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A Multi-Objective Trade-Off Model in Sustainable Construction Projects

Guangdong Wu

Department of Construction Management, Jiangxi University of Finance & Economics, Nanchang 330013, China; wuguangdong@jexufe.edu.cn; Tel.: +86-791-8384-2078

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Abstract: Based on the consideration of the relative importance of sustainability-related objectives and the inherent nature of sustainable construction projects, this study proposes that the contractor can balance the levels of efforts and resources used to improve the overall project sustainability. A multi-objective trade-off model using game theory was established and verified through simulation and numerical example under a moral hazard situation. Results indicate that effort levels of the contractor on sustainability-related objectives are positively related to the outcome coefficient while negatively to the coefficients of effort cost of the relevant objectives. High levels of the relative importance of sustainability-related objectives contribute to high levels of effort of the contractor. With the variation in effort levels and the coefficient of benefit allocation, the project net benefit increases before declining. The function of project benefit has a marked peak value, with an inverted "U" shape. An equilibrium always exists as for the given relative importance and coefficients of the effort costs of sustainability-related objectives. Under this condition, the owner may offer the contractor a less intense incentive and motivate the contractor reasonably arranging input resources. The coefficient of benefit allocation is affected by the contractor characteristic factors and the project characteristic factors. The owner should balance these two types of factors and select the most appropriate incentive mechanism to improve the project benefit. Meanwhile, the contractor can balance the relative importance of the objectives and arrange the appropriate levels of effort and resources to achieve a sustainability-related objective. Very few studies have emphasized the effects of the relative importance of sustainability-related objectives on the benefits of sustainable construction projects. This study therefore builds a multi-objective trade-off model to bridge this research gap. This study sheds significant theoretical and practical insights regarding the objective management of sustainability-related objectives, as well as insights into the improvement of performance in sustainable construction projects.

Keywords: sustainable construction; multi-objective; relative importance; trade-off

1. Introduction

Sustainable construction satisfies the demands of sustainable development and aims at incorporating the sustainability concept into conventional building practices [1,2]. It can be defined as efforts to ensure economic development and social health, whilst reducing the negative impacts on the environment [3,4]. The level of complexity in sustainable projects with the ultimate goal to deliver sustainability, is higher than that of the traditional types [5]. This is due to the increased number of stakeholders involved (i.e., governments, financiers, developers, consultants, suppliers, designers, owners, supervisors, contractors, subcontractors and end users) and also because of the balanced nature amongst the environmental, economic and social objectives [6–10]. Compared to traditional projects, sustainable projects affect various stakeholders with different social, environmental and economic interests [11]. Successful sustainable construction cannot be achieved solely by considering environmental issues. Economic and social issues must be considered as well in any balanced approach towards improved sustainability [12]. Therefore, the role of a multi-objective trade-off is crucial in ensuring that sustainability-related objectives are met when undertaking a project of this type.

Sustainable construction is an adaptive complex system that requires the collaboration of various stakeholders to pursue a high level of sustainability [13]. With the increasing demands of ecological principles and resource efficiency, collaboration between the owner and contractor becomes essential to implement sustainable practices. As a key driver of sustainability, the owner play an leading role during the process [14]. Contractors are, however, the promoters for realizing the sustainability spirit. They both should bear the responsibility of minimizing the negative impacts on the nearby environment and society, and maximizing the economic contribution [15]. The owner, contractor and other stakeholders are all independent legal entities or rational individuals with independent benefits [16,17]. Due to the different types of core knowledge and capabilities, and given the information asymmetry that is likely to occur in the course of project implementation, the groups of owner and contractor may both exhibit moral hazard behaviors [5,18,19]. Furthermore, the successful delivery of sustainable projects should simultaneously achieve the objectives related to the environment, society and economics. The relative importance of different objectives varies in each sustainable project. Real-life sustainable projects are challenged by various constraints e.g., strict deadlines and limited resource [20,21]. One of the most challenging tasks faced by a sustainable project planner is to optimize resource allocation and resource leveling, whilst simultaneously achieving sustainability-related objectives [9]. If one of the control objectives is weighted too heavily towards resource allocation and utilization, this could divert the resources needed for other objectives and weaken the degree of achievement, thus potentially having a destructive effect on project benefits [22].

Sustainability is a balanced approach that focuses equally on the environment, economy and society [7]. One major barrier that hinders enacting sustainable construction is the absence of an appropriate method that balances sustainability-related objectives in construction practices. Considering the relative importance of sustainability-related objectives, this study aims to investigate the effects of a multi-objective trade-off on project benefits and stakeholder behaviors. The trade-off between economic and environmental objectives is selected since this conflict is more essential for sustainable development [12,23,24]. The collaboration between the owner and contractor is adopted in order to balance the sustainability-related objectives. In the process of sustainable construction implementation, an appropriate method to solve the multi-objective trade-off problem is increasingly important when attempting to achieve sustainable development [25]. Therefore, a mathematical model incorporating game theory was developed to explore the multi-objective trade-off problem. Game theory has been widely used before to examine the behaviors of conflict and cooperation between rational decision makers [26–28]. It not only provides a useful approach to study the conceptual aspects of construction projects [29–31], but also offers valuable insights into the way that participants utilize resources in different situations. As such, game theory is suggested as the basis for the efficient allocation of the incremental benefits of collaboration between stakeholders in sustainable construction projects. The grounded model can be used to simulate and analyze the effects of multi-objective trade-off on stakeholder expected benefits, the project net benefit and the benefit allocation strategy. It is well documented in literature that multi-objective trade-off is crucial for sustainable development. However, quantitative approaches have not been commonly used to explore the effects of multi-objective trade-offs in sustainable construction projects. In this regard, this study bridges the research gap and provides practical insights which can help achieve the sustainable projects in an inter-organizational context. Besides, this study also offers a theoretical reference for properly handling the relationships between the environment, society and economy in sustainable construction practices.

2. Literature Review

2.1. Objectives of Sustainable Projects

The core objective of sustainable construction is to meet the requirements of sustainability as planned [32]. The concept of sustainability in sustainable construction relies on the achievement of economic efficiency, environmental performance and social responsibility [33,34]. Over the past few years, numerous studies have been undertaken to explore the criteria of sustainability. Zimmermann et al. (2005) suggested that environmental sustainability is a basic prerequisite for sustainable economic and social development in sustainable construction [35]. Environmental effects exist throughout the project life cycle, including the planning, design, construction, operation and maintenance stages [36]. Bassioni et al. (2005) proposed that the category of special objectives in sustainable construction should consist of stakeholder-related objectives, project-related objectives, and organizational-related objectives [37]. In addition, the indicators of resource conservation, energy conservation, cost savings, and waste reduction are essential if the project-related objectives are to be manifested [8]. Robins (2006) argued that the "triple-bottom line" (economic, social, and environmental) is a simplified way to categorize sustainability into three primary components [3]. Chen et al. (2010) similarly proposed that sustainable performance criteria can be grouped into three dimensions, namely economic factors, social factors, and environmental factors [38]. Ding (2008) suggested that the objectives of sustainable construction include financial return, low energy consumption, external benefits, and minimal environmental impact [39]. Shen et al. (2009) proposed the minimization of construction waste is a critical aim in pursuing the practice of sustainable construction [40]. As for the measurement of objectives, Presley and Meade (2010) proposed that: (i) the economic objective can be measured regarding project cost, client satisfaction, profitability, and timeliness; (ii) the environmental objective by the sustainability of the site, water efficiency, energy conservation, material usage, and the indoor environment; and (iii) the social objective by internal human resources, external population, quality and stakeholders' participation [41]. Czarnecki and Kaproń (2010) proposed that sustainable construction should meet nine requirements including a minimum quantity of materials used, maximum reuse of components, the possibility to renovate or recycle, environmental protection, waste management, minimum emission of pollutants, construction process management, health aspects and comfort of use [4]. Huang and Hsu (2011) established an indexing system for assessing the performance of sustainable construction. This indexing system comprises economic issues, social issues, and environmental issues [42]. Fortunato et al. (2012) believed that social issues should include an indicator of safety [43]. Whang and Kim (2015) proposed that a balanced application between environmental, economic, and social issues is essential for successfully achieving sustainability [12]. Kibwami and Tutesigensi (2016) suggested that sustainable construction can be interpreted as having three objectives, namely economy, society and environment types [44]. The driving forces for change in the construction industry are rather diverse, not least of which are health, environmental, and social issues under economic constraints [45]. According to Karakhan and Gambatese (2017), stakeholders should place equal focus on the environment, economy, and society [7]. This study therefore follows most literature by considering the environment, society and economy as the main objectives of sustainable construction.

2.2. Multi-Objective Trade-off in Sustainable Construction

In sustainable projects, most efforts related to sustainable development have concentrated on environmental issues [34]. With reference to construction business, sustainability is about achieving a win-win outcome. This outcome includes contributing to an improved environment and an advanced society, whilst gaining economic benefits for the involved stakeholders [9,33]. Therefore, implementing sustainability requires the commitment of all stakeholders and a higher level of cooperation amongst various stakeholder groups. Due to resource constraints in construction projects, it has been a well-known challenge providing an effective method to solve the multi-objective tradeoff problem [46].

Various methods and algorithms that determine strategies have been used to investigate this issue [47]. Many studies have explored the time-cost tradeoff problem of project scheduling and related algorithms under certain conditions [48–52]. In light of this, the balanced methods can provide reliable references that help to solve the multi-objective trade-off problem between the environmental, social and economic objectives. However, some concerns regarding the collaboration between stakeholders which is associated with organizational capabilities and behaviors still exist [53–55]. In the process of project implementation, the responsibilities for resource exchange and utilization are related to different stakeholders [5]. The endowment of resource input on different objectives reflects the effort levels of the various stakeholders. Therefore, this study attempts to solve the multi-objective trade-off problem, taking into consideration organizational behaviors of stakeholders.

3. Model Description and Solution

3.1. Model Description

In this study, an assumption is made that in a specific sustainable construction project, two equal cooperative parties exist, namely the owner and the contractor. Both these party's efforts concentrate on the overall project benefits, with consideration given to the sustainable construction project's inherent nature. On this basis, and without considering the time value of investments, this study comprehensively weighs up the influence of the multi-objective trade-off on project benefits. The following hypotheses are proposed:

Hypothesis 1. *The effort levels of the contractor on the economic and environmental objectives are $a = (a_1, a_2)$, while $a > 0$. The efforts of the contractor on the sustainability-related objectives can generate incremental benefits to the sustainable construction. The incremental benefits can be shared by the owner and contractor, and the allocation mechanism is designed by the owner [56]. Assuming that the contractor can balance the economic and environmental objectives, and assuming the constant returns to scale, the outcome function of sustainable construction follows the Cobb-Douglas production function [57,58]:*

$$R(a_1, a_2) = A a_1^p a_2^q + \varsigma \tag{1}$$

where A is the outcome coefficient of the effort levels of the contractor, which can manifest by the integrated technical level and comprehensive management ability of the contractor [17]. The outcome coefficient of the effort levels is related to the operational management capability, project experiences and employee competences of the contractor. In different types of sustainable construction projects, the relative importance of the economic and environmental objectives varies, due mainly to contractual requirements. Thus, the contractor needs to balance the efforts exerted on achieving the economic and environmental objectives. The levels of effort can be presented by the degrees of the resource input. To facilitate the solution of the model, the social objective of sustainable construction is neglected. The parameters of p and q denote the relative importance of the economic and environmental objectives, satisfying the restricted conditions of $p > 0$, $q > 0$ and $p + q = 1$. To ensure the stability of the outcome function, ς is set to follow a normal distribution $(0, \sigma^2)$, reflecting the influence of the uncertainty of external environment.

Hypothesis 2. *The effort cost function of the contractor $C(a_1,a_2)$ is a strictly monotonic increasing function of a_i $(i = 1, 2)$ [59,60]:*

$$C(a_1, a_2) = \frac{1}{2}\eta_1 a_1^2 + \frac{1}{2}\eta_2 a_2^2 \tag{2}$$

where the parameters of η_1 and η_2 are the coefficients of effort cost for the economic and environmental objectives. The coefficients of effort cost denote the marginal cost of the contractor to achieve the fixed objectives, thus satisfying the restricted conditions of $\eta_1 > 0$ and $\eta_2 > 0$. In reality, the coefficients of effort cost on the economic and environmental objectives are correlative with each other [12,61]. According to analogous studies, *this study assumes that η_1 and η_2 are mutually independent in guaranteeing the existence of a numerical solution of the model [62,63].*

Hypothesis 3. *In sustainable construction, the owner is the dominant enterprise and is risk-neutral. The contractor is the executive enterprise and is risk-averse. The owner has the absolute authority to design a motivation mechanism for the implementation of the project. Both the owner and the contractor are rational economic entities, and they both tend to behave in ways that will maximize their own benefits. According to the relationship between risk attitude and utility function, the utility function of the contractor can be expressed as $U(\omega) = -a^{-\rho\omega}$ [64]. In this equation, ω is the benefit function of the contractor, and ρ is the degree of absolute risk aversion calculated through the Arrow-Pratt method.*

Hypothesis 4. *The owner and the contractor sign a principal-agent contract in order to successfully deliver the project. The owner's payment to the contractor follows a linear function [17,60]. The benefit allocation coefficient and the constant payments for the contractor are β and ϖ, respectively.*

$$s = \varpi + \beta R(a_1, a_2) \tag{3}$$

Based on the above hypotheses, the expected benefit functions of the contractor can be calculated as follows:

$$U_1 = s - C(a_1,\ a_2) - \frac{1}{2}\rho\beta^2\sigma^2 \tag{4}$$

where $0.5\rho\beta^2\sigma^2$ is the risk premium of the contractor. This indicates that the contractor is willing to abandon the benefits of $0.5\rho\beta^2\sigma^2$ in exchange for a stable deterministic benefit. The expected benefit functions of the owner can be calculated as follows:

$$U_2 = R(a_1, a_2) - s \tag{5}$$

Consequently, the net project benefit function can be calculated as follows:

$$U = R(a_1, a_2) - C(a_1, a_2) - \frac{1}{2}\rho\beta^2\sigma^2 \tag{6}$$

As for the owner and contractor, both of their benefits come directly from the project benefits. The project benefits will almost certainly be reduced if both the owner and contractor tend to maximize and prioritize their own benefits [17,65]. Therefore, the optimal behavioral arrangements of these two parties are to achieve their own maximum benefits, but under the strict condition of maximizing the project benefit. Under the condition of information asymmetry, the multi-objective trade-off problem is determined by the effort levels of the contractor (a_i) and the benefit allocation coefficient (β). This is equivalent to solving the following linear optimization problem under certain constraint conditions:

$$\begin{aligned} &\max_{a_i,\beta} U \\ &s.t. \quad a_i, \beta \in \arg\max U_1 \\ &\qquad\ \ a_i, \beta \in \arg\max U_2 \end{aligned}$$

3.2. Model Solution

To solve the above model, the first partial derivatives of a_1 and a_2 were calculated respectively, and the values were then set to zero. Thus, the following equation set can be obtained:

$$\begin{cases} \frac{\partial U_1}{\partial a_1} = A\beta p a_1^{p-1} a_2^q - \eta_1 a_1 = 0 \\ \frac{\partial U_1}{\partial a_2} = A\beta q a_1^p a_2^{q-1} - \eta_2 a_2 = 0 \end{cases}$$

To solve the above simultaneous equation with regard to a_1 and a_2, we can obtain:

$$\begin{cases} a_1 = A\beta\left(\frac{p}{\eta_1}\right)^{\frac{1+p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{q}{2}} \\ a_2 = A\beta\left(\frac{p}{\eta_1}\right)^{\frac{p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{1+q}{2}} \end{cases}$$

Additionally, the second partial derivatives of a_1 and a_2 were calculated respectively, in order to determine the extremum of the model, which is presented as follows:

$$\begin{cases} \frac{\partial^2 U_1}{\partial (a_1)^2} = A\beta p(p-1)a_1^{p-2}a_2^q - \eta_1 < 0 \\ \frac{\partial^2 U_1}{\partial a_1 a_2} = A\beta pqa_1^{p-1}a_2^{q-1} > 0 \\ \frac{\partial^2 U_1}{\partial (a_2)^2} = A\beta q(q-1)a_1^p a_2^{q-2} - \eta_2 < 0 \end{cases}$$

According to the extremum attributes of functions with two variables, the equilibrium point of $a = (a_1^*, a_2^*)$ is the maximal value of U_1. Thus, we can obtain:

$$\begin{cases} a_1^* = A\beta\left(\frac{p}{\eta_1}\right)^{\frac{1+p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{q}{2}} \\ a_2^* = A\beta\left(\frac{p}{\eta_1}\right)^{\frac{p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{1+q}{2}} \end{cases} \tag{7}$$

Substituting Equation (7) into Equation (6), the partial derivatives of β were calculated, and then the value was set to zero. Thus, the following equation can be obtained:

$$\frac{\partial U}{\partial \beta} = Apa_1^{p-1}a_2^q\frac{\partial a_1}{\partial \beta} + Aqa_1^p a_2^{q-1}\frac{\partial a_2}{\partial \beta} - \eta_1 a_1\frac{\partial a_1}{\partial \beta} - \eta_2 a_2\frac{\partial a_2}{\partial \beta} - \rho\beta\sigma^2 = 0$$

Solving the above equation, we can obtain:

$$\beta = \frac{A^2}{A^2 + \rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2}$$

Additionally, the second partial derivatives of β are $\frac{\partial^2 U}{\partial \beta^2} = -A^2\left(\frac{p}{\eta_1}\right)^p\left(\frac{q}{\eta_2}\right)^q - \rho\sigma^2 < 0$. Thus, β^* is the maximal value of U. Therefore, the following equation can be obtained:

$$\beta^* = \frac{A^2}{A^2 + \rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2} \tag{8}$$

Substituting Equation (8) into Equation (7), we can obtain:

$$\begin{cases} a_1^* = \frac{A^3}{A^2+\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2}\left(\frac{p}{\eta_1}\right)^{\frac{1+p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{q}{2}} \\ a_2^* = \frac{A^3}{A^2+\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2}\left(\frac{p}{\eta_1}\right)^{\frac{p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{1+q}{2}} \end{cases} \tag{9}$$

4. Model Analysis and Simulations

4.1. Model Analysis

Proposition 1. *The levels of efforts expended by the contractor (a_1, a_2) in order to achieve the economic and environmental objectives are positively associated with the outcome coefficient (A) and are negatively associated with the effort cost coefficients (η_1, η_2). A higher level of outcome coefficient means the contractor is more* *likely to transform input resources into project benefits. This reflects the fact that higher levels of productive ability lead to higher levels of efforts on the part of the contractor to achieve the economic and environmental objectives. During the implementation of sustainable construction, a higher level of effort cost coefficients means the contractor must input more resources, in order to maintain equal project benefits with respect to lower cost coefficients. This reduces the willingness of the contractor to strive for the economic and environmental objectives, accordingly reducing their effort levels to achieve the planned economic and environmental objectives.*

Proof.

$$\begin{cases} \frac{\partial a_1^*}{\partial A} = \frac{1+(A^{-2}+A^{-3})\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2}{\left[A^2+\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]^2}\left(\frac{p}{\eta_1}\right)^{\frac{1+p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{q}{2}} > 0 \\ \frac{\partial a_1^*}{\partial \eta_1} = -\frac{\left[\frac{1+p}{2}A^3\left(\frac{\eta_1}{p}\right)^{-\frac{3+p}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{q}{2}}\right]\left[A^2+\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]+\rho\left(\frac{\eta_1}{p}\right)^{p-1}\left(\frac{\eta_2}{q}\right)^q\sigma^2}{\left[A^2+\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]^2} < 0 \end{cases}$$

Obviously, the function of a_1 is a monotonic increasing function related to A and a monotonic decreasing function related to η_1. The function of a_2 is a monotonic increasing function related to A and a monotonic decreasing function related to η_2. This can be proved with a similar method as that detailed above.

Proposition 2. *The effort levels of the contractor (a_1, a_2) are positively associated with the relative importance (p, q) of the economic and environmental objectives. Placing a higher level of the relative importance on the sustainability-related objectives leads to higher levels of effort being expended to achieve the relevant objectives. Combined with Proposition 1, the higher the outcome coefficient of the contractor, the lower is the coefficient of effort cost of the contractor. Also, the greater the relative importance of the objectives, the higher the levels of effort required from the contractor to achieve the relevant objectives. As for the contractor, if the relative importance of one objective is obviously greater than another, the contractor may neglect the less-important objective and increase the resource input to achieve the more important objective. Accordingly, the effort level to achieve the more important objective is higher. In order to achieve the objective effectively, the contractor may devote the available resources to the more important objective, while simultaneously ignoring the other objective. When the sustainable construction project is resource-constrained, this may result in lower levels of effort being expended on another objective. For example, if the contractor excessively emphsizes the environmental objective, the achievement degree of the economic objective may be damaged.*

Proof.

$$\frac{\partial a_1^*}{\partial p} = \frac{\left[\frac{1+p}{2}A^3\left(\frac{\eta_1}{p}\right)^{\frac{p-1}{2}}\left(\frac{q}{\eta_2}\right)^{\frac{q}{2}}\right]\left[A^2+\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]+\rho p\left(\frac{p}{\eta_1}\right)^{-p-1}\left(\frac{\eta_2}{q}\right)^q\sigma^2}{\left[A^2+\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]^2} > 0$$

Obviously, the function of a_1 is a monotonic increasing function related to p. The function of a_2 has a similar situation to q, so the proposition has been proved.

Corollary 1. *In accordance with the hypothesis $p + q = 1$, when $p \to 1$, it means the economic objective is extremely important. This prompts the contractor to input the vast majority of available resources to the economic objective, thereby, at least to some extent, sacrificing the environmental objective. This situation is common in both "achievement projects" and "image projects" in China. These sustainable construction projects are dominated by the local governments seeking to achieve political goals. These projects simply pursue the project's delivery at a fixed time, while the economic and environmental issues are often neglected. When $q \to 1$, this means the environmental objective is extremely important. This prompts the contractor to input the vast* *majority of available resources into achieving the environmental objective, thereby, at least to some extent, sacrificing the economic objective. This may result in a cost overrun (at least to some extent) in sustainable construction projects. Therefore, the owner needs to comprehensively balance the importance of both the economic and environmental objectives. The owner can certainly differentiate between the sustainability-related objectives, but they should not excessively pursue one objective. The contractor, on the other hand, needs to balance the levels of effort expended on sustainability-related objectives, so as to better realize the project's intended benefits.*

Proposition 3. *The coefficient of benefit allocation (β) is positively related to the outcome coefficient (A) and negatively related to both the degree of absolute risk aversion (ρ) and the uncertainty of the external environment (σ^2). That is, the coefficient of benefit allocation (β) is a monotonic increasing function related to A and a monotonic decreasing function related to both ρ and σ^2. As for the contractor, higher levels of the degree of absolute risk aversion and the uncertainty of the external environment in turn reflect higher levels of risk cost to obtain a stable deterministic benefit. The benefit allocation of the contractor will decrease because of high levels of risk cost. A higher level of outcome coefficient means the contractor is more likely to create more benefits with certain resource inputs, and thereby the contractor's benefit allocation will increase.*

Proof.

$$\frac{\partial\beta^*}{\partial A} = \frac{2\rho A^{-3}\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2}{\left[1+\rho A^{-2}\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]^2} > 0, \quad \frac{\partial\beta^*}{\partial\rho} = -\frac{A^{-2}\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2}{\left[1+\rho A^{-2}\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]^2} < 0, \quad \frac{\partial\beta^*}{\partial\sigma^2} = -\frac{A^{-2}\rho\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q}{\left[1+\rho A^{-2}\left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q\sigma^2\right]^2} < 0$$

Corollary 2. *The attitudes of contractors with different risk preferences are inconsistently associated with risk. Therefore, the owner should design incentive schemes with different bonus-penalty structures, basing those incentives on both the risk preferences of the contractor and the relative importance of the sustainability-related objectives. High levels of uncertainty regarding the external environment will aggravate the degree of information asymmetry between the owner and the contractor. This may make it difficult for the owner to judge whether or not the outcome increment is being brought about by the contractor's effort or the external uncertainty. Thus, the owner will tend to reduce the degree of benefit sharing with the contractor. A higher level of outcome coefficient means the contractor is more likely to transform the input resources into project benefits. This in turn indicates that the contractor can obtain more incremental benefits with the same level of effort level. Thus, the contractor will have greater enthusiasm for inputting resources into pursuing better benefits. Therefore, under different external conditions, the owner should weigh up the relative factors, according to the different contractors with different risk preferences. The owner should also adopt different types of incentive schemes with bonus-penalty structures to promote the improvement of the effort levels of the contractor.*

Proposition 4. *Premised* $z = \left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q$*, it is obvious that the function of β is a monotonic decreasing function related to z. The higher z is, the lower β is. This indicates that, with regard to given economic and environmental objectives in sustainable contruction, if the owner can balance the relative importance of the relationship between the two objectives and stimulate the contractor input resources in a balanced and coordinated approach, then a reasonable and effective incentive* interval *can be formed near the poles of z. Meanwhile, the owner can incentivize the contractor who adopts higher levels of efforts on the sustainability-related objective with a lower incentive degree.*

Proof. A linear programming problem regarding z was established as follows:

$$\begin{aligned} \max_{p,q}\ z &= \left(\frac{\eta_1}{p}\right)^p\left(\frac{\eta_2}{q}\right)^q \\ s.t.\quad & 0 < p, q < 1 \\ & p + q = 1 \end{aligned}$$

To solve the above equation regarding p and q, a Lagrange function was constructed under the constraint conditions:

$$F = \left(\frac{\eta_1}{p}\right)^p \left(\frac{\eta_2}{q}\right)^q - \lambda(1 - p - q)$$

We calculated the partial derivatives of p, q and λ, respectively, and set their values to zero. The simultaneous equations were solved, and then the following equation was obtained:

$$\begin{cases} p = \frac{\eta_1}{\eta_1 + e\eta_2} \\ q = \frac{e\eta_2}{\eta_1 + e\eta_2} \end{cases}$$

Where e is the Euler constant. According to the extremum attributes of functions with two variables, the equilibrium point of $(p^*, \quad q^*)$ is the maximal value of z. Thus, the proposition has been proved.

Corollary 3. *The coefficient of benefit allocation is determined by two aspects of factors. The first is the contractor's characteristic-related factors. These include factors such as the comprehensive outcome level, the coefficient of effort cost and the degree of risk aversion. The second is the project-related characteristic factors, which include the degree of external environmental uncertainty and the relative importance of the sustainability-related objectives in sustainable construction projects. Therefore, the owner should fully balance these two aspects of factors (and their correlations) when determining the benefit allocation coefficient. Meanwhile, when the owner designs the incentive scheme for the contractor, a balance between these two aspects of various factors should be considered in sustainable construction projects.*

Proposition 5. *The relationship between the levels of effort to achieve the economic and environmental objectives (a_1, a_2) and the project net benefit (U) firstly increases and then decreases. The function of the project's net benefit has a marked peak value with an inverted "U" shape. Under a situation of balanced effort levels towards achieving sustainability-related objectives, a project net benefit reaches its marked peak value. Therefore, when the relative importance (p, q) of the economic and environmental objectives reaches a state of equilibrium, the effort levels expended on achieving the relevant objectives also reaches a state of equilibrium. Under this condition, the owner and contractor can maximize the project's benefits, whilst the coefficient of the benefit allocation is optimal.*

Proof. According to Equation (6), we calculated the partial derivation of a_1 and a_2 and set their values to zero. The simultaneous equations was solved, and then the following equation was obtained:

$$\begin{cases} a_1^{**} = A\left(\frac{p}{\eta_1}\right)^{\frac{1+p}{2}} \left(\frac{q}{\eta_2}\right)^{\frac{q}{2}} \\ a_2^{**} = A\left(\frac{p}{\eta_1}\right)^{\frac{p}{2}} \left(\frac{q}{\eta_2}\right)^{\frac{1+q}{2}} \end{cases}$$

Additionally, the second partial derivatives of a_1 and $a_{2,}$ respectively, were calculated, in order to determine the extremum of U, which is presented as follows:

$$\begin{cases} \frac{\partial^2 U}{\partial (a_1)^2} = Ap(p-1)a_1^{p-2}a_2^q - \eta_1 < 0 \\ \frac{\partial^2 U}{\partial a_1 a_2} = Apqa_1^{p-1}a_2^{q-1} > 0 \\ \frac{\partial^2 U}{\partial (a_2)^2} = Aq(q-1)a_1^p a_2^{q-2} - \eta_2 < 0 \end{cases}$$

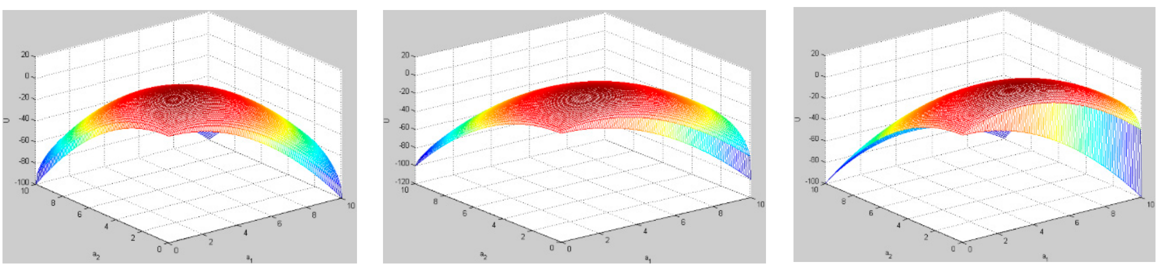
According to the extremum attributes of functions with two variables, the equilibrium point of $a = (a_1^{**}, \quad a_2^{**})$ is the maximal value of U.

Corollary 4. *$a = (a_1^{**}, \quad a_2^{**})$ can be regarded as the optimal solution when there are no moral hazard behaviors being adopted by the owner and the contractor. Otherwise, $a = (a_1^{**}, \quad a_2^{**})$ is the optimal solution when moral hazard behaviors exist between the owner and the contractor. Under certain conditions, there is $a_1^{**} > a_1^*$ and $a_2^{**} > a_2^*$. This indicates that the existence of moral hazard behaviors can reduce the levels of effort expended on the contractor's sustainability objectives. This in turn has a destructive effect on the project benefits. Therefore, the owner should adopt a reasonable and effective incentive scheme, which is designed to reduce the destructive effects that could be caused by the contractor's moral hazard behavior.*

4.2. Model Simulations

4.2.1. The Effects of the Effort Levels of the Contractor (a_1, a_2) on the Project Benefits (U)

According to Equations (6) and (8), we set $A = 10$, $\eta_1 = 2$, $\eta_2 = 2$, $\rho = 0.5$ and $\sigma^2 = 0.005$. We then simulate the relationships using MATLAB software (Natick, America) between the effort levels of the contractor (a_1, a_2) and the project benefits (U) under different levels of the relative importance of sustainability-related objectives (p, q). The results are shown in Figure 1. The simulation results are consistent with the analysis of Proposition 5. We can conclude that the function of the project net benefit has a marked peak value with an inverted "U" shape. This indicates that the relationship between the levels of effort expended on the economic and environmental objectives, and the project net benefit, firstly increases and then decreases. This means the contractor should balance the levels of efforts expended on sustainability-related objectives to ensure the resource inputs more effectively transform into project benefits. Comparing the project benefits under different degrees of the relative importance of sustainability-related objectives, we can conclude that higher levels of the relative importance of sustainability-related objectives contribute to higher levels of efforts being expended to achieve those objectives. The simulation results are consistent with the analysis of Proposition 2. Furthermore, the relative importance of sustainability-related objectives affects the effort levels, thus in turn affecting the project's benefits. Through the comparison between Figure 1a–c, we can conclude that the project's benefits reach the optimal value under conditions of placing a balanced degree of importance on the economic and environmental objectives. Therefore, the contractor should comprehensively consider the relative importance of sustainability-related objectives, balance the levels of effort expended on sustainability-related objectives, optimize his or her own resource input and management measures, and then adopt beneficial behavioral strategies.

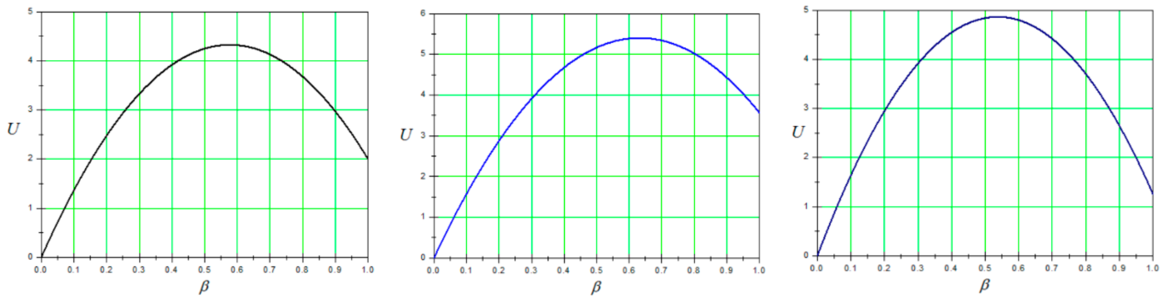


(**a**) $p = 0.5$, $q = 0.5$ (**b**) $p = 0.7$, $q = 0.3$ (**c**) $p = 0.9$, $q = 0.1$

Figure 1. The effects of the effort levels of the contractor (a_1, a_2) on the project benefits (U).

4.2.2. The Effects of the Benefit Allocation Coefficient (β) on the Project Benefits (U)

According to Equations (6), (7) and (8), we set $A = 10$, $\eta_1 = 2$, $\eta_2 = 2$, $\rho = 0.5$ and $\sigma^2 = 0.005$. We then simulate the relationships between the coefficient of the benefit allocation (β) and the project benefits (U) under different degrees of the relative importance of sustainability-related objectives (p, q). The results are shown in Figure 2. From Figure 2, we find that the project benefit function first increases and then decreases with the growth of the coefficient of the benefit allocation under conditions of the different degrees of the relative importance of sustainability-related objectives. The change process represents an inverted "U" shape, which verifies the correctness of the model solution process. Under the given parameters, when the coefficient of benefit allocation locates in the interval (0.4, 0.6), the project benefit reaches its maximum value. Conversely, when the coefficient is in the limit states of $\beta \to 0$ and $\beta \to 1$, the project benefit is minimum. This reflects that only when the coefficient of benefit allocation locates in a reasonable interval, can the owner motivate the contractor to adopt and use high levels of effort on sustainability-related objectives. Furthermore, for any given degree of the relative importance of the economic and environmental objectives (p, q), the coefficient of benefit allocation is always able to reach an optimal value, in order to maximize the project benefits. Under this situation, the owner can provide the contractor with relatively low incentive intensity and motivate the contractor to rationally distribute his/her own resources on sustainability-related objectives. Thus, Proposition 4 has been verified.

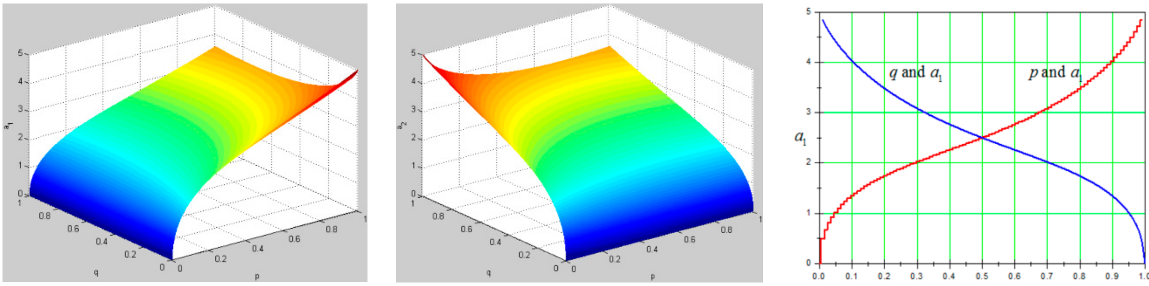


(**a**) $p = 0.5$, $q = 0.5$ (**b**) $p = 0.7$, $q = 0.3$ (**c**) $p = 0.9$, $q = 0.1$

Figure 2. The effects of the benefit allocation coefficient (β) on the project benefits (U).

4.2.3. The Effects of the Objective Relative Importance (p, q) on Effort Levels of the Contractor (a_1, a_2)

According to Equations (7)–(9), we set $A = 10$, $\eta_1 = 2$, $\eta_2 = 2$, $\rho = 0.5$ and $\sigma^2 = 0.005$. We then simulate the relationships between the effort levels of the contractor (a_1, a_2) and the relative importance of sustainability-related objectives (p, q). The results are shown in Figure 3, where Figure 3c is the generated function after the substitution of $q = 1 - p$ and $p = 1 - q$ into a_1. Through the comparison between Figure 3a,b, we find that higher levels of the relative importance of the sustainability-related objectives contribute to higher levels of contractor effort to achieve the relevant objectives. This in turn leads to lower levels of effort being expended to achieve the other objectives. This indicates that the contractor may correspondingly reduce the level of effort expended on other objectives, in order to achieve the more important objective. Thus, Proposition 2 was verified. It is worth noting that, under the condition of $\eta_1 = \eta_2 = 2$, the levels of contractor effort expended to achieve the economic and environmental objectives (a_1, a_2) follows symmetric distribution. The prioritization and scarcity of the resources requires the contractor to reasonably allocate the limited resources towards the economic and environmental objectives, rather than excessively emphasizing just one objective. Excessive pursuit of a controlled objective will reduce the degree of the achievement of another objective. Therefore, the contractor should balance the relative importance of sustainability-related objectives and reasonably allocate balanced levels of effort and resources.

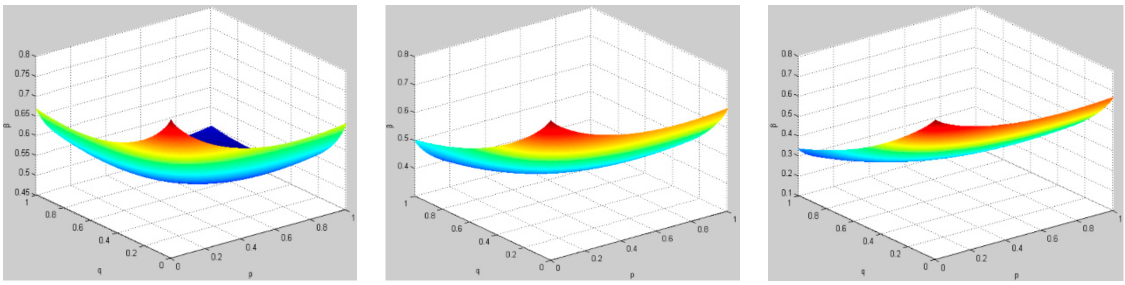


(**a**) p, q and a_1 (**b**) p, q and a_2 (**c**) p, q and a_1

Figure 3. The effects of the objective relative importance (p, q) on effort levels of the contractor (a_1, a_2).

4.2.4. The Effects of the Objective Relative Importance (p, q) on the Benefit Allocation Coefficient (β)

According to Equation (8), we set A = 10 and $\rho\sigma^2$ = 25. We then simulate the relationships between the coefficient of the benefit allocation (β) and the relative importance of sustainability-related objectives (p, q) under different coefficients of cost of effort. The results are shown in Figure 4. From Figure 4, we can see that the function of the benefit allocation coefficient (β) first decreases and then increases with corresponding changes in the relative importance of the sustainability-related objectives. Under different coefficients of cost of efforts, the change process represents a "U" shape, which verifies the analysis of Proposition 4. Excessive emphasis on any of the sustainability-related objectives will cause the coefficient of benefit allocation to develop towards the direction which is detrimental to maximizing the project benefit. This indicates that, even though the coefficients of the effort costs of the sustainability-related objectives are different, an equilibrium of the relative importance of the sustainability-related objectives (p^*, q^*) always exists. This minimizes the coefficient of the benefit allocation (β^*). At this time, around the pole (p^*, q^*), the owner can stimulate effort with a relatively low degree of incentive intensity, in order to prompt the contractor to balance the relative importance of the sustainability-related objectives and allocate the appropriate levels of effort.

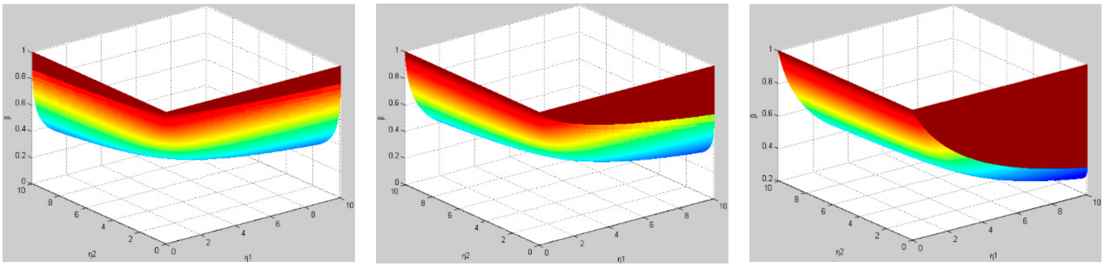


(**a**) $\eta_1 = 2$, $\eta_2 = 2$ (**b**) $\eta_1 = 2$, $\eta_2 = 4$ (**c**) $\eta_1 = 2$, $\eta_2 = 8$

Figure 4. The effects of the objective relative importance (p, q) on the benefit allocation coefficient (β).

4.2.5. The Effects of Effort Cost Coefficients (η_1, η_2) on the Benefit Allocation Coefficient (β)

According to Equation (8), we set A = 10 and $\rho\sigma^2$ = 25. We then simulate the relationships between the coefficient of the benefit allocation (β) and the coefficients of effort costs (η_1, η_2) under different situations of the relative importance of sustainability-related objectives (p, q). The results are shown in Figure 5. From Figure 5, we can see that the function of the benefit allocation coefficient (β) first decreases and then increases with the corresponding change in the coefficients of effort costs. Under different situations of the relative importance of sustainability-related objectives, the change process represents a "U" shape, which further verifies the analysis of Proposition 4. If the coefficient of effort cost of any sustainability-related objective is overly high, the contractor will reduce the level of effort expended on the relevant objective. Accordingly, the owner will reduce the incentive intensity related to the relevant objective. This simulation result is consistent with Proposition 1. Thus, the contractor should balance the coefficients of effort costs between different sustainability-related objectives. If a wide gap exists between the coefficients of effort costs of sustainability-related objectives, the owner needs to provide the contractor more in terms of benefit sharing, in order to encourage the contractor to maintain sufficient efforts and achieve the optimal project benefit. Additionally, the contractor needs to determine the coefficients of effort costs combined with the relative importance of the sustainability-related objectives. The ratio of the two factors is also a critical parameter, which should be used by the owner to determine the coefficient of the benefit allocation. Therefore, the owner should comprehensively balance the relative importance of the sustainability-related objectives, the coefficients of effort costs and the ratio of the two factors, so as to reasonably determine the degree of incentive intensity for the contractor.

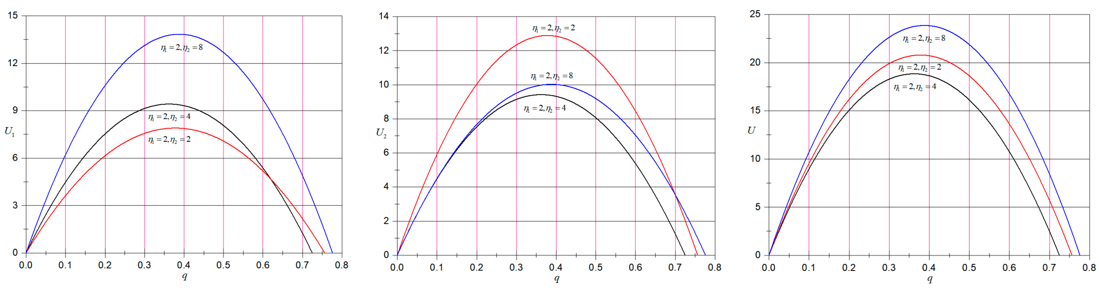


(**a**) $p = 0.5$, $q = 0.5$ (**b**) $p = 0.7$, $q = 0.3$ (**c**) $p = 0.9$, $q = 0.1$

Figure 5. The effects of effort cost coefficients (η_1, η_2) on the benefit allocation coefficient (β).

4.2.6. The Effects of the Objective Relative Importance (p, q) on the Project Benefits (U)

According to Equations (4)–(6), we set $A = 10$ and $\rho\sigma^2 = 25$. We then simulate the relationships between the relative importance of sustainability-related objectives (p, q) and the expected benefit of the contractor (U_1), the expected benefit of the owner (U_2), and the project benefits (U) under different coefficients of effort cost. The results are shown in Figure 6. From Figure 6, we can see that the functions of the benefits (U_1, U_2 and U) first increases and then decreases with the corresponding change in the relative importance of sustainability-related objectives (q) under different coefficients of effort cost. Obviously, the change tendencies represent an inverted "U" shape, which further verifies the correctness of the Proposition 4. Additionally, the ratio of effort cost coefficients (η_1, η_2) can affect the peak value of the function of project benefits, while cannot affect the shape of the function of project benefits. As for sustainable projects, if the contractor overlooked or overvalued the sustainability-related objectives, the expected benefit of the contractor will decrease. Furthermore, the expected benefit of the owner and the project benefits will decrease accordingly. The potential explanation for this is that the contractor should balance the relative importance of sustainability-related objectives to enhance its expected benefit and project benefits. Therefore, the contractor should synthetically balance its resources allocation on sustainability-related objectives, under which condition the Pareto improvement can be achieved of project benefits.



(**a**) U_1 and p (**b**) U_2 and p (**c**) U and p

Figure 6. The effects of the objective relative importance (p, q) on the project benefits (U).

4.2.7. The Numerical Example of the Multi-Objective Trade-off Model

According to the multi-objective trade-off model and the related parameters, the levels of efforts expended on the economic and environmental objectives, the coefficient of the benefit allocation, the expected benefits of the owner and contractor, and the project's net benefit are calculated under different situations of different coefficients of effort costs and the relative importance of the economic and environmental objectives. The results are shown in Table 1. We can see that in Table 1: (i) under the conditions of different coefficients of effort costs, higher levels of the relative importance of the sustainability-related objectives contribute to higher levels of contractor effort. (ii) If a wide gap exists between the coefficients of effort costs and the economic and environmental objectives, the effort level with a greater coefficient of effort cost increases with the growth of the relative importance of the relevant objective. On the other hand, the effort level with a greater coefficient of effort cost is lower than the counterpart with a smaller coefficient of effort cost and is also lower than the counterpart under a balanced condition of the two coefficients of effort costs. (iii) Under different situations of different coefficients of effort costs and the relative importance of the economic and environmental objectives, there exists an equilibrium (p^*, q^*) that can minimize the coefficient of the benefit allocation (β^*). Meanwhile, the contractor can reasonably allocate the required effort levels and optimize the expected benefit. (iv) Under different situations of different coefficients of effort costs and the relative importance of the economic and environmental objectives, there exists an equilibrium (a_1^*, a_2^*) that can maximize the project's net benefit (U^*). Meanwhile, the expected benefits of the owner and contractor can be relatively improved.

Table 1. The numerical example results of the multi-objective trade-off model.

		(a_1, a_2)	β	U_1	U_2	U
$\eta_1 = 2, \eta_2 = 2$	$p = 0.5, q = 0.5$	(1.25, 1.25)	0.5	2.06	2.06	4.12
	$p = 0.7, q = 0.3$	(1.60, 1.05)	0.52	2.72	2.51	5.23
	$p = 0.9, q = 0.1$	(2.38, 0.79)	0.59	2.63	1.84	4.47
$\eta_1 = 2, \eta_2 = 4$	$p = 0.5, q = 0.5$	(2.10, 1.49)	0.41	3.62	5.21	8.83
	$p = 0.7, q = 0.3$	(2.78, 1.29)	0.46	5.07	5.95	11.02
	$p = 0.9, q = 0.1$	(3.89, 0.92)	0.57	6.18	4.66	10.84
$\eta_1 = 4, \eta_2 = 2$	$p = 0.5, q = 0.5$	(1.49, 2.10)	0.41	3.62	5.21	8.83
	$p = 0.7, q = 0.3$	(1.71, 1.48)	0.40	3.34	5.01	8.35
	$p = 0.9, q = 0.1$	(2.09, 0.98)	0.43	4.16	5.51	9.67
$\eta_1 = 2, \eta_2 = 8$	$p = 0.5, q = 0.5$	(1.77, 0.88)	0.33	2.06	4.18	6.24
	$p = 0.7, q = 0.3$	(2.50, 0.82)	0.42	3.75	5.19	8.94
	$p = 0.9, q = 0.1$	(3.76, 0.63)	0.55	4.25	3.47	7.72
$\eta_1 = 8, \eta_2 = 2$	$p = 0.5, q = 0.5$	(0.88, 1.77)	0.33	2.06	4.18	6.24
	$p = 0.7, q = 0.3$	(0.95, 1.24)	0.29	1.49	3.65	5.14
	$p = 0.9, q = 0.1$	(1.08, 0.72)	0.30	1.56	3.63	5.19

5. Conclusions and Implications

Considering the relative importance of the sustainability-related objectives and the inherent nature of sustainable construction projects, this study proposes that the contractor should balance the levels of efforts and resources required to achieve various sustainability-related objectives. A multi-objective trade-off model based on game theory was build and analyzed under moral hazard conditions. A simulation analysis and numerical example were then provided so as to verify the model. The results indicated that the levels of contractor efforts towards sustainability-related objectives are positively related to the outcome coefficient however negatively to the coefficients of effort costs of the relevant objectives. High levels of the relative importance of sustainability-related objectives contribute to high levels of efforts. As for the given relative importance and coefficients of effort costs of sustainability-related objectives, an equilibrium always exists prompting the contractor to adopt higher levels of effort with a lower degree of incentive intensity. Meanwhile, the contractors should balance the relative importance and allocate the appropriate levels of efforts and resources for achieving sustainability-related objectives. This in turn can maximize the project's net benefits and improve the contractor's expected benefit.

In sustainable construction projects, the core capabilities of owners and contractors are mutually complementary. Both of them are willing to collaborate so as to achieve the sustainability-related objectives. This study establishes a multi-objective trade-off model based on game theory to explore how the relative importance of sustainability-related objectives affects sustainable construction. The model is validated by simulation analysis and a numerical example. Some implications for management conclude this study and these include: (i) the coefficient of benefit allocation depends on the contractor's characteristic-related factors and the project's characteristic-related factors. The complex external environment of a sustainable construction project makes it difficult for the owner to determine the actual effort level of the contractor. In this situation, the owner can adopt a relatively low degree of incentive intensity; (ii) balancing the relative importance of the sustainability-related objectives and the resource arrangement and allocation can allow the risk distribution (between the owner and the contractor) to be more reasonable. The owner should design a fair and rational incentive scheme, which is beneficial to the improvement of the expected benefits of both the owner and the contractor; (iii) the owner should construct a fair and reasonable benefit allocation mechanism and a mutual trust mechanism with the contractor. This can enhance the degree of information exchange and optimize the levels of effort and resources shared between the two parties, as well as reducing the potentially detrimental effects of the contractor's moral hazard behavior.

As few studies to date have emphasized the effects of the relative importance of sustainability-related objectives on sustainable construction, this study constructed a multi-objective trade-off model as a means to bridge this gap. This study contributes significant theoretical and practical insights into objective management in sustainable construction, as well as how to enhance overall project benefits. However, the proposed model and conclusions must be considered in light of the study's limitations. First, the multi-objective trade-off model was constructed based on a series of theoretical hypotheses, whilst some other factors (such as the interaction between sustainability-related objectives) were ignored. Secondly, the proposed model only considers the relationship between the owner and contractor, while neglecting the effects of any other stakeholders. Thirdly, the proposed model only considers the economic and environmental objectives, while neglecting the social issues inherent in sustainable construction projects. However, with the evolution of the project's whole life cycle, the interest demands of the stakeholders will gradually change. Importantly, the relative importance of the sustainability-related objectives will change as well. These limitations point out the direction for future work. In any case, this study contributes to the existing knowledge by proposing and validating a multi-objective trade-off model that can be used by project managers when managing sustainability-related objectives for sustainable construction development. When managing sustainability-related objectives, project managers should consider the relative importance of sustainability-related objectives and reasonably arrange and allocate the appropriate levels of effort and resources. Practical implications can be drawn based on this model, which provides a clear understanding of the effects of the relative importance of sustainability-related objectives on the benefits in sustainable construction projects.

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References

1. Matar, M.M.; Georgy, M.E.; Ibrahim, M.E. Sustainable construction management: Introduction of the operational context space (OCS). *Constr. Manag. Econ.* **2008**, *26*, 261–275. [CrossRef]
2. Czarnecki, L.; Kaproń, M.; Van Gemert, D. Sustainable construction: Challenges, contribution of polymers, researches arena. *Restor. Build. Monum.* **2013**, *19*, 81–96. [CrossRef]
3. Robins, F. The challenge of TBL: A responsibility to whom? *Bus. Soc. Rev.* **2006**, *111*, 1–14. [CrossRef]
4. Czarnecki, L.; Kaproń, M. Sustainable construction as a research area. *Int. J. Soc. Mater. Eng. Resour.* **2010**, *17*, 99–106. [CrossRef]
5. Schröpfer, V.L.M.; Tah, J.; Kurul, E. Mapping the knowledge flow in sustainable construction project teams using social network analysis. *Eng. Constr. Archit. Manag.* **2017**, *24*, 229–259. [CrossRef]
6. Glass, J. The state of sustainability reporting in the construction sector. *Smart Sustain. Built Environ.* **2012**, *1*, 87–104. [CrossRef]
7. Karakhan, A.A.; Gambatese, J.A. Identification, quantification, and classification of potential safety risk for sustainable construction in the United States. *J. Constr. Eng. Manag.* **2017**, *143*, 1–10. [CrossRef]
8. Manoliadis, O.; Tsolas, I.; Nakou, A. Sustainable construction and drivers of change in Greece: A Delphi study. *Constr. Manag. Econ.* **2006**, *24*, 113–120. [CrossRef]
9. Sfakianaki, E. Resource-efficient construction: Rethinking construction towards sustainability. *World J. Sci. Technol. Sustain. Dev.* **2015**, *12*, 233–242. [CrossRef]
10. Shi, L.; Ye, K.; Lu, W.; Hu, X. Improving the competence of construction management consultants to underpin sustainable construction in China. *Habitat Int.* **2014**, *41*, 236–242. [CrossRef]
11. Li, H.; Zhang, X.; Ng, S.T.; Skitmore, M. Quantifying stakeholder influence in decision/evaluations relating to sustainable construction in China—A Delphi approach. *J. Clean. Prod.* **2017**, 1–11. [CrossRef]
12. Whang, S.W.; Kim, S. Balanced sustainable implementation in the construction industry: The perspective of Korean contractors. *Energy Build.* **2015**, *96*, 76–85. [CrossRef]
13. Karakhan, A.A. LEED-certified projects: Green or sustainable? *J. Manag. Eng.* **2016**, *32*, 1–3. [CrossRef]
14. Gan, X.; Zuo, J.; Ye, K.; Skitmore, M.; Xiong, B. Why sustainable construction? Why not? An owner's perspective. *Habitat Int.* **2015**, *47*, 61–68. [CrossRef]
15. Tan, Y.; Shen, L.; Yao, H. Sustainable construction practice and contractors' competitiveness: A preliminary study. *Habitat Int.* **2011**, *35*, 225–230. [CrossRef]
16. Xue, X.; Shen, Q.; Ren, Z. Critical review of collaborative working in construction projects: Business environment and human behaviors. *J. Manag. Eng.* **2010**, *26*, 196–208. [CrossRef]
17. Wu, G.; Zuo, J.; Zhao, X. Incentive model based on cooperative relationship in sustainable construction projects. *Sustainability* **2017**, *9*, 1191. [CrossRef]
18. Schieg, M. Strategies for avoiding asymmetric information in construction project management. *J. Bus. Econ. Manag.* **2008**, *9*, 47–51. [CrossRef]
19. Dai, R.; Zhang, J.; Tang, W. Cartelization or cost-sharing? Comparison of cooperation modes in a green supply chain. *J. Clean. Prod.* **2017**, *156*, 159–173. [CrossRef]
20. Menesi, W.; Golzarpoor, B.; Hegazy, T. Fast and near-optimum schedule optimization for large-scale projects. *J. Constr. Eng. Manag.* **2013**, *139*, 1117–1124. [CrossRef]
21. Chakraborty, S.; Jo, B.W.; Jo, J.H.; Baloch, Z. Effectiveness of sewage sludge ash combined with waste pozzolanic minerals in developing sustainable construction material: An alternative approach for waste management. *J. Clean. Prod.* **2017**, *153*, 253–263. [CrossRef]
22. Kerkhove, L.P.; Vanhoucke, M. Incentive contract design for projects: The owner's perspective. *Omega* **2016**, *62*, 93–114. [CrossRef]
23. Zhong, Y.; Wu, P. Economic sustainability, environmental sustainability and constructability indicators related to concrete- and steel-projects. *J. Clean. Prod.* **2015**, *108*, 748–756. [CrossRef]
24. Jafari, H.; Hejazi, S.R.; Rasti-Barzoki, M. Sustainable development by waste recycling under a three-echelon supply chain: A game-theoretic approach. *J. Clean. Prod.* **2017**, *142*, 2252–2261. [CrossRef]
25. Kerkhove, L.P.; Vanhoucke, M. A parallel multi-objective scatter search for optimising incentive contract design in projects. *Eur. J. Oper. Res.* **2017**, *261*, 1066–1084. [CrossRef]
26. Myerson, R. *Game theory: Analysis of Conflict*; Harvard University: Cambridge, MA, USA, 1991.

27. San Cristobal, J. The use of Game Theory to solve conflicts in the project management and construction industry. *Int. J. Inf. Syst. Proj. Manag.* **2015**, *3*, 43–58.
28. Huang, X.; He, P.; Zhang, W. A cooperative differential game of transboundary industrial pollution between two regions. *J. Clean. Prod.* **2016**, *120*, 43–52. [CrossRef]
29. Chen, T.C.; Lin, Y.C.; Wang, L.C. The analysis of BOT strategies based on game theory—Case study on Taiwan's high speed railway project. *J. Civ. Eng. Manag.* **2012**, *18*, 662–674. [CrossRef]
30. He, W.; Tang, W.; Wei, Y.; Duffield, C.F.; Lei, Z. Evaluation of cooperation during project delivery: Empirical study on the hydropower industry in southwest China. *J. Constr. Eng. Manag.* **2016**, *142*, 1–10. [CrossRef]
31. Javed, A.A.; Lam, P.T.I.; Chan, A.P.C. Change negotiation in public-private partnership projects through output specifications: An experimental approach based on game theory. *Constr. Manag. Econ.* **2014**, *32*, 323–348. [CrossRef]
32. Chong, W.K.; Kumar, S.; Haas, C.T.; Beheiry, S.M.; Coplen, L.; Oey, M. Understanding and interpreting baseline perceptions of sustainability in construction among civil engineers in the United States. *J. Manag. Eng.* **2009**, *25*, 143–154. [CrossRef]
33. Shen, L.; Tam, V.W.Y.; Tam, L.; Ji, Y. Project feasibility study: The key to successful implementation of sustainable and socially responsible construction management practice. *J. Clean. Prod.* **2010**, *18*, 254–259. [CrossRef]
34. Ahn, C.; Lee, S.H.; Peña-Mora, F.; Abourizk, S. Toward environmentally sustainable construction processes: The U.S. and Canada's perspective on energy consumption and GHG/CAP emissions. *Sustainability* **2010**, *2*, 354–370. [CrossRef]
35. Zimmermann, M.; Althaus, H.J.; Haas, A. Benchmarks for sustainable construction: A contribution to develop a standard. *Energy Build.* **2005**, *37*, 1147–1157. [CrossRef]
36. Huang, R.; Yeh, C. Development of an assessment framework for green highway construction. *J. Chin. Inst. Eng.* **2008**, *31*, 573–585. [CrossRef]
37. Bassioni, H.A.; Price, A.D.F.; Hassan, T.M. Building a conceptual framework for measuring business performance in construction: An empirical evaluation. *Constr. Manag. Econ.* **2005**, *23*, 495–507. [CrossRef]
38. Chen, Y.; Okudan, G.E.; Riley, D.R. Sustainable performance criteria for construction method selection in concrete buildings. *Autom. Constr.* **2010**, *19*, 235–244. [CrossRef]
39. Ding, G.K.C. Sustainable construction-The role of environmental assessment tools. *J. Environ. Manag.* **2008**, *86*, 451–464. [CrossRef] [PubMed]
40. Shen, L.; Tam, V.W.Y.; Li, C. Benefit analysis on replacing in situ concreting with precast slabs for temporary construction works in pursuing sustainable construction practice. *Resour. Conserv. Recycl.* **2009**, *53*, 145–148. [CrossRef]
41. Presley, A.; Meade, L. Benchmarking for sustainability: An application to the sustainable construction industry. *Benchmarking An Int. J.* **2010**, *17*, 435–451. [CrossRef]
42. Huang, R.Y.; Hsu, W.T. Framework development for state-level appraisal indicators of sustainable construction. *Civ. Eng. Environ. Syst.* **2011**, *28*, 143–164. [CrossRef]
43. Fortunato, B.R.; Hallowell, M.R.; Behm, M.; Dewlaney, K. Identification of safety risks for high-performance sustainable construction projects. *J. Constr. Eng. Manag.* **2012**, *138*, 499–508. [CrossRef]
44. Kibwami, N.; Tutesigensi, A. Enhancing sustainable construction in the building sector in Uganda. *Habitat Int.* **2016**, *57*, 64–73. [CrossRef]
45. Marjaba, G.E.; Chidiac, S.E. Sustainability and resiliency metrics for buildings—Critical review. *Build. Environ.* **2016**, *101*, 116–125. [CrossRef]
46. Ozcan-Deniz, G.; Zhu, Y. A multi-objective decision-support model for selecting environmentally conscious highway construction methods. *J. Civ. Eng. Manag.* **2015**, *21*, 733–747. [CrossRef]
47. He, K.; Tang, R.; Jin, M. Pareto fronts of machining parameters for trade-off among energy consumption, cutting force and processing time. *Int. J. Prod. Econ.* **2017**, *185*, 113–127. [CrossRef]
48. Brucker, P.; Drexl, A.; Möhring, R.; Neumann, K.; Pesch, E. Resource-constrained project scheduling: Notation, classification, models, and methods. *Eur. J. Oper. Res.* **1999**, *112*, 3–41. [CrossRef]
49. Heilmann, R. A branch-and-bound procedure for the multi-mode resource-constrained project scheduling problem with minimum and maximum time lags. *Eur. J. Oper. Res.* **2003**, *144*, 348–365. [CrossRef]

50. Xu, N.; McKee, S.A.; Nozick, L.K.; Ufomata, R. Augmenting priority rule heuristics with justification and rollout to solve the resource-constrained project scheduling problem. *Comput. Oper. Res.* **2008**, *35*, 3284–3297. [CrossRef]
51. Agarwal, A.; Colak, S.; Erenguc, S. A Neurogenetic approach for the resource-constrained project scheduling problem. *Comput. Oper. Res.* **2011**, *38*, 44–50. [CrossRef]
52. Chen, R.M. Particle swarm optimization with justification and designed mechanisms for resource-constrained project scheduling problem. *Expert Syst. Appl.* **2011**, *38*, 7102–7111. [CrossRef]
53. Dave, B.; Koskela, L. Collaborative knowledge management—A construction case study. *Autom. Constr.* **2009**, *18*, 894–902. [CrossRef]
54. Hanna, A.S.; Thomas, G.; Swanson, J.R. Construction risk identification and allocation: Cooperative approach. *J. Constr. Eng. Manag.* **2013**, *139*, 1098–1107. [CrossRef]
55. Khanzadi, M.; Eshtehardian, E.; Chalekaee, A. A game theory approach for optimum strategy of the owner and contractor in delayed projects. *J. Civ. Eng. Manag.* **2016**, *22*, 1066–1077. [CrossRef]
56. Wang, Y.; Liu, J. Evaluation of the excess revenue sharing ratio in PPP projects using principal-agent models. *Int. J. Proj. Manag.* **2015**, *33*, 1317–1324. [CrossRef]
57. Weeusen, W.; van Den Broeck, J. Efficiency estimation from Cobb-Douglas production functions with composed error. *Int. Econ. Rev.* **1997**, *18*, 435–444.
58. Von der Osten, F.B.; Kirley, M.; Miller, T. Sustainability is possible despite greed—Exploring the nexus between profitability and sustainability in common pool resource systems. *Sci. Rep.* **2017**, *7*, 2307. [CrossRef] [PubMed]
59. Wu, G.D. Project-based supply chain cooperative incentive based on reciprocity preference. *Int. J. Simul. Model.* **2014**, *13*, 102–115. [CrossRef]
60. Fu, Y.; Chen, Y.; Zhang, S.; Wang, W. Promoting cooperation in construction projects: An integrated approach of contractual incentive and trust. *Constr. Manag. Econ.* **2015**, *33*, 653–670. [CrossRef]
61. Shi, J.; Wu, G.; Tang, D. Project-based supply chain cross-organizational incentives based on duration-quality coordinative equilibrium. *J. Ind. Eng. Eng. Manag.* **2012**, *26*, 58–64.
62. Wu, G.D. Knowledge collaborative incentive based on inter-organizational cooperative innovation of project-based supply chain. *J. Ind. Eng. Manag.* **2013**, *6*, 1065–1081. [CrossRef]
63. Hosseinian, S.M.; Carmichael, D.G. Optimal gainshare/painshare in alliance projects. *J. Oper. Res. Soc.* **2013**, *64*, 1269–1278. [CrossRef]
64. Wu, G.D.; Tang, D.Z. Inter-organizational cooperative innovation of project-based supply chains under consideration of monitoring signals. *Int. J. Simul. Model.* **2015**, *14*, 539–550. [CrossRef]
65. Wang, Y.; Ma, X.; Li, Z.; Liu, Y.; Xu, M.; Wang, Y. Profit distribution in collaborative multiple centers vehicle routing problem. *J. Clean. Prod.* **2017**, *144*, 203–219. [CrossRef]