A Game-Theoretic Approach to Brownfield Redevelopment: Negotiation on Cost and Benefit Allocation

Lizhong Wang, Liping Fang, Senior Member, IEEE, and Keith W. Hipel, Fellow, IEEE

Abstract—A game-theoretic approach to brownfield redevelopment is presented to support negotiations on related cost and benefit allocation. The process of brownfield redevelopment is discussed and three types of key decision makers (DMs) are identified, namely the landowner, the developer and the government. Based on a qualitative analysis of coalitions among the key DMs, a cooperative game model is formulated for the brownfield redevelopment cost and benefit allocation problem. To initiate the negotiation on the cost and benefit allocation, a common understanding of the estimates of relevant costs and benefits in a brownfield redevelopment project is required. The proposed modeling framework utilizes various nucleolus concepts and the Shapley value to find alternative fair cost and benefit allocations from which the DMs can make the final selection. An illustrative example is used to demonstrate the application of the proposed approach.

I. INTRODUCTION

Brownfields are defined as abandoned, idled, or under-used industrial and commercial sites where expansion or redevelopment is complicated by real or perceived environmental contamination [17]. Brownfields, now commonly seen in industrial countries, result from the gradual migration of industries from urban to suburb greenfield areas since the mid-1970s [6]. It has been estimated that about 450,000 brownfield sites exist in the US and costs of cleanup for these sites are in the $30 to $40 billion range [17]. According to some estimates, as much as 25% of the Canadian urban landscape is potentially contaminated as a result of previous industrial activities [2].

Because of the environmental and health risks associated with contamination, there has been a growing interest from policy makers and urban researchers in North America and Europe in remediating and redeveloping brownfields to renew urban areas for the purpose of improving the quality of life in cities [7], [15]. A range of environmental, economic and social benefits can be generated by brownfield redevelopment, such as cleanup of contaminated lands, increase of property values, expansion of the tax base, creation of jobs, and promotion of a revitalized and positive image of urban life. State and federal laws in the US and some other countries can require the assessment and remediation of a contaminated site. As a result, landowners, developers and other private sector stakeholders are often reluctant to put former industrial and commercial properties back into productive use for fear that they may be contaminated and thus too expensive, time-involving and risky to redevelop profitably. In order to entice investment in brownfield redevelopment, governments at all levels in the US and Europe have implemented a variety of policies and programs to offer a package of financial and in-kind assistance to make the private sector interested in purchasing and cleaning up a site, including grants, loans, tax incremental financing, technical assistance, acquisition assistance and insulation from liability [15].

However, Canada has been moving slower than the US and Europe in brownfield redevelopment, which has started to receive more attention [5]. With respect to financing brownfield projects, most provinces in Canada do not offer financial incentives except for Quebec and Ontario. Quebec’s Revi-Sols program introduced in 2001 funds up to 70 percent of site assessment and cleanup costs [7]. Ontario’s Brownfields Statute Law Amendment Act of 2001 allows municipalities to provide grants and loans to brownfield owners and to freeze or cancel the municipal portion of the property tax on contaminated sites through financing tools such as the Brownfield Financial Tax Incentive Program and Tax Incremental Financing [1], [12].

The methods for assessing and remediating contaminated sites have become relatively standard. The barriers in brownfield redevelopment come from policy and planning aspects including liability uncertainty, limited funding, regulatory complexity, insufficient information about the locations and conditions of brownfields and confusion regarding cleanup levels. The most fundamental problem is the additional costs associated with cleanup and redevelopment that often make brownfields uncompetitive with greenfields. [7]. Consequently, there are numerous challenges for governments to encourage the redevelopment of brownfields since there are additional costs and financial risks associated with environmental liability. This necessitates the mediation of local governments to bring the current owners and potential purchasers (developers) to the negotiation table to determine if sufficient resources can be
pooled for remediation and redevelopment, and how the costs and benefits can be fairly and cooperatively shared among the involved stakeholders.

The literature on the negotiation problem in brownfield redevelopment is extremely limited. The first (and possible the only one until now) published quantitative model is developed by Sounderpandian et al. [15] for negotiating the allocation of the cleanup cost, which optimizes a weighted utility function of the 3-parties (landowner, developer, and government) involved in the negotiation and searches the solution within a feasible domain defined by the willingness to pay of the involved parties. Accordingly, the purpose of this paper is to develop a methodology for supporting negotiation on how remediation and redevelopment costs and benefits can be allocated in a more explicit and equitable way. Multiple party modeling is considered. A new framework is designed, utilizing cooperative game theory, to allocate the costs as well as the associated benefits of the involved parties. An illustrative example is used to demonstrate the application of the new framework.

II. BROWNFIELD REDEVELOPMENT THROUGH NEGOTIATION

The process of a brownfield redevelopment project consists of three stages: land use planning and regulation, development and construction, and end use. For each stage, there are a number of stakeholders involved. Five types of stakeholders can be classified and grouped according to their positions in the development process [4]:

- **Group 1**: regulators, statutory consultees, service providers, and councillors (e.g., environmental agency regulators, local authority regulators, utility regulators and service providers);
- **Group 2**: nonstatutory consultees, interest groups, and individuals (e.g., business interests, community group interests);
- **Group 3**: property developers and developer interests (e.g., landowners, public and private developers, investors such as banks, pension funds);
- **Group 4**: professional advisors (e.g., civil and environmental engineers, lawyers, insurers and valuers); and
- **Group 5**: end users (e.g., home buyers, public service providers, retailers, manufacturers and their suppliers, employees and customers).

Notice that the Groups 1 and 2 are associated with the first stage of redevelopment, Groups 3 and 4 with the second stage, and Group 5 the third stage. Undoubtedly, decision makers (DMs) are important stakeholders determining outcomes. The key DMs in brownfield developments are the current landowners, the prospective developers (or investors or buyers), and the governments (usually local governments) [4], [15]. These DMs are equally important. A development cannot proceed without planning permission and without the actions of public-sector and private-sector developers and landowners. Although end users are also important stakeholders for the redevelopment, they are not viewed as the key DMs in the negotiation because they do not directly participate and affect negotiations over the cost and benefit allocation.

A typical brownfield redevelopment project involves only 3 DMs, identified as the landowner, the developer, and the government. However, a project with more than 3 parties is also possible. For example, there could be two landowners holding two pieces of adjacent brownfields. They can either initiate two 3-party redevelopment projects separately or they can cooperatively participate in a 4-party redevelopment project consisting of the two landowners, a developer and the local government. Since the same developer does the job for two sites and the environmental or social benefits may be higher when both sites are redeveloped at the same time, it could be postulated that the combined 4-party redevelopment project would generate a higher total net benefit than the two 3-party redevelopment scenarios. Thus, in general this is a negotiation problem involving multiple DMs.

DMs have their own preferences in the negotiation. The current landowners usually have statutory obligations to bear the costs for cleaning up contaminations, but often lack the funds or are unwilling to do so. Hence, the brownfield owners are reluctant to enter into negotiations with a potential purchaser (developer) because the purchasers are likely to require environmental testing which may generate information confirming the contamination that could be consequently used by an enforcement agency to order remediation. The current landowners are usually obliged to attend the negotiation due to looming legal liabilities. Once entering the negotiation, the current owners are interested in shedding some of their financial responsibilities for cleanup by negotiating a favourable sale price that limits their current and future liabilities for clean-up. The prospective developers, usually real estate developers, are attracted by the business prospects of the sites. However, many other options for investment are also available for the developers. The brownfield redevelopment presents an economic opportunity only to the extent that the returns are commensurate with returns from other investments. Furthermore, being the future owner, the developer faces several financial risks: cleanup may not be complete and costs for future environmental liability may be more than expected; and a stigma may be attached to the site which may affect future business. The governments are interested in seeing the brownfields redeveloped because of the environmental, economic and social benefits to be brought to the communities. They are key players because the level of resources (e.g., financial assistances) that the governments bring to the negotiation table determines whether a deal can be made, especially when the brownfield redevelopment is uncompetitive with development on a greenfield. The prospective developers can be induced to participate in the negotiation if they believe that mediation is likely to result in a better deal than other investment options.

III. MODEL FORMULATION

The model proposed in this paper for the brownfield redevelopment negotiation assumes that all the key DMs...
agree to participate in a negotiation, usually initiated by the local government. The negotiation focuses on how the costs and benefits associated the remediation and redevelopment can be fairly allocated among the stakeholders involved.

A. Qualitative Coalition Analysis

Cooperative game theory has been successfully applied to cost allocation problems such as those in water resources projects [8], [9], [10], [18] where the completed properties (facilities) for individual stakeholders are the same no matter whether they are built under the cases of full or partial or no cooperation of stakeholders. For those situations, the stakeholders can be induced into full cooperation just because it saves money for each of them through the cost allocation process. However, for a brownfield redevelopment project, the key DMs will have different cost inputs as well as benefits (incomes) under various possible coalitions that they can form. Thus, the costs and benefits, i.e., net benefits, should be equitably allocated among the stakeholders in order to encourage all of the DMs to reach an agreement for the brownfield redevelopment. The negotiation process to achieve such a purpose can be modeled as a net benefit game.

Fig.1 shows the possible coalitions of DMs involved in the negotiation of a typical 3-party brownfield redevelopment project. The landowner may choose to cooperate with either government or the developer, and all three DMs can form a grand coalition. Note that the developer and government alone cannot form a coalition because without the landowner it is impossible for them to complete a redevelopment project on the landowner’s site. Consider the coalition of the landowner and developer. To complete the redevelopment project, it will cost the coalition more without the participation and financial assistance from the government. Under the coalition of the landowner and government, the landowner can do the cleanup but is unlikely to redevelop the site. If each of all of the three parties acts separately without any cooperation, then normally there is neither cleanup nor redevelopment, since the landowner would have no incentive to cleanup or redevelop the brownfield without the government’s or developer’s assistance.

![Fig.1. Coalitions of stakeholders involved in the negotiation of a typical 3-party brownfield redevelopment project.](image)

Note that each of the three main DMs could consist of two or more parties. In this situation, each DM could represent a consortium (e.g., landowners, developers, levels of governments). Fig. 2 shows the possible coalitions of DMs involved in the negotiation of a typical 4-party brownfield redevelopment project. Similar to Fig. 1, either the landowner 1 or 2 may form 2-member coalitions with the developer or government, and form 3-member coalitions with both the developer and government. It is also possible for both the landowners 1 and 2 to form 3-member coalitions with either the developer or government. Of course, all of the 4 stakeholders can form a grand coalition which would execute the most efficient cost and benefit brownfield cleanup and redevelopment project.

![Fig.2. Coalitions of stakeholders involved in the negotiation of a 4-party brownfield redevelopment project.](image)

B. Mathematical Formulation

Let \( N = \{1, 2, \ldots, n\} \) denote the set of DMs or stakeholders involved a brownfield redevelopment project and sitting at the negotiation table, and \( i \in N \) be a typical stakeholder. A group of DMs \( S \subseteq N \) working together and entering a cooperative agreement is called a coalition. \( N \) itself is called the grand coalition which consists of all DMs. A coalition structure is a partition \( \{S_1, S_2, \ldots, S_m\} \) of the \( n \) DMs, in which \( \bigcup_{i=1}^{m} S_i = N \) and for all \( i \neq j \), \( S_i \cap S_j = \emptyset \). For a game with \( n \) DMs, there are \( 2^n \) possible coalitions, or \( 2^n - 1 \) if the null coalition is excluded. The notion \( \nu(S) \) is used to represent the aggregate value gained by the members of coalition \( S \), while the values of individual DMs acting alone are represented as \( \nu(\{i\}), \nu(\{2\}), \ldots, \nu(\{n\}) \).

Allocation of net benefits through cooperation of all DMs is an \( n \)-person cooperative game \((N, \nu)\), where \( N \) is the set of DMs, and \( \nu \) is the characteristic function relating each coalition \( S \subseteq N \) to a real number \( \nu(S) \), denoting the total value (net benefit) which \( S \) is able to gain through internal cooperation, with the convention that \( \nu(\emptyset) = 0 \). The value \( \nu(S) \) generated by the coalition \( S \) is estimated using the concept of alternative value, which is defined as the total net benefit that coalition \( S \) can gain by its coalition members through an alternative project or business activity.

\[
\nu(S) = NB(S) = \sum_{i \in S} NB_i = \sum_{i \in S} (B_i - C_i) \tag{1}
\]

where, \( NB(S) \) is the net benefit of coalition \( S \); \( B_i \) and \( C_i \) are the benefit, cost and net benefit of DM \( i \) participating in coalition \( S \), respectively. All monetary items are expressed in present values in the model since costs and benefits associated with brownfield redevelopment may extend over
years.

Guidelines for estimating the net benefits of the singletons and coalitions are summarized as follows:

(1) When each of all DMs acts separately, a landowner is assumed to remain idle and hold the value of the contaminated land which is the price of a hypothetical “clean” land of the same size at the location minus the future environmental liability of the contaminated land. Since a developer normally has options other than brownfield redevelopment, it is reasonable to assume that a developer operating individually gains an alternative net benefit obtained by investing in other projects. The value of the government acting alone is set to be zero.

(2) For a coalition involving landowners and developers, the total redevelopment cost includes the contaminated lands, all cleanup and construction expenses, while the benefit equals the avoided environmental liabilities of the remedied lands plus the income from the sale of product or commercial service.

(3) For coalitions involving landowners and governments, the gain of a landowner is the avoided environmental liability of the remedied land plus the financial assistance from the government minus the cleanup cost. The gain of the government equals the increase of social and real estate property values minus the financial assistance.

(4) Developers and governments cannot form effective coalitions since no cleanup or redevelopment can be carried out on the site without the landowner’s participation. The values of those pseudo coalitions are set to be the values gained by the developers’ individual operations.

(5) For the grand coalition, the value is the sum of the avoided environmental liabilities of the remedied lands, the product or commercial service incomes and the increase of social and real estate values, minus the total redevelopment cost.

For the example in Fig. 1., one has:

\[\begin{align*}
u(1) &= V_{clean\, land} - C_{liability} \\
u(2) &= NB_{alter\, invest} \\
u(3) &= 0 \\
u(1,2) &= C_{liability} + B_{product} - C_{redevelop} \\
u(1,3) &= C_{liability} + B_{social\, clean} - C_{cleanup} \\
u(2,3) &= u(2) \\
u(1,2,3) &= C_{liability} + B_{product} + B_{social\, redevelop} - C_{redevelop}
\end{align*}\]  

where,  
- \(C_{liability}\) = cost due to the environmental liability of the contaminated land,  
- \(C_{cleanup}\) = cost to cleanup the brownfield,  
- \(V_{clean\, land}\) = value of a hypothetical “clean” land of the same size at the location of the brownfield project,  
- \(C_{redevelop}\) = total cost of redevelopment,

\[C_{redevelop} = V_{unclean\, land} + C_{cleanup} + C_{develop},\]

and \(C_{develop}\) is the development cost following the cleanup.

Note that the aforementioned estimation of coalition values accounts for the costs and benefits for each coalition as a whole, which does not specify how the costs and benefits are allocated to DMs. The environmental liability, commercial service income, and the increase of social and real estate property values are parameters depending on the length of the time period considered for the cost and benefit estimation. Hence, the time period of the allocation planning is also an important concern in negotiation. The game model can be applied to each scenario defined by different levels (including the average level) of contamination, insurance status, cleanup cost, redevelopment cost and income. The outcomes of the modeling under various scenarios form the contingency plan for the cost/benefit allocation of brownfield redevelopment.

A “solution” to a game is a vector of the payoffs received by each DM. This payoff or reward vector after a trade can be written as \(\mathbf{x} = (x_1, x_2, \ldots, x_n)\). The payoff vector is called an imputation to the cooperative game. The basic stability concept in cooperative game theory is the core, \(C(N, \upsilon)\), defined as follows [16], [18]. For a cooperative game \((N, \upsilon)\), a payoff vector \(\mathbf{x} = (x_1, x_2, \ldots, x_n)\) is in the core \(C(N, \upsilon)\), if:

\[\sum_{i \in S} x_i \geq \upsilon(S) \quad \text{for all } S \subseteq N\]  

The condition expressed by (3) ensures that the payoff vector is feasible for the grand coalition \(N\), which is called the joint efficiency condition. The condition shown in (4) states that no coalition \(S\) by acting on its own can achieve an aggregate value higher than the share that it receives under the payoff vector. For coalitions with multiple DMs, it is labeled the group rationality condition; for singleton coalitions which consist of only one DM, it is called the individual rationality requirement. Therefore, once an allocation from the core has been selected, no coalition on its own can improve the payoff of all its DMs. However, the core of a cooperative game may be empty. If it exists, there is no guarantee that it has a unique feasible solution.

C. Solving a Brownfield Redevelopment Game

The nucleolus (core-based) and the Shapley value (noncore-based) concepts are adopted for solving the game.

1) Nucleolus and Related Solutions

The nucleolus is the reward vector for which excesses for all coalitions are as small as possible. An excess is defined to be the amount by which the worth of a coalition exceeds the aggregate payoff to its members in isolation. Let \(x(S) = \sum_{i \in S} x_i\),

\[NB_{alter\, invest} = \text{net benefit return from alternative investments with the same amount of brownfield redevelopment cost},\]

\(B_{product}\) = income from the sale of product or commercial service obtained from redevelopment,  

\(B_{social\, clean}\) = increase of social and real estate property values due to cleanup of the brownfield, and  

\(B_{social\, redevelop}\) = increase of social and real estate property values due to cleanup and redevelopment of the brownfield.

Authorized licensed use limited to: Tsinghua University Library. Downloaded on July 21,2010 at 08:31:00 UTC from IEEE Xplore. Restrictions apply.
and \( x(N) = \sum_{i=0}^{n} x_i \). Then the excess of \( S \) with respect to \( x \) is 
\[
e(S, x) = \nu(S) - x(S) = \nu(S) - \sum_{i=0}^{n} x_i .
\]
The excess \( e(S, x) \) is a measure of the inequity (dissatisfaction) of an imputation \( x \) for a coalition \( S \), which can be considered as a tax or punishment to force the subcoalition DMs to participate in the grand coalition when \( e(S, x) > 0 \), and as a subsidy to encourage participation in the grand coalition when \( e(S, x) < 0 \). The nucleolus minimizes the maximum excess of any coalition \( S \) lexicographically. The nucleolus \( \nu(X) \) of a cooperative game always exists and consists of a unique point. The nucleolus satisfies the joint efficiency and group rationality. Note that the triangle can be used to measure of the inequity (dissatisfaction) of an imputation \( x \) for a coalition \( S \), which can be considered as a tax or punishment to force the subcoalition DMs to participate in the grand coalition when \( e(S, x) > 0 \), and as a subsidy to encourage participation in the grand coalition when \( e(S, x) < 0 \). The nucleolus minimizes the maximum excess of any coalition \( S \) lexicographically. The nucleolus \( \nu(X) \) of a cooperative game always exists and consists of a unique point. The nucleolus satisfies the joint efficiency and individual rationality conditions. If the core is not empty, the nucleolus is in the core [13]. Variations of the nucleolus are individual rationality conditions. If the core is not empty, the point. The nucleolus satisfies the joint efficiency and cooperative game always exists and consists of a unique point. The nucleolus satisfies the joint efficiency and individual rationality conditions. If the core is not empty, the nucleolus is in the core [13]. Variations of the nucleolus are obtained by changing the definition of the excess function as shown in Table 1 [10], [18].

Table 1. Nucleolus solution concepts and coalition excesses

<table>
<thead>
<tr>
<th>Solution concept</th>
<th>Coalition excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleolus</td>
<td>( \nu(S) - x(S) )</td>
</tr>
<tr>
<td>Weak Nucleolus</td>
<td>( \nu(S) - x(S) )</td>
</tr>
<tr>
<td>Proportional Nucleolus</td>
<td>( \nu(S) - x(S) )</td>
</tr>
<tr>
<td>Normalized Nucleolus</td>
<td>( \nu(S) - x(S) )</td>
</tr>
</tbody>
</table>

2) Shapley Value

With the Shapley value solution concept, each DM’s reward or value to the game should equal a weighted average of the contributions the DM makes to each coalition of which he or she is a member. The weighting depends on the number of total DMs and the number of DMs in each coalition. There exists a unique payoff vector \( x = (x_1, x_2, \ldots, x_n) \) satisfying the Shapley axioms, of which the payoff to the \( i \)th DM is given by the Shapley value [14],

\[
x_i = \sum_{S \subseteq N} \frac{|S|!}{|N|!} \left( \nu(S) - \nu(S - \{i\}) \right), \quad (i \in N)
\]

where, \(|S|\) and \(|N|\) are the cardinalities of coalition \( S \) and the grand coalition \( N \), respectively. The Shapley value given above assumes equal probability for the formation of any coalition of the same size. This assumption can also be relaxed and generalized [11]. Note that the Shapley value is not always in the core. It may fail to be in the core even if the core is not empty.

3) Initial Assignments and Net Benefit Allocation

Suppose at the beginning of the negotiation, initial costs \( C_i \) and benefits \( B_i \) are arbitrarily assigned to DMs as long as satisfying (1). Once the payoff vector is obtained by solving the game model, side payments and the additional values for DMs to participate in the grand coalition can be derived. The side payment to other DMs is the difference of the value gained by participating in the grand coalition and allocated payoff, \( p_i = NB_i - x_i \). Note, a negative side payment means receiving payment from others. For DM \( i \), the value (or gain) of participation in the grand coalition \( g_i = -e(\{i\}, x) = x_i - \nu(\{i\}) \).

IV. ILLUSTRATIVE EXAMPLE

Consider a hypothetical example of a small brownfield project in which three DMs are identified, namely the current landowner (DM 1), the developer (DM 2) and the government (DM 3). Through the initial negotiation, the DMs reach some common understanding on the average estimates of the relevant costs and benefits as listed in Table 2 where a 20-year term is assumed and the unit of all monetary items is $1000 in present value terms. The proposed methodology is used to find the fair allocations of the net benefits among the DMs.

Table 2. Average estimates of costs and benefits for the brownfield redevelopment project ($1000)

<table>
<thead>
<tr>
<th></th>
<th>( C_i )</th>
<th>( C_{clean} )</th>
<th>( C_{develop} )</th>
<th>( V_{clean,	ext{land}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NB_{alter,\text{mid}} )</td>
<td>20</td>
<td>100</td>
<td>200</td>
<td>40</td>
</tr>
<tr>
<td>( B_{product} )</td>
<td>200</td>
<td>510</td>
<td>120</td>
<td>140</td>
</tr>
</tbody>
</table>

Based on the estimates in Table 2, and formula (2), the values of all singletons and coalitions are calculated as:

\[
\nu(1) = 20 \quad \nu(2) = 200 \quad \nu(3) = 0 \\
\nu(1,2) = 210 \quad \nu(1,3) = 40 \quad \nu(2,3) = 200 \\
\nu(1,2,3) = 350
\]

Fig.3. Core of the brownfield redevelopment net benefit allocation game.

The core of this brownfield redevelopment game is drawn in Fig. 3, in which the triangle shows the set of all possible nonnegative allocations of the total net benefit of the grand coalition ($350,000) among the competing DMs. For each point in the triangle, the perpendicular distances from the three edges indicate the allocated net benefit to each DM. The distance from the lower edge gives the allocation to the landowner, while the perpendicular distances from the upper-right and upper-left edges provide the allocations to the developer and government, respectively. Only the shaded area, the core, is the subset of allocations satisfying individual and group rationality. Note that the triangle can be used to
explain the allocation only in three-DM cooperative games. For games with more than three DMs, the core cannot be drawn and the existence of the core can be checked using the nucleolus solution concept.

The fair allocations of the total net benefit obtained for the grand coalition are found by using GAMS and the MINOS solver [3] and are summarized in Table 3. Note that theoretically, the Proportional Nucleolus is inapplicable in this example due to the zero value of \(\nu(3)\). To avoid division by zero in computations, a small number for \(\nu(3)\) is adopted instead. Given the initial assignment of the costs and benefits to the DMs involved in the grand coalition, for each scenario of net benefits allocation, the corresponding side payments and gains can be computed by the game model. For example, Table 4 shows the complete cost/benefit allocation scheme when the Shapley value is utilized. It is assumed in this table that at the beginning of the negotiation the landowner, developer and government would like to pay $20,000, $300,000 and nil to cover the project cost, and are supposed to have $20,000, $510,000 and $140,000 of benefits, respectively. The net benefit allocation determines that the government should pay $65,000 and $25,000 to the landowner and developer, respectively, to promote fair cooperation toward the brownfield redevelopment project.

Table 3. Fair allocation of net benefits ($1000)

<table>
<thead>
<tr>
<th>Solution concept</th>
<th>Landowner</th>
<th>Decision maker</th>
<th>Government</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleolus</td>
<td>63.333</td>
<td>243.333</td>
<td>43.333</td>
</tr>
<tr>
<td>Weak Nucleolus</td>
<td>76.667</td>
<td>236.667</td>
<td>36.667</td>
</tr>
<tr>
<td>Proportional Nucleolus</td>
<td>36.992</td>
<td>291.667</td>
<td>21.341</td>
</tr>
<tr>
<td>Normalized Nucleolus</td>
<td>36.992</td>
<td>291.667</td>
<td>21.341</td>
</tr>
<tr>
<td>Shapley value</td>
<td>65</td>
<td>235</td>
<td>50</td>
</tr>
</tbody>
</table>

To avoid division by zero in computation, a small number 0.004 for \(\nu(3)\) is used instead of zero.

Table 4. Cost/benefit allocation scheme found by Shapley value ($1000)

<table>
<thead>
<tr>
<th>Item</th>
<th>Decision maker</th>
<th>Landowner</th>
<th>Developer</th>
<th>Government</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial benefit ((B_i))</td>
<td></td>
<td>20</td>
<td>510</td>
<td>140</td>
</tr>
<tr>
<td>Initial cost ((C_i))</td>
<td></td>
<td>20</td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>Initial net benefit ((NB_i))</td>
<td></td>
<td>0</td>
<td>210</td>
<td>140</td>
</tr>
<tr>
<td>Allocated net benefit ((\xi))</td>
<td></td>
<td>65</td>
<td>235</td>
<td>50</td>
</tr>
<tr>
<td>Payment ((p_i))</td>
<td></td>
<td>-65</td>
<td>-25</td>
<td>90</td>
</tr>
<tr>
<td>Gain of participation ((g_i))</td>
<td></td>
<td>45</td>
<td>35</td>
<td>50</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

The proposed game-theoretic approach to brownfield redevelopment provides a structured procedure supporting the negotiation on the allocation of related costs and benefits in a brownfield project. From both theoretical analyses and practical experience, governmental financial assistance is a crucial incentive to redevelopment. By providing sufficient inducements, including both financial and technical assistance to both the current owners and developers, governments can often bring them to the negotiation table and reach some cooperative and fair allocations of costs and benefits associated with the brownfield remediation and redevelopment. Some general guidelines for estimating coalition values have been proposed. Future research to complement the model includes representing the coalitions’ characteristic functions in a more generic mathematical form, incorporating the methods for estimating the relevant costs and benefits, and developing a computerized decision support system allowing convenient multiple scenario analyses.

REFERENCES