies	Initial Shapley value	Modified Shapley value		Carbon emissions(t)
		Considering 3 factors	Considering 4 factors	
Cement manufacturer	4.75	3.64	2.55	11,255.90
Concrete manufacturer	5.22	5.66	4.31	2384.68
Construction enterprise	12.03	12.70	15.14	35.09

materials are based on a real-life project. In addition, the carbon emission factors used in this paper are based on those suggested by the Intergovernmental Panel on Climate Change [39] and on previous studies that calculated and constructed carbon emission factor tables [40-41]. For the cement manufacturer, the carbon emissions are evaluated for the phases of production and transportation. The amount of cement is 16058.82 tons, and the carbon emission factor is 0.700 tons of CO_2 per ton of cement [42]. The load and the relevant emission factor of the diesel vehicles are 60 tons and 1.1kg/km, respectively, and the transport distance is 50 km. The calculations show that the carbon emissions are 11241.17 tons for the production phase and 14.72 tons for the transportation phase. Therefore, the total amount of carbon emissions for the cement manufacturer is 11255.90 tons.

For the concrete manufacturer, this study considers the carbon emissions of the production processes, transportation and mixing the concrete. The amount of concrete is 34834.75 m^3. Based on the conventional mixing ratio of C30 concrete, the amount of the raw materials needed, and the relevant carbon emissions can be calculated (Table 6).

Regarding transportation and mixing the concrete, the capacity of a concrete agitation truck is 12 m^3, and the transport distance is 20 km. When mixing the concrete, the capacity, productivity and energy use of the concrete mixers are 3 m^3, 90 m^3/h and 75 kw, respectively. Based on previous studies, the carbon emission factor of electric power generation is 0.723 kg/Kw·h. The results of the calculation show that the carbon emissions for transportation and concrete mixing are 63.87 tons and 20.99 tons, respectively. The total carbon emissions of the concrete manufacturer are 2384.68 tons.

For the construction enterprise, this study considers the carbon emissions from the vibration of concrete and pump construction. The productivity and energy use of the concrete pump tuck are 80 m^3/h and 110 kw, respectively. The productivity and energy use of the concrete vibrator are 2 m^3/min and 2.2kw, respectively. Based on the above data, the carbon emissions for pumping and vibrating concrete are 34.63 tons and 0.46 tons, respectively. The total amount of carbon emissions for the construction enterprise are 35.09 tons.

According to the discussion above, the carbon emissions of the three companies w_1, w_2, w_3 are 11255.90 tons, 2384.68 tons and 39.09 tons, respectively. Correspondingly, b_{14}, b_{24}, b_{34} are 0.823, 0.174 and 0.003, and a_{14}, a_{24}, a_{34} are 0.003, 0.017 and 0.980, respectively.

In this paper, four correction factors are considered for modifying the initial Shapley value, and the impact weight of each factor is estimated as λ = [0.462 0.274 0.086 0.178]^T.

According to formulas (5) and (6), the total influence of the three companies and the modified Shapley value can be obtained:

$$\left[D_1, D_2, D_3\right]^T = B\times\lambda = \begin{bmatrix} 0.284 & 0.261 & 0.346 & 0.003 \\ 0.319 & 0.416 & 0.316 & 0.017 \\ 0.397 & 0.323 & 0.338 & 0.980 \end{bmatrix} \times \begin{bmatrix} 0.462 \\ 0.274 \\ 0.086 \\ 0.178 \end{bmatrix} = \begin{bmatrix} 0.233 \\ 0.292 \\ 0.475 \end{bmatrix}$$

$$\phi'(1) = \phi(1) + (D_1 - \frac{1}{n}) \times v(N) = 4.75 + 22\times\left(0.233 - \frac{1}{3}\right) = 2.55$$

Similarly, $\varphi'(2) = 4.31$, $\varphi'(3) = 15.14$

When considering the correction factors, with the exception of the contribution rate of carbon emissions, the results are:

$$\phi''(1) = 3.64,\ \phi''(2) = 5.66,\ \phi''(3) = 12.70$$

To demonstrate the effects of the correction factors on the benefit allocation more directly, we integrate both the initial and modified Shapley values, as well as the carbon emissions of the companies in the supply chain (Table 7).

Results and Discussion

This section focuses on the insights and implications that extend beyond the results of the models proposed in this study.

The analysis of the coalition game concentrates on two issues: coalition formation and benefit allocation. The benefits for three types of coalitions, non-cooperation, partial cooperation and full cooperation, are displayed in Table 2. The results show that the benefit of non-cooperation is lower than that of a partly or fully cooperative coalition. The maximum benefit is 22 million, which occurs with full cooperation. Notably, the enterprises are inclined to cooperate to obtain the maximum benefits. Thus, achieving a satisfactory and reasonable allocation scheme is of vital importance.

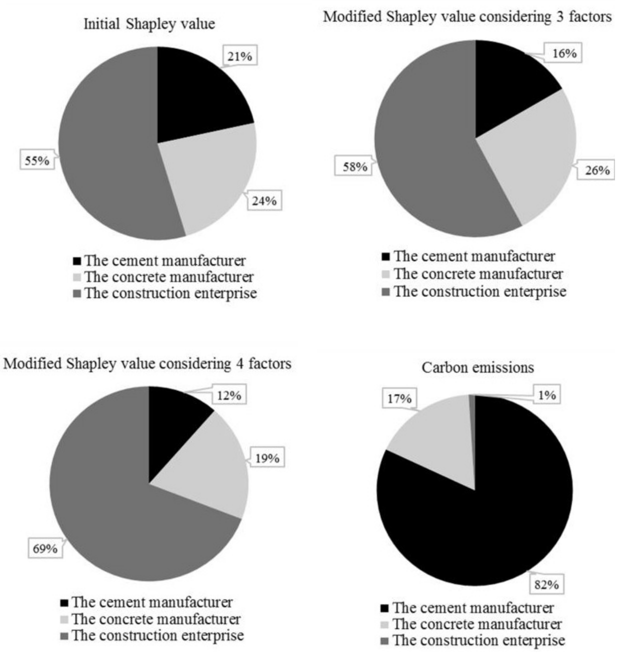

Fig. 2. Proportion of benefit allocation for three situations and the carbon emissions of the enterprises.

The results for the initial Shapley values are calculated and displayed in Tables 3-5 and are used to develop an original benefit allocation scheme. However, to illustrate the most practical operation of the supply chain, the initial Shapley values of the enterprises are modified based on the four correction factors. Gan et al. proposed some problems of the correction factors determined currently, such as single considered factors, comprehensive correction coefficients which show obvious subjective tendency, etc. [43]. In this paper, the selection and determination of the correction factors have made up for these deficiencies to some extent. The proportions of the benefit allocation for each of the three enterprises are shown in Fig. 2.

As shown in Fig. 2, the proportions of the benefit allocation for the construction enterprise are relatively higher than that for the other participants; its allocations are 55%, 58% and 69%, which indicates that the construction enterprise generates more benefit and has greater marginal contribution to the supply chain than the other enterprises. Then the benefit allocation of the concrete manufacturer and the cement manufacturer follows. For each enterprise, the proportions of the benefit allocation change for the different situations because of the influence of the practical factors that affect the supply chain, but the impacts of these factors are limited, and the overall proportions of the benefit allocation are not affected. That is because in this supply chain, the value of the three enterprises produced is quite different, and the influencing factors can only affect the distribution of their benefits to a lesser degree. To clearly reflect the changes in the allocated benefits of the three enterprises, their initial and modified Shapley values are shown in Fig. 3.

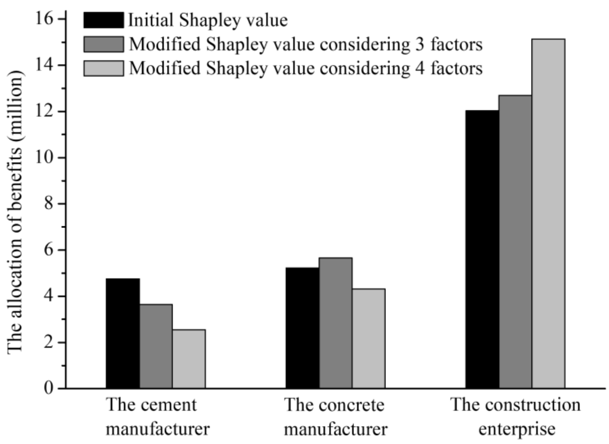

Fig. 3. Initial and modified Shapley values for all three enterprises.

Fig. 3 indicates that when three factors are considered (the contribution rate of carbon emissions is excluded from the analysis), the benefit of the cement manufacturer decreases by 1.11 million, while the concrete manufacturer and the construction enterprise obtain an increase in their allocations of 0.44 million and 0.67 million, respectively. This occurs because, compared to the concrete manufacturer and the construction enterprise, the cement manufacturer inputs fewer resources and is subjected to less risk. In addition, since it represents the middle part of the supply chain, the concrete manufacturer acts as a bridge between the upstream and downstream enterprises and plays the most important role in ensuring the cooperation of all three companies. Therefore, it can be safely concluded that the cement manufacturer is in a vulnerable bargaining position, and its modified Shapley value is lower than the initial allocation, while the concrete manufacturer and construction enterprise have stronger bargaining power and their modified Shapely values are higher than in the initial allocation of benefits.

When considering the contribution rate of carbon emissions as a correction factor, the results of the allocated benefit change. Under the influence of carbon tax, the emissions of the enterprises have an impact on their benefits and their Shapley values are affected depending on their responsibilities for carbon reduction. Compared with the situation considering three correction factors, the benefits allocated to the cement manufacturer and concrete manufacturer decrease by 1.09 million and 1.35 million, respectively, while the benefits allocated to the construction enterprise increase by 2.44 million. These results imply that the factor of carbon emissions increases the allocated benefit for construction enterprise and decreases the allocated benefits for both the cement and concrete manufacturers. Furthermore, we use $\Delta\phi_i/\phi_i$ to identify the impact of the correction factors on the benefit allocation, and the results are shown in Table 8.

Table 8. Impact of the correction factors.

Participants	ϕ	ϕ'	ϕ''	$\lvert\phi' - \phi\rvert/\phi$	$\lvert\phi'' - \phi\rvert/\phi$
Cement manufacturer	4.75	2.55	3.64	0.46	0.23
Concrete manufacturer	5.22	4.31	5.66	0.17	0.08
Construction enterprise	12.03	15.14	12.70	0.26	0.06

Table 8 shows that the correction factors play an important role in the benefit allocation. These factors have the largest effect on the benefit allocations for the cement manufacturer; the impact coefficients reach 0.23 and 0.46 in two situations. These values are much higher than those for the concrete manufacturer (0.08 and 0.17) and the construction enterprise (0.06 and 0.26). These results indicate that the cement manufacturer is vulnerable to the practical influence factors, which may occur because of the complex manufacturing process of cement, and the fact that the cement manufacturer is in an upstream industry. For the analysis that does not consider the contribution rate of carbon emissions, the impact coefficients of the three enterprises are 0.23, 0.08 and 0.06, but when all the factors are considered, the impact coefficients increase to 0.46, 0.17 and 0.26. These results imply that the carbon emissions have a non-negligible effect on the benefit allocations in the supply chain. Jokar and Mokhtar presented the idea that the growth trend of the manufacturer profit depends on the benefit of implementing energy conservation [44]. Thus it is advisable for construction companies with large emissions to implement carbon emission reduction, which to some extent improves the economic performance of the companies in their future developments.

The proportion of carbon emissions for the cement manufacturer, the concrete manufacturer and the construction enterprise are 82%, 17% and 1% respectively, as denoted in Fig. 2. The carbon emissions produced by the cement manufacturer are far higher than those produced by the concrete manufacturer and the construction enterprise, which further illustrates that the cement industry is one of the main contributors to global carbon emissions and achieves a consistency between our results and the existing research [45-46]. The carbon emissions of the cement manufacturer and the concrete manufacturer are relatively higher than that of the construction enterprise, and therefore they will pay higher carbon taxes, which has an evident impact on their benefit allocations. Compared with the benefit allocation scheme that considers only three of the correction factors, the benefit allocations of the cement and concrete manufacturers decreases because of their higher carbon emissions. Moreover, when considering these three correction factors, the impact coefficients of the cement and concrete manufacturers are 0.23 and 0.08. When considering all four correction factors, the impact coefficients of these two manufacturers increase by 0.23 and 0.09, respectively. This result may occur because the carbon emissions of the cement manufacturer are much higher than those of the concrete manufacturer. Correspondingly, carbon emissions have a much greater effect on the benefit allocation of the cement manufacturer than that of the concrete manufacturer. Overall, carbon emissions are mainly generated during the production process, a result that is consistent with that of Zhang and Wang [4]. Therefore, it is necessary to develop innovative production processes and improve operations management in the supply chain to reduce carbon emissions and to enhance the benefits of all three enterprises.

However, in practice there is still another possibility. For a company that generates large carbon emissions but less profits, the pressure from emission reduction and related policies has a great impact on its earnings, thus they may not be willing to cooperate with other companies because the emission reduction costs caused by larger carbon emissions may affect the distribution of its benefit. This type of company may not want to participate in the benefit allocation or even actively promote emissions reduction. Therefore, perhaps sufficient benefit can better promote these companies to cooperate with each other and energetically take measures to reduce carbon emissions. The government can help these companies improve their production in capital, or provide incentives for competing companies to share and transfer emission-reducing information and technologies and assist them in achieving low carbon [38]. In turn, these companies can reflect the social corporate responsibility and shape the corporation's reputation by controlling environmental pollution under a government advocating emission reduction and energy conservation [47].

There are also some other factors that can be considered in the benefit allocation. For a company with large emissions, when it adopts some measures and achieves better emission reduction effects, such as increasing prefabrication rates, increasing the template turnover rate, and increasing the recycling rate of materials, etc. Even if its carbon emissions are still larger than the others, its benefit allocation should also be increased as an incentive. And this situation can be taken into consideration for further research.

Furthermore, social welfare is impacted by carbon emissions. An increase in carbon emissions decreases the total benefits of the supply chain and increases the government's cost to address environmental issues. Both of these changes would ultimately decrease the social welfare of the government, which may have a negative impact on the benefit that should be allocated. From another perspective, social welfare is also affected by carbon tax, which is a common way to reduce carbon emissions currently, but it has been proven that in production link, only a small amount of carbon tax is beneficial to social welfare, and taxation in the link of consumption and redistribution leads to the decrease of social welfare [48]. Therefore, the member companies should reduce carbon emissions to increase the total profits of the supply chain and also help to enhance social welfare.

Conclusions

In this paper, a modified Shapley value model is developed to study the benefit allocation in a construction supply chain. Though this supply chain is based on a specific project, this model is common in most construction supply chains. Therefore, the results from this study are general and can provide references for the benefit allocation in some other construction supply chains. For this study, four correction factors are considered to modify the initial Shapely value and to ensure that the benefit allocation scheme is reasonable and reliable. These four factors are the contribution rate of inputs, the coefficient of risk sharing, the degree of cooperation and the contribution rate of carbon emissions. In addition, to determining the contribution rate of carbon emissions, the carbon emissions of the three companies are calculated by considering the process of material production, transportation and on-site construction. The illustrative example is analysed, and the main conclusions of the paper are as follows.

First, compared with the other subset coalitions, the supply chain that includes the full cooperation of all three companies has the best economic performance. The benefit allocations of all three companies were compared, and the results show that construction enterprises have greater power to extract a larger share of the benefits of the supply chain. In addition, the allocated benefit of the three companies before and after modification were compared, and the results imply that other social and environmental factors have a great impact on the initial benefit allocation. The modified Shapley value of the cement manufacturer is lower than its initial allocation, while that of the construction enterprise is higher than its initial allocation, which proves that the cement manufacturer is in a vulnerable bargaining position, while the construction enterprise is in a stronger bargaining position.

Second, the benefit allocation is greatly impacted by carbon emissions. The enterprises that emit more carbon emissions obtain lower profits. The carbon emissions of all three companies are calculated, and the results show that the carbon emissions are primarily generated during the production process. Therefore, the manufacturer should develop innovative production technologies and improve operations management to reduce carbon emissions. Additionally, an increase in carbon emissions would ultimately, decrease the expected social welfare, which indicates that member companies should increase their efforts to reduce carbon emissions and minimize their adverse effects on social welfare.

Based on the conclusions mentioned above, this study presents additional opportunities for enterprises to explore emissions reduction and energy savings. For enterprises that have high production-related emissions, it is necessary to use more clean energy and improve resource utilization efficiency. Raw materials and construction technologies that cause low levels of environmental damage should be given priority in practical applications. Enterprises that have high consumption-related emissions should focus more on the emissions of the firms that operate upstream and downstream of the supply chain. All enterprises should promote the use of recyclable materials and utilize appropriate construction management strategies for both construction transportation and equipment use. Meanwhile, as the development of a low carbon economy has been widely accepted and green and environmentally friendly projects have been highlighted in recent years, construction enterprises should be actively engaged in these types of projects to promote carbon emission reduction and energy savings.

Furthermore, according to the model, the price of carbon tax affects the benefit allocation significantly. A suitable price of carbon tax is conductive to coordinating the relationship between the stakeholders. Therefore, policy makers should make a proper carbon tax price to promote the smooth progress of projects and to improve the emission reduction effect.

In future research, some limitations can be overcome. First, the construction supply chain considered in this paper consists of three participants. In future work, the supply chain can be extended to be more complicated cases. Second, this study considers four key correctional factors that affect the benefit allocation. In the following studies, more factors could be considered, such as the satisfaction of customers and the impact of other similar supply chains. Third, this study considers the impact of carbon tax. In reality, carbon taxes and subsidies would be implemented simultaneously, and emission trading has also become a popular tool to promote carbon abatement. The effect of a combination of multiple carbon emission policies on the benefit allocation of supply chains can be considered in future studies.

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Conflicts of Interest

The authors declare no conflict of interest.

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