Combine Product Design and Supply Chain Decisions to Minimize Carbon Footprint

Jack C. P. Su, Chih-Hsing Chu, Yu-Te Wang*

Department of Industrial Engineering and Engineering Management

National Tsing Hua University

101 Kuang Fu Rd, Sect. 2, Hsinchu 300, Taiwan

**su@ie.nthu.edu.tw*

Abstract - Researchers in product design have devoted their effort to apply environment friendly material and manufacturing process to reduce environmental impact. However, if the designer only considers those impacts caused by the material and manufacturing process and ignore the impacts caused by the supply chain configurations, the effort to minimize environmental impact through product design could be compromised. In this research, we seek to develop a system combining product design and supply chain decisions to minimize the total carbon footprint. The proposed system generates the reference design for the product designers. It also helps supply chain managers to choose the suppliers and to determine the routings by which the work-in-process is transported. The result shows that the total carbon footprint can be reduced by coordinating product design and supply chain management.

Keywords - Design for Environment, Life Cycle Analysis, Green Supply Chain.

I. INTRODUCTION

People pay more and more attention to environmental issues due to recent deterioration of climate and environmental condition. In order to avoid further damage, the governments and international organizations establish the environmental protection related regulations and guidelines, such as the Tokyo Protocol, Montreal Convention, and WEEE, RoHS and EuP Directive of EU. These guidelines setup environmental norms for the manufacturers. In addition, the demands of green products are growing due to rising awareness of environmental protection. The green concept is not just a slogan. Many companies have begun to develop green specifications for their products. The concept of Design for Environment (DfE) emerges. DfE adopts the life-cycle view to limit the environmental impact in the process of product development from design to disposal to reduce the negative environmental impact.

However, product design decisions and supply chain decisions are often made by two different entities. Product designers try to use environment friendly materials and manufacturing methods to reduce environmental impact. Unfortunately, many designers do not have access to supply chain decisions. Without considering supply chain decisions such as which suppliers are used and how the work-in-process are transported, product designer's effort to reduce environmental impact can be compromised since transportation typically accounts for 10% to 20% of environmental impact (O'Donnell et al [1]). Thus, how to combine product design and supply chain decisions to minimize environmental impact is an important research topic.

In this paper, we seek to develop a decision framework combining product design and supply chain decisions to minimize carbon footprint. Four major stages are carried out in the decision framework. They are component identification, design generation, supply chain configuration, and design evaluation. Data required for each stage is identified. Decision variables and constraints in each stage are formulated. Algorithms needed to find the solution in each stage is developed. A real world case regarding a computer chair design is used to demonstrate the decision framework.

The rest of the article is organized as follows. The detail information of decision stages are described in Section II. In Section III, results and analysis based on a real world case are discussed. Section IV summarizes the paper with conclusions and future research.

II. DECISION STAGES

In this section, we present the detail information regarding each decision stages including component identification, design generation, supply chain configuration, and design evaluation.

A. Component Idnetification

In this decision stage, we seek to identify the required components to satisfy the product functions designer or customer demand. Each component in the component database is specified by two features: functional feature and assembly feature. Functional feature represents those features that meet specific function. Assembly feature represent those features that are required to attach to the other component. Take the arm rest component in Fig. 1 as an example, *plane01* is the functional feature to support elbow while *plane02* and *hole01* are assembly features to attach arm rest to the seat cushion.

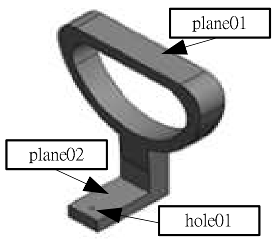

Fig. 1 Features of Arm Rest Component

Once all the components are specified by two features, the designer can identify the required components to meet desirable functions using Feature-Function Table. Table I shows a fraction of a Feature-Function Table. Assume ground movement is one of the desirable functions. The components that have functional feature to support this function are wheel, wheel caster, gas spring, and five fingernails. These four components together is the functional module to support the function of ground movement. If the designer lists all the desirable functions, the components required to support these functions can be identified.

TABLE I
FRACTION OF FEATURE-FUNCTION TABLE

Comp \ Fea \ Func	Ground movement	Height adjustment	Fix seat cushion	Fix back cushion
Wheel	axis 01+ plane 01			
Friction rod				
Wheel caster	hole 01+ hole 02			
Gas spring	plane 01+ plane 02	plane 01+ plane 02		
Five fingernails	hole (02+03+ 04+05+06)	hole 01		

Note that several components may be required to support a given function and a component may have functional features to support more than one function. For example, the *plane01+plane02* of gas spring support both ground movement and height adjustment.

B. Design Generation

Once the required components are identified, the design can be generated by combining different component material and variant, assembly structures, and assembly sequence while taking into account engineering constraints.

Given a component, the designer can determine what material and which component variant to use. Different material influences the carbon footprint not only by the material itself but also through its impact on manufacturing method. For example, if plastic is selected as the material, the manufacturing method has to be injection molding.

Components can be designed into different variants. Fig. 2 shows three design variants of the wheel caster.

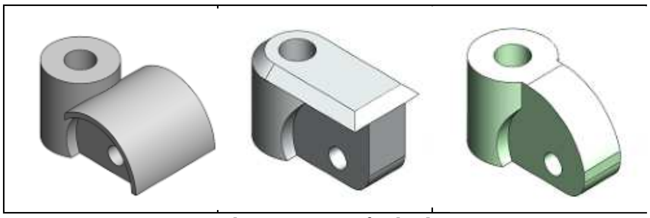

Fig. 2 Three Variants of Wheel Caster

Different assembly structures will yield different design. Assume each time only two components or sub-assembly will be assembled. This is not a very strict assumption, because we are not assuming that a functional module can only consist of two components. If a functional module consists of 3 components, we can assemble two components first, and attach the third component to the sub-assembly. Fig. 3 shows three assembly structures for a product consists of five components. The squares represent the components and the circles represent sub-assembly. To ensure all possible designs are available, this paper develops an algorithm to identify all assembly structures. Due to page limitation, the detail of the algorithm is omitted.

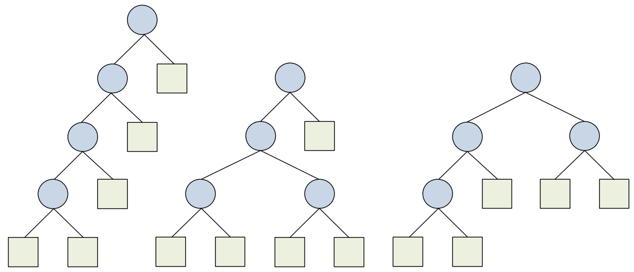

Fig. 3 Assembly Structures for Five Components

Different Assembly sequence will yield different design as well. Fig. 4 shows four designs with a product consisting of four components. The assembly structures are identical, but the sequences to assemble the components are different.

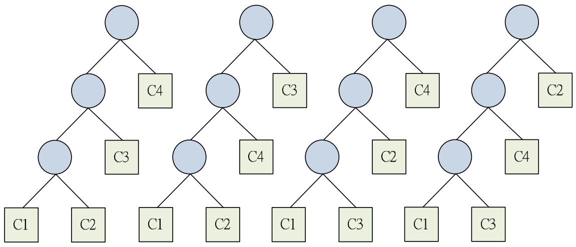

Fig. 4 Four Assembly Sequences with the Same Assembly Structure

Two engineering constraints are taking into accounts. One is sequence constraint. The other is interface constraint. A component can not be assembled at any sequence. A feasible sequence has to take into account the geometry and physical limitations. Fig. 5 shows two possible assembly sequences of a ball point pen. The left one is a feasible sequence while the right one is infeasible. The right one is infeasible because the outer case of the ball point pen is fully assembled before the refill is assembled. To check the feasibility of the assembly sequence, we use Solidworks 2008™, a computer aided design (CAD) software, to generate precedence relationship matrix between different components and revise the algorithm developed by Moore et al [2]. The detail of the algorithm is omitted due to page limitation.

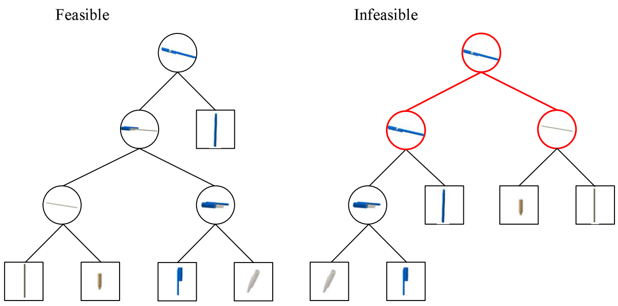

Fig. 5 Feasible and Infeasible Assembly Sequence of a Ball Point Pen

The interface constraint exams whether two components have required interface to assemble to each other. The information of assembly features is used. In this research we consider two ways to assemble components. One is plane fitting and the other is axis fitting. Plane fitting means two components are assembled by fitting two planes with opposite normal vectors or by specifying a fixed distance between them. Axis fitting means two components are assembled by aligning two linear axes. Fig. 6 shows the example of an arm rest and a seat cushion. They can be assembled by plane fitting using the assembly feature of *plane02* of the arm rest and *plane02* of the seat cushion. Or, they can be assembled by axis fitting using *hole01* of the arm rest and *hole03* of the seat cushion.

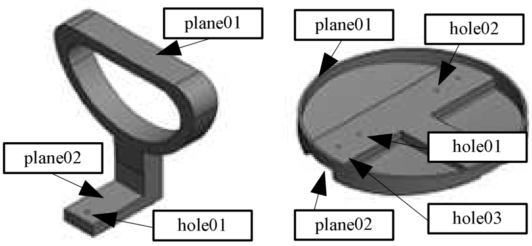

Fig. 6 Example to Illustrate Plane Fitting and Axis Fitting

We develop an algorithm to check all the assembly features between two components. If all assembly features are check and no proper interface is found, two components can not be assembled. The detail of the algorithm is omitted due to page limitation.

The product design decisions in this stage including materials and variants of components, assembly structure, and assembly sequence. The total number of possible design is too large to find the optimal design by complete enumeration. Therefore, we develop an evolution based genetic algorithm to search a good design in a reasonable time. The detail description of the genetic algorithm is omitted due to page limitation.

C. Supply Chain Configuration

Given a product design generated by design generation stage, two supply chain decisions are made in this stage to minimize carbon footprint. The first decision is to select suppliers. The second decision is to determine how the components and sub-assembly are transported from one supplier to the other. Different supplier has different geographic locations and manufacturing capability. Geographic location has great impact on transportation carbon footprint. The decision maker prefers suppliers closed to each other to minimize the carbon footprint. However, this option is not always available since not all suppliers can supply all materials and has capability to manufacture all component variants.

A dynamic programming based algorithm is developed to optimize the supply chain performance. The detail of the algorithm is omitted due to page limitation.

D. Design Evaluation

In this research, we adopt Life Cycle Assessment (LCA) approach to evaluate the carbon footprint. LCA is used to evaluate the environmental impact of a product through its life cycle (Ilgin and Gupta [3]). A comprehensive LCA evaluation often referred as cradle-to-grave approach including those impacts caused by extraction and processing of raw material, manufacturing, transportation, usage, recycling and disposal of a product. Since the impact of usage, recycling, and disposal is not available at the design stage (Biswas G, et al [4]), in this research, we only include the environmental impact of material, manufacturing and transportation. This approach is referred as cradle-to-gate approach. Gate stands for factory gate.

LCA is based on life cycle inventory (LCI) which quantifies the natural resources a production system consumes and generates. LCI usually is performed based on dedicated software system or database. In general, LCI database only contains the data specific to the life cycle activities occurring in certain geographic regions. In this paper, we use DoItPro™ to evaluate carbon footprint. DoItPro™ is developed by Industrial Technology Research Institute (ITRI) under the support of Ministry of Economic Affairs (MOEA) to support the LCA needs of the country.

III. RESULTS AND DISCUSSION

We use a real world computer chair case to illustrate the decision framework. This study use Dev C++™ as programming tool and Solid Works 2008™ as three-dimensional modeling tool. The input data include Feature-Function Table of the computer chair. From this table, the required components to satisfy all the functions are identified. The variant and material candidates of each component are given. The unit carbon footprints of material, manufacturing, and transportation are evaluated based on DoItPro™. Manufacturing capability of each supplier is specified. Distances between suppliers are derived based on their geographic locations.

The output data includes the variant, material, and supplier of each component and the assembly structure, assembly sequence, and assemblers used for sub-assemblies. The design given by the decision framework generates 20.48Kg of CO_2. 10.71Kg of CO_2 is generated by material related activities. Manufacturing and Transportation generate 8.17Kg and 1.6Kg of CO_2 with respectively.

The decision framework proposed by this study combines product design and supply chain decisions to minimize the carbon footprint. Thus, we call it the integrated approach. To show the importance of combing these decisions, we compare the results of the integrated approach with that of the two steps approach. Two steps approach means the design generation algorithm will search for the optimal design based only on material and manufacturing carbon footprint before supply chain decisions. Once the design is identified, the dynamic programming algorithm will determine the best suppliers to produce the design and the best way to transport work-in-processes. The two steps approach mimics the common practice of the industry. The design of two step approach generates 23.97Kg of CO_2. 10.64Kg of CO_2 is generated by material related activities. Manufacturing and Transportation generate 7.88Kg and 5.45Kg of CO_2 with respectively. The comparison between the carbon footprint of the integrated approach and that of the two steps approach is shown in Table II.

TABLE II
COMPARISON OF CARBON FOOTPRINT BETWEEN TWO APPROACHES

	Integrated Approach	Two Steps Approach	Carbon footprint Difference
Total	20.48Kg	23.97Kg	-3.49Kg (-14.56%)
Material	10.71Kg	10.64Kg	0.07Kg (0.66%)
Manufacturing	8.17Kg	7.88Kg	0.29Kg (3.68%)
Transportation	1.6Kg	5.45Kg	-3.85Kg (-70.54%)

The integrated approach reduces carbon footprint by 3.49Kg or 14.56% compared to the two steps approach. In the two steps approach, the designer tends to adopt the material and manufacturing process that has lowest carbon footprint without considering how these decisions would impact the transportation aspect of carbon footprint. Therefore, in the two steps approach, the carbon footprint from material and manufacturing are less than those of the integrated approach. However, the result of this case suggests that it is better to tradeoff material and manufacturing carbon footprint. By not choosing the suppliers that are capable of supplying the most environment friendly material or offering the manufacturing process with lowest carbon footprint, the company can choose suppliers that are close to each other to reduce environmental impact caused by transportation.

IV. CONCLUSION AND FUTURE RESEARCH

Due to customer's rising awareness of environmental protection and government's stringent environmental regulation, the capability to design and manufacture environmental friendly product is one of the most important competitive advantages. In this paper, we develop a decision framework to combine product design and supply chain decisions to minimize carbon footprint. Four decision stages are carried out. They are component identification, design generation, supply chain configuration, and design evaluation. The decision tools required in each design stage are developed including the Feature-Function Table to identify components, the evolution based generic algorithm to search a good design, the dynamic programming based algorithm to optimize supply chain performance, and the LCA model and database to evaluate the design. A real world computer chair case is used to illustrate the design framework. The result shows that the approach proposed by this paper, the integrated approach, can significantly reduce the carbon footprint compared to the two steps approach, the common practice of the industry.

There are limitations in this paper and many potential future researches. First, in this paper, we only consider carbon footprint but not cost. Cost is no doubt an important driver for decision making. It will be an interesting extension to include cost into the decision frame work to study the tradeoffs between the ecological drivers like carbon footprint and economic drivers like cost. Second, in this research we treat the LCA data as deterministic parameters. However, more and more researchers are interested in the uncertainty of LCA data. It will be interesting to extend our research to incorporate this uncertainty and to study how the uncertainty influences our decision.

REFERENCES

[1] O'Donnell, B., Goodchild, A., Cooper, J., and Ozawa T., "The relative contribution of transportation to supply chain greenhouse gas emissions: A case study of American wheat," *Transportation Research Part D: Transport and Environment*, Vol. 14, No. 7 (2009), pp. 487-492.

[2] Moore, K. E., Gungor, A., and Gupta, S. M., "Petri net approach to disassembly process planning for products with complex AND/OR precedence relationships," *European Journal of Operational Research*, Vol. 135, No. 2(2001), pp.428-449.

[3] Ilgin, M. A. and Gupta, S. M., "Environmentally conscious manufacturing and product recovery (ECMPRO): A review of the state of the art," *Journal of Environmental Management*, 91(2010), 563–591.

[4] Biswas, G., Kawamura, K., Saad, A., and Curtin, M., "Intelligent and environmentally conscious manufacturing systems state of the art," *International Journal of Environmentally Conscious Design and Manufacturing*, 4(2) (1995), 1–10.