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Life Cycle Engineering (LCE) aspects in Design using MADM approach

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ABSTRACT: *This research article focuses on various life cycle engineering (LCE) aspects in the design and development of various systems. Life Cycle Engineering has become the major thrust area for product designers and manufacturers during the past few decades. A methodology (MADM) based on digraph and matrix method for the systematic evaluation of various life cycle engineering issues is presented here. These aspects have been considered as attributes. An index is used to evaluate these attributes and the ideal value of this index is also obtained, which is useful in assessing the relative index value. A step-by-step procedure for evaluation of life cycle engineering aspects is presented and illustrated with the help of an example.*

Keywords: *Life Cycle Engineering, MADM, Digraph, Index, Design*.

I. INTRODUCTION

Life Cycle Engineering (LCE) is an integrated mechanism which involves several parameters that influence the product / system development and its sustainability over a period of time. Life Cycle Engineering is a vast envelope within which the important functionaries of product life cycle are the key constituents. There are various issues in a LCE approach analysis. However, in this article some of the important issues have been taken into consideration. In order to take into account all aspects of LCE during the system design stage, it will involve a very major research study. In this research study the focus is on issues like manufacturing, safety, maintenance, marketing, cost, recyclability/disposability. An attempt has been made through this research article to highlight the relevance of various life cycle engineering issues in a product development process.

Therefore, it is inevitable that the designer needs an appropriate and efficient methodology/tool that aid the designer in the design and evaluation of a system from life cycle engineering point of view. Various methodologies have been developed by the researchers for sustainability of systems.

Fitch and Cooper (2004) have proposed a methodology for life cycle analysis of systems at design stage, based on cost of energy for materials used in the systems. In this research study, authors have evaluated total energy required for reinforcing beam material throughout life cycle.

Kobayashi [4] in his research investigation, proposed a new methodology called lifecycle planning methodology which helps in the selection of life cycle strategies using Quality Function Deployment (QFD) technique. Kwak et al. [5] proposed a methodology to evaluate the product end-of-life recovery. In this research study, the researchers have taken into consideration the product design and recovery network.

Ishii (1995) has proposed a methodology for evaluation of life cycle cost of systems. In this methodology, the author has estimated cost of serviceability during ownership period of a system. The author has also obtained labor step cost based on labor time, labor penalty (hours) and logistic support.

Lida et al., (2007) have proposed a decision support system for system design under concurrent engineering environment, using fuzzy decision making mathematical approach. In this method, the evaluation of a system design is carried out on the basis of two concurrent subsystems, i.e., external concurrent subsystem and internal concurrent subsystem. These include market investigation, material, and external components, functional design, assembly design, manufacturing design and environment design. Suh and Huppes (2005) have carried out the review of various proposed life cycle inventory methods for the system design. In this review, the authors have compared six life cycle inventory methods with one another and have also compared these methods with ISO standards.

Wani and Tak (2013) carried out a research study on the Feasibility Analysis of Nano-Lubricants at Conceptual Design Stage. In this research study, the researchers have taken into consideration the feasibility analysis parameters of a nano-lubricant and accordingly evaluated their index values based on a scoring criterion.

Kato and Kimura (2003) proposed a new system life cycle technology using the Quality Function Deployment (QFD). Tomiyama et al., **(**1997) have proposed a holistic approach to life cycle design, marketing, material acquisition, manufacturing, serviceability and disposal / recycling.

Kato and Kimura (2004) have developed a system life cycle design method using a strategic analysis. In this methodology, the authors have modeled the relationship of price and cost in each process of part exchange, transportation, remanufacture and selling.

Kainuma (2004) proposed multi-criteria decision analysis for life cycle assessment (LCA) on the basis of five attributes. These are air pollution, water pollution, energy consumption, waste generated and customer satisfaction. Hundal (1997) and Hundal (1998) have carried out a detailed design analysis on environment and other aspects of life cycle need to be considered during system development process. In this research study, it was revealed that consideration of eco-design, waste prevention, innovation, etc. at design stage are useful for successful development of system.

In addition, these researchers have also considered that system sustainability is a multi-criteria decision making process. The various design concepts are considered as the various alternatives for system design. LCE parameters such as, design, manufacture, safety etc., have been considered as the design criteria for evaluation and comparison of different concepts of system design. However, these researchers have not taken into consideration all aspects of sustainability of a system and also their interrelationship / interdependence with each other. These models can be analyzed using appropriate matrix to develop sustainability expression of a system [14-25].

The recent standards of ISO -14040 (2006) has made it necessary for manufacturers and end-user of the system to carry out LCA to reduce environmental hazards, created due to solid waste, disposal and recycling methods of systems [27]. In addition, it also suggests ways and means to be adopted at design stage for designing sustainable systems. The results thus obtained from these LCA studies are useful for a decision making process at system design stage.

It is evident from these research studies, that various attempts have been made for design and evaluation of sustainability of a system separately or in combination. In addition, various sustainability features/attributes of a system in general have been identified.

Literature review, presented in above section, indicated the identification of all the attributes of system sustainability. These have been thoroughly investigated previously by Anand and Wani [26]. These are discussed in following subsections.

1.1.1 Manufacturability

The Life Cycle Design features which facilitates the ease of manufacturing, reducing cost of manufacturing, less emission of toxic gases during processing and machining, minimum material wastage, material and energy conservation, reuse of the material at the end of life etc., potentially contribute towards designing the system from manufacturing point of view. All these aspects contribute towards an attribute. This attribute is called manufacturability and is abbreviated as (M).

1.1.2 Maintainability

LCC of a system is determined to a large extent by the cost of maintenance incurred during operational stage. Therefore, designers need to include system design features/characteristics which facilitate maintenance of system at operational stage, with minimum cost of labor and spares. A designer need to in-built these features / characteristics in the system at design stage. This is possible if the designer includes maintainability as one of the attributes called Maintainability (Maint).

1.1.3 Safety

Failures at operational stage are inevitable. These failures not only culminate into losses and wastage of resources but also lead to human losses at times during the operational stage of systems. This is achieved by the principle of fail-safe, failure–free systems and also by increasing the redundancy of the system. Moreover, methods such as, FTA, FMEA, FMCEA etc., have also been used for increasing the safety, reliability and for identification of critical components and assemblies of the system. This attribute is termed as safety and is abbreviated as S.

1.1.4 Environmental Consciousness

The increasing problem of environmental degradation is a serious threat to humanity. The industries are one of the major sources of pollutants which adversely affect the environment. Environmental consciousness has become a major thrust area for all designers in the recent years. Designers have to take into consideration, conservation of energy, conservation of materials, minimum waste systems, reduction in emission of toxic substances, eco-friendly technology, reduction in air and noise pollution, use of longevity materials and components, etc. for the design of system at system conceptual design stage. This attribute is termed as environment and is abbreviated as E.

1.1.5 Disposability / Recyclability

At the final phase of system life cycle, its disposal becomes equally important for the end user. In the recent years, it has been observed that Municipal Solid Waste (MSW) is of serious concern for designers, manufacturer and end user of the system. Moreover, increasing concern for material and energy conservation, demand that designers need to design the system and its components in such a way that there is further scope for recycling or reuse of the material and retention of quality. Therefore, Disposal /Recycle forms another important parameter (D/R).

1.1.6 Economical Aspects: Cost also forms an important parameter in dealing with LCE issues. Costing in Life Cycle development includes all costs from cradle to grave and are vital in understanding the various life cycle engineering philosophies. Therefore another area of focus is cost and it forms an attribute called Economical Aspects (EA).

LCE issues/ attributes for a system, in general are identified in this section. For this, the attributes like Manufacturability (M), Maintainability (Maint), Safety (S), Environmental Consciousness (EC), Disposability/ Recyclability (D/R) and Economic Aspects (EA) are identified and are represented by A^d_i.

The LCE attributes identified above are represented mathematically as :

$$A^d = (A^d_1, A^d_2, \ldots\ldots\ldots\ldots A^d_n) \quad (1)$$

where A^d represents the LCE attribute and A^d_n represents n^{th} attribute.

These LCE attributes are used in developing system model and it leads to the evaluation of sustainability of a given system. Using this, a designer can evaluate various design alternatives of a system at system conceptual design stage. These are discussed in the following sections.

1.2 Life cycle Modelling

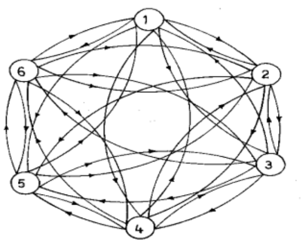
LCE attributes of a system have been identified in the previous section. Each attribute facilitates the system sustainability through its contributing factors/features. Each Attribute possesses distinctive characteristics which helps to develop relationship among these attributes,

The relationship among the attributes is called degree of relationship. The relationship between the attributes varies. It may be taken as, strong, to none as two extremes of degree of relationship. In between, this is assumed as medium and weak relationship.

It is however, mentioned again that the relationship among these attributes need to be derived by a concurrent engineering team comprising of designers and experts from other fields of system life cycle. LCE modelling of system requires consideration of Sustainability attributes and their relationship. This can be conveniently represented using graph–theoretical concepts [18-20].

LCE^g is a graphical representation of attributes and their interrelationship. The graphical representation augments further understanding the Sustainability of systems, which needs to be exploited at design stage. This shows a clear visual picture of system Sustainability.

However, for handling the digraph conveniently it is represented by matrix due to the fact that presence of more number of nodes and edges may lead to a complex figure.



1.M

2.M_{aint}

3.S

Fig. 1 LCE Attributes Relationship Digraph

1.3 Matrix Representation of A LCE Attributes Digraph

Matrix representation of the $Sust^g$ for a system consisting of all the important LCE attributes e.g., M, Maint, S, E, D/R and EA. In this case, the facilitation among all these attributes is considered to develop the LCE expression of the system. The $Sust^g$ of these seven attributes is developed based on the discussion in above section and is shown in Fig. 1.

Let the $Sust^g$ in general, with N nodes be represented by N^{th} order binary matrix $[r_{ij}]$, where r_{ij} represents relationship of i^{th} attribute with j^{th} attribute with r_{ij}=1, if i^{th} attribute is related to j^{th} attribute, otherwise r_{ij}= 0, as an attribute cannot have relationship with itself. Sustainability matrix for the $Sust^g$ is shown in of Fig. 1 and is written as:

$$R^l = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \quad (1.2)$$

Variable Sustainability Attributes Relationship Permanent Matrix for the digraph shown in Fig. (1) is given as:

$$Q^l = [H^l+] = \begin{bmatrix} L & 1 & 1 & 1 & 1 & 1 \\ 1 & L & 1 & 1 & 1 & 1 \\ 1 & 1 & L & 1 & 1 & 1 \\ 1 & 1 & 1 & L & 1 & 1 \\ 1 & 1 & 1 & 1 & L & 1 \\ 1 & 1 & 1 & 1 & 1 & L \end{bmatrix} \quad (1.3)$$

It may be noted that any matrix expression (1.3), represents value of attributes (L_i's) and their relationship (r_{ij}'s) for the given system. Permanent of this matrix (or Per (L)) i.e., $VSust^{per}$, is called variable sustainability attributes relationship permanent function, abbreviated as VPF-l. VPF-l is characteristic of the system sustainability as it contains number of terms, which are its variant. The equation consists of number of terms. These are arranged in seven (i.e., N+1 = 7, with N=7 in this case) groupings in descending order of number of attributes value. It is once again stated that VPF-l when expanded takes into consideration all terms of the matrix expression and thus no information is lost. This shows that VPF-l is a powerful expression for analyzing sustainability of a system.

Table 1: Scoring Criteria for Sustainability attribute - M

S. No.	**Description of Scoring Criterion**	**Score (L_i)**
1.	Ease to machine with minimum emission of gases to the environment, Ease of assembly/ disassembly, and Environmental hazards are less.	4
2.	Fulfils a few of the above requirements	2
3.	None of the above.	0

Table 2: Scoring Criteria for Sustainability attribute –D/R

S. No.	**Description of Scoring Criterion**	**Score (L_i)**
1.	Bio compatible materials, innovative disposal and recycling strategies, Minimum emission of toxic gases during recycling/disposal, Minimum energy	4

	requirements.	
2.	Fulfils a few of the above requirements	2
3.	None of the above.	0

Numerical value of permanent, i.e., VPF-l becomes a powerful means for LCE and evaluation of a system as it contains various structure invariant of LCE. An index called LCE index is defined as the numerical value of the permanent ($VLCE^{per}$). Based on the index value, the design alternatives are evaluated. The best alternative is the one having the highest index value and is selected . The ideal value I^d_{ideal} of Sustainability index is calculated to be $14.3*10^6$. Comparison of Sustainability value of system (I^d_i) can be relatively made with ideal value I^d_{ideal} .This comparison show to what level Sustainability of the system is achieved of the ideal value. This is obtained as:

$$I^d_r = \frac{I^l_i}{I^d_{ideal}} \times 100\ \% \qquad (1.4)$$

where, I^l_r is the relative Sustainability index, which represents Sustainability value of the system as % of the ideal value of index. This relative index provides designer qualitative information for improving Sustainability of the system. A scale 0-4 is proposed for assigning value to attributes and their degree of relationship. The user may select an appropriate scale e.g., 0-5, 0-10 or 0-100. However, it is desirable to select lower scale value to obtain manageable value of index and also to reduce subjectivity.

STEPS - SUSTAINABILITY ANALYSIS AND INDEX EVALUATION

The procedure proposed previously for Sustainability and evaluation of index for a system is given now. Consider the given system and its various conceptual design alternatives (q= 1, 2,……). Study functions and structure details, and design features from life cycle design point of view.

1. Consider the first alternative of the system (i.e., q=1). Identify LCE attributes (A^l_i, i=1,2,3……,N^l) of the system and also assign values to attributes i.e., L_i, i= 1,2,…..,N^d.
2. Identify the relationship among attributes i.e., in terms of degree of relationship (r_{ij}). Assign value to r_{ij}.
3. Develop LCE^g for the system alternative.
4. Write $VLCE^{per}$. This will be a N x N matrix with diagonal elements L_i's and off diagonal elements r_{ij}'s.
5. Derive LCE expression (VPF-l) or permanent function i.e., permanent ($VLCE^{per}$).
6. Evaluate the ideal value of LCE index I^l_{ideal} from VPF-l obtained above by substituting L_i= 4 and r_{ij} as obtained in step 3.
7. Use VPF-l and substitute the value of L_i and r_{ij} obtained in step 2nd and 3rd to evaluate Sustainability index I^l_i.
8. Consider the 2nd alternative (i.e., q=2) and repeat step 2 to 5 and 7.
9. Compare the LCE of all alternatives based on step 6 to 8 and identify the best alternative from life cycle point of view.

1.6 EXAMPLE

The proposed methodology can be used for both new and existing designs for design and evaluation of life cycle of a system. An example of a mechanical brake system is considered here in this section. The example considered here is of a mechanical brake system with two design alternatives, and is meant for illustrating the proposed procedure.

1.6.1 Example – Gearing System

An example of LCE of a gearing system is considered here for illustrating the proposed procedure. The designer has developed two design concepts/alternatives for this system. These are Spur gearing system and, Helical gearing system. The two design alternatives are to be evaluated from LCE point of view and then compared for selecting best design alternative. In both the gearing systems available, the objective is to transmit the power.

First of all, it is necessary to study the system concept details of first design alternative i.e., Spur gearing system.

The relationship among these attributes, i.e., the degree of interrelationship r_{ij} are also identified.

The ideal value of index is also obtained from matrix expression as discussed above and this completes step 6 of the design procedure.

Now, the second design alternative, i.e., helical gear is taken into consideration for carrying out the analysis.

It is observed that the LCE index decreases from $11.23*10^5$ to $6.26*10^5$ for the two design alternatives considered here in this example. The relative index value also decreases from 76.51 % to 24.22%.

However, the alternative with highest value of LCE index is considered as the best design alternative from LCE point of view.

This simple example has been elaborated for the benefit of readers. Although the procedure may appear troublesome and time consuming if performed manually, however it is not so when using a computer and more so using an expert system.

Table 1.7: Gearing System – LCE Comparison

S. No.	**Design Alternative**	**Index Value (I^d_i)** ($*10^5$)	I^d_r **Value** (%)
1.	Spur Gear System	11.23	76.51
2.	Helical Gear System	6.26	24.22

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