An Improved Binary Linear Programming Approach for Life Cycle Assessment System Boundary Identification

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Abstract - **According to ISO standards life cycle assessment (LCA) consists of goal definition and scoping, inventory analysis, life cycle impact assessment and interpretation. In goal definition and scoping LCA system boundary is defined. Since LCA is time consuming then there is a need for a systematic approach to determine which processes needed to be included in the system boundary. This paper fulfills the need by proposing an improved binary linear programming model for LCA system boundary identification. The objective function of the model is to minimize the number of processes included in the system boundary and its constraints are the specified mass, energy and economic value ratios. In order to demonstrate its applicability an example is presented. A sensitivity analysis is also conducted in order to illustrate how the change in the specified mass, energy and economic value ratio will affect current optimum system boundary.**

Keywords - **LCA, linear programming, system boundary**

I. INTRODUCTION

As environmental awareness of the society increases, industries find that it is beneficial to produce environmental friendly products. In order to achieve this, the first step to do is to measure product's environmental impacts. One of the tools that can be used is life cycle assessment (LCA) which assesses environmental impacts of products from material extraction to end-of-life treatment. LCA consists of four phases: (1) goal definition and scoping, (2) inventory analysis, (3) life cycle impact assessment (LCIA) and (4) interpretation [1]. Furthermore, according to SAIC [2], in goal and scoping, system boundary of the LCA study is defined.

Tillman et al. [3] classified LCA system boundary into boundaries between the technological system and nature, geographical area, time horizon, capital goods and boundaries between the life cycle of the studied product and related life cycles. Other authors such as Guinée et al., as cited in [4], distinguished LCA system boundaries into boundaries between technical systems and the environment, between technological systems under study and other technological systems, and boundaries between significant and insignificant processes.

This paper focuses on boundaries between significant and insignificant processes. Since LCA is a time consuming process, in practice, there is a need for a systematic method to define which processes needed to be included or excluded in the LCA system boundary.

II. EXISTING APPROACHES FOR LCA SYSTEM BOUNDARY IDENTIFICATION

In ISO standards, the system boundary is defined through the following procedures [5]: (1) define an initial system boundary, (2) conduct sensitivity analysis and (3) improve the system boundary by adding new unit processes shown to be significant by sensitivity analysis. According to Suh et al. [5] and Reynold et al. [6], this approach has practical difficulties because environmental impacts need to be quantified before system boundary is defined.

By considering the weakness of the guideline provided by the ISO standards, Reynolds et al. [6] proposed a method known as Relative Mass-Energy-Economic (RMEE) to help practitioners in defining LCA system boundary. The RMEE compares mass, energy and economic value ratios of a unit process to a parameter known as boundary cut-off ratio. However, in RMEE, the procedure needs to be done all over again if the boundary cut-off ratio changes [7].

Other methods in defining LCA system boundary can be found in Suh et al. [5] and Suh and Huppes [8]. Three methods are discussed by the authors, process analysis approach, economic input/output (I/O) approach and hybrid approach. Furthermore, the hybrid approach is distinguished into tiered hybrid, I/O based hybrid and I/O based hybrid [8].

The disadvantage of the process analysis approach is that it is limited to the processes included to the chosen system boundary therefore subjectivity is involved [5]. For the I/O LCA, since monetary value is used then price variability may distort physical flows within industrial sectors [5]. For the hybrid approach, according to [5], tiered hybrid approach has problem with double counting and integrated hybrid approach is time consuming. Furthermore, significant error may occur when significant processes are modeled by using the aggregated data available in I/O based hybrid approach [8].

The application of the optimization approach in defining the LCA system boundary can be found in Afrinaldi et al. [7]. The authors employed a binary linear programming model. Since the approach is an optimization technique then sensitivity analysis is easy to be done. However, this approach possesses several problems. The authors present two objective functions that can be selected by the analysts, (1) total number of processes minimization and (2) mass, energy and economic value ratios maximization, and one of the

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constraints is the budget constraint. It does not seem appropriate to include budget constraints in LCA because if particular processes have significant environmental impacts then they have to be included in the LCA study although much cost is needed to assess their impacts. Moreover, it is not necessary to maximize mass, energy and economic value ratios because those ratios are predetermined.

III. PROPOSED METHODOLOGY

This methodology improves the binary linear programming approach presented in Afrinaldi et al. [7]. Here, budget constraints are omitted. Specified mass, energy and economic value ratios are treated as the constraints. Consequently, only the total number of processes minimization is treated as the objective function. The use of mass, energy and economic value ratios in this paper and in Afrinaldi et al. [7] was based on Raynolds et al. [6]. Let us consider that $i = \{1, 2, 3\}$ represents life cycle stage of a product where 1 is material production, 2 is manufacturing and 3 is end-of-life treatment. The decision variables are defined as the following.

$x_j^{(i)}$ = The j^{th} process of life cycle stage *i*.
$x_{jk}^{(i)}$ = The k^{th} process of process *j*.
$x_{jkl}^{(i)}$ = The l^{th} process of process *jk*.

The value of the decision variables is binary as given by (1). An example of decision variable structure is presented in Fig. 1.

$$x_j^{(i)} = x_{jk}^{(i)} = x_{jkl}^{(i)} = \begin{cases} 1, \ if \ \ inside \ the \ boundary \\ 0, \ if \ \ outside \ the \ boundary \end{cases} \qquad (1)$$

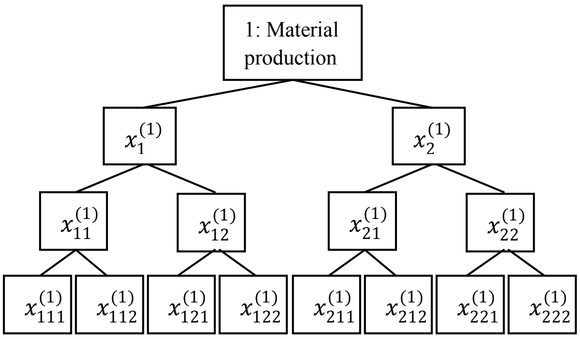

Fig. 1. An example of decision variable structure

As shown in decision variable definition and in Fig. 1, only processes with up to three subscripts are considered. This is done for simplification purpose. Furthermore, let us define the following.

α = Specified ratio of total mass flowing inside system boundary to total mass flowing inside product life cycle.
β = Specified ratio of total energy flowing inside system boundary to total energy flowing inside product life cycle.
γ = Specified ratio of total economic value of processes inside system boundary to total economic value of processes inside product life cycle.
$m_j^{(i)}$ = mass flowing in the j^{th} process of life cycle stage *i*.
$m_{jk}^{(i)}$ = mass flowing in the k^{th} process of process *j*.
$m_{jkl}^{(i)}$ = mass flowing in the l^{th} process of process *jk*.
$e_j^{(i)}$ = energy flowing in the j^{th} process of life cycle stage *i*.
$e_{jk}^{(i)}$ = energy flowing in the k^{th} process of process *j*.
$e_{jkl}^{(i)}$ = energy flowing in the l^{th} process of process *jk*.
$v_j^{(i)}$ = economic value of the j^{th} process of life cycle stage *i*.
$v_{jk}^{(i)}$ = economic value of the k^{th} process of process *j*.
$v_{jkl}^{(i)}$ = economic value of the l^{th} process of process *jk*.

The specified minimum mass, energy and economic value ratios are given by (2), (3) and (4).

$$\frac{\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} m_j^{(i)} x_j^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} m_{jk}^{(i)} x_{jk}^{(i)} \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} m_{jkl}^{(i)} x_{jkl}^{(i)} \end{array}\right)}{\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} m_j^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} m_{jk}^{(i)} \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} m_{jkl}^{(i)} \end{array}\right)} \geq \alpha \qquad (2)$$

$$\frac{\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} e_j^{(i)} x_j^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} e_{jk}^{(i)} x_{jk}^{(i)} \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{jkl}^{(i)} x_{jkl}^{(i)} \end{array}\right)}{\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} e_j^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} e_{jk}^{(i)} \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{jkl}^{(i)} \end{array}\right)} \geq \beta \qquad (3)$$

$$\frac{\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} v_j^{(i)} x_j^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} v_{jk}^{(i)} x_{jk}^{(i)} \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} v_{jkl}^{(i)} x_{jkl}^{(i)} \end{array}\right)}{\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} v_j^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} v_{jk}^{(i)} \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} v_{jkl}^{(i)} \end{array}\right)} \geq \gamma \qquad (4)$$

The binary linear programming model is given by the following.

$$Min \sum_{i=1}^{3}\sum_{j=1}^{J} x_j^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} x_{jk}^{(i)} + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{jkl}^{(i)} \qquad (5)$$

subject to

$$\sum_{j=1}^{J} x_j^{(i)} \le M \qquad \text{for } i = 1, 2, 3. \qquad (6)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} x_{jk}^{(i)} \le M x_{j'}^{(i)} \qquad \text{for } i = 1, 2, 3; \quad \text{for } j' = 1, 2, \ldots J. \qquad (7)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} x_{jkl}^{(i)} \ge M x_{j'k'}^{(i)} \quad \text{for } i = 1, 2, 3; \quad \text{for any combination of } j' \text{ and } k'; \; j' = 1, 2, \ldots J \text{ and } k' = 1, 2, \ldots K. \qquad (8)$$

$$\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} m_j^{(i)}\left(\alpha - x_j^{(i)}\right) + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} m_{jk}^{(i)}\left(\alpha - x_{jk}^{(i)}\right) \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} m_{jkl}^{(i)}\left(\alpha - x_{jkl}^{(i)}\right) \end{array} \right) \le 0 \qquad (9)$$

$$\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} e_j^{(i)}\left(\beta - x_j^{(i)}\right) + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} e_{jk}^{(i)}\left(\beta - x_{jk}^{(i)}\right) \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} e_{jkl}^{(i)}\left(\beta - x_{jkl}^{(i)}\right) \end{array} \right) \le 0 \qquad (10)$$

$$\left(\begin{array}{l} \sum_{i=1}^{3}\sum_{j=1}^{J} v_j^{(i)}\left(\gamma - x_j^{(i)}\right) + \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K} v_{jk}^{(i)}\left(\gamma - x_{jk}^{(i)}\right) \\ \sum_{i=1}^{3}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} v_{jkl}^{(i)}\left(\gamma - x_{jkl}^{(i)}\right) \end{array} \right) \le 0 \qquad (11)$$

$$x_j^{(i)}, x_{jk}^{(i)}, x_{jkl}^{(i)}, x_{j'}^{(i)}, x_{j'k'}^{(i)} \in \{0, 1\} \qquad (12)$$

Note that (2), (3) and (4) are not linear. They are linearized by applying simple algebra and the results are (9), (10) and (11). Inequalities (6), (7) and (8) are linking constraints implying that if a particular process is selected than its parent process has to be selected too. This is done by introducing a variable denoted as M where its value at least has to be equal to upper bound of any sum of variables in the problem.

IV. NUMERICAL EXAMPLE

Let's assume that an LCA study is conducted to assess a product. The life cycle of the product is divided into three stages, material production, manufacturing and end-of-life treatment. Table I presents all processes inside the product's life cycle, the amount of mass flowing inside each process, the amount of energy flowing inside each process and the economic value of each process. Note that all values in Table I are per functional unit of the product. In order to conduct the study it is specified that $\alpha = \beta = \gamma = 0.90$. The objective is to define the system boundary of the study so that the specified requirements are met. Substituting the value of α, β, γ, mass, energy and economic values presented in Table I to the model, (5) to (12), yields the following binary linear programming model.

$$Min \; x_1^{(1)} + x_2^{(1)} + \cdots + x_{222}^{(3)}$$

subject to

$$x_1^{(1)} + x_2^{(1)} \le M$$
$$x_1^{(2)} + x_2^{(2)} \le M$$
$$x_1^{(3)} + x_2^{(3)} \le M$$
$$x_{11}^{(1)} + x_{12}^{(1)} \le M x_1^{(1)}$$
$$x_{21}^{(1)} + x_{22}^{(1)} \le M x_2^{(1)}$$
$$x_{11}^{(2)} + x_{12}^{(2)} \le M x_1^{(2)}$$
$$x_{21}^{(2)} + x_{22}^{(2)} \le M x_2^{(2)}$$
$$x_{11}^{(3)} + x_{12}^{(3)} \le M x_1^{(3)}$$
$$x_{21}^{(3)} + x_{22}^{(3)} \le M x_2^{(3)}$$
$$x_{111}^{(1)} + x_{112}^{(1)} \le M x_{11}^{(1)}$$
$$x_{121}^{(1)} + x_{122}^{(1)} \le M x_{12}^{(1)}$$
$$x_{211}^{(1)} + x_{212}^{(1)} \le M x_{21}^{(1)}$$
$$x_{221}^{(1)} + x_{222}^{(1)} \le M x_{22}^{(1)}$$
$$x_{111}^{(2)} + x_{112}^{(2)} \le M x_{11}^{(2)}$$
$$x_{121}^{(2)} + x_{122}^{(2)} \le M x_{12}^{(2)}$$
$$x_{211}^{(2)} + x_{212}^{(2)} \le M x_{21}^{(2)}$$
$$x_{221}^{(2)} + x_{222}^{(2)} \le M x_{22}^{(2)}$$
$$x_{111}^{(3)} + x_{112}^{(3)} \le M x_{11}^{(3)}$$
$$x_{121}^{(3)} + x_{122}^{(3)} \le M x_{12}^{(3)}$$
$$x_{211}^{(3)} + x_{212}^{(3)} \le M x_{21}^{(3)}$$
$$x_{221}^{(3)} + x_{222}^{(3)} \le M x_{22}^{(3)}$$

$$\left(\begin{array}{l} 18.62\left(0.9 - x_1^{(1)}\right) + 8.97\left(0.9 - x_2^{(1)}\right) + \cdots + \\ 82.98\left(0.9 - x_{222}^{(3)}\right) \end{array} \right) \le 0$$

$$\left(\begin{array}{l} 14.92\left(0.9 - x_1^{(1)}\right) + 82.16\left(0.9 - x_2^{(1)}\right) + \cdots + \\ 98.18\left(0.9 - x_{222}^{(3)}\right) \end{array} \right) \le 0$$

$$\left(\begin{array}{l} 12.76\left(0.9 - x_1^{(1)}\right) + 63.55\left(0.9 - x_2^{(1)}\right) + \cdots + \\ 82.04\left(0.9 - x_{222}^{(3)}\right) \end{array} \right) \le 0$$

$$x_1^{(1)}, x_2^{(1)}, \cdots, x_{222}^{(3)} \in \{0, 1\}$$

In order to solve the above binary linear programming problem $M = 100$ is applied. The optimum solution is that all processes are inside the system boundary except processes denoted as $x_{11}^{(1)}, x_{111}^{(1)}, x_{112}^{(1)}, x_{212}^{(1)}, x_{221}^{(1)}, x_{122}^{(3)}$ and $x_{222}^{(3)}$ which are equal to zero. Optimum objective function value of this solution is equal to 35 meaning that there are 35 processes inside the system boundary. This solution produces mass ratio = 0.908, energy ratio = 0.901 and economic value ratio = 0.90.

TABLE I
DATA FOR THE NUMERICAL EXAMPLE

Life cycle	Process	Mass	Energy	Economic value	Process	Mass	Energy	Economic value	Process	Mass	Energy	Economic value
Material Production $x^{(1)}$	$x^{(1)}_1$	18.62	14.92	12.76	$x^{(1)}_{11}$	1.16	57.35	5.56	$x^{(1)}_{111}$	4.71	2.77	1.26
									$x^{(1)}_{112}$	3.75	18.06	36.27
					$x^{(1)}_{12}$	20.84	92.23	5.01	$x^{(1)}_{121}$	55.51	80.11	66.71
									$x^{(1)}_{122}$	34.36	27.51	68.13
	$x^{(1)}_2$	8.97	82.16	63.55	$x^{(1)}_{21}$	95.02	78.00	18.61	$x^{(1)}_{211}$	11.48	68.76	48.42
									$x^{(1)}_{212}$	34.42	6.32	6.03
					$x^{(1)}_{22}$	64.60	40.41	90.77	$x^{(1)}_{221}$	10.63	6.78	43.75
									$x^{(1)}_{222}$	55.94	89.44	65.60
Manufacturing $x^{(2)}$	$x^{(2)}_1$	59.91	96.70	1.01	$x^{(2)}_{11}$	3.24	58.49	69.45	$x^{(2)}_{111}$	23.20	55.68	11.15
									$x^{(2)}_{112}$	48.31	74.48	46.60
					$x^{(2)}_{12}$	76.93	19.63	89.79	$x^{(2)}_{121}$	95.77	22.72	95.06
									$x^{(2)}_{122}$	98.22	59.21	52.37
	$x^{(2)}_2$	96.54	54.14	37.75	$x^{(2)}_{21}$	13.41	25.08	18.25	$x^{(2)}_{211}$	97.09	17.84	70.21
									$x^{(2)}_{212}$	71.56	64.70	18.37
					$x^{(2)}_{22}$	36.12	94.01	1.87	$x^{(2)}_{221}$	93.52	93.93	33.57
									$x^{(2)}_{222}$	90.69	67.61	62.82
End-of-life $x^{(3)}$	$x^{(3)}_1$	96.63	86.98	53.12	$x^{(3)}_{11}$	10.24	83.77	88.13	$x^{(3)}_{111}$	92.16	48.51	47.55
									$x^{(3)}_{112}$	44.78	63.45	73.41
					$x^{(3)}_{12}$	86.18	62.26	58.38	$x^{(3)}_{121}$	75.40	69.09	16.25
									$x^{(3)}_{122}$	65.72	46.44	11.27
	$x^{(3)}_2$	3.55	67.85	76.99	$x^{(3)}_{21}$	82.63	74.27	54.16	$x^{(3)}_{211}$	41.86	87.96	96.01
									$x^{(3)}_{212}$	78.31	16.67	59.22
					$x^{(3)}_{22}$	41.19	76.40	41.04	$x^{(3)}_{221}$	97.62	29.31	90.25
									$x^{(3)}_{222}$	82.98	98.18	82.04

V. SENSITIVITY ANALYSIS FOR THE NUMERICAL EXAMPLE

The purpose of the sensitivity analysis is to see how the change in the values of the specified mass ratio (α), energy ratio (β) and economic value ratio (γ) will affect current optimum system boundary. It is known that the closer the values of those parameters are to one the more processes are included in the system boundary. However the magnitude of the effect needs to be known. In order to see how the total number of processes inside system boundary changes the following approaches will be followed.

- One parameter will be varied from 0.9 to 1.0 and the other two parameters will be kept at 0.90, shown in Fig. 2.
- Two parameters will be varied from 0.9 to 1.0 and the other parameter will be kept at 0.9, shown in Fig. 3, 4 and 5.

Fig. 2 shows that all parameters have the same effect to the change in total number of processes included inside the system boundary if they are varied from 0.9 to 0.92. From 0.92 to 0.94 the change in β and γ has more effect to total number of processes inside the system boundary than the change in α. From 0.94 to 0.95, γ has the highest effect to total number of processes included inside the system boundary and is followed by β. The effect of β and γ stops at 0.95 because when β and γ are higher than 0.95 then there is no feasible solution for the problem. Furthermore, Fig. 2 shows that the highest effect to the change in total number of processes included inside the system boundary occurs when α is varied from 0.95 to 0.96. Finally the effect of α stops at $\alpha = 0.96$ because when $\alpha > 0.96$ there is no feasible solution for the problem.

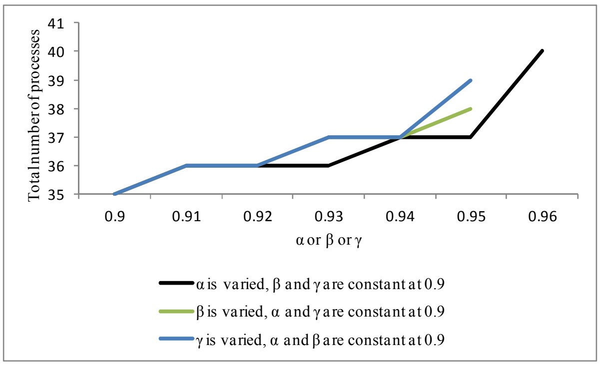

Fig. 2. Change in total number of processes inside system boundary when one parameter is varied one at a time

Fig. 3 shows that when α and β are simultaneously changed and economic value ratio γ is kept at 0.90 then the change in total number of processes included inside the system boundary increases from 36 to 40. From Fig. 3, it can be inferred that the total number of processes included inside the system boundary significantly increases when α increases from 0.95 to 0.96. The change in total number of processes included inside the system boundary when α and γ are simultaneously changed and β is kept at 0.90 is shown in Fig. 4. Fig. 4 shows that the minimum number of processes that can be achieved inside the system boundary is 35 and the highest number of processes inside the system boundary is 40. Similar to

Fig. 3, in Fig. 4 the total number of processes inside the system boundary significantly increases when *α* increases from 0.95 to 0.96. This result confirms Fig. 2.

Fig. 5 shows how total number of processes included inside the system boundary changes when *β* and *γ* are simultaneously changed and *α* is kept at 0.90. From the figure, it can be seen that the minimum and maximum number of processes obtained are 35 and 39 respectively. Fig. 5 also shows that the total number of processes increases gradually from 35 to 39.

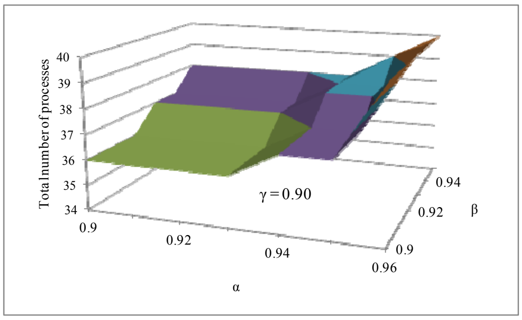

Fig. 3. Change in total number of processes inside system boundary when *α* and *β* are varied, *γ* = 0.90

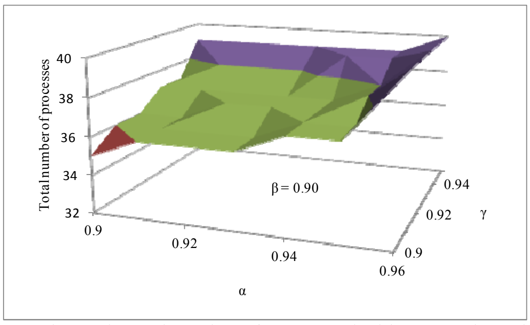

Fig. 4. Change in total number of processes inside system boundary when *α* and *γ* are varied, *β* = 0.90

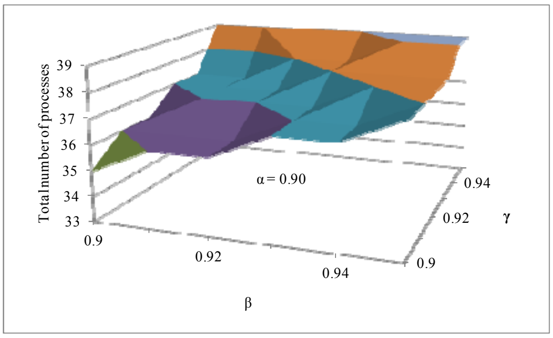

Fig. 5. Change in total number of processes inside system boundary when *β* and *γ* are varied, *α* = 0.90

VI. DISCUSSION AND CONCLUSION

This paper presents an improved binary linear programming approach for LCA system boundary identification. The main contribution of this work is that it provides an alternative methodology in determining which unit processes are to be included or excluded in an LCA study system boundary. According to [6], LCA system boundary selection method should be quantitative and repeatable, simple, reflect the significant of input/output relative to the system as a whole. The propose approach satisfies these criteria. However it also posses some limitations: (1) similar to the process analysis approach, the unit processes included in the model are limited within the chosen system boundary and (2) the propose method cannot reflect the environmental significant of the unit processes since only mass, energy and economic ratios are used in the model. By considering the above strength and weaknesses, for future research, it is suggested that before the optimization approach is conducted, a systematic approach is utilized in order to determine unit processes included in the model. It is seemed that the I/O LCA approach has potential for this purpose.

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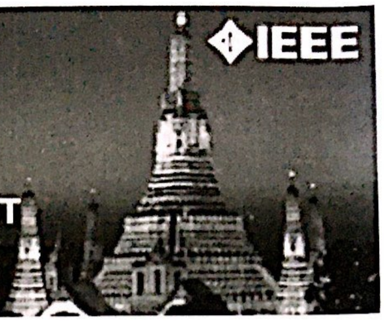

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