

# Improving the Sustainability of Products Based on Sustainability Target Method

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**Abstract** - Increasing global population and consumption are causing declining natural and social systems. Sustainable development addresses these issues by integrating strategies for economic successes, environmental quality, and social equity. A Sustainability Target Method (STM) provides a practical sustainability target for individual businesses and products through determining the relative indicator resource productivity for environmental performance and the absolute indicator Eco-Efficiency for sustainability. Based on the indicators in STM, this paper investigates the sustainability relationship between a product and its components, between a manufacturer and its suppliers, and proposes a decision making approach to improve product sustainability through component selection and supplier selection. The approaches are illustrated through examples of a generalized product consisting of multiple components, which relates easily to circuit board assemblies and other type of electronic products.

**Index Terms** - Sustainable Development, Sustainability Target Method (STM), Eco-efficiency, Decision making

## 1. INTRODUCTION

Increasing public concern and statutory regulations about the environment and sustainable development are making environmental protection an important issue for industry. It is very important to develop and implement an unambiguous and quantitative measure for environmental impacts of products, processes and activities. There are various environmental impact assessment methods that are comprehensive in nature and generate a single numerical value reflecting the composite magnitude of global impact associated with a specific product. These include Eco-indicator 95 [7], Eco-indicator 99 [8], Ecological Footprint [12], and Sustainability Target Method (STM) [1-2].

Compared to other environmental impact assessment methods, the Sustainability Target Method (STM) shifts the focus from environmental impact to sustainability.

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Please refer to Ref. [9] for detailed comparison. STM explicitly considers economic or market value and is equally applicable to analyzing products/processes, services or facilities. By directly considering economic value, resource productivity measures can be generated, and comparison can be drawn between products or services that are not necessarily “functionally equivalent” but are instead economically equivalent. Thus, the STM approach provides a basis for decision making in different suppliers and manufacturers. The brief description of STM will be introduced in Section 2.

Some research has been conducted to investigate how to calculate the STM indicators [10, 13]. However, little work has done on how those indicators help decision makers improve product’s sustainability and global sustainability. Based on our previous work [5-6], this paper utilizes the STM indicator information to investigate the methods to support a manufacturer to improve its product sustainability. In general, a product can be viewed as the one that consists of its components, which are either produced by the assembly company itself or bought from its suppliers. This paper attempts to help the company make right decision to reach desired profitability and environmental performance in both cases.

The paper is organized as follows: Section 2 introduces the STM. Section 3 presents the general product tree structure. Section 4 proposes a sensitivity analysis-based decision making method to enhance a product’s sustainability through improving the sustainability of its components. Section 5 discusses decision making methods to sustainability improvement through supplier selection. Examples are presented in both Sections 4 and 5 to illustrate the corresponding methods. The conclusions are given in Section 6.

## 2. SUSTAINABILITY TARGET METHOD

The STM approach utilizes the earth’s carrying capacity estimates and economic information to provide a practical sustainability target for individual businesses and products. The principle of this approach is to establish a relationship between carrying capacity and both the environmental impact and economic value of products/processes. Initially formulated at Lucent Technologies Bell Laboratories, the STM is under continuing development through the collaboration of the Multi-lifecycle Engineering Research Center (MERC) at

New Jersey Institute of Technology (NJIT) with Lucent Technologies and Agere Systems. The key and unique feature of this method is the link between carrying capacity, economic value, and environmental impact to provide an absolute or “target” criterion for sustainability that is practical for use by business [3].

This section gives a brief description about this approach. The basic STM concept and key parameter estimation/calculation methods are described in detail in [1-2]. STM involves interpreting different types of environmental impact based on a single dimensionless indicator, i.e., the environmental impact per unit production rate, as denoted by  $EI_{PR}$ . Its computation is accomplished via normalization by using impact reference levels that relate impact with economic value and sustainability.  $EI_{PR}$  provides the basis for calculating the relative indicator Resource Productivity (RP) for environmental performance and the absolute indicator Eco-Efficiency (EE) for sustainability.

**2.1 Environmental Impact (EI)**

The Environmental Impact (EI) resulting from an activity, such as manufacturing a product or providing a service, is quantified by normalizing each associated impact using an impact reference level that relates in a specific way to sustainability. EI is aggregated by adding the ratios to obtain a single dimensionless indicator of total impact:

$$EI = I_1 / I_{R1} + I_2 / I_{R2} + \dots + I_N / I_{RN}$$

Each impact reference level  $I_R$  is the level at which the impact is environmentally sustainable at a rate of value generation  $V_R$ , i.e., the value reference level. Both the impact level and impact reference level are expressed per unit time (e.g., kg/year for emissions), and the same for  $V_R$  (e.g., \$/year).

For production rate  $P$  (product items per unit time), the environmental impact per unit production rate  $EI_{PR}$  is then:

$$EI_{PR} = EI / P = I_1^* / I_{R1} + I_2^* / I_{R2} + \dots + I_N^* / I_{RN}$$

where each  $I_i^* = I_i / P$  is the impact quantity per product item (e.g., kg CO<sub>2</sub> emissions per kWh of energy or kg of material).

**2.2 Resource Productivity (RP)**

Resource Productivity (RP) is the production rate achieved per unit environmental impact:

$$RP = P / EI = 1 / EI_{PR}$$

RP serves as a relative indicator of environmental performance that allows for direct comparison, such as between products or alternative product designs. The larger its RP, the better a product. An increasing trend in the resource productivity indicator RP would be an

indication that the firm is moving in the direction of using resources more efficiently and yielding less environmental impact.

**2.3 Eco-Efficiency (EE)**

Eco-Efficiency (EE) is defined as:

$$EE = \beta / EI$$

where  $\beta = V / V_R$  (value ratio);  $V$  is value creation, e.g. revenue (\$/year). The value of the product is established by the market.  $V_R$  is the value reference level corresponding to the impact reference levels. Then,

$$\begin{aligned} EE &= (V / V_R) / EI \\ &= (V_{PR} \times P) / (V_R \times EI) \\ &= V_{PR} \times (P / EI) / V_R \\ &= V_{PR} \times RP / V_R \end{aligned}$$

i.e.  $EE = V_{PR} \times RP / V_R$

where  $V_{PR}$  is the revenue per product unit or value added per unit. EE is an absolute indicator of sustainability.

**Definition 1:** A product is sustainable if its  $EE \geq 100\%$ .

EE is the ratio of the actual rate of value generation ( $V = V_{PR} \times P$ ) to the rate that is sustainable given the level of environmental impact ( $V_R \times EI$ ). It can be interpreted as the benefit achieved compared to the minimum allowable benefit given the level of environmental impact incurred in manufacturing the product. Thus, the criterion for sustainability is  $EE \geq 100\%$  ( $EE > 100\%$  simply indicates even less impact than the sustainable level given the value being provided). EE serves as an absolute indicator of sustainability of not only a product but also any activity. The activity could be processing materials, manufacturing components, or assembling a product. A more general definition is given below.

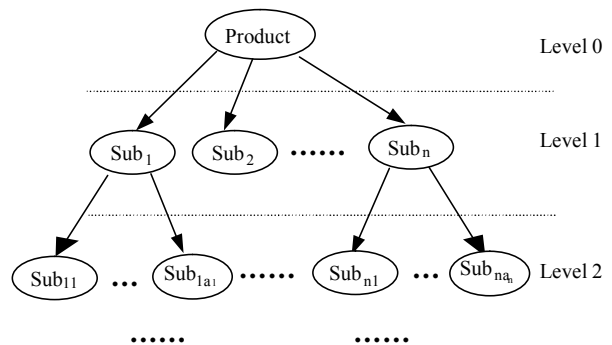


Fig.1 Tree structure of a product

**Definition 2:** An activity is sustainable if its  $EE \geq 100\%$ .

$EE > 100\%$  indicates less impact than the sustainable level given the value being created in an activity. Based on

Definition 2, “a product is sustainable” can be interpreted to “the activity of manufacturing the product is sustainable”. In other words, the value created is more than the minimum allowable increased value given the level of environmental impact incurred in the whole procedure of producing the product. Definition 2 is a general definition. A company/manufacturer is defined sustainable if the activities it performs are sustainable.

**Definition 3:** A company is sustainable if its  $EE \geq 100\%$ .

A company being sustainable means that less impact is generated by activities of the company than the sustainable level given the value being created by those activities. From the above discussion, sustainability depends on the value generation and environmental generation in activities. The STM provides a practical sustainability target for individual businesses and products through determining the relative indicator RP for environmental performance and the absolute indicator EE. It is expected that the values of RP and EE as high as possible to make products/companies most sustainable. The higher these values, the higher production rate achieved per unit of environmental impact and more sustainable. The methods to compute these values can be found in [2-3] and [13], and is out of the scope of this paper.

### 3. PRODUCT TREE STRUCTURE

In general, a product can be viewed as one consisting of its components. Its structure can be represented as a tree shown in Fig. 1 [14]. The root of the tree is the product itself. The assembly at level  $k$  can be composed of several subassemblies/parts at level  $k+1$ , which are called immediate components of the assembly, and so forth. An assembly or component that cannot be separated is a leaf node. If it is made of a single material, it is called a part; otherwise, it is a final subassembly (FS) [4]. A product's components can be a part, an FS or an assembly.

A company can improve a product's performance through improving its components' performances. One of the most important performances a company is facing to improve is sustainability, which integrates the strategies for economic success, environmental quality and social equity [10]. Given the STM information of the components, how a company is able to utilize the information to improve its product's sustainability is a decision-making issue we discuss in this paper.

The components are either produced by a company itself or bought from its suppliers. The suggestions on sustainability improvement in both cases are necessary to company decision makers. Both cases will be discussed in the following two sections respectively.

## 4. IV. SUSTAINABILITY IMPROVEMENT THROUGH IMPROVING PERFORMANCE OF COMPONENTS

In this section, it is assumed that the components of the product are produced by the company itself. We discuss how to improve efficiently the product's sustainability through improving the performance of its components. In order to do that, we need to understand the sustainability relationship between a product and its components.

### 4.1 Sustainability relationship between a product and its components

**Proposition 1:** Assuming that the value of each component in a product tree is fixed, the RP and EE of the product is the largest if the RP of each of its components is the largest.

*Proof:*

Assume that an assembly in a product tree has  $N$  immediate components. The quantity of Component  $i$  is  $n_i$ , and RP associated to Component  $i$  is  $RP_i$ ,  $i=1, 2, \dots, N$ . Then, RP and EE of the assembly are

$$RP = \frac{1}{\frac{n_1}{RP_1} + \frac{n_2}{RP_2} + \dots + \frac{n_N}{RP_N} + EI_{PR-Assembly}} \quad (4.1)$$

where  $EI_{PR-Assembly}$  is the environmental impact produced in assembling the assembly from its immediate components.

$$EE = V_{PR} \times RP / V_R \quad (4.2)$$

where  $V_{PR}$  is the accumulated value per assembly.

According to Eq. (4.1), an assembly has higher RP value if its immediate components have higher RP values. Since  $V_{PR}$  is fixed,  $V_{PR} / V_R$  is a constant. According to Eq.(4.2), for the assembly, a larger value of RP is corresponding to a larger EE value. Hence, an assembly will have the largest RP and EE values if its immediate components have the largest RP value. Applying this rule from leaf level to root, we can conclude that if all the components in a product tree have their largest RP values, RP and EE of the product are the largest. ♦

According to the above proposition, if a company attempts to make a product most sustainable, it should try to improve RPs of the components as much as possible. An issue is raised in this attempt. The problem is which component should be given the first priority consideration and requires most urgent improvement, such that the product is most sustainable. Next, a sensitivity analysis approach will be proposed to help a company make such a decision based on STM indicators.

### 4.2 Sensitivity analysis based on STM indicators

Based on the STM approach, a sensitivity analysis approach can be used to determine the RP improvement of which component has the most significant effect on the product's RP and EE. Without loss of the generality, this paper assumes that a company product is composed of  $N$  types of components – component  $i$ ,  $i=1, \dots, N$ . The quality

of Component  $i$  in it is  $n_i$ ; the unit value of Component  $i$  is  $V_{PR_i}$ ; and the RP and EE indicators associated to Component  $i$  are  $RP_i$  and  $EE_i$  respectively,  $i=1, \dots, N$ . Please note that these components are not necessary to be the product's immediate components.

### 1) The Product's RP Analysis

$$RP = \frac{1}{\frac{n_1}{RP_1} + \frac{n_2}{RP_2} + \dots + \frac{n_N}{RP_N} + EI_{PR-Assembly}}$$

where  $EI_{PR-Assembly}$  is the environmental impact produced in assembling a product from its components. RP is the production rate achieved per unit environmental impact for the product.

For brevity and clarity, let

$$x = \frac{n_A}{RP_A} + \frac{n_B}{RP_B} + \dots + \frac{n_N}{RP_N} + EI_{PR-Assembly}.$$

It is the environmental impact per unit production rate of the product. The sensitivity of  $RP_i$ 's effect on the product's RP is obtained by taking the first deviation of RP with respect to  $RP_i$ :

$$\begin{aligned} \frac{d(RP)}{d(RP_i)} &= \left(-\frac{1}{x^2}\right) \cdot \frac{dx}{d(RP_i)} \\ &= \left(-\frac{1}{x^2}\right) \cdot n_i \cdot \left(-\frac{1}{RP_i^2}\right) = \frac{1}{x^2} \cdot \frac{n_i}{RP_i^2}, \end{aligned}$$

which is the change of RP of the product per unit change of RP of Component  $i$ .

A company may improve RP of different components with different efforts. Assuming that  $C_i$  is the cost per unit change in  $RP_i$ . Considering this, the sensitivity of  $RP_i$ 's effect on the change of RP of the product with unit cost is:

$$\frac{d(RP)}{d(RP_i) \cdot C_i} = \frac{1}{x^2} \cdot \frac{n_i}{RP_i^2 \cdot C_i}$$

### 2) The Product's EE Analysis

$$EE = V_{PR} \times RP / V_R$$

where  $V_{PR}$  is the accumulated value per unit product.

Assuming that  $V_{PR}$  is fixed,  $V_{PR}/V_R$  is a constant. Thus, The sensitivity of  $RP_i$ 's effect on the product's EE is

$$\frac{d(EE)}{d(RP_i)} = \frac{V_{PR}}{V_R} \cdot \frac{d(RP)}{d(RP_i)} = \frac{V_{PR}}{V_R} \cdot \frac{1}{x^2} \cdot \frac{n_i}{RP_i^2}$$

which is the change of product's EE per unit RP change of Component  $i$ .

Considering the cost per unit change in  $RP_i$ , the sensitivity of  $RP_i$ 's effect on the change of EE of the product with unit cost is:

$$\frac{d(EE)}{d(RP_i) \cdot C_i} = \frac{V_{PR}}{V_R} \cdot \frac{1}{x^2} \cdot \frac{n_i}{RP_i^2 \cdot C_i}$$

The company should try to improve the RP of the component that can generate the largest improvement to its

product's RP and EE. From RP and EE analysis, we achieve the following consistent rules:

**Rule 1:** A company is producing a product composed of  $N$  types of components. The number of type- $i$  component is  $n_i$ , the RP associated to it is  $RP_i$ , and the cost per unit change in  $RP_i$  is  $C_i$ ,  $i=1, \dots, N$ . In order to make the product more sustainable, the company should choose the component with the maximum value of  $\frac{n_i}{RP_i^2 \cdot C_i}$  first to

improve the component's RP.

**Rule 2:** In the case that the cost for resource productivity improvement is not an issue or unknown, a company should select the component with the maximum value of

$$\frac{n_i}{RP_i^2} \text{ to improve first.}$$

These rules are interesting results and tell the decision makers in the company: to improve a product's sustainability efficiently, the components with lowest RP or EE may not be chosen to improve with highest priority; and the sequence of priority is determined by the value of

$$\frac{n_i}{RP_i^2 \cdot C_i} \text{ or } \frac{n_i}{RP_i^2}.$$

### 4.3 Example

In this section, we use a simple example to illustrate the above analysis and verify the above conclusions. It assumes that a company is producing a printed circuit board, which is composed of 4 type-A chips (ID: A) and 2 type-B chips (ID: B) and Baseboard (ID: C) respectively. The relevant parameters are shown in Table 1.

Table 1: Components of a product, and their production rates per unit environmental impact (RP), costs per unit change of RP (C), eco-efficiency (EE)

ID	Quantity	RP	C	EE
A	4	200	0.05	1
B	2	120	0.08	1.2
C	1	150	0.07	1.1

#### 1) Based on RP and Costs Per Unit Change of RP

$$\frac{n_A}{RP_A^2 \cdot C_A} = \frac{4}{200^2 \cdot 0.05} = \frac{1}{500}$$

$$\frac{n_B}{RP_B^2 \cdot C_B} = \frac{2}{120^2 \cdot 0.08} = \frac{1}{576}$$

$$\frac{n_C}{RP_C^2 \cdot C_C} = \frac{1}{150^2 \cdot 0.07} = \frac{1}{15750}$$

$$\frac{n_A}{RP_A^2 \cdot C_A} > \frac{n_B}{RP_B^2 \cdot C_B} > \frac{n_C}{RP_C^2 \cdot C_C}$$

According to Rule 1, in this example, the company should focus on Chip A's performance improvement first, then Chip B, finally the baseboard because that Chip A's

RP has the most significant effect on the product with per unit cost, and baseboard has the least effect.

Initially, the RP and EE of the product:

$$RP = \frac{1}{\frac{n_A}{RP_A} + \frac{n_B}{RP_B} + \frac{n_C}{RP_C} + EI_{PR-Assembly}}$$

$$= \frac{1}{\frac{4}{200} + \frac{2}{120} + \frac{1}{150} + 0.01} = 18.87$$

$$EE = V_{PR} \cdot RP / V_R = 20 \times 18.87 / 400 = 0.94$$

Assume that the RPs of Chip A, Chip B and the baseboard are increased by 50 per unit environmental impact. We analyze their effects on the product's sustainability, respectively.

First consider that RP of Chip A is increased by 50 per unit environmental impact, and RPs of Chip B and the baseboard keep unchanged, i.e.,  $RP_A=250$ ,  $RP_B=120$ , and  $RP_C=150$  per unit environmental impact. Assume that  $EI_{PR-assembly} = 0.01$ ,  $V_{PR} = \$20$  per unit product,  $V_R = \$400$  per unit environmental impact.

$$RP = \frac{1}{\frac{n_A}{RP_A} + \frac{n_B}{RP_B} + \frac{n_C}{RP_C} + EI_{PR-Assembly}}$$

$$= \frac{1}{\frac{4}{250} + \frac{2}{120} + \frac{1}{150} + 0.01} = 20.26$$

$$\text{cost} = C_A \cdot \Delta RP_A = 0.05 \times 50 = 2.5$$

$$\frac{\Delta RP}{\text{cost}} = \frac{20.26 - 18.87}{2.5} = 0.556$$

$$\frac{\Delta EE}{\text{cost}} = \frac{1.013 - 0.94}{2.5} = 0.029$$

Similarly, if RP of Chip B is increased by 50 per unit environmental impact, and RPs of Chip A and the baseboard keep unchanged,

$$RP = 20.63$$

$$EE = 1.032$$

$$\text{cost} = 4$$

$$\frac{\Delta RP}{\text{cost}} = 0.44 \text{ and } \frac{\Delta EE}{\text{cost}} = 0.023$$

If RP of the based board is increased by 50 per unit environmental impact, and RPs of Chip A and Chip B keep unchanged.

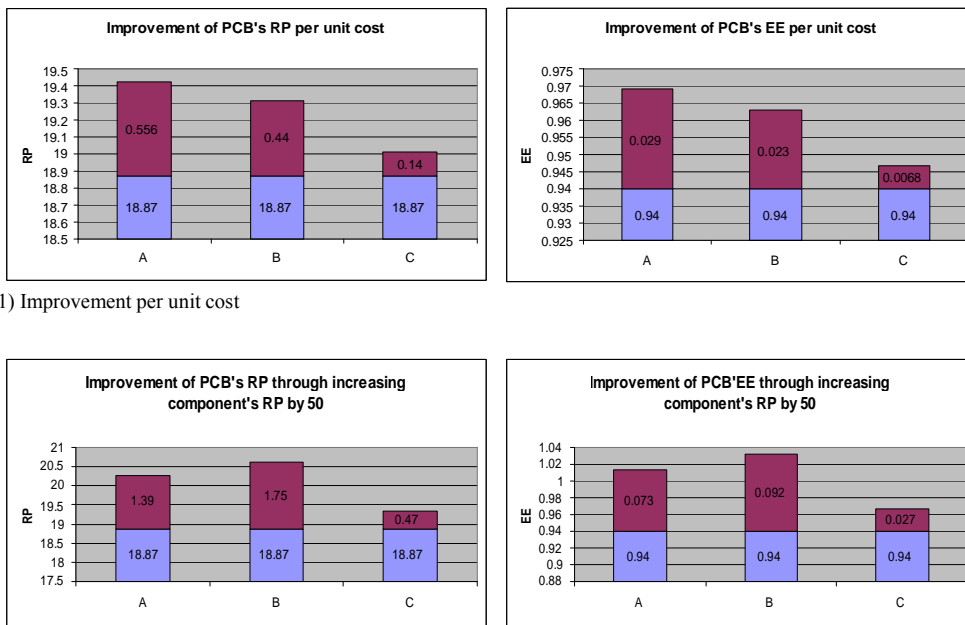
$$RP = 19.34$$

$$EE = 0.967$$

$$\text{cost} = 3.5$$

$$\frac{\Delta RP}{\text{cost}} = 0.14 \text{ and } \frac{\Delta EE}{\text{cost}} = 0.0068$$

From the above calculation, we can see the Chip A has the most significant effect on the product's sustainability by the same performance improvement as Chip B and the



2) Improvement per 50 units of RP increase

Fig. 2 Improvement of RP and EE values of the PCB using different strategies

$$EE = V_{PR} \times RP / V_R = 20 \times 20.26 / 400 = 1.013$$

The cost for improvement is:

baseboard with per unit cost. The result can be clearly observed from Chart 1 in Figure 2. Thus, in this example, the company should focus on Chip A's RP performance

improvement first to improve the product's sustainability. Therefore, Rule 1 in Section 4.2 is verified by this example.

## 2) Based on RP Information of Components without considering costs

When the cost per unit change of a component's RP is not an issue or unknown,

$$\frac{n_A}{RP_A^2} = \frac{4}{200^2} = \frac{1}{10000}$$

$$\frac{n_B}{RP_B^2} = \frac{2}{120^2} = \frac{1}{7200}$$

$$\frac{n_C}{RP_C^2} = \frac{1}{150^2} = \frac{1}{22500}$$

$$\frac{n_B}{RP_B^2} > \frac{n_A}{RP_A^2} > \frac{n_C}{RP_C^2}$$

According to Rule 2 in Section 4.2, without considering the cost for RP improvement, the company should focus on Chip B's performance improvement first, then Chip A, and finally the baseboard. Please see Chart 2 of Figure 2. In this example, EE of the product is improved by 0.092 if RP of Chip B is increased by 50, while the EE is improved by 0.073 and 0.027 respectively if Chip A and the baseboard are selected to be improved. We can see the Chip B has the most significant effect on the product's sustainability by the same performance improvement as Chip A and the baseboard. The results are consistent with the rules we derived in Section 4.2.

## 5. SUSTAINABILITY IMPROVEMENT THROUGH SUPPLIER SELECTION

In the last section, it is assumed that the components are produced by the company itself. A sensitivity analysis-based approach is proposed to help the company efficiently improve the sustainability by choosing the proper component to work on. With the development of supply chain and co-operations among individual companies, the cycle between components, manufacturers and end customers has been greatly shortened. Many companies buy parts from their suppliers instead of producing every component by themselves, specially in rapidly developing electronics manufacturing industry. Therefore, how to choose the suppliers to balance profitability and environmental performance is among the crucial decisions a company has to make.

In this section, it is assumed that the components are provided by multiple suppliers. A company/ manufacturer buys components from suppliers and assembles them into final products. The following discussions thus focus on the supplier selection problem, i.e., how to select proper suppliers to achieve the desired profitability and environmental performance. Since the STM indicators provide a communication bridge between manufacturers and suppliers, the discussions are based on the analysis of

STM indicators. Before making such decisions, we need to understand the sustainability relationship among suppliers, manufacturers, and overall economy.

### 5.1 Sustainability relationship analysis

*Proposition 2: If the components of a product are sustainable and the company who assembles the product is sustainable, the whole product is sustainable.*

*Proof:*

Eco-Efficiency of Component  $i$  is

$$EE_i = Price_i \times RP_i / V_R$$

where  $Price_i$  is the price of Component  $i$  a supplier asks for. According to the definition in Section 2,  $EE_i \geq 1$  if Component  $i$  is sustainable.

$$EE_i \geq 1$$

$$\Rightarrow Price_i \times RP_i \geq V_R$$

$$\Rightarrow RP_i \geq \frac{V_R}{Price_i}$$

$$\Rightarrow \frac{n_i}{RP_i} \leq \frac{n_i \cdot Price_i}{V_R} \quad (5.1)$$

Let  $EI_{PR-Assembly}$  be the environmental impact involved in assembling a product from its components. The production rate achieved per unit environmental impact for assembling the product.

$$RP_{Assembly} = \frac{1}{EI_{PR-Assembly}}$$

Since the company who assembles the product is sustainable, the eco-efficiency of the company on this product is greater than or equal to one, i.e.

$$EE_{Assembly} = (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times RP_{Assembly} / V_R \geq 1$$

where  $V_{PR} - \sum_{i=1}^N n_i \cdot price_i$  is the added value created by the company.

$$EE_{Assembly} = (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times RP_{Assembly} / V_R \geq 1$$

$$\Rightarrow (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times \frac{1}{EI_{Assembly}} / V_R \geq 1$$

$$\Rightarrow EI_{Assembly} \leq \frac{V_{PR} - \sum_{i=1}^N n_i \cdot price_i}{V_R} \quad (5.2)$$

The production rate achieved per unit environmental impact for the product is

$$RP = \frac{1}{\sum_{i=1}^N \frac{n_i}{RP_i} + EI_{PR-Assembly}}$$

Eco-efficiency of the product is

$$EE = V_{PR} \times RP / V_R$$

$$= V_{PR} \times \frac{1}{\sum_{i=1}^N \frac{n_i}{RP_i} + EI_{PR-Assembly}} / V_R \quad (5.3)$$

From Eq. (5.1)-(5.3), it can be derived that

$$EE = V_{PR} \times \frac{1}{\sum_{i=1}^N \frac{n_i}{RP_i} + EI_{PR-Assembly}} / V_R$$

$$\geq V_{PR} \times \frac{1}{\sum_{i=1}^N \frac{n_i \cdot Price_i}{V_R} + \frac{V_{PR_i} - \sum_{i=1}^N n_i \cdot price_i}{V_R}} / V_R$$

$$= V_{PR} \times \frac{V_R}{V_{PR}} / V_R = 1$$

Therefore, the product is sustainable. ♦

Please note that the converse of the above proposition may not be true. The answer to the question how to choose the suppliers to balance profitability and environmental performance varies with different goals. Different cases are discussed next.

## 5.2 Decision making in different cases

*Case 1: A company needs to decide how to choose suppliers such that the overall economy is most sustainable.*

To make the overall economy most sustainable means to make the product most sustainable through a whole supply chain. The eco-efficiency of the product is

$$EE = V_{PR} \times RP / V_R$$

The objective of the case is to maximize the above value. Assuming that  $V_{PR}$  is fixed,  $V_{PR} / V_R$  is a constant. Maximizing EE is equivalent to maximizing RP.

$$RP = \frac{1}{\sum_{i=1}^N \frac{n_i}{RP_i} + EI_{PR-Assembly}}$$

Please note  $1/RP$  is the total environmental impact produced in the product's whole supply chain. To minimize the environmental impact, the supplier who provides the components with highest resource productivity should be chosen. In other words, larger  $RP_i$  ( $i=1,2,\dots,n$ ) result in larger RP.

From the above analysis, we can draw the following conclusion: to make the overall economy most sustainable, a company should buy Component  $i$  from the supplier with maximum  $RP_i$ . A company probably cares the sustainability of itself more than the overall economy. Next, we discuss the case that the company tries to make itself most sustainable.

*Case 2: The company makes itself most sustainable.*

The production rate achieved per unit environmental impact for assembling the product from its components is

$$RP_{Assembly} = \frac{1}{EI_{PR-Assembly}}$$

From this equation, it can be observed that the resource productivity of the company is not related to the components' RP and EE values.

Eco-efficiency of the company on the product is

$$EE_{Assembly} = (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times RP_{Assembly} / V_R$$

Assuming the value of the product  $V_{PR}$  is not affected by the prices of components, the increased value is higher with lower prices of components. Therefore, if the company tries to make itself most sustainable without considering sustainability of the overall economy and the suppliers, it always intends to choose the suppliers who ask for the lowest prices.

Cases 1 and 2 derive different conclusions on supplier selection. If the supplier provides a component with lowest price as well as the highest resource productivity, the supplier is definitely chosen because the sustainability of both the company and the overall economy is maximized. However, the component with the lowest price provided by a certain supplier may not have the highest RP. If sustainability of both overall economy and company are taken into consideration, the problem becomes a multi-objective decision making issue. How to make such decision depends on the company's missions and principles. A company probably cares the sustainability of itself more than the overall economy. However, when a company maximizes the sustainability of its own, it has to ensure that the sustainability of the overall economy is sustainable. Therefore, the following case probably is the principle a company most likely adopts.

*Case 3: Maximize the company's sustainability with the condition that the overall economy is sustainable, i.e., EE of the product is not less than 1.*

If this principle is applied, the supplier who provides sustainable components with the lowest price will be chosen. In other words, the company can filter out the components that are not sustainable first and then choose those with the lowest prices. According to Proposition 2 in this section, if the company is sustainable and the components are sustainable, the whole product is sustainable. Therefore, the sustainability of the overall economy does not need to evaluate as long as EE of the company is sustainable.

If EE of the company is less than one even though the components with the lowest prices are chosen, the problem is not supplier selection issue any more and the company has to improve its RP.

Since the decision making discussed in this section involves different manufactures/providers, we may need to

consider the reliability of RP and EE values provided by individual providers. In other words, if a provider claims that a component's RP=200 and EE=1.8, should we believe it? And to what degree? A score, i.e., supplier reputation, can be used to adjust those STM indicator values. In order to define the score, the values need to be assessed. For example, some components are selected randomly from a supplier and their RP and EE are evaluated by some unbiased organization and the score can be calculated as the ratio of assessed value and the value publicized by the provider.

**Definition 4:** The supplier's reputation on STM indicators is defined as

$$score = \sum_{i=1}^M (RP_{i\text{ assessed}} / RP_{i\text{ provided}}) / M$$

Where M is the number of components evaluated;  $RP_{i\text{ assessed}}$  is the assessed RP value of Component i while  $RP_{i\text{ provided}}$  is the value publicized by the supplier. The

score is also equal to  $\sum_{i=1}^M (EE_{i\text{ assessed}} / EE_{i\text{ provided}}) / M$  since

$EE = V_{PR} \times RP / V_R$  and  $V_{PR} / V_R$  is a constant for a certain component.

The score can be used to adjust the indicator values publicized by the provider.

**Definition 5:** The Adjusted RP (ARP) value of a component of a supplier is defined as

$$ARP = RP * score$$

where the score is defined in Definition 4; RP is the publicized RP value of the component. For example, if a component's RP value is 250 provided by a supplier with score of 0.8, then the adjusted RP value of the component is 200.

**Definition 6:** The Adjusted EE (AEE) value of a component of a supplier is defined as

$$AEE = EE * score$$

Where the score is defined in Definition 4; EE is the publicized EE value of the component.

If the scores of suppliers are available, this information can be used to refine the rules for different cases discussed in this section earlier by replacing the RP and EE value of each component by ARP and AEE.

*Case 1: A company needs to decide how to choose suppliers such that the overall economy is most sustainable.*

Rule: To make the overall economy most sustainable, a company should buy Component i from the supplier with maximum  $ARP_i$ .

*Case 2: The company makes itself most sustainable.*

Rule: To maximize sustainability of a company, it chooses the suppliers who ask for the lowest prices.

*Case 3: Maximize the company's sustainability with the condition that the overall economy is sustainable.*

Rule: The company should choose Component i from the supplier who provides the lowest price with  $AEE_i \geq 1$ .

### 5.3 An example

A similar example as in Section 4 is used to illustrate the sustainability improvement strategies through supplier selection. It assumes that a company is producing a printed circuit board, which is composed of 4 type-A chips (ID: A) and 2 type-B chips (ID: B) and Baseboard (ID: C) respectively. We assume  $EI_{PR\text{-assembly}} = 0.01$ ,  $V_{PR} = \$20.5$  per unit product,  $V_R = \$400$  per unit environmental impact. There are four suppliers. Supplier 1, 2 and 3 all provide both A and B. Supplier 3 and 4 provide C. The relevant parameters about the components are shown in Table 2.  $RP_A$ ,  $RP_B$ ,  $RP_C$ ,  $EE_A$ ,  $EE_B$ , and  $EE_C$  are the STM indicator values the supplier claims. We will see how the company should choose suppliers in two cases: 1) no company reputation score is available, so the decision will be based on the original RP and EE values provided by the suppliers; and 2) using adjusted RP and EE values.

#### 1) Based on original RP and EE values

*Case 1: A company needs to decide how to choose suppliers such that the overall economy is most sustainable.*

To make the overall economy most sustainable, a company should buy Component i from the supplier with maximum  $RP_i$ . Therefore, the company should buy Chip A from Supplier 2, Chip B from Supplier 3, and Chip C from Supplier 4.

RP of the product is:

$$RP = \frac{1}{\sum_{i=1}^N \frac{n_i}{RP_i} + EI_{PR\text{-Assembly}}} = \frac{1}{\frac{4}{250} + \frac{2}{200} + \frac{1}{150} + 0.01} = 23.45$$

EE of the product is:

$$EE = V_{PR} \cdot RP / V_R = 20.5 \times 23.45 / 400 = 1.2$$

EE of the company is:

$$EE_{\text{Assembly}} = (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times RP_{\text{Assembly}} / V_R = (20.5 - 4 * 1.6 - 2 * 3.6 - 3) \times \frac{1}{0.01} / 400 = 0.925$$

We can see that the company's EE is less than 1, which means that the company is not sustainable.

*Case 2: The company makes itself most sustainable.*

To maximize sustainability of a company, it chooses the suppliers who ask for the lowest prices. Therefore, the

company should buy Chip A from Supplier 2, Chip B from Supplier 1, and Chip C from Supplier 3.

EE of the company:

$$EE_{Assembly} = (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times RP_{Assembly} / V_R$$

$$= (20.5 - 4 * 1.6 - 2 * 3 - 2.5) \times \frac{1}{0.01} / 400 = 1.4$$

RP of the product is:

$$RP = \frac{1}{\sum_{i=1}^N \frac{n_i}{RP_i} + EI_{PR-Assembly}}$$

$$= \frac{1}{\frac{4}{250} + \frac{2}{120} + \frac{1}{100} + 0.01} = 18.99$$

EE of the product is:

$$EE = V_{PR} \cdot RP / V_R = 20.5 \times 18.99 / 400 = 0.97$$

We can see the company is sustainable. However, the product is not sustainable, which makes the overall economy not sustainable.

*Case 3: Maximize the company's sustainability with the condition that the overall economy is sustainable.*

To maximize the company most sustainable and at the

chip Supplier 3 provides is not sustainable. Thus, Supplier 4 is chosen as the provider of Baseboard.

EE of the company:

$$EE_{Assembly} = (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times RP_{Assembly} / V_R$$

$$= (20.5 - 4 * 1.6 - 2 * 3.2 - 3) \times \frac{1}{0.01} / 400 = 1.18$$

RP of the product is:

$$RP = \frac{1}{\sum_{i=1}^N \frac{n_i}{RP_i} + EI_{PR-Assembly}}$$

$$= \frac{1}{\frac{4}{250} + \frac{2}{150} + \frac{1}{150} + 0.01} = 21.74$$

EE of the product is:

$$EE = V_{PR} \cdot RP / V_R = 20.5 \times 21.74 / 400 = 1.11$$

According Proposition 2 in Section 5.1, if the components of a product are sustainable and the company who assembles the product is sustainable, the whole product is sustainable. The above calculation result confirms the proposition.

2) Based on adjusted RP and EE values

Table 2: Components of a product and their suppliers

1) Providers of Chip A

	score	price <sub>A</sub>	RP <sub>A</sub>	Adjusted RP <sub>A</sub> (ARP <sub>A</sub> )	EE <sub>A</sub>	Adjusted EE <sub>A</sub> (AEE <sub>A</sub> )
<b>Supplier 1</b>	1.4	\$2.2	200	280	1.1	1.54
<b>Supplier 2</b>	0.8	\$1.6	250	200	1	0.8
<b>Supplier 3</b>	1	\$2	220	220	1.1	1.1

2) Providers of Chip B

	score	price <sub>B</sub>	RP <sub>B</sub>	Adjusted RP <sub>B</sub> (ARP <sub>B</sub> )	EE <sub>B</sub>	Adjusted EE <sub>B</sub> (AEE <sub>B</sub> )
<b>Supplier 1</b>	1.4	\$3	120	168	0.9	1.26
<b>Supplier 2</b>	0.8	\$3.2	150	120	1.2	0.96
<b>Supplier 3</b>	1	\$3.6	200	200	1.8	1.8

3) Providers of Baseboard (Component C)

	score	price <sub>C</sub>	RP <sub>C</sub>	Adjusted RP <sub>C</sub> (ARP <sub>C</sub> )	EE <sub>C</sub>	Adjusted EE <sub>C</sub> (AEE <sub>C</sub> )
<b>Supplier 3</b>	1	\$2.5	100	100	0.60	0.60
<b>Supplier 4</b>	1	\$3	150	150	1.13	1.13

same time to guarantee the overall economy is sustainable, the company should choose the supplier who provides sustainable components with the lowest price.

All the suppliers provide sustainable Chip A, thus Supplier 2 who asks lowest price will be chose. For Chip B, filter out Supplier 1 first as EE<sub>B</sub> of Supplier 1 is less than 1, then choose lower price from Supplier 2 and 3. Supplier 2 is the winner. For Chip C, there are two suppliers, but the

*Case 1: A company needs to decide how to choose suppliers such that the overall economy is most sustainable.*

To make the overall economy most sustainable, a company should buy Component i from the supplier with maximum ERP<sub>i</sub>. Therefore, the company should buy Chip A from Supplier 1, Chip B from Supplier 3, and Chip C from Supplier 4.

EE of the company:

$$EE_{Assembly} = (V_{PR} - \sum_{i=1}^N n_i \cdot price_i) \times RP_{Assembly} / V_R$$

$$= (20.5 - 4 * 2.2 - 2 * 3.6 - 3) \times \frac{1}{0.01} / 400 = 0.375$$

EE of the product is:

$$EE = 20.5 \times \frac{1}{\frac{4}{280} + \frac{2}{200} + \frac{1}{150} + 0.01} = 1.25$$

The product is most sustainable. However, the company is far from sustainable.

*Case 2: The company makes itself most sustainable.*

To maximize sustainability of a company, it chooses the suppliers who ask for the lowest prices. The supplier selection decision is the same as in Section 5.3: 1) because the decision is not based on EE or RP values, but prices. Therefore, the company should buy Chip A from Supplier 2, Chip B from Supplier 1, and Chip C from Supplier 3.

EE of the company:

$$EE_{Assembly} = (20.5 - 4 * 1.6 - 2 * 3 - 2.5) \times \frac{1}{0.01} / 400 = 1.4$$

EE of the product:

$$EE = 20.5 \times \frac{1}{\frac{4}{200} + \frac{2}{168} + \frac{1}{100} + 0.01} = 0.978$$

The company is most sustainable while the product is not.

*Case 3: Maximize the company's sustainability with the condition that the overall economy is sustainable.*

To maximize the company most sustainable with the guarantee that the overall economy is sustainable, the company should choose the supplier who provides sustainable components with the lowest price.

Now, the adjusted EE values will be used to filter out components that are not sustainable. Therefore, Supplier 2 is filtered out for Chip A and Chip B; Supplier 3 is filtered out for Chip C. Finally, Supplier 3 is the winner for Chip A, Supplier 2 for Chip B, and Supplier 4 for Chip C.

EE of the company:

$$EE_{Assembly} = (20.5 - 4 * 1.6 - 2 * 3 - 3) \times \frac{1}{0.01} / 400 = 1.38$$

EE of the product:

$$EE = 20.5 \times \frac{1}{\frac{4}{220} + \frac{2}{168} + \frac{1}{100} + 0.01} = 1.1$$

Now, both the company and product are sustainable.

## 6. CONCLUSIONS

“Sustainable development” recently became a major theme in many countries. It is receiving more and more attention from governments, environmental organizations, and various industrial sectors. How to make its products most sustainable and keep the overall economy sustainable has become a company's one of the most important

decisions to make. Based on STM indicators, this paper exploits the relationship between a product and its components, and the relationship between the individual companies and overall economy on sustainability, and proposes the decision making rules to support a company to enhance its sustainability. Two primary cases are analyzed: 1) the product's components are produced by the same company as the product itself; and 2) a company chooses components for a product from multiple suppliers. Possible sub-cases are discussed in detail to help a company make good decisions based on the different principles a company adheres to. The paper discussed supplier selection problem only on a single layer of a supplier chain. Multi-layer supplier selection problem needs to be further investigated. The future work also includes integrating STM with lifecycle assessment, such as analysis of service, usage and recycling activities as well as the design and manufacturing processes. The data acquisition approaches for calculation and the decision-makings based on the uncertain information are also worthy for in-depth study.

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