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# A Study on Cost Allocation in Renovation of Old Urban Residential Communities

**Xiaoyan Zhuo and Hongbing Li ***

Engineering Management, School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China; zhuojiayou@whut.edu.cn
* Correspondence: lihongbing1010@whut.edu.cn

**Abstract:** The renovation of old residential communities not only meets the people's aspirations for a better life, but also promotes the image of a city. However, unreasonable cost allocation in the renovation of old residential communities seriously impedes the multi-channel fundraising and progress of renovation. The general aim of this study was to construct a cost allocation model for the renovation of old residential communities, so as to address unreasonable cost allocation and speed up the renovation. With the government, home owners, and private sectors as the main participants and stakeholders, we constructed a cost allocation model for the renovation of old residential communities based on the structural equation model and the Shapley value. The structural equation model is used for indicator screening and weight computing, while the Shapley value is used for cost allocation. Then, we improved the cost allocation model based on the influencing factors that were screened out. This discovery will increase the cooperation between the government, home owners, and private sectors to fund the renovation of old residential communities, and further improve the progress of renovation of old residential communities. The study results show that by fully taking into account the degree of participation, the degree of risk sharing, the degree of value-added return, and the degree of resource input of participants, the improved cost allocation model makes the cost allocation more reasonable and fairer.

**Keywords:** old residential communities; cost allocation; structural equation model; Shapley value



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## 1. Introduction

With continuous social development and improved living standards, there has been gradually increased demand for the renovation of old communities. By the end of May 2019, 170,000 old urban residential communities in need of renovation were reported across China, involving hundreds of millions of residents [1]. From 2019 to 2020, a total of 59,000 old urban residential communities had been renovated nationwide. In 2021, 53,000 old residential communities were planned to be renovated [2]. At present, most funds for the renovation of old residential communities come from the government, which leads to excessive financial burden on the government and slow renovation progress [3]. In a document issued by the General Office of the State Council on 20 July 2020, it was expressly pointed out that it was necessary to promote the participation of social forces, actively introduce private capital in the renovation of old residential communities, and proactively promote residents' capital contribution based on the principle that "those who are benefits shall contribute" [4]. In the renovation of old residential communities, the investment from private sectors and residents can speed up the process and improve the operation and management of the renovated communities.

At present, the cause of slow renovation of old residential communities in China lies in the single source of funds, which leads to excess financial burden on the government. This is due to the low degree of participation and less contribution of home owners and private sectors. The collaboration among stakeholders in the renovation of old residential communities is dependent on reasonable cost allocation and benefit distribution. At present, there are relatively few studies on cost allocation in the renovation of old residential communities at home and abroad. Such research on cost allocation is the key to attracting investment from private sectors and the contribution of home owners, as well as an important means to speed up renovation. Only when the cost allocation is fair and reasonable will all stakeholders actively participate in the renovation of old residential communities.

The renovation of old communities requires a lot of investment, and it is not easy to form a reasonable return mechanism. Therefore, it is necessary to establish a mechanism for the government, home owners, and private sectors to reasonably allocate the cost of renovation [5]. Cost allocation is to prevent the phenomenon that the home owners do not pay the renovation funds, but enjoy the renovation results [6]. The importance of this research is that its research methods and research ideas can provide new solutions to the unreasonable problem of cost allocation in the renovation of old residential communities. It can solve the problems of single renovation funds, slow renovation speed, and low participation of residents and private sectors in the renovation of old residential communities. Studying the renovation cost allocation will provide an important reference for old communities that have not yet been renovated across the country. Therefore, a structural equation model is proposed here to screen out the influencing factors of cost allocation in the renovation of old residential communities. After taking into account the factors that affect cost allocation in this context, a relatively complete cost allocation model is constructed based on the Shapley value. The model fully considers the degree of participation, the degree of risk sharing, the degree of value-added return, and the degree of resource input of participants, so that the cost allocation is fairer and more reasonable.

This paper contributes to the academic literature in this field by analyzing the current situation and problems of old community renovation, identifying the influencing factors of old community renovation cost allocation, and constructing an old community renovation cost allocation model. The analysis in this paper is based on current policies, official documents, and research by scholars on the renovation of old residential communities. Since 2019, the number of renovations of old residential communities in China has continued to increase. For this reason, the state has issued relevant documents to guide such renovations [4]. This study offers basic support and a decision-making reference for better introduction of private capital, promotion of residents' investment, and better cooperation among participants in the future. Moreover, it provides a reference model for the cost allocation of participants in the old community renovation projects in various countries.

We conducted a literature review with regard to the definition and present renovation of old residential areas, and the application of the Shapley value in cost allocation. The influencing factors of the cost allocation among participants were identified, after which they were further screened using the structural equation model. Then, an improved cost allocation model was constructed based on the Shapley value for actual case analysis. Here, we make a comparative analysis on the cost allocation results before and after the improvement, followed by a discussion and summarization of the study results.

## 2. Literature Review

### 2.1. Definition and Present Renovation of Old Residential Communities

An old residential community refers to a residential community (including a single residential building) which was built in early years with poor maintenance, management, municipal supporting facilities, and community service facilities and whose residents have strong willingness for renovation [4]. At present, there are still many difficulties and challenges in the renovation of old residential communities in China, which are reflected in building performance, public supporting facilities, road traffic, public environment, building appearance, safety management, and community culture [7]. In view of these difficulties and challenges, many scholars have conducted research on the renovation of old communities, covering the path, strategy, scheme, standard, benefit balance, etc.

Wang [8] put forward the development path and strategy for upgrading and renovation of old urban residential communities in China after analyzing current key problems in each link. Li and Pan [9] constructed an index rating renewal plan preference matrix, where Monte Carlo simulation was used to probe the relationship between the estimation of renovation potential of old residential communities and the three options of "retention, renovation and reconstruction". Xu et al. [10] adopted the fuzzy Delphi and proposed a set of standards for outdoor environmental renovation in old residential communities based on the standard of Weir community. Li and Meng [11] established a livableness index system and an evaluation model for the renovation of old residential communities. Proceeding from the "sense of localness" as a theoretical start point, Xu et al. [12] took the century-old East Street in Shaoguan as an example to construct a relationship model between residents' sense of localness and their willingness to support urban renovation. With improved urbanization in China, urban renewal has become the main way to meet residents' growing demand for urban space and facilities.

In order to better introduce private capital into the renovation of old residential communities, scholars have also begun their exploration of this aspect. Taking J Community in Beijing as an example, Shan and Li [13] analyzed the causes of difficulty in making profits during the renovation of old residential communities, as well as the series of explorations made by the project owner to achieve profitability. By identifying and analyzing the main obstacles confronting the private sector in terms of the collaboration of participants, access thresholds, and investment and financing returns, Xu and Xu [14] proposed a government-led multi-party coordination mechanism to clarify the conditions of participation and the means of profit making for private sectors and innovated a participation model of "investment—renovation—integrated operation". By analyzing the traditional mode of renovation of old residential communities and the existing problems, Xu [3] provided a discussion on the value and advantages of introducing private capital in the comprehensive renovation of old residential communities and expounded on three novel modes of renovation of old residential communities: "binding private capital to home owners' interests", "binding development to renovation commercially", and "renovation of old residential communities + property management". As to residents' low willingness to participate in the renovation of their communities, Li, et al. [15] analyzed relevant influencing factors using a multi-layer linear regression, so as to improve residents' participation.

### *2.2. The Application of Shapley Value in Cost Allocation*

The Shapley value is a method proposed by Shapley, L.S. (1953) for solving cost allocation in a cooperation with n players, where the cost is allocated based on the players' marginal contribution to the alliance. At any time, the Shapley value can be used to achieve a unique solution with satisfactory allocation results [16]. As a common method in cooperative games, the Shapley value is widely used in the studying profit distribution. In studying reverse logistics benefit distribution, Song [17] constructed a fuzzy DEA-based efficiency measurement model and proposed an improved Shapley value model for fair distribution of cooperative profits. Based on the traditional Shapley algorithm, Zhou et al. [18] proceeded from stakeholders to establish a benefit distribution model for IPD team, which improved the benefit distribution mechanism.

In addition to its application to benefit distribution, the Shapley value is also widely used in studying cost allocation, being the currently mostly used model in studying cost allocation among participants in dynamic cooperative alliances. Chen and Zha [19] proposed a cost sharing-based cooperative game model, and discussed the application of the Shapley value in cooperative games where the convexity condition is satisfied. After analyzing the main problems with cost allocation and the main cost allocation models, Qu [20] constructed a cost allocation model using the Shapley value and the Delphi method. Yu [21] applied an improved Shapley value to achieve scientific and reasonable allocation of supply chain costs by fully taking into account factors such as cooperation degree, risk sharing, and innovation ability of supply chain members. Upon in-depth analysis of participants' behaviors in cooperative games, Zhou et al. [22] proposed a cooperative surplus calculation method and a method of cost allocation and income distribution for comprehensive energy systems in industrial parks based on the Shapley value. Taking the waste incineration project in City H as a typical case, He and Liu [23] adopted improved Shapley value to design a cost-sharing scheme for multi-regional cooperation after full consideration of factors such as housing price change rate, environmental risk-bearing capacity, negotiation ability, and the degree of conflict avoidance among residents. Considering the relative importance of alliances and players, Ye et al. [24] determined the composite weight as per the demand rate and proposed a joint ordering cost allocation method based on the interval value variable weight Shapley value. Proceeding from the perspective of a cooperative game, Rao et al. [25] studied school bus cost allocation and revealed the huge deviation between the current school bus cost allocation method and the Shapley value method, thus further suggesting the necessity of using the Shapley value to allocate school bus costs. Focusing on the cost allocation problem in multi-operator cooperative operation, Wu [26] carried out an in-depth analysis of the cost structure, the allocation mechanism in a cooperative game, and various influencing factors; compared and selected cost allocation methods; and used the Shapley value to build a cost allocation model.

In addition to China, many countries are also facing the problem of renovation of old residential communities. Since the 1970s, the South Korean government has been redeveloping blighted residential environments and adopting large-scale redevelopment policies to solve urban housing-related problems [27]. Urban renewal was a project of the U.S. government that aimed to reconstruct poorly managed neighborhoods [28]. Turkey is also constantly exploring the renovation of old residential communities. Urban renewal offers an opportunity to improve the quality of life of the residents and to build sustainable cities [29]. Based on foregoing literature, it can be learned that there are problems with current renovation of old residential communities, such as a single source of funds, slow renovation, and low participation of residents and the private sector. Unreasonable cost allocation is a main cause of the low willingness of residents and private sectors to participate in the renovation of old residential communities. However, there are few studies on cost allocation in the renovation of old residential communities. As the most commonly used model in studying income distribution, cost sharing, and risk sharing among participants in a dynamic cooperative alliance, the Shapley value is quite mature, with wide application at present. The model established in this study can provide a reference for old residential renovation projects in various countries, make the cost allocation fairer and more reasonable, further enhance the willingness of residents to participate in renovation, and accelerate the renovation process.

## 3. Materials and Methods

The main participants involved in the renovation of old residential communities are the government, home owners, and private sectors. The government specifically refers to the local government; home owners refer to the collective name of all home owners in an old residential community; the private sector refers to the profit-making enterprises that undertake the construction and operation in the renovation of old residential communities through bidding and other means and expect to make profit therefrom. In this study, with government, community owners, and private sectors as the main participants, and based on the previous research experience, a fairer and more reasonable cost allocation model is built for the renovation of old residential communities, as shown in Figure 1. The renovation cost of the old communities in this study includes both the production cost and the transaction cost in the process of renovation. Transaction costs refer to the costs incurred by the government, home owners, and private sectors in collecting information, negotiating, signing contracts, or making payments during the renovation of old residential communities. The constantly changing negotiating positions of the government, home owners, and private sectors make it difficult to reach a renovation agreement during the renovation of old residential communities [30]. Transaction costs arise as a result of bounded rationality of people and uncertainties around transactions. For example, the time and effort required by the government to identify an older community for renovation, develop a renovation plan, negotiate with home owners and private sectors, review renovation applications, and obtain renovation permits can all be translated into transaction costs [31]. In an old community renovation project, considering the opinions of home owners and encouraging the participation of home owners and private sectors, although it may increase the transaction costs of "policy design", can reduce the costs of "policy implementation" through increasing the credibility and acceptability of a policy, raising public awareness, and building trust among parties involved [32].

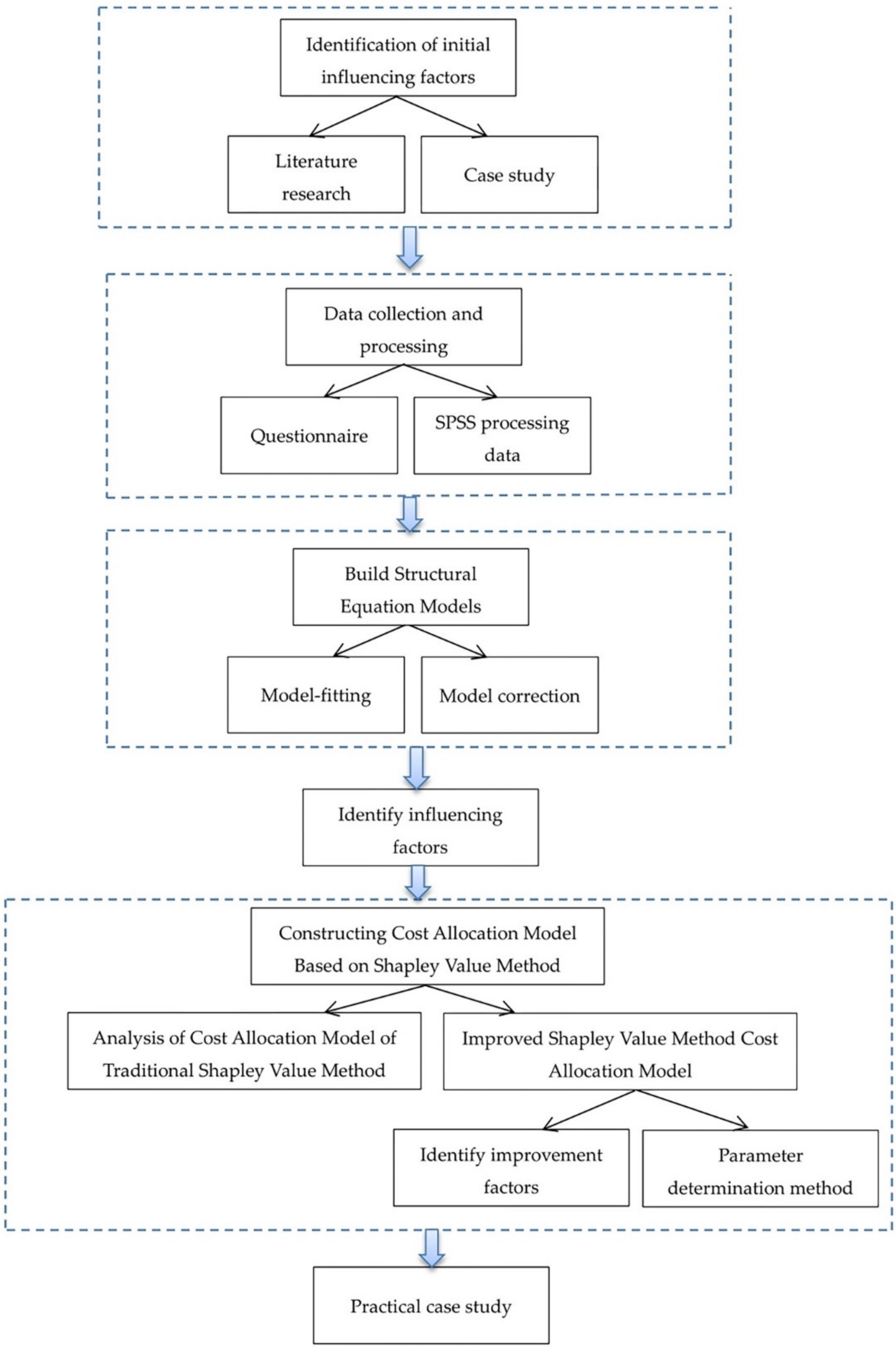



**Figure 1.** The cost allocation model for the renovation of old residential communities.

## *3.1. Analysis of Influencing Factors*

### 3.1.1. Collection of Impact Factors

Upon the review of relevant literature on cost allocation and benefit distribution and the analysis of cases of renovated old residential communities (as shown in Table 1), 17 secondary factors that mainly affect the cost allocation among participants in the renovation of old residential communities are summarized here. They are further categorized into four primary influencing factors: the degree of participation in renovation, the degree of risk sharing, the degree of value-added return, and the degree of resource input (as shown in Table 2).

**Table 1.** Summary of influencing factors based on resources.

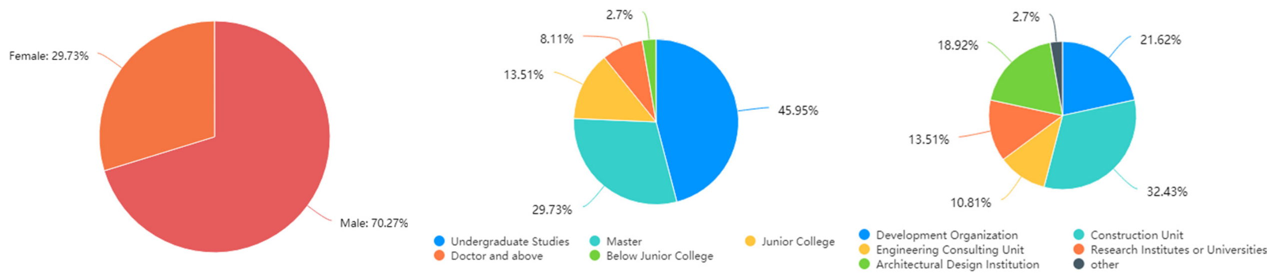
| Influencing Factors | Meaning | References |
| --- | --- | --- |
| Degree of Participation in Renovation | The degree of participation refers to the extent participants participate in the renovation of old residential communities. Based on its content, it is divided into basic renovation degree, improvement renovation degree, and updating renovation degree. | Mu [33]; Chen [34]; Wang [35] |
| Degree of Risk Sharing | The degree of risk sharing refers to the proportion of risk sharing among participants in the renovation of old residential communities. | Chen [34]; Zhou [18]; Song [36]; Hu [37]; Han [38]; Yang [39]; Xu [40] |
| Degree of Value-added Return | The degree of value-added return refers to the amount of expected value-added return brought to participants in the renovation of old residential communities, or the extent to which participants create value-added return. | Han [38]; Guo [41]; Xu [42]; Cheng [43]; Wei [44]; Yuan [45] |
| Degree of Resource Input | The degree of resource input refers to human resources, materials, finance, etc., which are input in the face of abrupt situations or which are unpredictable and unmeasurable at the beginning by participants in the renovation of old residential communities. | Chen [34]; Wang [35]; Zhou [18]; Xu [40]; Yu [21]; Ji [46] |

**Table 2.** Influencing factors of cost allocation.

| Latent Variable | S/N | Observed Variable | S/N |
|---|---|---|---|
| Degree of Participation in Renovation | DPR | Time of participation in renovation | DPR1 |
| | | Content of participation in renovation | DPR2 |
| | | Difficulty of renovation | DPR3 |
| Degree of Risk Sharing | DRS | Operation and maintenance risks | DRS1 |
| | | Cooperation risks | DRS2 |
| | | Construction risks | DRS3 |
| | | Economic risks | DRS4 |
| | | Policy and regulatory risks | DRS5 |
| Degree of Value-added Return | DVR | Social reputation | DVR1 |
| | | Social image | DVR2 |
| | | Social prestige | DVR3 |
| | | Money income | DVR4 |
| | | Material income | DVR5 |
| Degree of Resource Input | DRI | Equipment input | DRI1 |
| | | Intangible assets input | DRI2 |
| | | Personnel input | DRI3 |
| | | Fund input | DRI4 |

3.1.2. Collection and Processing of Data

In this paper, a questionnaire is designed to study the 17 secondary influencing factors which serve as observed variables. The questionnaire consists of two parts. The first part serves to gain a general understanding of the respondents' situation, and the second part seeks to judge the importance of the influencing factors. The Likert scale is used in the questionnaire to score the degree of influence of the observed variables, with 1 being very unimportant, 2 being unimportant, 3 being generally important, 4 being important, and 5 being very important. A total of 280 questionnaires were distributed, and 254 were recovered. There were 247 valid questionnaires, whose specific characteristics are shown in Figure 2.




(**a**) (**b**) (**c**)

**Figure 2.** (**a**) Proportion of male and female interviewees; (**b**) distribution of interviewees' academic background; (**c**) type of interviewees' employers.

The collected data were tested for reliability and validity using SPSS. The reliability test was carried out by calculating the Cronbach $\alpha$ value, while the validity test was carried out through the KMO test and Bartlett's spherical test.

The test results show that the Cronbach $\alpha$ value of each latent variable and the overall variable is greater than 0.8, indicating the high reliability of the data being studied (Table 3). The KMO values of the latent variables and the overall variable are both greater than 0.6, indicating a strong correlation between the variables. The mean $p$-value in Bartlett's spheroid test is less than 0.05, indicating satisfactory structure of the questionnaire. On the whole, the data satisfy the requirements for a structural equation model and can be used for fitting tests.

**Table 3.** Reliability and validity analysis.

| Latent Variable | Cronbach's Alpha | KMO Test Value | Bartlett's Spherical Test Value |
|---|---|---|---|
| Degree of Participation in Rebuilding | 0.880 | 0.683 | <0.001 |
| Degree of Risk Sharing | 0.904 | 0.856 | <0.001 |
| Degree of Value-added Return | 0.835 | 0.822 | <0.001 |
| Degree of Resource Input | 0.888 | 0.782 | <0.001 |
| Overall | 0.906 | 0.894 | <0.001 |

#### 3.1.3. The Fitting and Modification of Structural Equation Model

The structural equation model, also known as the latent variable model or covariance structural model, is a kind of hypothetical model with causal relationship firstly constructed based on theoretical literature or empirical rules. Then, proceeding from a hypothetical theoretical framework, variable data are collected to verify the rationality and correctness of the set structural relationship or model hypothesis, or the gap between the actual covariance and the theoretical covariance of the sample, attempting to minimize the gap [47,48]. It is a model that takes into account both the internal structure of factors and the causal relationship among the factors.

The structural equation model includes a measurement model and a structural model (as shown in Figure 3). The measurement model reflects the relationship between observed variables and latent variables, while the structural model reflects the causal relationship between latent variables, also known as a causal model.

(1) Measured Model

The equation in the measurement model is referred to as the measurement equation; its forms are shown in Equations (1) and (2).

$$x = \Lambda_x \xi + \delta \tag{1}$$

$$y = \Lambda_y \eta + \varepsilon \tag{2}$$

where $x$ is the observed index of $\xi$; $\delta$ is the measurement error of $x$; $\Lambda_x$ is coefficient matrix, consisting of $x$'s factor loading on $\xi$; $y$ is the observed index of $\eta$; $\varepsilon$ is the measurement error of $y$; and $\Lambda_y$ is the coefficient matrix, consisting of y's factor loading on $\eta$.

(2) Structural Model

The equation of the structural model is referred to as the structural equation, and its form is shown in Equation (3).

$$\eta = B\eta + T\xi + \zeta \tag{3}$$

where $\eta$ is the endogenous latent variable; $\xi$ is the exogenous latent variable; $\zeta$ is the random interference term, reflecting the unexplained part of $\eta$; $B$ is the $\eta$ coefficient matrix, describing the mutual influence between $\eta$; and $T$ is the $\xi$ coefficient matrix, describing the effect of $\xi$ on $\eta$.

AMOS is used for parameter estimation, obtaining the standard path coefficient structure diagram of the initial structural equation with parameters. DPR, DRS, DVR, and DRI are latent variables; DPR1-DPR3, DRS1-DRS5, DVR1-DVR5, and DRI1-DRI4 are observed variables. Each observed variable has its own observation error, and each exogenous latent variable has its own measurement error, as shown in Figure 4.

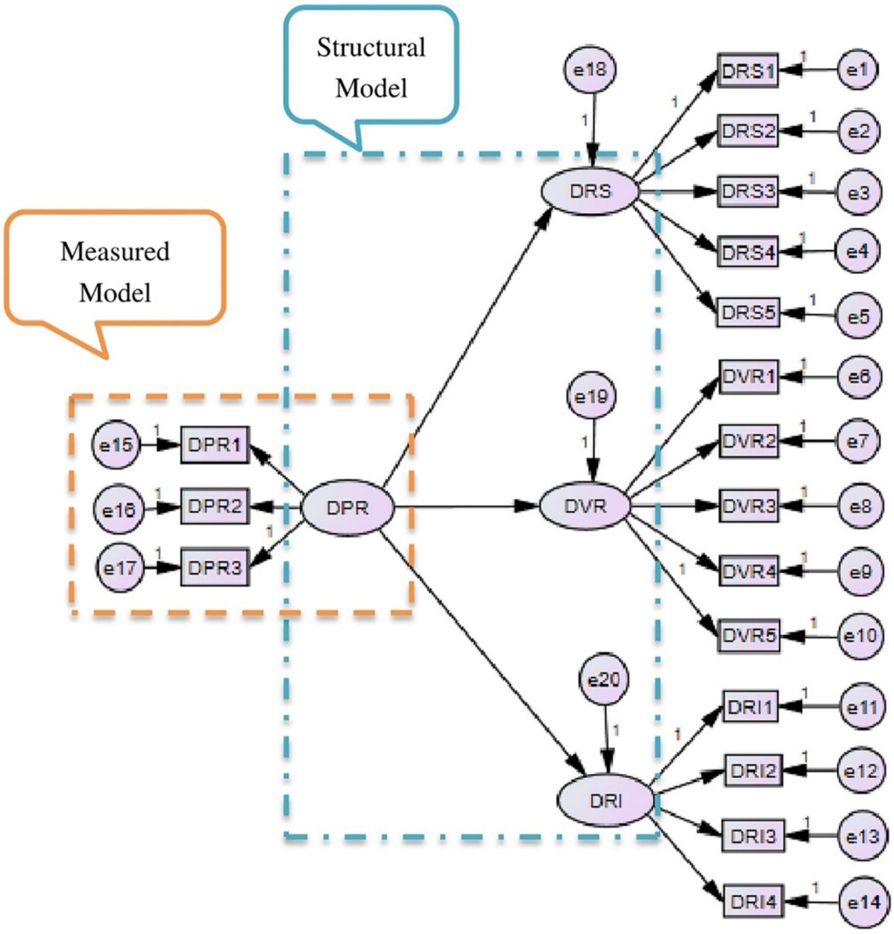



**Figure 3.** The path diagram of the structural equation model.

In order to ensure the quality of the studied model, the model should be tested, so as to delete the observed indexes whose path coefficient fails to meet the requirement from the measurement model (the path coefficient is deleted if it is less than 0.6). The modified structural equation model demonstrates a satisfactory degree of fitting and is acceptable, as shown in Figure 5 and Table 4.

**Table 4.** The overall fitness index before and after modification.

| Index | Before Correction | After Correction | Evaluation Standard | Evaluation Results |
|---|---|---|---|---|
| CMIN/DF | 2.093 | 1.489 | <2 | Qualification |
| GFI | 0.899 | 0.928 | >0.90 | Qualification |
| AGFI | 0.867 | 0.903 | >0.90 | Qualification |
| PGFI | 0.682 | 0.685 | >0.50 | Qualification |
| NFI | 0.905 | 0.934 | >0.90 | Qualification |
| RFI | 0.889 | 0.921 | >0.90 | Qualification |
| IFI | 0.948 | 0.977 | >0.90 | Qualification |
| TLI | 0.939 | 0.973 | >0.90 | Qualification |
| CFI | 0.948 | 0.977 | >0.90 | Qualification |
| RMR | 0.033 | 0.028 | <0.05 | Qualification |
| RMSEA | 0.067 | 0.045 | <0.08 | Qualification |
| PCFI | 0.808 | 0.812 | >0.50 | Qualification |
| PNFI | 0.772 | 0.776 | >0.50 | Qualification |

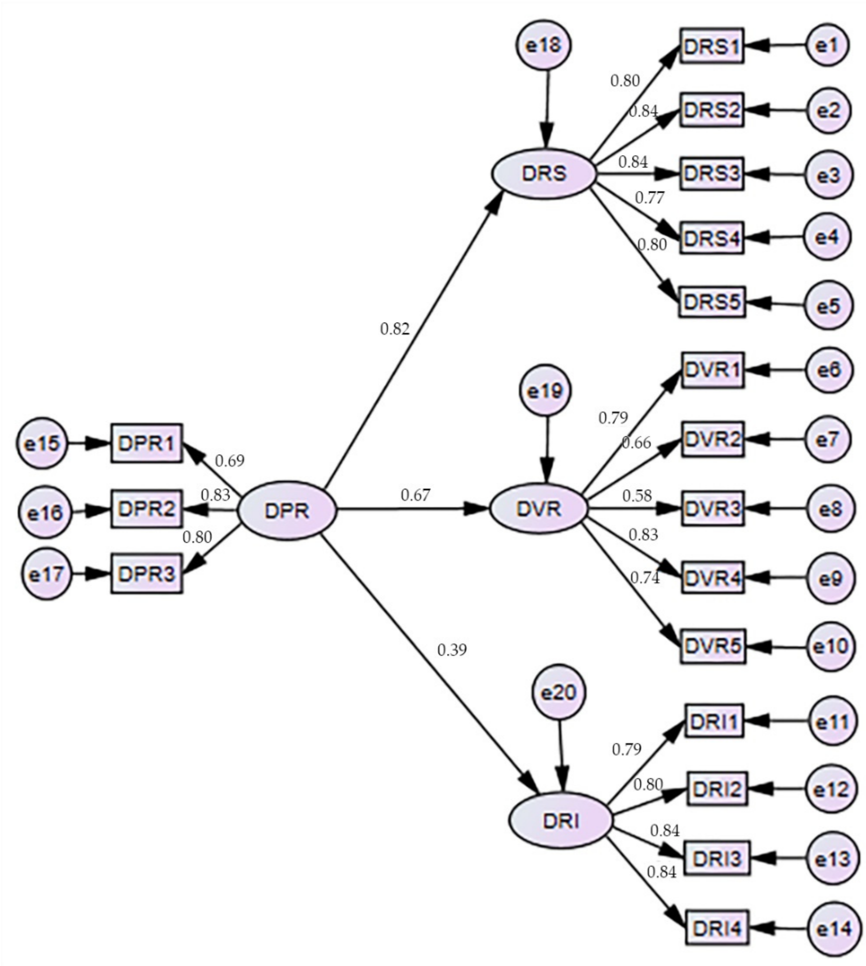



**Figure 4.** The diagram of the initial structural equation.

### *3.2. Determination of Influencing Factors*

Based on the modified structural equation model, the final influencing factors of cost allocation in the renovation of old residential communities can be obtained. According to Equation (4) and the path coefficient in the model, the weight of each influencing factor of cost allocation in the renovation of old residential communities can be calculated (as shown in Table 5).

$$w_i = \frac{\lambda_i}{\sum \lambda_i} \quad (4)$$

where $w_i$ refers to the weight of a specific influencing factor and $\lambda_i$ refers to the path coefficient of a specific influencing factor.

**Table 5.** Weight of influencing factor of cost allocation in the renovation of old residential communities.

| Latent Variable | Weight | Observed Variable | Weight |
|---|---|---|---|
| Degree of Participation in Rebuilding (DPR) | 0.247 | DPR1 | 0.294 |
| | | DPR2 | 0.360 |
| | | DPR3 | 0.346 |
| Degree of Risk Sharing (DRS) | 0.256 | DRS1 | 0.203 |
| | | DRS2 | 0.210 |
| | | DRS3 | 0.215 |
| | | DRS4 | 0.180 |
| | | DRS5 | 0.192 |
| Degree of Value-added Return (DVR) | 0.242 | DVR1 | 0.258 |
| | | DVR2 | 0.212 |
| | | DVR4 | 0.278 |
| | | DVR5 | 0.252 |
| Degree of Resource Input (DRI) | 0.255 | DRI1 | 0.223 |
| | | DRI2 | 0.260 |
| | | DRI3 | 0.241 |
| | | DRI4 | 0.276 |

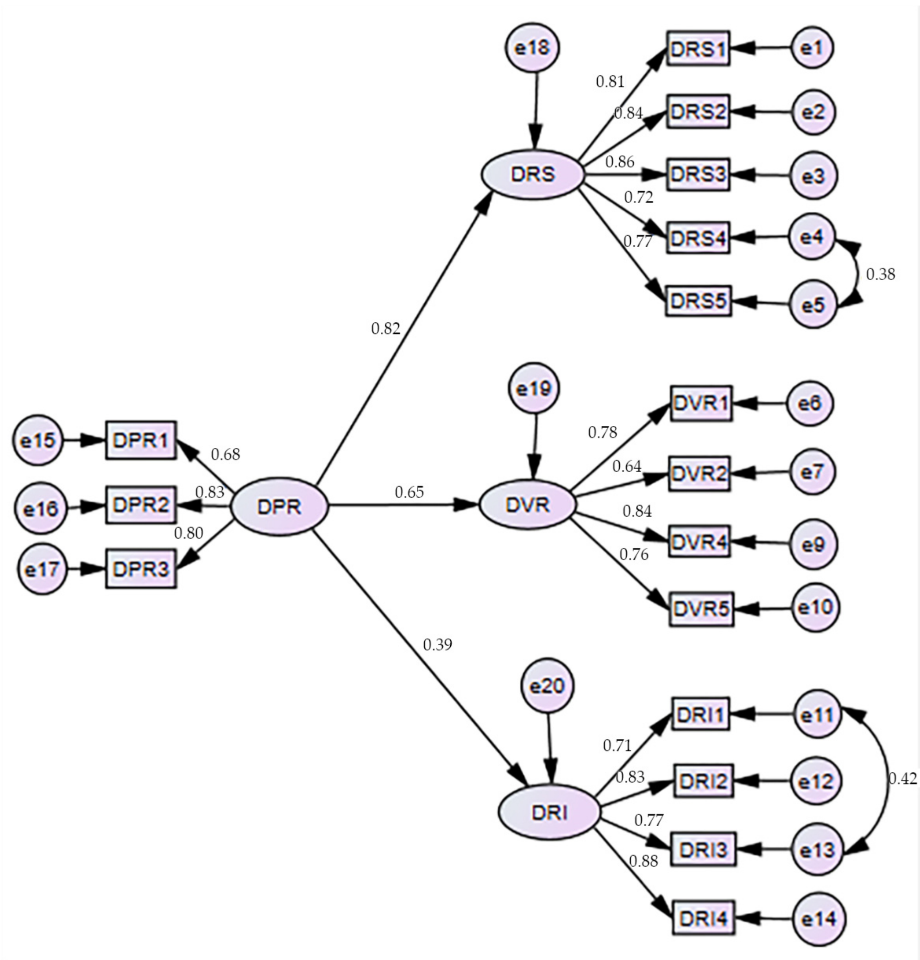



**Figure 5.** Modified structural equation model.

### 3.3. Cost Allocation Model Based on Improved Shapley Value

#### 3.3.1. Cost Allocation Model Based on Traditional Shapley Value

It is assumed that the set $N = \{1, 2, 3, \ldots, n\}$ represents the n members that make up the alliance $S$. The total cost of the alliance S is $C(S)$. The cost that the $i$th participant needs to share is $\varphi_i(C)$, and $\varphi(C) = \{\varphi_1(C), \varphi_2(C), \ldots\ldots \varphi_n(C)\}$ is called allocation strategies for cooperative games. The cost of each alliance meets the following conditions:

$$C(\varnothing) = 0 \tag{5}$$

$$C(S_1 \cup S_2) \leq C(S_1) + C(S_2) \tag{6}$$

$$C(S) = \sum_{i=1}^{n} \varphi_i(C) \tag{7}$$

where $S_1 \cap S_2 = \varnothing$, $S_1 \in N$, $S_2 \in N$.

According to the Shapley value:

$$\varphi_i(C) = \sum_{S \subseteq N} \frac{(|S|-1)!(n-|S|)!}{n!} \times (C(S) - C(S-i)) \tag{8}$$

where $|S|$ is the number of participants in the renovation of old residential communities in alliance $S$; $(|S|-1)!$ represents the number of permutations excluding player $i$ in the games; $(n-|S|)!$ represents the number of permutations of $N - S$; and $C(S-i)$ is the cost value after deducting the $i^{\text{th}}$ participant in the renovation of old residential communities in the alliance $S$.

#### 3.3.2. Cost Allocation Model Based on Improved Shapley Value

With full consideration of the factors that influence cost allocation in old residential communities and based on the analysis of the influencing factors of cost allocation in the preceding sections, the set of correction factors of the model is established: $J = \{j\}$. $j = 1, 2, 3, 4$, referring to the degree of participation in renovation, the degree of risk sharing, the degree of value-added return, and the degree of resource input, respectively. The measured value of the $i$th participant in relation to the $j$th correction factor is denoted as $a_{ij}$, as shown in Table 6.

**Table 6.** Measured value of correction factors.

| Participant | 1(DPR) | 2(DRS) | 3(DVR) | 4(DRI) |
|---|---|---|---|---|
| 1 (Government) | $a_{11}$ | $a_{12}$ | $a_{13}$ | $a_{14}$ |
| 2 (Home Owners) | $a_{21}$ | $a_{22}$ | $a_{23}$ | $a_{24}$ |
| 3 (Private Sectors) | $a_{31}$ | $a_{32}$ | $a_{33}$ | $a_{34}$ |

According to Table 6, the correction matrix $A$ that influences cost allocation is obtained:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \end{bmatrix} \tag{9}$$

The degree of influence of each influencing factor in cost allocation in the renovation of old residential communities is determined: $\lambda = \begin{bmatrix} \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 \end{bmatrix}^T$. After adjustment, the comprehensive influence of each influencing factor in cost allocation of each participant in the renovation of old residential communities is $B$:

$$B = A \times \lambda = \begin{bmatrix} B_1 & B_2 & B_3 \end{bmatrix}^T \tag{10}$$

After normalization of matrix $B$, $R = (R_1, R_2, R_3)^T$ is obtained, where $R_1$, $R_2$, and $R_3$ represent the comprehensive influence of each influencing factor to cost allocation among the government, home owners, and private sector, respectively, after adjustment. After adjustment, the actual cost to be shared by each participant is:

$$C_i = \varphi_i(C) + \left(\frac{1}{n} - R_i\right) \times C(S)(i = 1,2,3) \tag{11}$$

Upon calculation through above formula, the cost allocation scheme for the renovation of old residential communities based on the improved Shapley value can be obtained. This scheme comprehensively takes into account the four main factors that influence the cost allocation of each participant in the renovation of old residential communities: the degree of participation in renovation, the degree of risk sharing, the degree of value-added return, and the degree of resource input. Based on these four factors, the cost allocation scheme is further modified to better achieve objectivity, fairness, and rationality. This scheme can be applied not only to the total cost allocation of a project, but also to the cost allocation in the renovation of a specific facility.

#### 3.3.3. Determination of Parameters

(1) Degree of Participation

The relevant supervision department may be invited for scoring and evaluation of actual participation of each participant as per the performance appraisal standard of the project, thus obtaining the measured values $a_{11}$, $a_{21}$, and $a_{31}$ of each participant's degree of participation in renovation.

(2) The Degree of Risk Sharing

Each participant's degree of risk sharing is determined as follows:

① Obtain the weight $\gamma_i$ of each main risk through Table 5.

② Construct judgment matrix $U_i$. Set the comment set as $V_i = \{v_1, v_2, v_3, v_4, v_5\}$ = {high risk, relatively high risk, general risk, relatively low risk, low risk}. Then, experts in related fields are invited for scoring the risks borne by each participant. After normalization, the judgment matrix $U_i$ is obtained.

③ As $B_i = \gamma \times U_i$, the comprehensive evaluation vector Bi of risk sharing of each participant is obtained. According to the principle of maximum membership degree, the comprehensive evaluation value of risk sharing $K = BV^T$ of the government, community owners, and the private sector is obtained. Finally, $K$ is normalized, after which the risk-sharing degree measured values $a_{12}$, $a_{22}$, and $a_{32}$ of each participant are obtained.

(3) Value-added Return

The degree of value-added return can be measured by inviting a professional evaluation agency to evaluate the expected value-added return created by the government, home owners, and the private sector, denoted as $P_g$, $P_o$, and $P_s$, respectively. The measured value of the value-added return of each participant is:

$$a_{13} = \frac{P_g}{P_g + P_o + P_s} a_{23} = \frac{P_o}{P_g + P_o + P_s} a_{33} = \frac{P_s}{P_g + P_o + P_s} \tag{12}$$

(4) The Degree of Resource Input

The degree of resource input can be measured by calculating the total cost of human resources, materials, finance, and other resources invested by the government, home owners, and private sectors to ensure the smooth progress of renovation of old residential communities in response to emergencies, denoted as $C_g$, $C_o$, and $C_s$, respectively. The measured value of the resource input of each participant is:

$$a_{14} = \frac{C_g}{C_g + C_o + C_s}, \ a_{24} = \frac{C_o}{C_g + C_o + C_s}, \ a_{34} = \frac{C_s}{C_g + C_o + C_s} \quad (13)$$

## 4. Case Analysis

In this part, taking the renovation of the dormitory community of Hainan Design and Research Institute Co., Ltd. as an example, the solving steps and feasibility of the model are demonstrated through calculation in the real example. The dormitory community of Hainan Design and Research Institute Co., Ltd. was a typical old community build in 1987. The renovation of the community commenced on 8 October 2020. The renovation mainly included basic renovation of exterior walls, roof waterproofing, community roads, wires, water supply and drainage, charging piles, garbage room, unified anti-theft net, etc. (as shown in Figure 6). The funds for the renovation of the community were raised through multiple channels. At present, RMB 7,080,000 has been raised, consisting of five parts, including RMB 2,700,000 from government subsidies, RMB 620,000 from home owners, and RMB 3,480,000 from private sectors. Upon calculation and evaluation, the contribution of the government, home owners, and private sectors varies based on different portfolios of alliance. In the present renovation, the government provides $C$ ($S_g$) = RMB 2,700,000; the home owners raised $C$ ($S_o$) = RMB 620,000; the private sector invested $C$ ($S_s$) = RMB 3,480,000. In the case of joint contribution by the government and home owners, the needed amount is $C$ ($S_g \cup S_o$) = RMB 3,000,000; in the case of joint contribution by the government and private sector, the needed amount is ($S_g \cup S_s$) = RMB 5,700,000; in the case of joint contribution by home owners and private sectors, the needed amount is $C$ ($S_o \cup S_s$) = RMB 3,700,000; in the case of joint contribution by the government, home owners, and private sectors, the needed amount is $C$ ($S_g \cup S_o \cup S_s$) = RMB 6,000,000.

(**a**) (**b**)

**Figure 6.** (**a**) Exterior walls of the dormitory community of Hainan Design and Research Institute Co., Ltd. before renovation. (**b**) Exterior walls of the dormitory community of Hainan Design and Research Institute Co., Ltd. after renovation.

### *4.1. Cost Allocation Based on Traditional Shapley Value*

The cost allocation among the government, home owners, and private sectors in the project was calculated through Equation (8) based on the traditional Shapley value. The calculation results are shown in Tables 7–9.

**Table 7.** Cost shared by the government (unit: RMB 10,000).

| $S_1$ | {g} | {g, o} | {g, s} | {g, o, s} |
|---|---|---|---|---|
| $C\ (S)$ | 270 | 300 | 570 | 600 |
| $C\ (S-i)$ | 0 | 62 | 348 | 370 |
| $C\ C\ (S-i)$ | 270 | 238 | 222 | 230 |
| $\lvert S\rvert$ | 1 | 2 | 2 | 3 |
| $\frac{\lvert S\rvert-1!n-\lvert S\rvert!}{n!}$ | 1/3 | 1/6 | 1/6 | 1/3 |
| $(C(S)-C(S-i))\frac{\lvert S\rvert-1!n-\lvert S\rvert!}{n!}$ | 90 | 238/6 | 37 | 230/3 |

**Table 8.** Cost shared by home owners (unit: RMB 10,000).

| $S_2$ | {o} | {g, o} | {o, s} | {g, o, s} |
|---|---|---|---|---|
| $C\ (S)$ | 62 | 300 | 370 | 600 |
| $C\ (S-i)$ | 0 | 270 | 348 | 570 |
| $CC\ (S-i)$ | 62 | 30 | 22 | 30 |
| $\lvert S\rvert$ | 1 | 2 | 2 | 3 |
| $\frac{\lvert S\rvert-1!n-\lvert S\rvert!}{n!}$ | 1/3 | 1/6 | 1/6 | 1/3 |
| $(C(S)-C(S-i))\frac{\lvert S\rvert-1!n-\lvert S\rvert!}{n!}$ | 62/3 | 5 | 22/6 | 10 |

**Table 9.** Cost shared by private sectors (unit: RMB 10,000).

| $S_3$ | {s} | {g, s} | {o, s} | {g, o, s} |
|---|---|---|---|---|
| $C\ (S)$ | 348 | 570 | 370 | 600 |
| $C\ (S-i)$ | 0 | 270 | 62 | 300 |
| $C\ C\ (S-i)$ | 348 | 300 | 308 | 300 |
| $\lvert S\rvert$ | 1 | 2 | 2 | 3 |
| $\frac{\lvert S\rvert-1!n-\lvert S\rvert!}{n!}$ | 1/3 | 1/6 | 1/6 | 1/3 |
| $(C(S)-C(S-i))\frac{\lvert S\rvert-1!n-\lvert S\rvert!}{n!}$ | 116 | 50 | 308/6 | 100 |

Calculated based on the traditional Shapley value, the cost allocation among the participants is:

$$\varphi_g(C) = 90 + \frac{238}{6} + 37 + \frac{230}{3} = 243.33\text{tenthousandyuan} \tag{14}$$

$$\varphi_o(C) = \frac{62}{3} + 5 + \frac{22}{6} + 10 = 39.33\text{tenthousandyuan} \tag{15}$$

$$\varphi_s(C) = 116 + 50 + \frac{308}{6} + 100 = 317.33(\text{tenthousandyuan}) \tag{16}$$

### *4.2. Cost Allocation Based on Improved Shapley Value*

The measured value of the four influencing factors in cost allocation in the renovation of the dormitory community of Hainan Design and Research Institute Co., Ltd. before renovation is determined as follows:

(1) Measured value of the degree of participation in renovation

During the renovation of the dormitory community of Hainan Design and Research Institute Co., Ltd., the government, home owners, and private sectors participated in the work before, during, and after the renovation. Upon the appraisal of the project performance by relevant supervision departments, the degree of participation of the government, home owners, and private sectors can be measured ($a_{11}$, $a_{21}$, $a_{31}$) = (−1/3, −1/3, −1/3).

(2) Measured value of the degree of risk sharing

The comprehensive vector of risk sharing by the government, home owners, and private sectors in the renovation of the dormitory community of Hainan Design and Research Institute Co., Ltd. is calculated through fuzzy comprehensive evaluation. According to the principle of maximum membership, it can be learned that the risks borne by the government, home owners, and private sectors are low risks, lower risks, and general risks. Finally, the result is normalized to measure the degree of risks borne by the government, community owners, and the private sector ($a_{12}$, $a_{22}$, $a_{32}$) = (0.26, 0.34, 0.40).

(3) Measured value of the degree of value-added return

The expected value-added return created by the government, home owners, and the private sector in the renovation of the dormitory community of Hainan Design and Research Institute Co., Ltd. is evaluated by professional evaluation agencies, thus obtaining the measured value of the value-added return of each participant ($a_{13}$, $a_{23}$, $a_{33}$) = (0.35, 0.27, 0.38).

(4) Measured value of the degree of resource input

By referring to the renovation of existing similar old residential communities and the completed renovation of this community, the human resources, materials, finance, and other resources input by the government, home owners, and private sectors in response to emergencies to ensure smooth renovation of old residential communities are calculated, thus obtaining the measured value of the degree of resource input ($a_{14}$, $a_{24}$, $a_{34}$) = (0.3, 0.3, 0.4).

According to Table 5, the weight of each primary influencing factor is obtained as $\lambda$ = $(0.247, 0.256, 0.242, 0.255)^T$

After adjustment, the comprehensive influence of each factor to the cost allocation of each participant in the renovation of old residential communities is $B = A \times \lambda$ = (0.145, 0.147, 0.214). After normalization, $R$ = (0.288, 0.290, 0.422).

According to Equation (11), the cost allocation among participants based on the improved Shapley value is:

$$C_g = 243.33 + \left(\frac{1}{3} - 0.300\right) \times 600 = 263.33(\text{tenthousandyuan}) \tag{17}$$

$$C_o = 39.33 + \left(\frac{1}{3} - 0.309\right) \times 600 = 53.93(\text{tenthousandyuan}) \tag{18}$$

$$C_s = 317.33 + \left(\frac{1}{3} - 0.391\right) \times 600 = 282.73(\text{tenthousandyuan}) \tag{19}$$

The cost allocation before and after the improvement is shown in Table 10.

**Table 10.** Cost allocation before and after improvement.

| Participants | Cost Allocation Value of Traditional Shapley Value | Improvement of Cost Allocation Value of Shapley Value |
|---|---|---|
| Government | 243.33 ten thousand yuan | 263.33 ten thousand yuan |
| Home Owners | 39.33 ten thousand yuan | 53.93 ten thousand yuan |
| Private Sectors | 317.33 ten thousand yuan | 282.73 ten thousand yuan |

## 5. Discussion

Proceeding from the low willingness of residents and private sectors to participate in the renovation of old residential communities, in this study, we made an exploration with the conclusion that unreasonable cost allocation is one of the reasons. To this end, we constructed a cost allocation model for the renovation of old urban communities. First, 17 factors that affect the cost allocation in the renovation of old residential communities were collected. Then, these factors were subjected to screening and weight calculation with the structural equation model. Finally, a cost allocation model based on the improved Shapley value was established.

The results show that among the influencing factors of the cost allocation in the renovation of old residential communities, the importance of the four primary influencing factors is relatively small: DRS(0.256) > DRI(0.255) > DPR(0.247) > DVR(0.242). Among the indicators of the degree of risk sharing, the weight of construction risk is the greatest, which also conforms to the characteristics of old residential communities, such as dense population. The results before and after the improvement of the model is compared through a case analysis based on the cost allocation model established as per the Shapley value. Upon comparison, we found that the allocated cost of the government and home owners increased while that of private sectors reduced. The value-added return created by the government in renovation is at a medium level, with relatively low risk sharing and resource input. Therefore, the cost shared by the government should be increased. The value-added return created for home owners is relatively low, with medium risk sharing and resource input, as a result of which the shared cost is relatively smaller compared with that shared by the government. The degree of risk sharing, value-added return, and resource input of private sectors are all the highest. Therefore, the cost allocation is significantly reduced after the improvement. The study results show that the higher the degree of participation of participants in renovation, the more cost to be shared; the higher the degree of risk sharing, the less the cost to be shared; the higher the degree of value-added return, the less the cost to be shared; the higher the degree of resource input, the less the cost to be shared. The more responsibilities undertaken by a participant, the higher the degree of contribution and the less cost allocation, which conforms to the principles of cost allocation and economics. By comprehensively taking into account the degree of participation, the degree of risk sharing, the degree of value-added return, the degree of resource input, and the degree of contribution of participants, the improved model makes the cost allocation fairer and more reasonable.

According to the study results, several solutions are proposed for addressing the difficulties in cost sharing among participants in the renovation of old residential communities.

(1) Strengthen the awareness of cooperative games. The adoption of a cooperative game can increase the benefits of a project. Therefore, it is necessary that each participant in the renovation of old residential communities strengthen the awareness of the cooperative game, and use the cooperative game model to discuss the coordination of respective interests in the cooperation.
(2) Correctly deal with the relationship between cost allocation ability and cost allocation responsibility. To achieve a reasonable cost allocation, it is necessary to comprehensively take into account the relationship between cost allocation capability and cost allocation responsibility. Participants with higher cost-sharing ability should assume more cost-sharing responsibilities, so as to avoid increased renovation costs of old residential communities due to unbalanced ability and responsibility.
(3) Establish a mechanism for coordinating the interests of all participants. The smooth renovation of old residential communities is critically dependent on satisfying the interests and demands of all participants. The mechanism for coordinating the interests of participants can be established vertically and horizontally. Vertically, the relationship among the government, home owners, and private sectors should be coordinated to give play to the rationality of cost allocation; horizontally, attention should be paid to the fairness of cost sharing and benefit distribution among participants.

The cost allocation model constructed in this paper not only promotes contributions of private sectors and home owners in renovation, but also speeds up the renovation of old residential communities in China. Furthermore, it also serves as a reference model for the cost allocation among participants in the revocation of old residential communities in other countries. With the passage of time, there will be more residential communities demanding renovation in all other countries. By then, it is inevitable that the renovation may be impeded due to insufficient funds. For instance, in Germany, a model with joint contribution from three levels of governments (federal, state, and local governments) is adopted in the urban renovation plan, where private investment is attracted with public funds to relieve the financial burden of the government [49]. In the renovation of public residential communities in Singapore, the renovation costs of public space in residential communities are all borne by the government. As for homes or elevators, the government bears most of the costs and home owners bear from 5% to 14% [50]. In terms of reducing the financial burden of the government and guiding private sectors and home owners to participate in renovation, this model makes an estimation of cost allocation in the cooperation, providing strategic support for participants and offering references for other countries to some extent.

The study results also have certain limitations. Since old residential communities are mainly studied herein, the study results are not suitable for all urban renewal. As the study targets China, this model is only applicable to the renovation of old residential communities in China, and only serves as a reference for other countries.

## 6. Conclusions

With the gradual saturation of buildings in urban areas, the renovation of old residential communities has been promoted across China. However, unreasonable cost allocation not only reduces the willingness of residents and private sectors to participate in renovation, but also slows down the urban renewal. In view of unreasonable cost allocation in the renovation of old residential communities, with the government, home owners, and private sectors as main participants and based on the structural equation model and the Shapley value, we established a cost allocation model for the renovation of old residential communities. The cost allocation model is modified from four dimensions: the degree of participation, the degree of risk sharing, the degree of value-added return, and the degree of resource input. Furthermore, its effectiveness is proved through an actual case analysis, thus making cost allocation among participants in the renovation of old residential communities fairer and more reasonable. The study results are critically important for government preparation of financial strategies for the renovation of old residential communities, because it not only broadens the channels for fundraising, but also improves residents' sense of participation and happiness. The results of this study can promote private sectors' investment, encourage home owners to contribute, relieve the government's financial pressure, and further promote the renovation of old communities. As to the difficulty of cost allocation among the participants in the renovation of old residential communities, the participants should strengthen their awareness of cooperative games, correctly deal with the relationship between cost sharing ability and cost sharing responsibility, and establish a benefit coordination mechanism, thus promoting the renovation of old residential communities.

There are still some shortcomings and room for improvement in this study. For example, few influencing factors of cost allocation in the renovation of old residential communities were taken into account, without a comprehensive consideration of all factors. Moreover, this study was carried out from the perspective of renovation of old residential communities in China and is not generally applicable in other countries. Therefore, scholars should avoid these deficiencies in future studies.

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