Technology Evaluation and Decision Making for Sustainability Enhancement of Industrial Systems Under Uncertainty

Zheng Liu and Yinlun Huang

Dept. of Chemical Engineering and Materials Science, Wayne State University, Detroit, MI 48202

Technology-based sustainability enhancement is a key approach for industrial sustainability realization. However, identification of effective technologies for any industrial system could be very challenging. If the available data and information about the industrial system and technologies are incomplete, imprecise, and uncertain, then technology identification could be very difficult. In this article, the authors introduce a simple, yet systematic interval-parameter-based methodology for identifying quickly superior solutions under uncertainty for sustainability performance improvement. The methodology is general enough for the study of sustainability enhancement problems of any size and scope. A case study on sustainable development of biodiesel manufacturing demonstrates methodological efficacy. © 2012 American Institute of Chemical Engineers *AIChE J,* 58: 1841–1852, 2012
Keywords: sustainability enhancement, decision making, uncertainty, interval-parameter-based analysis, technology evaluation

Introduction

Depletion of natural resources, environmental pressure, economic globalization, etc., demand seriously industrial organizations to ensure that their manufacturing be sustainable.[1] Today, numerous advanced manufacturing technologies are available for the improvement of energy/material efficiency, product development and quality assurance, zero (waste) discharge, process safety assurance, productivity increment, etc (Sikdar et al., *Engineering*, 2011). Needless to say, technology adoption by industrial organizations must be financially justified. Industries seek continuously systematic methodologies and tools that can help them identify the most suitable technologies to achieve their sustainability goal at the minimum cost.[2]

Sustainability enhancement is always a very challenging task, even for a small industrial system, such as a plant or a product. To identify the strategies for sustainability enhancement, economic, environmental, and social sustainability assessments are always the first and critical step. In assessment, an unavoidable task is to identify an effective approach to process a variety of uncertainties that appear in system characterization, technology description, and beyond. For example, the combined economic, environmental, and social performance of technologies can be hardly determined precisely. It is usually not predictable when environmental regulations will change and how they will affect technology development and adoption. The interdependency of industrial systems and the relevance to sustainability are frequently difficult to model. The information about material or energy consumption, product, waste, or byproduct generation, and profitability of individual systems are often incomplete and imprecise. The uncertain situation can be more severe when predicting future sustainability performance, as market demand, supply chain structures, environmental policies, etc., change along the time.

Uncertainties can be generally classified into two categories: the aleatory and the epistemic uncertainties.[3] The aleatory uncertainty refers to the variations associated with physical systems and/or the environment; it is objective and irreversible. By contrast, the epistemic uncertainty is carried due to the lack of knowledge and/or information; it is subjective and reducible. The uncertainties encountered in the study of industrial sustainability problems, as exemplified above, could be either aleatory or epistemic.

A variety of mathematical and computational intelligence methods are available for uncertainty handling, such as those by resorting to statistical theory, fuzzy mathematics, and artificial intelligence.[4–11] For instance, probability bounds analysis (PBA)[6] is a method extended from probability theory.[7] It expresses uncertainty using a probability-box (or p-box) approach,[8] where a p-box represents a range of distribution functions. The method can provide a balance between expressiveness of imprecision and computational efficiency.[9] Note that since the availability of distribution functions is a requirement and modeling of uncertainty propagation is a real challenge, PBA methods are basically not suitable for the study of many types of sustainability problems.

Fuzzy logic- and fuzzy programming-based approaches are attractive in formulating and manipulating epistemic uncertainties, where rigorous logics are used to deal with fuzzy information that are difficult to compute using conventional mathematical methods.[10] Solution derivation is usually transparent, which makes solution reasoning easy to understand.

Correspondence concerning this article should be addressed to Y. L. Huang at yhuang@wayne.edu

Piluso et al.[11] and Liu et al.[12] introduced a fuzzy logic-based decision-making approach for industrial sustainability enhancement under uncertainty. Note that, however, decision quality is largely affected by the definition of fuzzy sets and fuzzy numbers, where subjective judgments are used to a large extent because of lack of sufficient precise data. Apparently, any poor judgment could be detrimental to decision quality. Sevionovic presented some general concepts surrounding fuzzy set approaches to process a few types of uncertainties appeared in water sustainability problems.[13] Hersh[14] demonstrated a need for conducting sensitivity analysis when investigating the dependence of decisions on uncertain parameters, weights, and models, but the success in problem solving is yet to be proven. Recently, Conner et al.[15] introduced a fuzzy logic-based method for sustainability assessment of nations and corporations under interval-based uncertainties. By their approach, sustainability index intervals are calculated through fuzzy logic-based operations. Again, how to define adequately a variety of fuzzy sets is a challenge.

Information gap theory (IGT)[16] is a fairly new method for expressing uncertainty and making decisions when only the best guess for a specific quantity is available.[17] Note that information gap is defined as a disparity between what is known and what needs to be known to make a responsible decision. It has some engineering applications.[17,18] However, the mathematics of IGT is complicated and, thus, the method is difficult to use in modeling decision problems.[19]

Interval-parameter (IP)-based uncertainty handling is an interesting approach, by which parameter uncertainties are expressed by interval numbers, each of which has the lower and upper bounds and there is no data distribution information required.[20] IP-based approaches have been used to study successfully many environmental problems.[21–24] This type of approaches should be suitable for various sustainability assessment and decision-making tasks, where no probability function is derivable from the accessible data. The approaches are particularly attractive for the tasks of technology-based sustainability enhancement, where the known data are usually limited and uncertain, data ranges of parameters are known, but no data distribution information is available.[11]

In this article, we introduce a simple, yet systematic IP-based methodology for sustainable technology assessment and decision making for sustainability enhancement of industrial systems under uncertainty. By this method, technology candidates can be thoroughly evaluated using suitable sustainability metrics, and optimal technology sets can be readily identified to meet the industrial organization's strategic goals under budget constraints. The developed methodology is general that can be applied to sustainability enhancement problems of any size and scope. The remainder of the article is organized as follows. We introduce first the basic definition of an interval number and arithmetic operation types. Then, a set of IP-based sustainability assessment formulations are introduced, and the IP-based approach is extended to the identification of sustainability enhancement needs. Next, an IP-based technology identification methodology is described in detail. The efficacy of the methodology is demonstrated through investigating a sustainable biodiesel manufacturing problem. Finally, we will discuss some application issues and conclude the significance of the introduced methodology.

IP-Based Uncertainty Handling

Let $\bar{X}$ be an interval number with known lower and upper bounds, for which parameter distribution within the interval is unknown. This interval number can be defined as

$$\bar{X} = \left[x^L, x^U\right], \tag{1}$$

where x^L and x^U are the real numbers and $x^L \leq x^U$. Note that if x^L equals x^U, then, $\bar{X}$ becomes a deterministic number, which means no uncertainty involved, and thus can be written as X. Obviously, the definition in Eq. 1 still applies to a deterministic number as it is a special case of an interval number.

Let symbol $* \in [+, -, \times, \div]$ be a binary operation on any interval number. The arithmetic operations of interval numbers, $\bar{X}$ and $\bar{Y}$, can be generalized as follows[20]

$$\bar{X} * \bar{Y} = [\min\{x * y\}, \max\{x * y\}], \quad \text{where } x^L \leq x \leq x^U,$$
$$y^L \leq y \leq y^U. \tag{2}$$

More specifically, we have

$$\bar{X} + \bar{Y} = \left[x^L + y^L, x^U + y^U\right], \tag{3}$$

$$\bar{X} - \bar{Y} = \left[x^L - y^U, x^U - y^L\right], \tag{4}$$

$$\bar{X} \times \bar{Y} = [\min\{x \times y\}, \max\{x \times y\}], \tag{5}$$

$$\bar{X} \div \bar{Y} = [\min\{x \div y\}, \max\{x \div y\}]. \tag{6}$$

Based on the definition of multiplication in Eq. 5, the following operation holds

$$\sqrt{\bar{X}} = \left[\sqrt{x^L}, \sqrt{x^U}\right]. \tag{7}$$

Note that the resulting interval ensures the lower bound not greater than the upper bound. Also note that the above definitions are applicable to the operations involving one or more deterministic numbers, since a deterministic number is a special case of an interval number. In the following text, every interval number is symbolized by a variable symbol with a bar above, and the operations of interval numbers will follow the definition in Eq. 2.

Sustainability Assessment

Various metrics systems are available for performing sustainability assessment, such as, the IChemE[25] and AIChE[26] sustainability metrics that are widely adopted by the chemical industries. For an industrial system named P, we assume that a set of sustainability metrics, namely set S, is selected by the decision maker. The set of metrics contains three subsets, each of which can have a number of specific indices

$$S = \{E, \quad V, \quad L\}, \tag{8}$$

where

$E = \{E_i | i = 1,2,\ldots,F\}$, the set of economic sustainability indices,

$V = \{V_i | i = 1,2,\ldots,G\}$, the set of environmental sustainability indices,

$L = \{L_i | i = 1,2,\ldots,H\}$, the set of social sustainability indices.

Note that all the sustainability indices in this text take normalized values for the convenience of discussion. Therefore in application, all the data should be normalized first.

Table 1. Sustainability Evaluation on the System and the Technologies

Category	Index	System (P)	Technologies			
			T_1	T_2	...	T_N
Econ. (E)	E_1	$\bar{E}_1\,(P)$	$\bar{E}_1\,(T_1)$	$\bar{E}_1\,(T_2)$	...	$\bar{E}_1\,(T_N)$
	...	...	...	...	...	...
	E_F	$\bar{E}_F\,(P)$	$\bar{E}_F\,(T_1)$	$\bar{E}_F\,(T_2)$	...	$\bar{E}_F\,(T_N)$
Environ. (V)	V_1	$\bar{V}_1\,(P)$	$\bar{V}_1\,(T_1)$	$\bar{V}_1\,(T_2)$	...	$\bar{V}_1\,(T_N)$
	...	...	...	...	...	...
	V_G	$\bar{V}_G\,(P)$	$\bar{V}_G\,(T_1)$	$\bar{V}_G\,(T_2)$	...	$\bar{V}_G\,(T_N)$
Soc. (L)	L_1	$\bar{L}_1\,(P)$	$\bar{L}_1\,(T_1)$	$\bar{L}_1\,(T_2)$	...	$\bar{L}_1\,(T_N)$
	...	...	...	...	...	...
	L_H	$\bar{L}_H\,(P)$	$\bar{L}_H\,(T_1)$	$\bar{L}_H\,(T_2)$	...	$\bar{L}_H\,(T_N)$

Using selected sustainability indices, the status quo of the sustainability of system P can be assessed using the data collected from the system. For those uncertain data, the corresponding parameters should be expressed as intervals with the upper and lower bounds specified. In this way, the index-specific assessment results, i.e., $\bar{E}_i(P)$s, $\bar{V}_i(P)$s, and $\bar{L}_i(P)$s, are also interval numbers (see the third column of Table 1). These data can be used to estimate categorized sustainability for the system, i.e., $\bar{E}(P)$, $\bar{V}(P)$, and $\bar{L}(P)$, which are called the composite sustainability indices and can be evaluated using the following formulas

$$\bar{E}(P) = \frac{\sum_{i=1}^{F} a_i \bar{E}_i(P)}{\sum_{i=1}^{F} a_i}, \qquad (9)$$

$$\bar{V}(P) = \frac{\sum_{i=1}^{G} b_i \bar{V}_i(P)}{\sum_{i=1}^{G} b_i}, \qquad (10)$$

$$\bar{L}(P) = \frac{\sum_{i=1}^{H} c_i \bar{L}_i(P)}{\sum_{i=1}^{H} c_i}, \qquad (11)$$

where a_i, b_i, and $c_i \in [1, 10]$ are the weighting factors associated with the corresponding indices, reflecting the relative importance of an individual index over others in overall assessment. If all the factors are equally important, then each factor can be set to 1.

It is understandable that at a higher level of management hierarchy, decision makers may be interested in their organization's overall sustainability rather than very specific index values. In this case, the overall sustainability level of the system, denoted by $\bar{S}(P)$, can be estimated as follows

$$\bar{S}(P) = \frac{\|(\,\alpha\bar{E}(P), \quad \beta\bar{V}(P), \quad \gamma\bar{L}(P)\,)\|}{\|(\,\alpha, \quad \beta, \quad \gamma\,)\|}, \qquad (12)$$

where α, β, and γ each has a value of 1 (default) or greater. Naturally, $\bar{S}(P)$ is still normalized.

The weighting factor issue

Equations 9–12 contain a number of weighting factors, which reflect the relevant importance of different sustainability aspects. It is widely recognized that the weighting factors should be determined by decision makers based on their understanding of an organization's development goal. The assessment framework introduced in this work provides opportunities for them to assign preferred values to weighting fac-

tors in their applications. They can also assign different values to those weighting factors and then compare the results.

Goal Setting and Need for Sustainability Performance Improvement

For any industrial system, sustainability improvement needs can be determined based on the organization's strategic goal.

Strategic goal

An industrial organization's strategic plan can be detailed by specifying detailed economic, environmental, and social development goals below:

$E^{sp}(P)$ = the economic sustainability goal for system P,

$V^{sp}(P)$ = the environmental sustainability goal for system P,

$L^{sp}(P)$ = the social sustainability goal for system P.

By following the same approach used in Eq. 12, the overall sustainable development goal can be expressed as

$$S^{sp}(P) = \frac{\|(\,\alpha E^{sp}(P), \quad \beta V^{sp}(P), \quad \gamma L^{sp}(P)\,)\|}{\|(\,\alpha, \quad \beta, \quad \gamma\,)\|}, \qquad (13)$$

where α, β, and γ should take the same values as those used in Eq. 12. Obviously, $S^{sp}(P)$ is also a normalized parameter. The sustainability goals could be achieved in one or multiple development stages. In this work, we assume that this is a one-stage improvement effort. For a multiple stage improvement, the organization should specify its sustainability goals for each stage.

Determination of improvement need

Whether the sustainability performance of system P should be improved or not is determined first by measuring the difference between the system's status quo and the sustainability goals in the following way

$$\Delta\bar{E}^{imp}(P) = E^{sp}(P) - \bar{E}(P), \qquad (14)$$

$$\Delta\bar{V}^{imp}(P) = V^{sp}(P) - \bar{V}(P), \qquad (15)$$

$$\Delta\bar{L}^{imp}(P) = L^{sp}(P) - \bar{L}(P). \qquad (16)$$

The deviation of the overall sustainability of the system from the goals is

$$\Delta\bar{S}^{imp}(P) = S^{sp}(P) - \bar{S}(P). \qquad (17)$$

Note that $\Delta\bar{E}^{imp}(P)$, $\Delta\bar{V}^{imp}(P)$, and $\Delta\bar{L}^{imp}(P)$, and thus $\Delta\bar{S}^{imp}(P)$ are rarely zero intervals. The industrial organization should set its satisfaction level about the system performance, and then decide whether actions should be taken for performance improvement. Let η_E, η_V, and η_L be the maximum acceptable deviations of the system's sustainability performance from the preset goals. They can be set to, for example, 5% each. If any of the following inequalities holds, a sustainability improvement effort is needed

$$\Delta E^{imp,L}(P) > \eta_E E^{sp}(P), \qquad (18)$$

$$\Delta V^{imp,L}(P) > \eta_V V^{sp}(P), \qquad (19)$$

$$\Delta L^{imp,L}(P) > \eta_L L^{sp}(P), \qquad (20)$$

where $\Delta E^{imp,L}(P)$, $\Delta V^{imp,L}(P)$, and $\Delta L^{imp,L}(P)$ are the lower bounds of the improvement intervals obtained in Eqs. 14–16.

Technology Evaluation on Sustainability

In this study, sustainability enhancement of system P is achieved through implementation of suitable technologies. Assume that N technology candidates are available. They should be evaluated by the same sustainability indices as those used for system P. The evaluation results expressed as interval numbers are entered in Table 1 (from the fourth column). It is very possible that technology inventors, providers, and users can provide some technology assessment information based on their tests and experience. The information, however, should be re-evaluated using the selected sustainability indices for system P through working with the industrial organization. In the case of missing technical data, a reliable system simulator can be used to generate reasonable performance data. Note that all the parameters in Table 1 have normalized values.

Based on the index-specific evaluation data for each technology, the categorized sustainability performance of each can be derived as follows

$$\bar{E}(T_j) = \frac{\sum_{i=1}^{F} a_i \bar{E}_i(T_j)}{\sum_{i=1}^{F} a_i}; \quad j = 1, 2, ..., N \quad (21)$$

$$\bar{V}(T_j) = \frac{\sum_{i=1}^{G} b_i \bar{V}_i(T_j)}{\sum_{i=1}^{G} b_i}; \quad j = 1, 2, ..., N \quad (22)$$

$$\bar{L}(T_j) = \frac{\sum_{i=1}^{H} c_i \bar{L}_i(T_j)}{\sum_{i=1}^{H} c_i}; \quad j = 1, 2, ..., N \quad (23)$$

where a_i, b_i, and $c_i \in [1, 10]$ are the same weighting factors as those used in Eqs. 9–11.

The suitability of each technology listed in Table 1 for the improvement of system P can be readily evaluated in the following way

$$\Delta\bar{E}_i(T_j; P) = \bar{E}_i(T_j) - \bar{E}_i(P); \quad i = 1, 2, ..., F; \quad j = 1, 2, ..., N \quad (24)$$

$$\Delta\bar{V}_i(T_j; P) = \bar{V}_i(T_j) - \bar{V}_i(P); \quad i = 1, 2, ..., G; \quad j = 1, 2, ..., N \quad (25)$$

$$\Delta\bar{L}_i(T_j; P) = \bar{L}_i(T_j) - \bar{L}_i(P); \quad i = 1, 2, ..., H; \quad j = 1, 2, ..., N \quad (26)$$

The above index-specific suitability evaluation results can then be used to calculate the categorized sustainability improvement level for system P as follows

$$\Delta\bar{E}(T_j; P) = \frac{\sum_{i=1}^{F} a_i \Delta\bar{E}_i(T_j; P)}{\sum_{i=1}^{F} a_i}; \quad j = 1, 2, ..., N \quad (27)$$

$$\Delta\bar{V}(T_j; P) = \frac{\sum_{i=1}^{G} b_i \Delta\bar{V}_i(T_j; P)}{\sum_{i=1}^{G} b_i}; \quad j = 1, 2, ..., N \quad (28)$$

$$\Delta\bar{L}(T_j; P) = \frac{\sum_{i=1}^{H} c_i \Delta\bar{L}_i(T_j; P)}{\sum_{i=1}^{H} c_i}; \quad j = 1, 2, ..., N \quad (29)$$

where a_i, b_i, and $c_i \in [1, 10]$ are the same weighting factors as those used in Eqs. 9–11. These results are summarized in Table 2, where the cost information for using each technology, i.e., $B(T_j; P)$, is also included.

Table 2. Technology Specific Sustainability Improvement and Cost Data

Sustainability Category and Cost for Technology Use	Improvement Levels by Individual Technologies			
	T_1	T_2	...	T_N
Econ. sust. improvement	$\Delta\bar{E}(T_1; P)$	$\Delta\bar{E}(T_2; P)$	...	$\Delta\bar{E}(T_N; P)$
Environ. sust. Improvement	$\Delta\bar{V}(T_1; P)$	$\Delta\bar{V}(T_2; P)$	...	$\Delta\bar{V}(T_N; P)$
Soc. sust. improvement	$\Delta\bar{L}(T_1; P)$	$\Delta\bar{L}(T_2; P)$	...	$\Delta\bar{L}(T_N; P)$
Overall sust. improvement	$\Delta\bar{S}(T_1; P)$	$\Delta\bar{S}(T_2; P)$	...	$\Delta\bar{S}(T_N; P)$
Cost for technology use ($)	$B(T_1; P)$	$B(T_2; P)$	...	$B(T_N; P)$

Identification of Superior Technologies

With the assessment information derived by the method described in the preceding section, technology identification can be systematically conducted, which is to generate a complete set of information about the capacities of technology combinations for sustainability enhancement under a given budget limit. The solution superiority here is defined as follows: by the identified technologies, the industrial system's sustainability performance can meet the goals satisfactorily at the cost under the budget limit. Very likely, multiple sets of technology combinations exist under cost constraint. Those technology combinations usually show different capacities in improving different areas of sustainability, although their overall sustainability performances may be so close that their superiority levels cannot be differentiated. Therefore, it is appropriate that all those superior solutions are provided with detailed information to the decision makers, who can make their decisions on technology adoption.

To assist the industrial organization in technology selection, the methodology can generate the following types of information that are summarized in Table 3.

(a) The technology sets numbered in Column 1 and listed in Column 2 of the table. Each technology set contains one or more technologies, such as $\{T_2\}$ and $\{T_3, T_5, T_{10}\}$. The total number of potential technology sets is $2^N - 1$, including all the combinations by N technology candidates.

(b) The capabilities of the technologies for economic, environmental, social, and overall sustainability improvement. This group of information shows not only the categorized sustainability improvement levels (i.e., $\Delta\bar{E}_i(T; P)$, $\Delta\bar{V}_i(T; P)$, and $\Delta\bar{L}_i(T; P)$) after implementing each technology set (in Columns 4–6 of the table) but also the extent of the overall sustainability of the system $[\bar{S}_i(T; P)]$ that can be reached (in Column 7 of the table). Assuming that the ith technology set has m technologies included, the improvement level by the set can be derived as follows

$$\Delta\bar{E}_i(T; P) = \sum_{j=1}^{m} \Delta\bar{E}_i(T_j; P), \quad (30)$$

$$\Delta\bar{V}_i(T; P) = \sum_{j=1}^{m} \Delta\bar{V}_i(T_j; P), \quad (31)$$

$$\Delta\bar{L}_i(T; P) = \sum_{j=1}^{m} \Delta\bar{L}_i(T_j; P). \quad (32)$$

Table 3. System Sustainability Improvement by Technology Sets

| No. | Tech. Set | Cost for Tech. Set | Achievable Categorized Sustainability | | | Overall Sust. by Tech. Set |
			Econ.	Environ.	Soc.	
1	$\{T_1\}$	$B_1\,(T;P)$	$\bar{E}_1\,(T;P)$	$\bar{V}_1\,(T;P)$	$\bar{L}_1\,(T;P)$	$\bar{S}_1\,(T;P)$
...	...	...	...	...	...	...
$N+1$	$\{T_1, T_2\}$	$B_{N+1}\,(T;P)$	$\bar{E}_{N+1}\,(T;P)$	$\bar{V}_{N+1}\,(T;P)$	$\bar{L}_{N+1}\,(T;P)$	$\bar{S}_{N+1}\,(T;P)$
...	...	...	...	...	...	...
2^N-1	$\{T_1, T_2, ..., T_N\}$	$B_{2^N-1}\,(T;P)$	$\bar{E}_{2^N-1}\,(T;P)$	$\bar{V}_{2^N-1}\,(T;P)$	$\bar{L}_{2^N-1}\,(T;P)$	$\bar{S}_{2^N-1}\,(T;P)$

The above categorized sustainability improvement results can be used to evaluate the overall sustainability, $\bar{S}_i(T;P)$ by first calculating the categorized sustainability that system P can achieve after implementing the ith technology set. The formulations are given as follows

$$\bar{E}_i(T;P) = \sum_{j=1}^{m} \Delta\bar{E}_i(T_j;P) + \bar{E}(P), \qquad (33)$$

$$\bar{V}_i(T;P) = \sum_{j=1}^{m} \Delta\bar{V}_i(T_j;P) + \bar{V}(P), \qquad (34)$$

$$\bar{L}_i(T;P) = \sum_{j=1}^{m} \Delta\bar{L}_i(T_j;P) + \bar{L}(P). \qquad (35)$$

Then, the overall sustainability after using a specific set of technologies becomes

$$\bar{S}_i(T;P) = \frac{\left\| \left(\alpha\bar{E}_i(T;P), \quad \beta\bar{V}_i(T;P), \quad \gamma\bar{L}_i(T;P) \right) \right\|}{\left\| (\alpha, \quad \beta, \quad \gamma) \right\|}, \qquad (36)$$

where α, β, and γ take the same values as those used in Eq. 12 for consistency. The information derived from Eqs. 33–36 should be entered in the fourth to seventh columns of Table 3. (c) The total cost for using the ith set of m technologies can also be readily calculated as follows

$$B_i(T;P) = \sum_{j=1}^{m} B(T_j;P). \qquad (37)$$

The cost data are listed in the third column of Table 3.

The effectiveness of technology sets in application can be further evaluated through calculating sustainability improvement percentages in the following way

$$\bar{E}_i^{\text{imp}}(T;P)(\%) = \frac{\bar{E}_i(T;P) - \bar{E}(P)}{\bar{E}(P)}, \qquad (38)$$

$$\bar{V}_i^{\text{imp}}(T;P)(\%) = \frac{\bar{V}_i(T;P) - \bar{V}(P)}{\bar{V}(P)}, \qquad (39)$$

$$\bar{L}_i^{\text{imp}}(T;P)(\%) = \frac{\bar{L}_i(T;P) - \bar{L}(P)}{\bar{L}(P)}, \qquad (40)$$

$$\bar{S}_i^{\text{imp}}(T;P)(\%) = \frac{\bar{S}_i(T;P) - \bar{S}(P)}{\bar{S}(P)}. \qquad (41)$$

Solution identification procedure

The sustainability performance of an industrial organization can be improved in many ways. For instance, a corporation may plan to introduce a number of new products, to replace existing energy systems using alternative energy, to replace some production lines for productivity improvement, to reduce energy consumption and emission, or any combination of these or others. The approach for technology identification described below includes two procedures: (i) the one for a single improvement task (SIT) and (ii) the one for a multiple improvement task (MIT). Detailed solution identification procedures are introduced below.

Procedure for an SIT. Assume that a total of N technology candidates are identified, i.e., $T = \{T_1, T_2, ..., T_N\}$. A five-step procedure is given below for identification of all technology sets that can be used to achieve the economic, environmental, and social sustainability goals.

Step 1. Generate a complete list of technology sets (denoted as list Q) through enumerating the combinations by N technology candidates. The list contains $2^N - 1$ distinct technology sets, each of which has a size of k ($1 \leq k \leq N$) and in the form of $\{T_a, ...\}$. These sets are numbered in the first column and listed in the second column of Table 3. In list Q, there should be $\binom{N}{1}$ sets containing one technology each, $\binom{N}{2}$ sets with two technologies each, ..., and $\binom{N}{N}$ set including all N technologies.

Step 2. Calculate the total cost required for adopting each set of technologies according to Eq. 37. The results should be entered in the third column of Table 3. Note that any technology set, if the total cost exceeds the budget limit, $B^{\text{lim}}(P)$, should be removed from the table.

Step 3. For each set remained in the table, evaluate $\Delta\bar{E}_i$ $(T; P)$s and $\bar{E}_i$ $(T; P)$s, respectively, using Eqs. 30 and 33, and then enter the values of $\bar{E}_i$ $(T; P)$s in the fourth column of Table 3. Note that any set, if the value of E_i^L $(T; P)$ is lower than $(1 - \eta_E)E^{\text{sp}}$ (P) (where η_E could be 0.05, e.g.), should be eliminated from the table, as it is incapable of improving the system to the level set by the economic sustainability goal.

Step 4. Calculate $\Delta\bar{V}_i$ $(T; P)$s and $\bar{V}_i$ $(T; P)$s using Eqs. 31 and 34, respectively, and enter the values of $\bar{V}_i$ $(T; P)$s in the fifth column of Table 3. If the value of V_i^L $(T; P)$ of the ith technology set is lower than $(1 - \eta_V)V^{\text{sp}}$ (P) (where η_V is 0.05, e.g.), the set should be deleted from the table, due to its incompetence of achieving the environmental sustainability goal.

Step 5. Calculate $\Delta\bar{L}_i$ $(T; P)$s and $\bar{L}_i$ $(T; P)$s using Eqs. 32 and 35, respectively, and enter the values of $\bar{L}_i$ $(T; P)$s in the sixth column of Table 3. Then, keep only those sets in the table whose L_i^L $(T; P)$s are equal to or greater than $(1 - \eta_L)$ (e.g., 0.95) of $L^{\text{sp}}(P)$.

Table 4. Sustainability Improvement by Combined Technology Sets

No.	Tech. Set	Cost	Achievable Categorized Sustainability			Overall Sustainability
			Econ.	Environ.	Soc.	
1	$\{\omega_{1,1}, \omega_{2,1}, ..., \omega_{M,1}\}$	$B_1^M\ (T;P)$	$\overline{E}_1^M\ (T;P)$	$\overline{V}_1^M\ (T;P)$	$\overline{L}_1^M\ (T;P)$	$\overline{S}_1^M\ (T;P)$
2	$\{\omega_{1,1}, \omega_{2,1}, ..., \omega_{M,2}\}$	$B_2^M\ (T;P)$	$\overline{E}_2^M\ (T;P)$	$\overline{V}_2^M\ (T;P)$	$\overline{L}_2^M\ (T;P)$	$\overline{S}_2^M\ (T;P)$
...	...	...	...	...	...	...
G_{tot}	$\{\omega_{1,G_1}, \omega_{2,G_2}, ..., \omega_{M,G_M}\}$	$B_{\text{Gtot}}^M\ (T;P)$	$\overline{E}_{\text{Gtot}}^M\ (T;P)$	$\overline{V}_{\text{Gtot}}^M\ (T;P)$	$\overline{L}_{\text{Gtot}}^M\ (T;P)$	$\overline{S}_{\text{Gtot}}^M\ (T;P)$

Step 6. Evaluate $\overline{S}_i(T; P)$ using Eq. 36 and enter the results in the seventh column of Table 3.

Note that the technology sets still remained in Table 3 after Step 5 are those that can be used to achieve the organization's sustainability goals under the preset budget limit.

Procedure for an MIT. In the case of achieving multiple objectives, the total budget limit, $B_{\text{tot}}^{\lim}\ (P)$, should be set first. Assuming that M objectives are defined, a solution search procedure is proposed below.

Step 1. For each objective, run the above SIT procedure to identify the optimal technology set(s) that are contained in Table 3. For the kth objective, for instance, the resulting table is named $\Omega_k = \{\omega_{k,1}, \omega_{k,2},...,\omega_{k,G_k}\}$, where $\omega_{k,i}$ is the ith technology set, and the total number of technology sets is G_k. Note that for a task of M objectives, a total of M tables are generated, namely $\Omega_1, \Omega_2, ...,$ and Ω_M.

Step 2. Generate a complete list of the grouped technology sets (denoted as list Q_{tot}) through enumerating all the combinations of the identified technology sets among the M tables; the total number of such combinations is $G_{\text{tot}} = \prod_{k=1}^{M} G_k$. These combined technology sets are numbered in the first column and listed in the second column of Table 4.

Step 3. Calculate the total cost for adopting each grouped technology set according to Eq. 37. The results should be entered in the third column of Table 4. Note that any technology set, if the total cost exceeds $B_{\text{tot}}^{\lim}\ (P)$, should be removed from the table immediately.

Step 4. For each grouped technology sets remained in Table 4, evaluate $\Delta\overline{E}_i^M\ (T; P)$s and $\overline{E}_i^M\ (T; P)$s using Eqs. 30 and 33, respectively, and then enter the values of $\overline{E}_i^M\ (T; P)$s in the fourth column of Table 4.

Step 5. Calculate $\Delta\overline{V}_i^M\ (T; P)$s and $\overline{V}_i^M\ (T; P)$s using Eqs. 31 and 34, respectively, and enter the values of $\overline{V}_i^M\ (T; P)$s in the fifth column of Table 4.

Step 6. The same type of actions is taken for deriving $\Delta\overline{L}_i^M\ (T; P)$s and $\overline{L}_i^M\ (T; P)$s using Eqs. 32 and 35, respectively, and then enter the values of $\overline{L}_i^M\ (T; P)$s in the sixth column of Table 4.

Step 7. Calculate the overall sustainability, $\overline{S}_i^M\ (T; P)$, and enter the results in the seventh column of Table 4.

All the grouped technology sets remained in Table 4 satisfy the strategic goals under the budget limits. In general, the technology sets demonstrate different categorized sustainability improvements. The table can be sorted in descending order according to the individual categorized sustainability performance or the overall performance at the decision makers' choice. The sustainability improvement percentages calculated using Eqs. 38–41 can provide additional valuable information for comparison of technology sets. With these, the industrial organization should be able to select the most preferred technology set for application. In reality, the technologies available for an industrial organization to choose are normally limited. This makes the computational solution search well manageable, even for a multiple objective problem.

Performance comparison by sustainability cube

The system's sustainability performance using different technology sets that is quantified in Table 3 (for a single objective) or Table 4 (for multiple objectives) can be shown using a sustainability cube, which was introduced by Piluso et al.[11] As shown in Figure 1, the three coordinates of the cube are labeled by the composite indices of economic, environmental, and social sustainability, which are all normalized. The corner at (0, 0, 0) represents no sustainability at all that is rare, while the opposite corner at (1, 1, 1) indicates complete sustainability that is ideal. In the figure, the dot labeled as $S(P)$ describes the status quo of an industrial system, while the small solid square labeled as $S^{\text{sp}}(P)$ plots the sustainability goal defined by the industrial organization. The small cycle labeled as $S_i(T;P)$ shows the sustainability achieved after adopting the ith technology set. Each sustainability status is quantified by three composite index values shown in the figure. This plot can help the industrial decision makers compare graphically the solutions in categorized and/or overall sustainability.

Case Study

The introduced methodology has been successfully used to study a number of complex industrial sustainability problems. In this section, a sustainability development problem about biodiesel manufacturing is selected to illustrate the efficacy of the introduced methodology. In this case, a biodiesel plant with the production capacity of 8000 tons/year plans to identify suitable technologies for waste reduction, energy recovery, and product quality improvement for its alkali-catalyzed biodiesel manufacturing process (Figure 2). The plant decides to solicit proposals from its engineering departments, which should contain recommended technologies with detailed sustainability assessment under budget limit.
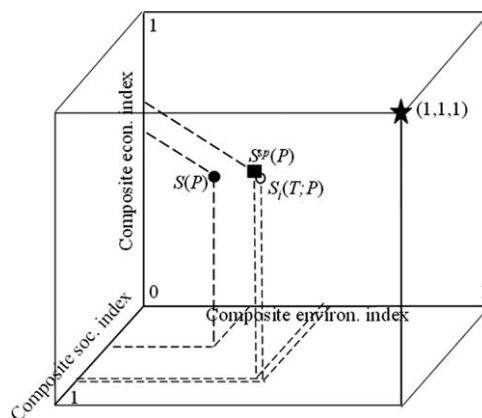

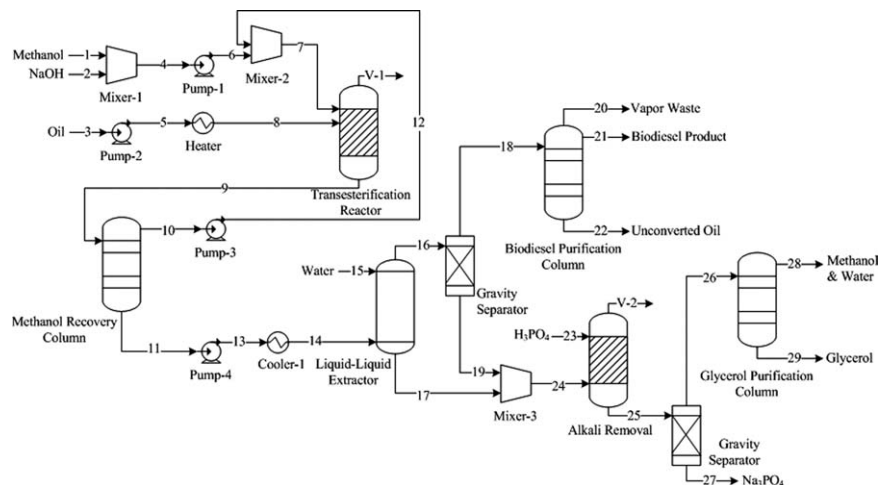**Figure 1. Sustainability cube representation.**

Figure 2. Flow sheet of an alkali-catalyzed biodiesel manufacturing process.

Technologies and classification

As a response, the engineering departments have identified 10 technologies from different sources,[27–29] which can be divided into the following two groups:

Group 1: Source waste reduction technologies. The four identified technologies are (1) $T_{1,1}$ – separation of methanol in the waste stream from the glycerol purification column and its recycle to the transesterificaiton reactor, (2) $T_{1,2}$ – recycle of the unconverted oil as part of the feedstock after pretreatment, (3) $T_{1,3}$ – recycle of waste stream of the glycerol purification column to the liquid–liquid extraction column as a washing solvent to replace fresh waster, and (4) $T_{1,4}$ – recovery of solid waste from the catalyst removal separator as a type of fertilizer.

Group 2: Energy efficiency and product performance improvement technologies. They are (1) $T_{2,1}$—redesign of product purification sequence, (2) $T_{2,2}$ – pretreatment of waste cooking oil as a new feedstock, (3) $T_{2,3}$ – adoption of new catalyst for the transesterification reactor to improve its conversion rate, (4) $T_{2,4}$ – energy recovery from the glycerol purification process, (5) $T_{2,5}$ – energy recovery from the transesterification reaction process, and (6) $T_{2,6}$ – energy recovery from the biodiesel purification system.

Sustainability indicator selection

To facilitate the illustration of methodology application, a small set of sustainability indicators are selected from the IChemE Sustainability Metrics system.[25] The economic indices include (1) value added (E_1) and (2) gross margin per direct employe (E_2). Note that price variation and market fluctuation affecting the calculation of the two indices are expressed by interval numbers. The environmental sustainability category contains three indices (1) total raw materials used per pound of product produced (V_1), (2) hazardous solid waste per unit value added (V_2), and (3) fraction of raw materials recycled (V_3). Uncertainties exist due to production fluctuation and feedstock quality variation. In the social sustainability category, the selected indices are (1) lost time accident frequency (L_1) and (2) number of complaints per unit value added (L_2). The available data for evaluation are insufficient and imprecise.

Sustainability assessment

Using the selected sustainability indices, the assessment results of the status quo of system P and the two groups of technologies are listed in Table 5, where most of the results are expressed as intervals due to data uncertainty. Then, the categorized sustainability assessment of the process and the two groups of technologies are derived using Eqs. 9–11 and 21–23; the results are shown in Table 6. For instance, the plant sustainability is quantified as [0.500, 0.510] for $\overline{E}(P)$, [0.393, 0.400] for $\overline{V}(P)$, and [0.344, 0.350] for $\overline{L}(P)$ as listed in the fourth column of Table 6. Note that the weighting factors for different indices listed in the third column of Table 6 are provided by the plant. The overall sustainability of the plant, $\overline{S}(P)$, evaluated by Eq. 12 is [0.417, 0.425], where parameters α, β, and γ took the default value of 1, meaning all are equally important.

Strategic goal setting

After reviewing the assessment results in Tables 5 and 6, the plant management set the plant's goal for the categorized sustainability to 0.580 for $E^{sp}(P)$, 0.455 for $V^{sp}(P)$, and 0.392 for $L^{sp}(P)$. The values of η_E, η_V, and η_L are set to 0.05, representing a minimum requirement of 95% goal achievement.

The difference between the sustainability goals and the system performance can be calculated using Eqs. 14–16, which are [0.070, 0.080], [0.055, 0.062], and [0.042, 0.048], for $\Delta \overline{E}^{imp}(P)$, $\Delta \overline{V}^{imp}(P)$, and $\Delta \overline{L}^{imp}(P)$, respectively. Using the preset values for η_E, η_V, and η_L, the values of $\eta_E E^{sp}(P)$, $\eta_V V^{sp}(P)$, and $\eta_L L^{sp}(P)$ are, respectively, 0.029, 0.023, and 0.020. According to Eqs. 18–20, a technology-based sustainability improvement is needed.

Technology recommendation

The introduced sustainability improvement procedure is executed under two budget constraints set by the plant (1) $B^{lim}(P)$ of \$300 K for a single objective task and (2) $B^{lim}_{tot}(P)$ of \$450 K for a two-objective task.

Proposal 1: Technology recommendation for source waste reduction. The single objective focused procedure is executed to identify the most appropriate technology set(s) from Group 1 that includes technologies $T_{1,1}$–$T_{1,4}$.

Table 5. Index-Specific Sustainability Assessment of the System and Two Groups of Technologies

Category	Index	System P	Technologies in Group 1				Technology in Group 2					
			$T_{1,1}$	$T_{1,2}$	$T_{1,3}$	$T_{1,4}$	$T_{2,1}$	$T_{2,2}$	$T_{2,3}$	$T_{2,4}$	$T_{2,5}$	$T_{2,6}$
Econ. (E)	E_1	[0.550, 0.570]	0.620	[0.620, 0.640]	0.580	[0.600, 0.610]	[0.600, 0.610]	[0.580, 0.600]	0.610	[0.620, 0.630]	0.580	[0.590, 0.600]
	E_2	0.450	[0.500, 0.530]	[0.480, 0.490]	[0.460, 0.480]	[0.490, 0.510]	0.510	[0.470, 0.480]	[0.460, 0.470]	0.460	[0.520, 0.530]	[0.460, 0.480]
Environ. (V)	V_1	0.400	0.430	0.450	[0.410, 0.420]	[0.420, 0.430]	[0.440, 0.450]	0.420	0.430	[0.460, 0.470]	[0.410, 0.420]	[0.460, 0.470]
	V_2	[0.350, 0.380]	0.400	0.360	[0.390, 0.400]	0.370	[0.360, 0.380]	[0.380, 0.400]	[0.360, 0.370]	0.350	0.400	[0.410, 0.420]
	V_3	0.420	[0.410, 0.420]	[0.450, 0.460]	0.400	0.430	0.450	[0.400, 0.410]	[0.430, 0.440]	[0.430, 0.440]	[0.420, 0.430]	0.410
Soc. (L)	L_1	[0.335, 0.340]	[0.355, 0.360]	[0.380, 0.390]	0.330	0.350	[0.310, 0.315]	[0.370, 0.380]	0.330	0.440	[0.390, 0.400]	[0.350, 0.365]
	L_2	[0.370, 0.380]	0.400	0.380	[0.378, 0.380]	[0.380, 0.385]	0.400	[0.390, 0.410]	[0.380, 0.390]	[0.360, 0.370]	[0.400, 0.410]	0.370

Table 6. Assessment of Categorized Sustainability of the System and Two Groups of Technologies

Category	Index	Weighting Factor	Categorized Sustainability Assessment										
			P	$T_{1,1}$	$T_{1,2}$	$T_{1,3}$	$T_{1,4}$	$T_{2,1}$	$T_{2,2}$	$T_{2,3}$	$T_{2,4}$	$T_{2,5}$	$T_{2,6}$
Econ. (E)	E_1	$a_1 = 1$	[0.500, 0.510]	[0.560, 0.575]	[0.550, 0.565]	[0.520, 0.530]	[0.545, 0.560]	[0.555, 0.560]	[0.525, 0.540]	[0.535, 0.540]	[0.540, 0.545]	[0.550, 0.555]	[0.525, 0.540]
	E_2	$a_2 = 1$											
Environ. (V)	V_1	$b_1 = 2$	[0.393, 0.400]	[0.418, 0.420]	[0.428, 0.430]	[0.403, 0.410]	[0.410, 0.415]	[0.423, 0.433]	[0.405, 0.413]	[0.413, 0.418]	[0.425, 0.433]	[0.410, 0.418]	[0.435, 0.443]
	V_2	$b_2 = 1$											
	V_3	$b_3 = 1$											
Soc. (L)	L_1	$c_1 = 3$	[0.344, 0.350]	[0.366, 0.370]	[0.380, 0.388]	[0.342, 0.343]	[0.358, 0.359]	[0.333, 0.336]	[0.375, 0.385]	[0.343, 0.345]	[0.390, 0.393]	[0.393, 0.403]	[0.355, 0.366]
	L_2	$c_2 = 1$											

Table 7. Sustainability Improvement by Source Waste Reduction Technologies

No.	Tech. Set	Cost for Tech. Set B_i (T;P)	System's Achievable Categorized Sustainability			Overall Sustainability $\bar{S}_i$ (T;P)
			$\bar{E}_i$ (T;P)	$\bar{V}_i$ (T;P)	$\bar{L}_i$ (T;P)	
1	$\{T_{1,1}\}$	$100 K	[0.560, 0.575]	[0.418, 0.420]	Deleted (environ. concern)	
2	$\{T_{1,2}\}$	$150 K	[0.550, 0.565]	Deleted (econ. concern)		
3	$\{T_{1,3}\}$	$50 K	[0.520, 0.530]	Deleted (econ. concern)		
4	$\{T_{1,4}\}$	$80 K	[0.545, 0.560]	Deleted (econ. concern)		
5	$\{T_{1,1}, T_{1,1}\}$	$250 K	[0.590, 0.650]	[0.438, 0.465]	[0.390, 0.420]	[0.480, 0.521]
6	$\{T_{1,1}, T_{1,3}\}$	$150 K	[0.560, 0.615]	[0.413, 0.445]	Deleted (environ. concern)	
7	$\{T_{1,2}, T_{1,3}\}$	$200 K	[0.550, 0.605]	Deleted (econ. concern)		
8	$\{T_{1,1}, T_{1,4}\}$	$180 K	[0.585, 0.645]	[0.420, 0.450]	Deleted (environ. concern)	
9	$\{T_{1,2}, T_{1,4}\}$	$230 K	[0.575, 0.635]	[0.430, 0.460]	Deleted (environ. concern)	
10	$\{T_{1,3}, T_{1,4}\}$	$130 K	[0.545, 0.600]	Deleted (econ. concern)		
11	$\{T_{1,1}, T_{1,2}, T_{1,3}\}$	$300 K	[0.600, 0.680]	[0.440, 0.483]	[0.382, 0.419]	[0.482, 0.539]
12	$\{T_{1,1}, T_{1,2}, T_{1,4}\}$	$330 K	Deleted (cost concern)			
13	$\{T_{1,1}, T_{1,3}, T_{1,4}\}$	$230 K	[0.595, 0.675]	[0.423, 0.468]	Deleted (environ. concern)	
14	$\{T_{1,2}, T_{1,3}, T_{1,4}\}$	$280 K	[0.585, 0.665]	[0.433, 0.478]	[0.373, 0.408]	[0.472, 0.528]
15	$\{T_{1,1}, T_{1,2}, T_{1,3}, T_{1,4}\}$	$380 K	Deleted (cost concern)			

Step 1. A total of 15 technology sets ($2^4 - 1$) are generated, which are listed in the second column of Table 7.

Step 2. The cost for using each technology set is calculated using Eq. 37 and listed in the third column of the same table. Note that technology sets Nos. 12 and 15 should be removed since the total cost for using each exceeds the budget limit of $300 K.

Step 3. For the remaining 13 technology sets, $\Delta\bar{E}_i$ (T; P)s and $\bar{E}_i$ (T; P)s are in turn evaluated using Eqs. 30 and 33, respectively; the values of $\bar{E}_i$ (T; P)s are listed in the fourth column of Table 7. As the values of E_2^L (T; P), E_3^L (T; P), E_4^L (T; P), E_7^L (T; P), and E_{10}^L (T; P) are all less than 0.551 [i.e., $(1-0.05)E^{sp}(P)$], the corresponding five technology sets must be deleted from the list. This makes the list containing only eight technology sets.

Step 4. The calculated values of $\bar{V}_i$ (T; P)s are listed in the fifth column of Table 7. It is shown that V_1^L (T; P), V_6^L (T; P), V_8^L (T; P), V_9^L (T; P), and V_{13}^L (T; P) are all less than 0.432 [i.e., $(1-0.05)V^{sp}(P)$]. Therefore, the corresponding five sets are not acceptable. This gives only technology sets Nos. 5, 11, and 14 still remained on the candidate list.

Step 5. For the remaining three technology sets, the values of $\bar{L}_i$ (T; P)s are listed in the sixth column of Table 7. The values of L_5^L (T; P), L_{11}^L (T; P), and L_{14}^L (T; P) are all greater than or equal to 0.373 [i.e., $(1-0.05)L^{sp}(P)$]. Therefore, these three source waste reduction technology sets, i.e., $\{T_{1,1}, T_{1,2}\}$, $\{T_{1,1}, T_{1,2}, T_{1,3}\}$, and $\{T_{1,2}, T_{1,3}, T_{1,4}\}$, are recommended for adoption to improve the process sustainability to the level preset by the plant under the budget limit.

Step 6. The overall sustainability value, $\bar{S}_i$ (T; P), for each of the three identified technology sets is listed in the seventh column of Table 7, which could be valuable for the plant management.

Proposal 2: Technology recommendation for energy efficiency and product quality improvement. In this case, six technologies in Group 2, namely $T_{2,1}$–$T_{2,6}$, should be evaluated. The single objective focused procedure needs to be executed again. Among 63 technology sets ($2^6 - 1$), 30 sets each costs more than $300 K, and thus should be removed from the list. After examining the values of $\bar{E}_i$ (T; P)s, 10 more technology sets are deleted. A comparison of the values of $\bar{V}_i$ (T; P)s with the environmental goal leads to an elimination of additional nine technology sets. Among the remaining 14 technology sets, five sets are disqualified after checking the values of $\bar{L}_i$ (T; P)s. Finally, nine sets are left on the list (Table 8); they all can be recommended to enhance the plant's sustainability under the budget limit.

Proposal 3: Technology recommendation for source waste reduction as well as energy efficiency and product quality improvement. In this case, all the improvement areas are targeted. The task is to identify the best possible technology combinations for the plant so that the management can decide if they want to invest more to achieve all or not. In this case, the plant sets the budget limit, B_{tot}^{lim} (P), to $450 K.

To search for technology combination, the MIT procedure described in the preceding section is executed. For the two-objective task, running Step 1 gives rise to two lists of recommended technology sets. They are $\Omega_1 = \{\omega_{1,1}, \omega_{1,2}, \omega_{1,3}\}$, where $\omega_{1,1} = \{T_{1,1}, T_{1,2}\}$, $\omega_{1,2} = \{T_{1,1}, T_{1,2}, T_{1,3}\}$, and $\omega_{1,3} = \{T_{1,2}, T_{1,3}, T_{1,4}\}$(see Table 7), and $\omega_2 = \{\omega_{2,1}, \omega_{2,2}, ..., \omega_{2,9}\}$, where the nine technology sets ($\omega_{2,i}$s) are listed in the second column of Table 8. The list, Q_{tot}, is

Table 8. Sustainability Improvement by Energy Efficiency and Product Quality Enhancement Technologies

No.	Tech. Set	Cost for Tech. Set B_i(T;P)	System's Achievable Categorized Sustainability			Overall Sustainability $\bar{S}_i$ (T;P)
			$\bar{E}_i$ (T;P)	$\bar{V}_i$ (T;P)	$\bar{L}_i$ (T;P)	
1	$\{T_{2,5}, T_{2,6}\}$	$140 K	[0.555, 0.605]	[0.438, 0.475]	[0.391, 0.431]	[0.466, 0.509]
2	$\{T_{2,1}, T_{2,4}, T_{2,5}\}$	$270 K	[0.615, 0.670]	[0.450, 0.505]	[0.408, 0.450]	[0.499, 0.550]
3	$\{T_{2,2}, T_{2,4}, T_{2,5}\}$	$290 K	[0.585, 0.650]	[0.433, 0.485]	[0.451, 0.499]	[0.494, 0.550]
4	$\{T_{2,3}, T_{2,4}, T_{2,5}\}$	$250 K	[0.595, 0.650]	[0.440, 0.490]	[0.419, 0.459]	[0.491, 0.539]
5	$\{T_{2,3}, T_{2,4}, T_{2,6}\}$	$270 K	[0.570, 0.635]	[0.465, 0.515]	[0.381, 0.423]	[0.478, 0.531]
6	$\{T_{2,1}, T_{2,5}, T_{2,6}\}$	$260 K	[0.600, 0.665]	[0.460, 0.515]	[0.374, 0.424]	[0.487, 0.544]
7	$\{T_{2,2}, T_{2,5}, T_{2,9}\}$	$280 K	[0.570, 0.645]	[0.443, 0.495]	[0.416, 0.473]	[0.481, 0.543]
8	$\{T_{2,3}, T_{2,5}, T_{2,6}\}$	$240 K	[0.580, 0.645]	[0.450, 0.500]	[0.384, 0.433]	[0.478, 0.533]
9	$\{T_{2,4}, T_{2,5}, T_{2,6}\}$	$230 K	[0.585, 0.650]	[0.463, 0.515]	[0.431, 0.480]	[0.497, 0.553]

Table 9. Sustainability Improvement by Combined Technology Sets for Two Objectives

| | | | System's Achievable Categorized Sustainability | | | Overall Sustainability |
No.	Tech. Set	Cost for Tech. Set B_i^M $(T;P)$	$\overline{E}_i^M$ $(T;P)$	$\overline{V}_i^M$ $(T;P)$	$\overline{L}_i^M$ $(T;P)$	$\overline{S}_i^M$ $(T;P)$
1	$\{T_{1,1}, T_{1,2}\},\{T_{2,5}, T_{2,6}\}$	\$390 K	[0.645, 0.745]	[0.483, 0.540]	[0.434, 0.501]	[0.528, 0.605]
2	$\{T_{1,1}, T_{1,2}\},\{T_{2,1}, T_{2,4}, T_{2,5}\}$	\$520 K		Deleted (cost concern)		
3	$\{T_{1,1}, T_{1,2}\},\{T_{2,2}, T_{2,4}, T_{2,5}\}$	\$540 K		Deleted (cost concern)		
4	$\{T_{1,1}, T_{1,2}\},\{T_{2,3}, T_{2,4}, T_{2,5}\}$	\$500 K		Deleted (cost concern)		
5	$\{T_{1,1}, T_{1,2}\},\{T_{2,3}, T_{2,4}, T_{2,6}\}$	\$520 K		Deleted (cost concern)		
6	$\{T_{1,1}, T_{1,2}\},\{T_{2,1}, T_{2,5}, T_{2,6}\}$	\$510 K		Deleted (cost concern)		
7	$\{T_{1,1}, T_{1,2}\},\{T_{2,2}, T_{2,5}, T_{2,6}\}$	\$530 K		Deleted (cost concern)		
8	$\{T_{1,1}, T_{1,2}\},\{T_{2,3}, T_{2,4}, T_{2,6}\}$	\$490 K		Deleted (cost concern)		
9	$\{T_{1,1}, T_{1,2}\},\{T_{2,4}, T_{2,5}, T_{2,6}\}$	\$480 K		Deleted (cost concern)		
10	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,5}, T_{2,6}\}$	\$440 K	[0.655, 0.775]	[0.485, 0.558]	[0.426, 0.500]	[0.531, 0.622]
11	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,1}, T_{2,4}, T_{2,5}\}$	\$570 K		Deleted (cost concern)		
12	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,2}, T_{2,4}, T_{2,5}\}$	\$590 K		Deleted (cost concern)		
13	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,3}, T_{2,4}, T_{2,5}\}$	\$550 K		Deleted (cost concern)		
14	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,3}, T_{2,4}, T_{2,6}\}$	\$570 K		Deleted (cost concern)		
15	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,1}, T_{2,5}, T_{2,6}\}$	\$560 K		Deleted (cost concern)		
16	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,2}, T_{2,5}, T_{2,6}\}$	\$580 K		Deleted (cost concern)		
17	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,3}, T_{2,5}, T_{2,6}\}$	\$540 K		Deleted (cost concern)		
18	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,4}, T_{2,5}, T_{2,6}\}$	\$530 K		Deleted (cost concern)		
19	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,5}, T_{2,6}\}$	\$420 K	[0.640, 0.760]	[0.478, 0.553]	[0.421, 0.489]	[0.521, 0.611]
20	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,1}, T_{2,4}, T_{2,5}\}$	\$550 K		Deleted (cost concern)		
21	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,2}, T_{2,4}, T_{2,5}\}$	\$670 K		Deleted (cost concern)		
22	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,3}, T_{2,4}, T_{2,5}\}$	\$530 K		Deleted (cost concern)		
23	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,3}, T_{2,4}, T_{2,6}\}$	\$550 K		Deleted (cost concern)		
24	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,1}, T_{2,5}, T_{2,6}\}$	\$540 K		Deleted (cost concern)		
25	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,2}, T_{2,5}, T_{2,6}\}$	\$560 K		Deleted (cost concern)		
26	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,3}, T_{2,4}, T_{2,5}\}$	\$520 K		Deleted (cost concern)		
27	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,4}, T_{2,5}, T_{2,6}\}$	\$510 K		Deleted (cost concern)		

generated in Step 2, which contains 27 combinations (see the second column of Table 9). After calculating the cost for using each combined technology set, only three out of 27 require the cost less than \$450 K (see the third column of Table 9). Using Eqs. 33–35, the values of $\overline{E}_i^M$ $(T; P)$, $\overline{V}_i^M$ $(T; P)$, and $\overline{L}_i^M$ $(T; P)$ for the combined technology sets, Nos. 1, 10, and 19, are derived, which are entered in the fourth, fifth, and sixth columns of Table 9. The overall sustainability levels for the three are listed in the seventh column of the same table.

Solution comparison

Different from Proposals 1 and 2, for which the sustainability goals are preset by the plant, Proposal 3 is developed with no prespecified sustainability goals, because the plant wants to review the detailed sustainability improvement levels for a given budget. The three identified combined technology sets shown in Table 9 are compared using Eqs. 38–41; the sustainability improvement analysis together with the costs for technology adoption are summarized in Table 10. To further help the plant management in technology selection, their sustainability performance data are plotted in Figure 3, which depicts the system's status quo $[S(P)]$, its goal $[0.95S^{sp}(P)]$, and the minimum achievable sustainability lev-

els by the combined technology sets $[S_1^L$ $(T; P), S_{10}^L$ $(T; P)$, and S_{19}^L $(T; P)]$.

Discussion

The solution identification approach used in the introduced methodology is essentially an exhaustive search approach. Therefore, the solution(s) identified should be guaranteed optimal. We all know that such an approach is not preferred when a solution search space is huge. However, this is not an issue for solution identification for sustainability improvement through adopting limited technologies. Note that for most industrial problems, the identified technologies are always for specific purposes; thus, they can be divided into a small number of purpose-based groups (practically no more than 10). In each group, the number of technology candidates is usually not large (rarely more than 10). Therefore, the number of solution candidates in each group is in the range of 1000 or so, and the total number of solution candidates for all groups will be simply an addition of those in all groups. Moreover, when evaluating solution candidates using the procedure for single or multiple objective tasks, those candidates with the costs beyond the given budget will be immediately removed from the candidate list. Only the remaining candidates will be required for economic

Table 10. Sustainability Improvement Percentage Comparison

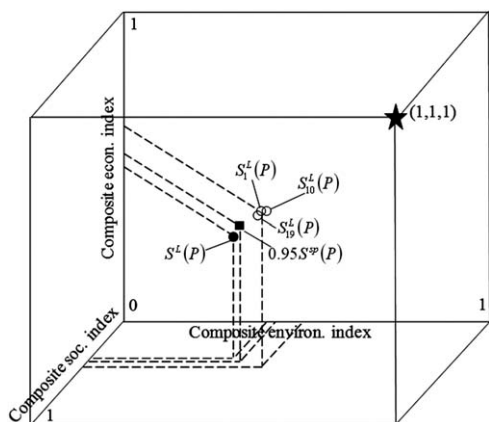| | | | System Sustainability Improvement (%) | | | |
No.	Tech. Set	Cost B_i^M $(T;P)$	$\overline{E}_i^{imp}$ $(T;P)$	$\overline{V}_i^{imp}$ $(T;P)$	$\overline{L}_i^{imp}$ $(T;P)$	$\overline{S}_i^{imp}$ $(T;P)$
1	$\{T_{1,1}, T_{1,2}\},\{T_{2,5}, T_{2,6}\}$	\$390 K	[26.5, 49.0]	[20.8, 37.4]	[24.0, 45.6]	[24.2, 45.1]
10	$\{T_{1,1}, T_{1,2}, T_{1,3}\},\{T_{2,5}, T_{2,6}\}$	\$440 K	[28.4, 55.0]	[21.3, 42.0]	[21.7, 45.3]	[24.9, 49.2]
19	$\{T_{1,2}, T_{1,3}, T_{1,4}\},\{T_{2,5}, T_{2,6}\}$	\$420 K	[25.5, 52.0]	[19.5, 40.7]	[20.3, 42.2]	[22.6, 46.5]

Figure 3. Sustainability performance of system, combined technologies, and strategic goals.

sustainability satisfaction checking. Again, only those candidates capable of making the process to meet the economic sustainability requirement will be kept. This further shortens the candidate list, which will be used to examine their capability of meeting the requirements of environmental and then social sustainability. Note that the computations involved in each step of checking are only algebraic calculations. Therefore, it is certain that for any industrial applications involving a few technology groups, each of which has 10–15 technology candidates, the computational time using a usual personal computer should be no more than a few seconds.

It is possible that for an industrial problem, an execution of the solution search procedure does not generate any feasible solution. This is mostly because the sustainability goals set by the industrial organization are not achievable by the technology candidates. In this case, the industrial organization should reset its goals more realistically. The other possible reason for no solution is the budget limit that is too low; this will eliminate some effective technology sets before being evaluated for sustainability improvement. In this case, the organization should consider a possibility of raising the budget limit.

Note that for an industrial organization seeking sustainability improvement of their systems, a commitment on capital investment is always required. The proposed methodology can then be used to provide recommendations on technology adoption. Each recommendation will include a detailed analysis on the categorized and overall sustainability improvement levels. In this work, only a few widely used indicators are selected from the IChemE Sustainability Metrics System for the illustration purpose. In real application, an industrial organization should carefully select sustainability indicators. For instance, in the economic sustainability category, it may include indicators related to the return on investment, the net profit after tax, etc. In the social sustainability category, the indicators related to job creation and the amount of tax paid could also be included.

Concluding Remarks

Numerous technologies have been developed for improving energy and material use efficiency; reducing source waste; ensuring process safety and health in production systems. These technologies, before adoption, should be evaluated carefully by sustainability metrics in order to ensure that system sustainability performance be improved cost-effectively. Note that the available data and information about the industrial system and technologies are frequently incomplete, imprecise, and uncertain. This can make technology identification very difficult. In this article, we have introduced a simple, yet systematic IP-based methodology for identifying quickly superior solutions to improve industrial system's sustainability performance. The IP-based information processing and decision-making method are capable of processing consistently and effectively a variety of uncertain information. The logically designed solution identification procedure can make the combinatorial problem to be solved efficiently through reducing the solution space stage wisely using different criteria set by the industrial organization. The derived solutions are sufficiently detailed which can greatly facilitate the industrial organization to make decisions on technology selection. This general methodology should be applicable to the study on sustainability enhancement problems of any size and scope.

Literature Cited

1. Batterham RJ. Ten years of sustainability: where do we go from here. *Chem Eng Sci*. 2003;58:2167–2179.
2. Beloff B, Lines M, Tanzil D, editors. *Transforming Sustainability Strategy into Action: the Chemical Industry*. Hoboken, NJ: Wiley, 2005.
3. Parry GW. The characterization of uncertainty in probabilistic risk assessment of complex systems. *Reliab Eng Syst Safe*. 1996;54:119–126.
4. Ruszczynski A. *Handbooks in Operations Research and Management Science: Stochastic Programming*. New York: Elsevier, 2004.
5. Li YP, Huang GH, Nie SL. An interval-parameter multistage stochastic programming model for water resources management under uncertainty. *Adv Water Resour*. 2006;29:776–789.
6. Tucker WT, Ferson S. *Probability Bounds Analysis in Environmental Risk Assessments, Applied Biomathematics*. New York, NY: Setauket, 2003.
7. Moore RE. *Interval Analysis*. NJ: Prentice-Hall, 1966.
8. Ferson S, Kreinovich V, Ginzburg L, Myers DS, Sentz K. *Constructing Probability Boxes and Dempster–Shafer Structures*. SAND2002-4015, Albuquerque, NW: Sandia National Laboratories, 2003.
9. Walley P. *Statistical Reasoning with Imprecise Probabilities*. London: Chapman and Hall, 1991.
10. Piluso C, Huang YL. Collaborative profitable pollution prevention: an approach for the sustainable development of complex industrial zones with uncertain information. *Clean Technol Environ Policy*. 2009;11:307–322.
11. Piluso C, Huang J, Liu Z, Huang YL. Sustainability assessment of industrial systems under uncertainty: a fuzzy-logic-based approach to short-to-mid-term predictions. *Ind Eng Chem Res*. 2010;49:8633–8643.
12. Liu Z, Piluso C, Huang YL. *Fuzzy logic based system modification for industrial sustainability enhancement*. In: *Design for Energy and the Environment*. Chicago, IL: CRC Press, 2009:841–849.
13. Sevionovic SP. *Risk in sustainable water resources management. Sustainability of Water Resources under Increasing Uncertainty*. In: *Proceedings of Rabat Symposium, SI*, Rabat, Morocco, April 1997.
14. Hersh MA. Sustainable decision making: the role of decision support systems. *IEEE Trans Syst Man Cybern Part C Appl Rev*. 1999;29:395–408.
15. Conner JA, Phillis YA, Manousiouthakis VI. On a sustainability interval index and its computation through global optimization. *AIChE J* 2011;105:60-63.
16. Ben-Haim Y. *Information-Gap Decision Theory: Decisions Under Severe Uncertainty*, 2nd ed. San Diego, CA: Academic Press, 2006.
17. Ben-Haim Y. *Info-gap decision theory for engineering design. Or: why 'Good' is preferable to 'Best'*. In: *Engineering Design Reliability Handbook*. Boca Raton, FL: CRC Press, 2005.
18. Hine D, Hall JW. Information gap analysis of flood model uncertainties and regional frequency analysis. *Water Resour Res*. 2010;46: W01514:19.

19. Gelman A. What is info-gap theory? 30 April 2009. Available at: http://www.stat.columbia.edu/cook/movabletype/archives/2009/04/what_is_info-ga.html. Accessed on July 25, 2011.
20. Xia J, Huang GH, Bass B. Combination of differentiated prediction approach and interval analysis for the prediction of weather variables under uncertainty. *J Environ Manage*. 1997;49:95–106.
21. Lin QG, Huang GH. IPEM: an interval-parameter energy systems planning model. *Energy Sources Part A*. 2008;30:1382–1399.
22. Lu HW, Huang GH, Liu ZF, He L. Greenhouse gas mitigation-induced rough-interval programming for municipal solid waste management. *J Air Waste Manage Assoc*. 2008;58:1546–1559.
23. Lv Y, Huang GH, Li YP, Yang ZF, Li CH. Interval-based air quality index optimization model for regional environmental management under uncertainty. *Environ Eng Sci*. 2009;26:1585–1597.
24. Li YP, Huang GH, Guo P, Yang ZF, Nie SL. A dual-interval vertex analysis method and its application to environmental decision making under uncertainty. *Eur J Oper Res*. 2010;200:536–550.
25. IChemE. *The sustainability Metrics—Sustainable Development Progress Metrics Recommended for Use in the Process Industries*. Rugby, UK: IChemE, 2002:105, 60–63.
26. Cobb C, Schuster D, Beloff B, Tanzil D. The AIChE sustainability index. *Chem Eng Prog*. 2009;105:60–63.
27. Zhang W, Dube MA, McLean DD, Kates M. Biodiesel production from waste cooking oil. 1. Process design and technological assessment. *Bioresour Technol*. 2003;89:1–6.
28. Glisic S, Skala D. The problems in design and detailed analyses of energy consumption for biodiesel synthesis at supercritical conditions. *J Supercrit Fluids*. 2009;49:293–301.
29. West AH, Posarac D, Ellis N. Assessment of four biodiesel production processes using HYSYS. *Plant. Bioresour Technol*. 2008;99:6587–6601.