Life Cycle Environmental and Economic Analysis for Engineering Decision Making - A Hybrid Exergetic Approach

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1. INTRODUCTION

Consideration of environmental issues in engineering design requires a multi-objective strategy that considers the trade-off between economic and environmental aspects. However, a formidable challenge faced by this kind of approach is that of evaluating multiple objectives and defining a fair and consistent system boundary. As in process LCA, defining the boundary by including only the relevant processes may result in large truncation errors, while expanding it to include all interactions is computationally intractable. In practice, data and models are available at multiple scales ranging from individual equipment and processes, to the supply and demand chains, to the economy and ecosystem. Nonetheless, indiscriminate combination of such models is prone to unreliable outcomes since data become more aggregated and uncertain at larger scales.

This paper presents a novel multiscale and multiobjective approach for utilizing available information at all these scales and providing the most comprehensive scenario on which process alternatives can be tested and better decisions at the plant scale be made. The multiscale approach is closely related to existing hybrid (tiered) LCA methods[1], but represents inputs and outputs in terms of cumulative exergy consumption (CEC)[2]. Contribution of labor and capital are also included in the analysis. Exergetic information at equipment and process scales is available from engineering, while that at economy and ecosystem scales is obtained from economic input-output analysis and systems ecology[3].

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[1] Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes,G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., 2004. System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Env. Sci. Tech.*, 38, 657 – 664.

[2] Szargut, J., Morris, D.R. and Steward, F.R. 1988. *Exergy Analysis of Thermal, Chemical and Metallurgical Processes* Hemisphere Pubs., New York.

[3] Ukidwe, N. U., B. R. Bakshi, Thermodynamic Accounting of Ecosystem Contribution to Economic Sectors with Application to 1992 US Economy, 2004. *Env. Sci. Tech.*, accepted, also see abstract submitted to InLCA, 2004.

The proposed methodology considers two objective functions: economic cost and exergy consumption of the process life cycle at multiple scales. Results provided by this methodology consist of a series of Pareto optimal surfaces at various scales. Case study of a cogeneration system compares the proposed approach with existing methods, and highlights the benefits of adopting a multiscale and multiobjective view. Opportunities for retrofitting existing industrial systems are also identified via the proposed approach.

2. CUMULATIVE EXERGY ANALYSIS

Exergy or *Available energy* is the maximum amount of *useful energy* that can be extracted when a system is brought to equilibrium with its surroundings. Although energy is neither created nor destroyed, it is converted from useful to useless as work is performed. For instance, kinetic energy is converted into dissipated heat through friction as a fluid is transported in a pipeline. In the process, exergy is lost as useful energy is consumed or converted. In fact, all industrial, biological, ecological and planetary systems are sustained and constrained by their inflow of exergy[4,2], making exergy the ultimate limiting resource.

Exergy of matter, in the absence of nuclear, magnetic, electrical and interfacial effects is defined for matter at temperature T and pressure P, relative to surroundings (reference state) at temperature T_0 and pressure P_0, as

$$B = \left(H - T_0 S + \sum_i \mu_i x_i + \dot{r}^2/2 + zg \right)_{T,P} - \left(H - T_0 S + \sum_i \mu_i x_i + \dot{r}^2/2 + zg \right)_{T_0,P_0} \quad (1)$$

where H is enthalpy, S is entropy, μ_i is chemical potential of component i, x_i is mass fraction of component i, $\dot{r}$ is relative velocity, z is relative height and g is acceleration of gravity. Exergy of heat streams $\dot{B}_Q$ can be calculated as

$$\dot{B}_Q = \left(1 - \frac{T_0}{T_i} \right) \cdot \dot{Q}(T_i) \quad (2)$$

where $\dot{Q}(T_i)$ is the flow of heat from a source at temperature T_i.

Exergy is able to jointly represent material and energy streams. It may also provide a proxy

[4] Ayres, R.U., 1994. *Information, Entropy and Progress: A New Evolutionary Paradigm*, (1st Edition). AIP Press, New York.

for the potential impact of the emissions[5]. Consequently, exergy can considerably reduce the dimensionality of design problems. Exergy considers the second law of thermodynamics, e.g. exergy is lost as entropy is produced. This makes it very useful for estimating missing information and assuring consistency of the data inventories, especially when collecting data from different sources.

As for other measures, accounting for exergy invested and consumed gives insightful information about the process or system. Cumulative Exergy Consumption (CEC) analysis is a method that accounts for the exergy of all the natural resources consumed in all steps of the process and previous processes in the production chain. It is closely related to the life cycle impact categories of land, material and energy use. It also shares the challenges that Life Cycle Assessment (LCA) faces.

In general, the industrial CEC (ICEC) of the production chain, C_p, is

$$C_p = C_n = \sum_{k=1}^{N_i} C_{n,k} \tag{3}$$

where, N_i denotes the number of process units included in the industrial production chain. $C_{n,k}$ and $C_{p,k}$ are respectively the cumulative exergy of the natural resource entering and of the product leaving the *k-th* process unit. An important concept is Industrial Cumulative Degree of Perfection (ICDP), η. It is defined as the ratio of the exergy of the final product(s) to the cumulative exergy consumed to make the product(s).

$$\eta_p = \frac{\sum_{k=1}^{N_i} B_{p,k}}{\sum_{k=1}^{N_i} C_{n,k}} = \frac{B_p}{C_p}; \qquad \eta_{p,k} = \frac{B_{p,k}}{C_{p,k}} \tag{4}$$

where, η_p and $\eta_{p,k}$ represent the ICDP of the production chain, and the *k-th* product, respectively. ICDP is regarded as a measure of efficiency, and is described in more detail by Szargut et al.[2], with applications to LCA available in [6,7,3].

[5] Ayres, R.U., 1998. Eco-thermodynamics: economics and the second law. *Ecol. Econ.*, 26, 189-209.
[6] Cornelissen, R.L., Hirs, G.G., 2002. The value of the exergetic life cycle assessment besides the LCA. *Energy Conversion and Management* 43 (9-12), 1417-1424.
[7] Hau, J. L., Bakshi, B. R., 2004. Expanding Exergy Analysis to Account for Ecosystem Products and Services, *Env. Sci. Tech.*, 38, 13, 3768 - 3777

3. METHODOLOGY

A typical Cumulative Exergy Consumption analysis focuses only on the exergy of material and energy streams of the process. CEC analysis in this paper also includes exergy of labor and capital. A systematic way to setup the network is to classify the units according to Figure 1. The physical units are u_s process units. The virtual or added dummy units are: a capital investment K, labor input Λ, n_s material and energy inputs n_i and p_s final products p_i (including waste and emissions).

Let i and j be units in the subsystem S_s, then $B_{ij}^{(s)}$ and $C_{ij}^{(s)}$ are respectively the exergy and cumulative exergy transferred from the *i-th* to the *j-th* unit at the *s-th* scale. Notice that the superscript indicates the scale for which the streams are defined. Similarly, $B_{n,i}^{(s)}$ and $C_{n,i}^{(s)}$ are the external exergy and cumulative exergy inputs to the *i-th* unit at the *s-th* scale. $B_{p,i}^{(s)}$ and $C_{p,i}^{(s)}$ are the external exergy and cumulative exergy outputs from the *i-th* unit at the *s-th* scale. Based on this network representation, cumulative exergy of subsystem S_s, denoted $C_{S_s}^{(s)}$, is

$$C_{S_s}^{(s)} = \sum_{i=1}^{N_s} B_{n,i}^{(s)} \tag{5}$$

where N_s is the total number of units in subsystem S_s, this is

$$N_s = 2 + n_s + u_s + p_s \tag{6}$$

Exergetic efficiency of subsystem S_s, denoted η_{S_s}, is

$$\eta_{S_s}^{(s)} = \frac{\sum_{i=1}^{N_s} B_{p,i}^{(s)}}{\sum_{i=1}^{N_s} B_{n,i}^{(s)}} = \frac{\sum_{i=1}^{N_s} B_{p,i}^{(s)}}{C_{S_s}^{(s)}} \tag{7}$$

The levels of analysis considered here are *Equipment*, *Life Cycle*, *Economy*, and *Ecosystem* — denoted S_0, S_1, S_2 and S_3 respectively. Only the supply chain has been considered in this work. The rest of this section describes how each level is incorporated into the analysis and how the optimization problem is set up and solved.

3.1. Equipment Scale

The equipment scale encloses the range of typical process engineering cost-benefit analysis, i.e. the set of units that constitute the main process. The equipment scale represents the plant itself, but it can also be limited to a piece of equipment or a subsystem of the plant. At this scale, the level of information is expected to be of the highest quality. Based on a setup described by Figure 1 and the network algebra presented by Hau and Bakshi[7], the transaction matrix $\boldsymbol{\gamma}^{(0)}$ can be determined with coefficients defined as

$$\gamma_{ij}^{(0)} = \frac{B_{ij}^{(0)}}{\sum_{j \in S_0} B_{ij}^{(0)} + B_{p,i}^{(0)}} \tag{8}$$

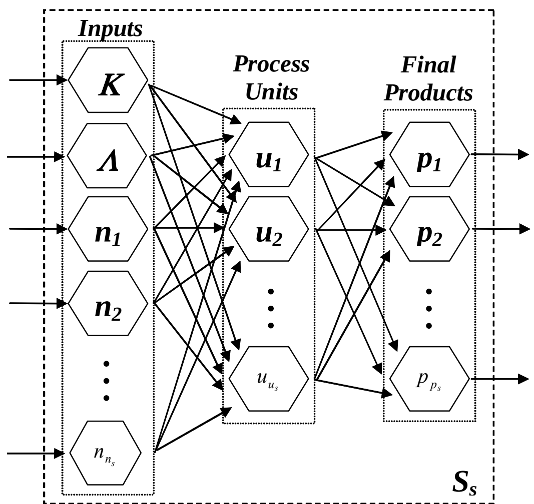

Figure 1: Types of units present in subsystem S_s.

The diagonal matrix $\boldsymbol{\gamma}_{\mathbf{p}}^{(0)}$ can also be determined with the coefficients given by

$$\gamma_{p,i}^{(0)} = \frac{B_{p,i}^{(0)}}{\sum_{j \in S_0} B_{ij}^{(0)} + B_{p,i}^{(0)}} \tag{9}$$

The vector of cumulative exergy of the outputs $\mathbf{C}_{\mathbf{p}}^{(0)}$ with coefficients $C_{p,i}^{(0)}$ is given by

$$\mathbf{C}_{\mathbf{p}}^{(0)} = \boldsymbol{\gamma}_{\mathbf{p}}^{(0)} \cdot \left(\mathbf{I} - (\boldsymbol{\gamma}^{(0)})^{\mathbf{T}}\right)^{-1} \cdot \mathbf{B}_{\mathbf{n}}^{(0)} \tag{10}$$

where $\mathbf{B}_{\mathbf{n}}^{(0)}$ is the vector of the exergy of the inputs with the coefficients $B_{n,i}^{(0)}$. The cumulative exergy of the process $C_{S_0}^{(0)}$ can be calculated as

$$C_{S_0}^{(0)} = \sum_{i \in S_0} C_{n,i}^{(0)} = \sum_{i \in S_0} B_{n,i}^{(0)} \tag{11}$$

with $C_{n,i}^{(0)} = B_{n,i}^{(0)}$. Similarly, the exergetic efficiency of the process $\eta_{S_0}^{(0)}$ can be calculated as

$$\eta_{S_0}^{(0)} = \frac{\sum_{i \in S_0} B_{p,i}^{(0)}}{C_{S_0}^{(0)}} \tag{12}$$

3.2. Life Cycle Scale

The Life Cycle Scale includes the most relevant processes of the supply and demand chain of the process. The set S_1 is defined by the units of S_0 plus the additional units selected. An additional unit may be a plant, a section or a piece of equipment. Like the Equipment scale, the Transaction matrix $\boldsymbol{\gamma}^{(1)}$ consists of coefficients defined as

$$\gamma_{ij}^{(1)} = \frac{B_{ij}^{(1)}}{\sum_{j \in S_1} B_{ij}^{(1)} + B_{p,i}^{(1)}} \tag{13}$$

The diagonal matrix $\boldsymbol{\gamma}_{\mathbf{p}}^{(1)}$ can also be determined with the coefficients given by

$$\gamma_{p,i}^{(1)} = \frac{B_{p,i}^{(1)}}{\sum_{j \in S_0} B_{ij}^{(1)} + B_{p,i}^{(1)}} \tag{14}$$

The vector of cumulative exergy of the outputs $\mathbf{C}_{\mathbf{p}}^{(1)}$ with coefficients $C_{p,i}^{(1)}$ is given by

$$\mathbf{C}_{\mathbf{p}}^{(1)} = \boldsymbol{\gamma}_{\mathbf{p}}^{(1)} \cdot \left(\mathbf{I} - (\boldsymbol{\gamma}^{(1)})^{\mathbf{T}}\right)^{-1} \cdot \mathbf{B}_{\mathbf{n}}^{(1)} \tag{15}$$

where $\mathbf{B}_{\mathbf{n}}^{(1)}$ is the vector of the exergy of the inputs with the coefficients $B_{n,i}^{(1)}$. The streams crossing the boundaries at the Equipment scale may be disaggregated when the system expands to the Life Cycle scale. For instance, as shown in Figure 2, stream $B_{n,1}^{(0)}$ is composed of streams coming from the units added and from outside the boundaries of the expanded system. Consistency across scales results in the following identities

$$B_{n,i}^{(0)} = \sum_{j \in S_1 \setminus S_0} B_{ji}^{(1)} + B_{n,i}^{(1)} \text{ for } i \in S_0 \tag{16}$$

$$B_{p,i}^{(0)} = \sum_{j \in S_1 \setminus S_0} B_{ij}^{(1)} + B_{p,i}^{(1)} \text{ for } i \in S_0 \tag{17}$$

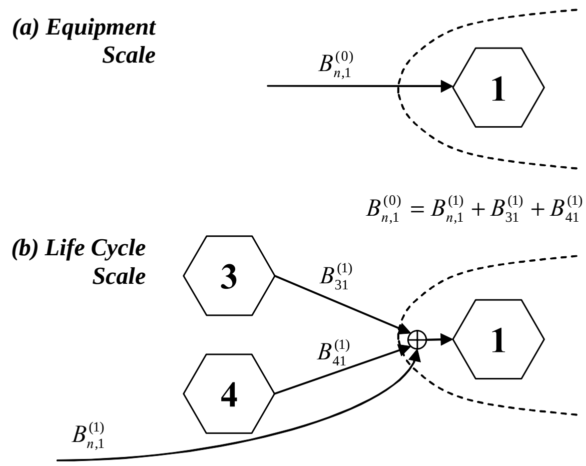

Figure 2: Exergy streams across the Equipment scale.

The cumulative exergy of the process $C_{S_0}^{(1)}$ can be calculated as

$$C_{S_0}^{(1)} = \sum_{i \in S_0} C_{n,i}^{(1)} + \sum_{i \in S_1 \backslash S_0} \sum_{j \in S_0} C_{ij}^{(1)} \tag{18}$$

with $C_{n,i}^{(1)} = B_{n,i}^{(1)}$. Similarly, the exergetic efficiency of the process $\eta_{S_0}^{(1)}$ can be calculated as

$$\eta_{S_0}^{(1)} = \frac{\sum_{i \in S_0} B_{p,i}^{(1)} + \sum_{i \in S_0} \sum_{j \in S_1 \backslash S_0} B_{ij}^{(1)}}{C_{S_0}^{(1)}} = \frac{\sum_{i \in S_0} B_{p,i}^{(0)}}{C_{S_0}^{(1)}} \tag{19}$$

3.3. Economy Scale

The Economy scale includes the rest of the processes in the value chain that were excluded from the system defined at the Life Cycle scale. Since it is intractable to include them as done at the Life Cycle scale, a different approach is used. Closely related to existing hybrid (tiered) LCA methods[1], the rest of the economy is included by using cumulative-exergy-to-money ratios based on the cumulative exergy analysis of the U.S Economy by Ukidwe and Bakshi[3].

Let $\xi_1, \xi_2, \ldots, \xi_E$, form a partition of the whole Economy represented by the set S_2, i.e. ξ_i is the *i-th* sector of the economy. As shown in Figure 5, strictly speaking the sectors should exclude the units that constitute the set S_1. However, by assuming that the sum of cumulative exergy of the units of S_1 that belong to the *i-th* sector is infinitesimally small as compared to the cumulative exergy of that sector, then the exclusion of these units from the sector will not make a significant difference. This is

$$\sum_{j \in \xi_i \cap S_1} C_j^{(2)} << C_{\xi_i}^{(2)} \text{ for } \xi_i \in S_2 \quad \Rightarrow \quad C_{\xi_i \backslash S_1}^{(2)} = C_{\xi_i}^{(2)} - \sum_{j \in \xi_i \cap S_1} C_j^{(2)} \cong C_{\xi_i}^{(2)} \tag{20}$$

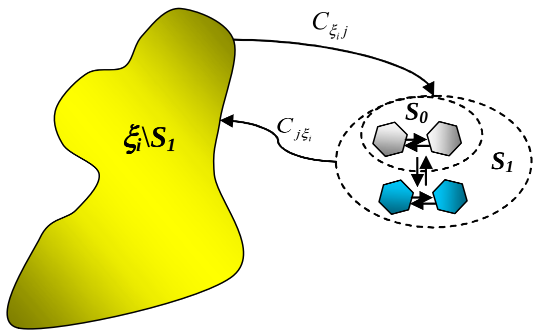

Figure 3: Exergy streams across the Life Cycle scale.

By assuming

$$\frac{C^{(2)}_{\xi_i j}}{Z^{(2)}_{\xi_i j}} \cong \frac{C^{(2)}_{\xi_i}}{Z^{(2)}_{\xi_i}} \tag{21}$$

where $Z^{(2)}_{\xi_i j}$ is the monetary transaction from the sector ξ_i to the *j-th* unit and $Z^{(2)}_{\xi_i}$ is the monetary activity of the sector. The following equality has to hold

$$Z^{(1)}_{n,j} = \sum_{\xi_i \in S_2} Z^{(2)}_{\xi_i j} \tag{22}$$

where $Z^{(1)}_{n,j}$ is the cost associated with the *j-th* unit. Then

$$C^{(2)}_{n,j} = \sum_{\xi_j \in S_2} \left(\frac{C^{(2)}_{\xi_i}}{Z^{(2)}_{\xi_i}} \cdot Z^{(2)}_{\xi_j i} \right) \text{ for } j \in S_1 \tag{23}$$

The vector of cumulative exergy of the units $\mathbf{C}^{(2)} = (C^{(2)}_i)$ is given by

$$\mathbf{C}^{(2)} = \left(\mathbf{I} - (\boldsymbol{\gamma}^{(1)})^{\mathbf{T}}\right)^{-1} \cdot \mathbf{C}^{(2)}_{\mathbf{n}} \tag{24}$$

where $\mathbf{C}^{(2)}_{\mathbf{n}}$ is the vector of the exergy of the inputs with the coefficients $C^{(2)}_{n,j}$. The vector of cumulative exergy of the outputs $\mathbf{C_p} = (C^{(2)}_{p,i})$ is given by

$$\mathbf{C}^{(2)}_{\mathbf{p}} = \boldsymbol{\gamma}^{(1)}_{\mathbf{p}} \cdot \left(\mathbf{I} - (\boldsymbol{\gamma}^{(1)})^{\mathbf{T}}\right)^{-1} \cdot \mathbf{C}^{(2)}_{\mathbf{n}} \tag{25}$$

The cumulative exergy of the process $C^{(2)}_p$ is then

$$C^{(2)}_p = \sum_{j \in S_0} C^{(2)}_{n,j} + \sum_{i \in S_1 \backslash S_0} \sum_{j \in S_0} \gamma^{(1)}_{ij} \cdot C^{(2)}_i \tag{26}$$

Similarly, the exergetic efficiency of the process $\eta^{(2)}_p$ can be calculated as

$$\eta^{(2)}_p = \frac{\sum_{i \in S_0} B^{(0)}_{p,i}}{C^{(2)}_p} \tag{27}$$

3.4. Ecosystem Scale

The Ecosystem scale includes the ecological goods and services that contribute to the functioning of the system. Based on the concept of ecological cumulative exergy consumption (ECEC)[7], Ukidwe and Bakshi[3] have calculated ECEC-to-money ratios for sectors of the U.S. economy. This level of analysis is incorporated in the same way as the economy scale. Similarly, it is assumed that

$$\sum_{j\in\xi_i\cap S_1} C_j^{(3)} << C_{\xi_i}^{(3)} \text{ for } \xi_i \in S_2 \quad \Rightarrow \quad C_{\xi_i\setminus S_1}^{(3)} = C_{\xi_i}^{(3)} - \sum_{j\in\xi_i\cap S_1} C_j^{(3)} \cong C_{\xi_i}^{(3)} \tag{28}$$

and

$$\frac{C_{\xi_i j}^{(3)}}{Z_{\xi_i j}^{(2)}} \cong \frac{C_{\xi_i}^{(3)}}{Z_{\xi_i}^{(2)}} \tag{29}$$

then

$$C_{n,j}^{(3)} = \sum_{\xi_j\in S_2}\left(\frac{C_{\xi_i}^{(3)}}{Z_{\xi_i}^{(2)}} \cdot Z_{\xi_j i}^{(2)}\right) \text{ for } j \in S_1 \tag{30}$$

The vector of cumulative exergy of the units $\mathbf{C}^{(3)} = (C_i^{(3)})$ is given by

$$\mathbf{C}^{(3)} = \left(\mathbf{I} - (\boldsymbol{\gamma}^{(1)})^{\mathbf{T}}\right)^{-1} \cdot \mathbf{C}_{\mathbf{n}}^{(3)} \tag{31}$$

where $\mathbf{C}_{\mathbf{n}}^{(3)}$ is the vector of the exergy of the inputs with the coefficients $C_{n,j}^{(3)}$. The vector of cumulative exergy of the outputs $\mathbf{C_p} = (C_{p,i}^{(3)})$ is given by

$$\mathbf{C}_{\mathbf{p}}^{(3)} = \boldsymbol{\gamma}_{\mathbf{p}}^{(1)} \cdot \left(\mathbf{I} - (\boldsymbol{\gamma}^{(1)})^{\mathbf{T}}\right)^{-1} \cdot \mathbf{C}_{\mathbf{n}}^{(3)} \tag{32}$$

The cumulative exergy of the process $C_p^{(3)}$ is then

$$C_p^{(2)} = \sum_{j\in S_0} C_{n,j}^{(2)} + \sum_{i\in S_1\setminus S_0}\sum_{j\in S_0} \gamma_{ij}^{(1)} \cdot C_i^{(2)} \; C_p^{(3)} = \sum_{j\in S_0} C_{n,j}^{(3)} + \sum_{i\in S_1\setminus S_0}\sum_{j\in S_0} \gamma_{ij}^{(1)} \cdot C_i^{(3)} \tag{33}$$

Similarly, the exergetic efficiency of the process $\eta_p^{(3)}$ can be calculated as

$$\eta_p^{(3)} = \frac{\sum_{i\in S_0} B_{p,i}^{(0)}}{C_p^{(3)}} \tag{34}$$

3.5. Optimization Problem

Since the cost of the plant is invariant to the scale of analysis, the economic objective is the same for every scale, this is

$$Z_p^{(s)} = Z_p^{(0)} = \sum_{i\in S_0} Z_{n,i}^{(0)} \tag{35}$$

Given the $m \times 1$ vector of decision variables **X**, the design problem is to minimize economic cost and cumulative exergy of the process at every scale of analysis, this is

Find X to

Minimize $Z_p^{(0)}$ (36)

Minimize $C_p^{(s)}$ (37)

s.t. $\mathbf{X} = \{\mathbf{X} \in \Re^m \mid \mathbf{X}\ is\ feasible\}$ (38)

Such formulation corresponds to the most general. Solving this problem directly can be quite challenging because relation between the decision variables and the objectives involves various computation and iterative steps. The technique used in this approach is known as *Data Envelopment Analysis* (DEA). DEA was initially created to compare the relative efficiency of different production units in economics, such as banks, mail centers and manufacturing plants, referred as *decision making units* (DMU)[8]. These efficiencies range from zero to unity. A DMU is Pareto-efficient if its efficiency is unity. The set of Pareto-efficient DMUs forms what is called the *efficient frontier*, i.e. a surface where the improvement of an objective is only possible in detriment of the others. The efficient frontier is not necessarily the Pareto optimal surface. Before DEA can be applied to the multiobjective problem encountered here, the DMUs have to be produced. This can be done by creating a set of discrete alternatives from the feasible region. Whether the efficient frontier and the Pareto optimal surface coincide depends on the extent of the set and the resolution of the grid on the feasible region. Among the advantages of using DEA to solve multiobjective optimization problems are that the decision maker does not have to establish neither a preference structure nor prior explicit targets on the multiple objectives[9].

There are various models in DEA. The model used here is known as the input oriented Banker-Charnes-Cooper (BCC) Model, designed to deal with variable returns-to-scale problems. The design problem can then be formulated as

Find μ, v, μ_0^+, μ_0^- to

Maximize $\mu Y_0 + \mu_0^+ - \mu_0^-$ (39)

s.t.

$vX_0 = 1$ (40)

$\mu Y_j - vX_j + \mu_0^+ - \mu_0^- \le 0 \quad j = 1, \ldots, n$ (41)

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[8] Charnes, A.; Cooper, W.W.; Lewin, A.Y.; Seiford, L.M. 1993. *Data Envelopment Analysis: Theory, Methodology, and Applications*. Kluwer Academic Publishers, Boston.

[9] Cabrera-Rios, M., 2002. Multiple Criteria Optimization Studies in Reactive In-Mold Coating. Ph.D. Dissertation, Department of Industrial, Welding, and Systems Engineering, The Ohio State University.

$$\mu, \nu \geq \varepsilon \tag{42}$$

$$\mu_0^+, \mu_0^- \geq 0 \tag{43}$$

where μ and ν are multipliers for the economic and the exergetic functions, respectively. μ_0^+ and μ_0^- are scalar variables whose value represents an intercept, n is the number of DMUs or discrete elements of the feasible set, and ε is a non-Archimedean infinitesimal. The economic and the exergetic functions, respectively Y_0 and X_0, are defined as

$$Y_j = Z_{p,max}^{(0)} + Z_{p,min}^{(0)} - Z_{p,j}^{(0)} \tag{44}$$

$$X_j = C_{p,j}^{(s)} \tag{45}$$

where $Z_{p,max}^{(0)}$ and $Z_{p,min}^{(0)}$ are the largest and smallest value of $Z_{p,j}^{(0)}$ in the feasible set. The optimization problem is solved for each DMU at each scale, this is $4n$ times. More details on DEA can be found in [8]. The general algorithm for multiscale multiobjective analysis of process systems is shown in Figure 4.

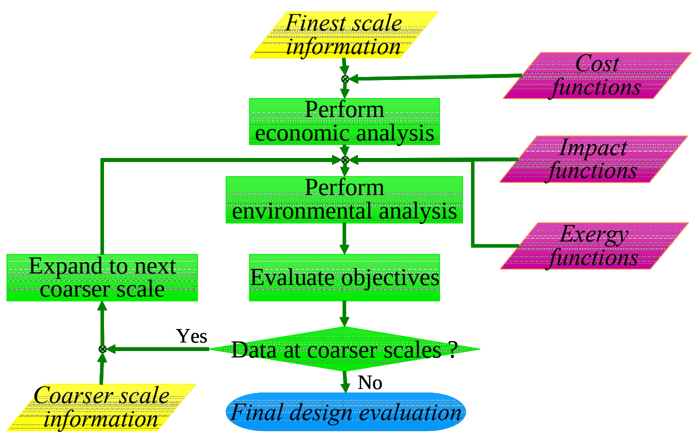

Figure 4: Algorithm for multiscale and multiobjective process design approach.

4. CASE STUDIES

Figure 5 shows the process diagram of a cogeneration system described in Bejan et al.[10] The system uses a mixture of air and methane to produce 30 MW of power. Air passes through a compressor (AC) and a pre-heater (PH) before entering the combustion chamber (CC). Power generated in the turbine (GT) is also used to move the compressor. Part of the exergy of the combustion gases leaving the turbine (GT) is used to preheat air and to produce 14 kg/s of

[10] Bejan, A., Tsatsaronis, G., Michael M. 1996. *Thermal design and optimization*, John Wiley, New York.

saturated steam. The design variables comprise isentropic efficiency of both the compressor and the turbine, temperatures T_3 and T_4, and mass flow of methane. The preliminary results are shown in Figure 6 and are based on a two-objective optimization at three spatial scales. The two objectives are economic cost of the system and CEC. The three scales are equipment, life cycle and economy. Trade-off between these objectives is represented via a series of Pareto optimal surfaces at various scales, indicated by the curves. These surfaces were obtained via data envelopment analysis[8]. Suboptimal solutions are also shown to illustrate their behavior as the system boundaries expand through the scales of analysis. Since the cost of the plant is the same regardless of the scale of analysis, the solutions do not shift horizontally along the cost axis. However, the environmental impact increases with larger boundaries. The economic optimum is the point on the extreme left of the Pareto optimal curve at each scale, while the environmental optimum is on the extreme right. The disparity between these optima decreases with increasing scale. However, it does not disappear entirely at the coarsest scale implying a mismatch between economic value and exergy content. Such a mismatch may be due to factors such as, ignoring externalities in prices, and uncertainties in data, and seems to indicate a "win-lose" situation for the cogeneration process. Attractive features of this approach is that arbitrary combinations of the objectives is avoided until the final stages of decision making and that uncertainty at each level can be treated separately. Application of this approach to many practical case studies is in progress, and may lead to unique insight and methods to guide environmentally conscious engineering decision making.

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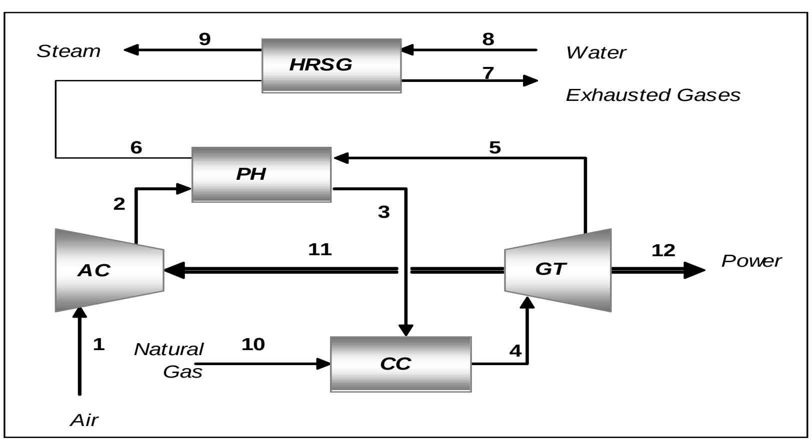

Figure 5: The Cogeneration System.

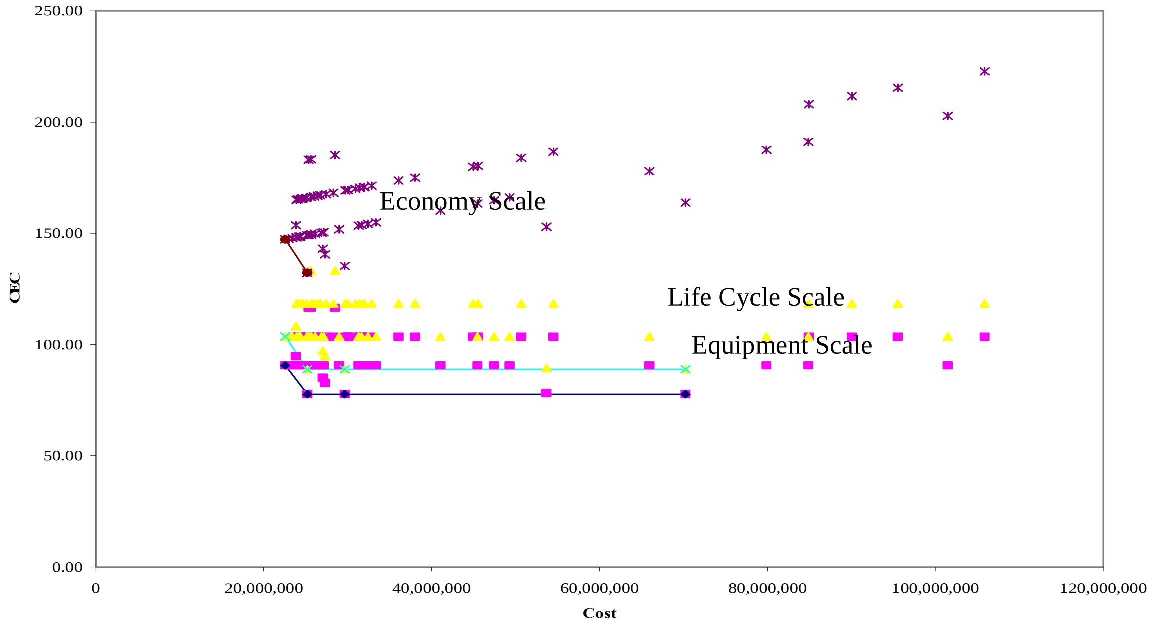

Figure 6: Optimization Results of the Cogeneration System.