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Green Manufacturing Systems : Integrated Product Design Development

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Abstract

The terminology such as ecology, environmental problems, ecosystems, ecofactory, and others related to environmental problems have been recently used in manufacturing systems, since the modern industries have to consider a global ecological crisis. The indifference of recent environmental problems which may be faced now has been paid attention to all engineering areas. In this paper, manufacturing functional requirements such as disassembly, disposal, or recycling are considered in the integrated product design development, which have not been considered well in the preliminary design stage. Those functions will contribute to reduce the waste and to long the product life cycle, which also satisfies the business benefits and customer requirements. The concurrent design concepts should be applied to integrate all possible factors. Therefore, few practical concurrent engineering tools are presented in here. The objective of this paper is to develop a called green manufacturing systems for integrated product design development by concurrent design concept which can give the desirable result in product design.

1. Introduction

The global environment problems have caused the common recognition that the engineering development should be reconciled with the current needs of the environment. In our society, industrial production has become an indispensable major part of human endeavor in the cycles of global ecological system. If environment problems cause a global ecological crisis, confidence in recent technological civilization would fall, possibly resulting in difficulties maintaining standards of life. For

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this reason, modern industry is expected to make an important contribution to solve global environment problems.

Integrated product design development is an idealized model for product development which is integrated in terms of creation of market, product and production, and which clarifies integration between project and management, including the need for continual product planning.

Hence, product design development should be integrated with other development activities, and contribute to renewal and adoption within the flexible manufacturing system. Especially, the global environmental problems identifies that the technological development should be reconciled with the need of the environment, whereas modern industries have not paid attention to a fact that it is vital to embark on the development of innovative technologies or optimization to alleviate the burden on the global ecological system.

The establishment of innovative technologies for the realization of effective utilization of finite valuable resources is the target of the Green Manufacturing Systems (GMS). GMS aims to make good harmony between manufacturing activities and global ecology by taking into consideration additional manufacturing functions such as disassembly and recycling in product design concurrently. For detailed review and application of GMS and its advantages, see [2,4,6,7,8,10,11,12,13,14,15]

In a sense, attention should be paid to a fact that concurrent engineering is promising to optimize total environment burden by solving trade-off relations among various estimation factors which naturally tend to conflict each other, especially product design stage and processing operation in a manufacturing systems. Many concurrent engineering methods are applicable in the integrated design system environment since the assessment at the stage of product designing and production is obligated by law for promoting waste production and recycling, and many trade off problems remain to be solved in the GMS from the global view.

However, the scope of assessment of the GMS has to optimize product design development on the basis of assessment criteria such as the functional requirements and design parameters. In Japan, there have deserved special note in the emphasis on solving the waste problem on recycling and adopting preventive measures early of the 1990s. They also enforced the law for promotion of utilization of recyclable resources from October 25, 1991[5].

The functional requirements in product design development in here include processing, assembly, material handling, inspection, control, disassembly, and recycling. The design parameters can be classified as durability, performance, producibility, safety, maintainability, schedulibility, esthetics, reliability, and marketability. As the design phase is the very first of all processes, product design effects the environmental burdens in the entire life cycle [1]. Figure 1 presents the concurrent design system for the integrated product design development.

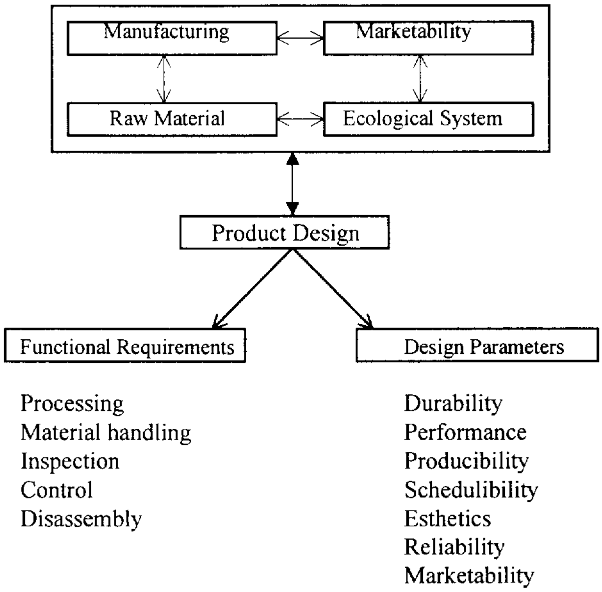

Figure 1. Concurrent Design System For Integrated Product Design Development

Product design must include design of the products to minimize the burden on the ecology system in all aspects of production, marketing and restoration systems, more specifically, the use of minimum necessary volumes of materials, incorporation of the minimum necessary functions, designing with longer service life and easy maintenance, adoption of modular design enabling only the troubled parts to be replaced, the use of minimal kinds of materials with high degree of recycling, disuse of materials detrimental to the environment, the use of standardized materials and structures, designing of structures which enable users to disassemble and separate the products with ease and safety to increase the recycling ratio, and introduction of structural designs enabling automatic disassembling with ease.

The contents of the integrated product design will be influenced by the degree of difficulty of the disassembling and recycling functions, so it will be desirable to establish design optimization not only for product performances but also for alleviating the needs for technological advances of the manufacturing system. Figure 2 describes the green manufacturing system for global ecology.

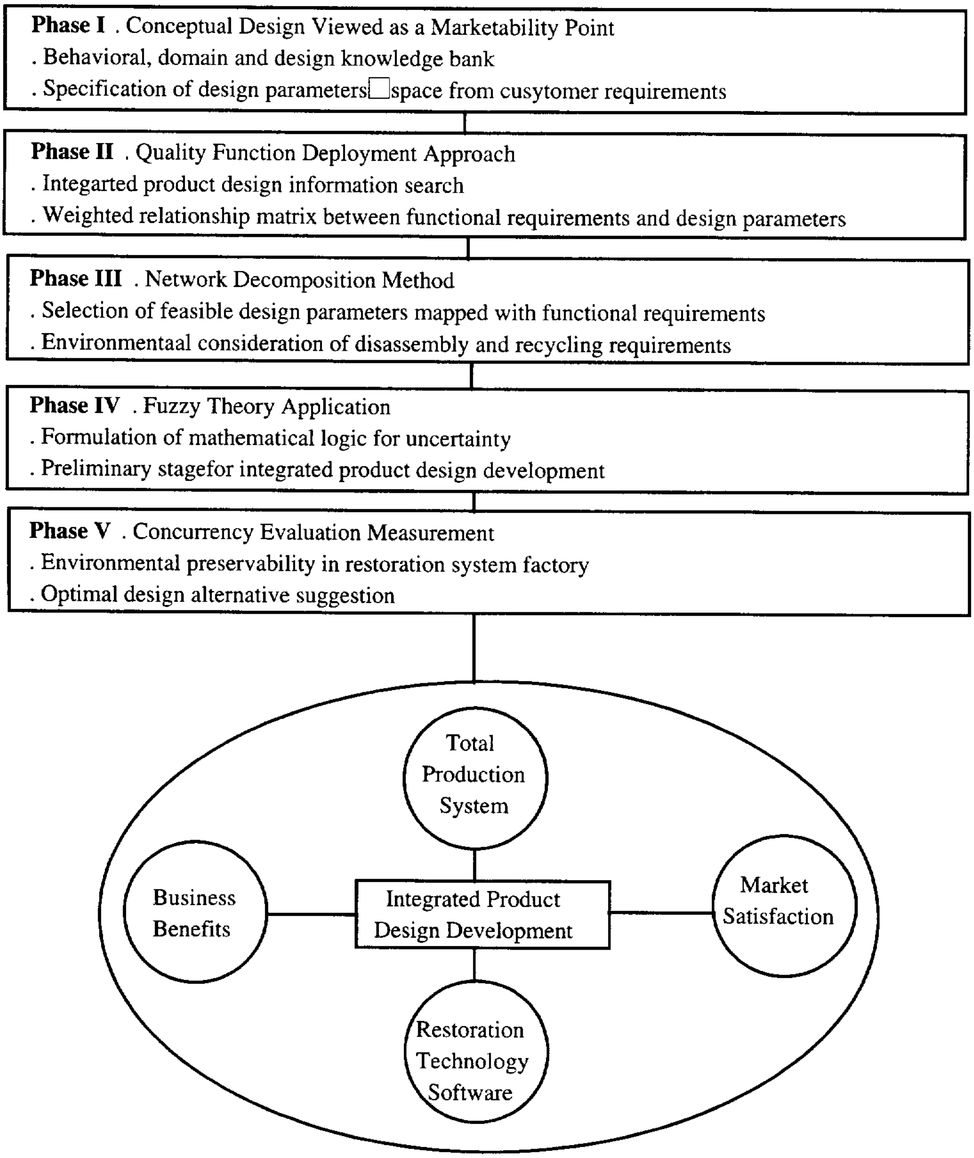

Figure 2. Green Manufacturing Systems For Global Ecology

The GMS requires efforts to establish a life model capable of assessing and minimizing the burden on the ecological system over the entire system including not only enterprises and factories but also outside these enterprises, up to the time the products are placed on the market and eventually treated for restoration.

The integrated product design will strongly influence the assessment of the ecological burden in all aspects of the manufacturing system, market and restoration system, so concurrent design including the criteria for assessing the burdens on the ecological system will be indispensable. It also extends over all systems which has to optimize products design, production design and restoration design on the basis of assessment criteria such as environmental preservability, productivity, economy and marketability.

2. Global Concurrent Engineering

Alleviating the ecological burden in the production system may conversely increase the ecological burden in the restoration system. Therefore, in the case of designing, for example, it will be necessary to assess the disassemblability in the restoration system in addition to assessing the assemblability in the production system. In addition, the product safety must not be sacrificed on the market by overly emphasizing disassemblability in the restoration system.

Also, as with the automobile, alleviating the burden on the ecological system on the market (by improving the fuel efficiency through vehicle weight reduction for example), may require compatibility to satisfy the disassemblability of disposed cars in the restoration system, the recyclability of waste materials and disposability of wastes.

The design, development, and production of a product is one of the greatest challenges which flexible manufacturing systems face today. No matter how a company refines and controls the manufacturing process, if the product is not properly designed, it will not operate correctly or performed well. Hence, the focus on quality of design must be balanced. One such strategy certain to address the managerial and manufacturing of the future is concurrent engineering. Concurrent engineering calls for the consideration and inclusion of product design attributes satisfying all the design constraints such as customer requirements.

Furthermore, concurrent engineering has been recently promoted in many industries as a response to competitive marketing pressures. Viewed as a more systematic approach of creating high quality products and bringing them to market at lower cost and in significantly less time, it also attracts the attention of quality designers.

Concurrent engineering approaches to organizational and cultural changes, information systems, software design, artificial intelligence, computer aided design and manufacturing integration, design for assembly, and other engineering related subjects. A review of published literature in the application of concurrent engineering to modeling of the product design provides an inadequate amount of information. The lack of a formal theory of design and universal design principles has caused major difficulties in product design [3].

In the case of product design, manufacturing functional requirements and relative design parameters are two main targets to be optimized. It is essential to balance and optimize estimation factors among function-related, and environment-related criteria while solving trade-off problems which seem to be incompatible with each other.

Main estimation factors can be described the design parameters. Taking into consideration the priorities of design parameters, which may be determined by quality function deployment approach, each factor should be assessed and be compatible each other.

From an engineering point of view, multi-dimensional estimation factors are basis for further comprehensive or total estimation. Non dimensional index or total estimation index which indicates evaluation value from total point of view, is desirable for solving the trade-off problems. Such type of index can be called as design evaluation index or concurrency evaluation measurement. Evaluation methods such as fuzzy theory application and design for manufacture can be desirable.

3. Optimization Model For Integrated Product Design Development

Phase I. Conceptual Design Viewed as a Marketability Point

A new optimization model for product design is proposed. Most of product design is based on the customer requirements.

Phase II. Quality Function Deployment Approach

The weighted matrix between functional requirements and design parameters from the customer requirements can be formed. The unrelated relationship between functional requirements and design parameters can be also reduced by the network decomposition method [9]. Then all the weights of given design parameters are normalized. Those normalized weights of design parameters are applied to proposed optimization modeling.

Formulate the weighted matrix (W_{ij}) which shows the relationship between functional requirements (FR_i) and design parameters (DP_j) as follows:

$$\text{Weighted matrix } (W_{ij}) = \begin{cases} \text{weight,} & \text{if there is any relationship between } FR_i \text{ and } DP_j \\ 0. & \text{otherwise} \end{cases}, \text{ where}$$

$$\text{Weight} = \begin{cases} p & \text{if the relationship is very strong} \\ p-1 & \text{if the relationship is strong} \\ p-2 & \text{if the relationship is slightly strong} \\ \cdot & \\ 0 & \text{if there is no relationship} \end{cases}$$

Phase III. Network Decomposition Method

Having applied network decomposition method developed by Kusiak and Cho [9] to initial weighted matrix, and rearrange the weighted matrix which identifies and removes the unnecessary components. The selection of feasible design parameters mapped by necessary functional requirements is proceeded, however, the disassembly and recycling requirements should be considered.

Among those selected design parameters, formulation of mathematical logic such as fuzzy theory would be applied to optimize the integrated product design development model from the following phases [16].

Phase IV. Fuzzy Theory Application

(a) Calculate and normalize each design parameters' weights (W_j) as follows. The design parameters' weights are applied to final step of the proposed optimization model.

$$\text{Normalized design parameters weight } (W_j) = \sum_{i=1}^{m} W_{ij} \Big/ \sum_{j=1}^{n} \sum_{i=1}^{m} W_{ij}, \text{ where}$$

m = total number of functional requirements (FR_i)

n = total number of design parameters (DP_j), and $\sum_{j=1}^{n} W_j = 1$

(b) Calculate and normalize each design parameters' value (V_j) as follows. A modified and expanded version of the rating system. The seven-level rating system allows the expert to assign rates (r_j) to various combinations of design attributes among the design specifications (DS_k). The highest value 7 is assigned to an absolutely superior design attribute while the lowest value 1 is assigned to a significantly inferior design attribute. The total rating values assigned to any two design attributes for each pairwise comparison must be equal to 8. One base design parameter (for example D_1) is compared against all other design parameters in sequential order.

The design parameters value before normalizing process $(V'_j) = W_{jrj} / W_{1r1}$

Then the normalized design parameter value $(V_j) = V'_j / \sum_{j=1}^{n} W_{jrj} / W_{1r1}$

(c) Calculate the utility value for each design alternatives by choosing three design parameters with the highest normalized value V_j. Add these values and consider it a utility value for that particular design alternative.

Phase V. Concurrency Evaluation Measurement

(a) For the efficiency of solving design problem, it is more desirable to select a design alternatives which combines all the given design specifications rather than to select designs for each design specification. In that sense, the design alternatives (A_j) are grouped based on the design variations.

(b) Fuzzy theory is applied to find out the optimal design alternative. The membership function $d_i(a,b)$ is defined to give outranking degree of design alternative b by the design alternative a under fuzziness regarding only the ith design specification. For a specific pair of design alternatives (a,b) and more generally for any pair, the following membership function. Then the partial outranking relation will be produced. When g(b) varies within the interval $[g_j(a), g_j(a) + t_j]$, and given the inherent fuzziness of the evaluations, a continues to be at least as good as b but its credibility is less and less great.

$$d_i(a,b) = \begin{cases} 1, & \text{if } gi(b) - gi(a) < 0 \\ 0, & \text{if } gi(b) - gi(a) > ti \\ \text{between 0 and 1}, & \text{otherwis e} \end{cases}$$

For $g_i(b) - g_i(a)$ [0, ti], the decrease of $d_i(a,b)$ can be determined by linear interpolation or any other formula as $d_i(a,b) = [\, 1 - (\, gi(b) - gi(a) / \;)]$.

(c) In order to prevent the case which the divergence is too unfavorable, the fuzzy discordance relation is produced by a threshold values.

$$D_i(a,b) = \begin{cases} 1, & \text{if } gi(b) - gi(a) < t'i \\ 0, & \text{if } gi(b) - gi(a) > ti \\ \text{between 0 and 1}, & \text{otherwis e} \end{cases}$$

For $g_i(b) - g_i(a)$ $[t_i, t'_i]$, the decrease of $D_i(a,b)$ can be determined by linear interpolation or any other formula as $D_i(a,b) = [\, 1 - (gi(b) - gi(a) / \;)]$.

(d) Fuzzy concordance relation C(a,b) can be produced with the decision making factor P_i which are normalized as same as previous process, as C(a,b) = $\Sigma_{j=1}^{m}$ Pidi(a,b). Also fuzzy outranking relation d(a,b) can be defined as following manner.

$$d(a,b) = \begin{cases} C(a,b), & \text{if } C(a,b) > Di(a,b) \\ C(a,b) \prod [1 - Di*(a,b)] / 1 - C(a,b), & \text{with } i * \{Di(a,b) > C(a,b)\} \end{cases}$$

(e) The following fuzzy domination relation d^D, and the complementation operation d^{ND} in the fuzzy set theory are produced as follows.

$$d^D(a,b) = \begin{cases} d(a,b) - d(b,a), & \text{if } d(a,b) > d(b,a) \\ 0, & \text{othe rwise} \end{cases}$$

$$d^{ND}(a,b) = 1 - d^D(a,b)$$

(f) The fuzzy set of non-dominated design alternative is determined by the intersection operation between fuzzy sets in the following ways. ND = min $d^{ND}(a,b)$ = 1- min [1- $d^D(a,b)$] = 1- max $d^D(b,a)$ = 1- max [d(b,a) - d(a,b)], where ^{N} $^{ND}(a)$ = 1 defines the unfuzzv set of non-dominated design alternatives. Consequently, D(a) represents the non-domination degree of design alternative (Aj) simultaneously by all the other design alternatives. The interpretation is that the non-transitivity of d(a,b) may give rise to the empty set of design alternatives for which $^{ND}(a)$ = 1. This value identifies the optimal design alternative among the alternatives.

(g) The design evaluation measure can be defined as following:

$$\text{optimal design alternative 's utility value} \Big/ \text{possible combination of design attribute utility value}$$

4. Discussion

A methodology for analyzing the environmental impact of simple example is presented. The main factors in this analysis are estimation of disassembly and recycling functional requirements during concurrent design stage and a comparative assessment of design parameters.

Therefore the influences exerted by the machining and assembly type industry on the global ecology system are considerable. Although there are many ways in which research and development in the engineering areas can contribute to solving existing global environmental disruption issues from the viewpoint of whole product life cycle, conducting the advanced concurrent design for the integrated product development in the design stage may lead to the creation of a new field of innovative technologies.

The proposed methodology for the integrated product design development can be a next-generation technology to be established by taking the production factory, market and restoration into perspective, and is designed to harmonize industrial activities with the global ecology system.

Since there have been many searches for the selection of optimal or best design alternative, most of studies are founded as statistical, fuzzy, possibilities, minimax techniques which are performed under uncertainty. However, when the design parameter utility values are determined, the selection of design alternatives is getting easier regardless cost and time considerations. Mathematical programming such as mixed integer programming or p-median programming only select the design specifications with the highest value of design attribute utility.

The proposed methodology and model provide a systematic approach to the optimization of the integrated product design development where various constraints associated with a concurrent engineering environment. The advantages and disadvantages of the proposed one is described as follows.

Advantages.

1. The systematic approach to the integrated product design development views the design process as stepwise, and new process that gradually refines the design transformation from a set of customer requirements to a set of feasible design parameters.
2. The utilization of design attribute values incorporate numerical values rather than rely on unstructured decision making process.
3. Components reduction gives rise to decrease cost and time constraints.
4. Grouping design alternatives provides simplicity

Disadvantages.

1. The proposed model and methodology is particularly effective for design problems with recognizable set of initial description.
2. Design alternatives combined components may cause less choice variability of special designs, or some combination problem may rise.
3. Knowledge-based expert experience may be required to complete various steps of optimization procedure to product design.
4. The overall design process requires accurate information for the designers to be able to render a reasonable judgment about the generation of optimal design alternatives, feasible design specifications.

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References

[1] Azarm, S. and W.C. Li. (1986) Optimal Design Using a Two-Level Monotonicity-Based Decomposition Method, ***Technical Paper***, Department of Mechanical Engineering and Systems Research Center, University of Maryland.

[2] Beckman, S., Worhach, P., and Sheng, P (1996) Environmentally-Conscious Supply Chain Management, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 185-190.

[3] Dixon, J.R. (1989) On Research Methodology Towards a Scientific Theory of Engineering Design, ***Design Theory '88: Proceedings of the 1988 NSF Grantee Workshop on Design Theory and Methodology***, Springer-Verlag, New York.

[4] Gune, P., and Sheng, P (1996) Influence of Site-Specific Factors on Environmentally-Conscious manufacturing, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 191-202.

[5] Hattori, M., Nomura, N., Sommer, D., and Inoue, H. (1995) Fundamentals of Environmentally Conscious Product Design, ***International Journal of Environmentally Conscious Design & Manufacturing***, 4 (1), 3-23.

[6] Hertwich, E., Pease, W., and Koshland, C (1996) Evaluating the Environmental Impact of Products and Production Process - A Comparison of Six Methods, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 235-250.

[7] Hertwich, E., Sheng, P., and Koshland, C (1996) A Flexible Method for Including Environmental Toxicity in DfE and LCA, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 211-218.

[8] Hideo, I., Yoshinori, N., and Naotake, O. (1992) Ecofactory -Concept and R&D Themes, ***Mechanical Engineering Laboratory, Agency of Industrial Science and Technology,***

Ministry of International Trade and Industry (Japan).

[9] Kusiak, A. and M.S. Cho. (1992) Concurrent Engineering: A Quality Function Deployment Approach, ***Proceedings of TIMS/ORSA-Orlando-92' Joint National Meeting***, April.

[10] Mitsuro, H., Noboru, N., and Hideo, I. (1994) Ecofactory From Product Life Cycle Aspects, ***Advancement of Intelligent Production*** (eds. Eiji Usui), Elservier Science B.V./The Japan Society for Precision Engineering.

[11] ORourke, D., and Koshland, C (1996) Industrial Ecology : A Critical Review, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 251-270.

[12] Sheng, P., Dornfield, D., and Worhach, P. (1996) Integration Issues in Green Design and Manufacturing, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 21-34.

[13] Sheng, P., and Hertwich, E. (1996) Indices for Comparative Waste Assessment in Environmentally ***-Conscious Manufacturing, Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 69-90.

[14] Sheng, P., and Srinivasan, M (1996) Green Agents for Distributed Manufacturing, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 219-234.

[15] Sheng, P., Worhach, P., and Gune, P (1996) A Network Optimization Framework for Green Process Planning and Product Design, ***Consortium on Green Design and Manufacturing, Combined Research Reports 1994-1996***, University of California Berkeley, Engineering Systems Research Center, 133-142.

[16] Siskos, J., J. Lochard, and J. Lombard. (1984) A Multicriteria Decision-Making Methodology Under Fuzziness: Application to the Evaluation of Radiological Protection in Nuclear Power Plants, ***Studies in the Management Science: Fuzzy Sets and Decision Analysis*** (eds. Zimmermann, H.J., L.A. Zadeh, and B.R. Gaines), 20, 261-283.