An Integrated Approach to Sustainable Product Development at the System Design Stage

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Abstract
This paper presents an integrated approach to reducing the environmental impact of product development at the system design stage, by a simultaneous consideration of product design, manufacturing, and the supply chain. The approach incorporates a number of factors that ecologically influence the product lifecycle activities into product architecture design. CAD-based functions are developed to systematically generate manufacturing bills of material (BOM) by varying these factors. Lifecycle assessment is applied to evaluate the environmental impact of the generated BOM's. Optimization schemes guide the variation process to search for optimal results. This work realizes computer-aided sustainable product development by offering a system design tool of ecological decision making.

Keywords:
Lifecycle assessment, sustainable design, product architecture, bill of materials, product development

1 INTRODUCTION

Environmental issues like global warming and energy consumption have become an imperative for the contemporary world. However, current product development activities in manufacturing companies are still mainly driven by cost/profit analysis. A concern is that to integrate the eco-design principle into product development could impose additional design constraints and costs. Most ecological design methods were developed as assessment tools that can only estimate the environmental impact of an existing product or finished design [1]. They are difficult to be integrated into modern product development.

Grote et. al [2] proposed an eco-design method that helps a design engineer make design decisions without a trade-off on economic issues, with a focus on concept design and detail design phases. Feldmann et al. [3] proposed Green Design Advisor (GDA) that computes an overall score for environmental impact using multi-attribute value theory, considering metrics related to the number of materials, materials used in the product, and the disassembly and recyclability of the product. Mascle and Zhao [4] evaluated the environmental impacts for parts, assembly and operations during material extraction, material processing, manufacturing, usage and product disposal using feature modelling techniques. Most previous sustainable design methods were developed for facilitating decision making in the detail design stage. Product architecture has a profound impact on the entire product lifecycle [5]. Most of the past studies investigated the influence of product architecture from the perspectives of design for assembly/disassembly. Product architecture has been identified as the crucial factor that links product design and supply chain activities for environmental decision makings [6-7]. Supply chain considerations should be incorporated early in the design process to ensure the greatest possible reduction in environmental impacts. However, fewer methods have been developed to reduce environmental impacts with approaches at the system design stage.

In this research, we have developed an integrated framework that reduces the environmental impact of product development which considers design, manufacturing, and the supply chain at the same time. This framework incorporates a number of factors into the system design stage that ecologically influence the product development activities. CAD-based functions are applied to generate manufacturing BOM's (bills of material) by varying these factors. The environmental impact of each generated BOM is estimated based on LCA databases for three product development stages: raw material production, part assembly/manufacturing, and the supply chain. Optimization schemes are integrated with the variation process to search for the optimal result with a minimized amount of CO_2 emission. A real bicycle design is tested to validate the proposed framework. The test results show that it provides a useful tool for environmental decision making in the system design stage.

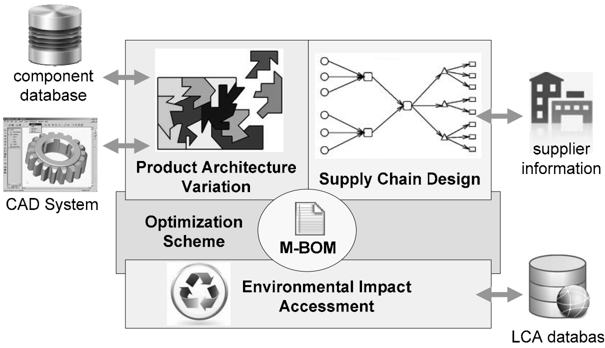

Figure 1: Framework of the proposed methodology

2 METHODOLOGY

The motivation for this research is to provide a systematic approach that assists engineers to make environmentally-friendly decisions in the system design stage. There are several pieces of functional elements in our method, as shown in Figure 1. A mechanism is first proposed to generate various options of the product architecture that satisfy product functional specifications. The next step is to estimate a quantitative measure for each design with a given environmental metric. A computation procedure is then applied to guide the variation mechanism based on the measure to produce optimal results. Several data sources are required to support the computation process. A component database offers the information of all part models that can be used in the product architecture variation. An ecological database enables product lifecycle assessment and the supply chain design depends on the supplier information.

2.1 Variation of Product Architecture

Product architecture links physical components or modules with functional specifications. To automatically generate all feasible options of product architecture is a challenging task. We assume that the components to be used are given. It is assumed that the relationships between physical chunks and product functions have been known. A finished product model contains the information of function-feature mapping specified by the designer. Such relationships need to be specified for all of the components that will be used for BOM variation. Many factors can be varied to generate different options for product architecture. The variation result is described as a manufacturing BOM with an assembly plan that specifies the assembly sequence and the assembly method for each step. Material type is perhaps the simplest factor to be varied. Some components have several variants produced from the past design process and each variant is denoted by a revision. These variants can be used to produce different designs of product architecture while all satisfying the product functions.

A second category of factors is related to product assembly. There are different assembly methods in practice. An assembly operation is accomplished with certain geometry or group of geometric elements in each method. It is manifested with rules like co-axis, co-plane, extended angle, and offset distance between geometric elements in a CAD model. In this work, we only consider the assembly operations defined by the co-axis and co-plane conditions [7]. A valid assembly operation needs to satisfy the geometric and physical constraints during the assembly. Components to be assembled must satisfy two conditions: (1) have a compatible assembly interface and (2) they do not interfere with each other when put together in space. The assembly interface is defined as the set of assembly features used in an assembly operation, which involves one or multiple assembly features in a component.

A component may contain multiple assembly interfaces when it can be assembled in different ways. The following procedure is applied to determine if two given components satisfy the assembly conditions:

I. *Match assembly interface:* this step identifies all of the assembly interface pairs of the same number and types of assembly features. For each assembly interface, components are automatically assembled in SolidWorks™ to check if the corresponding assembly features are aligned correctly.

II. *Check interference:* for each interface pair passing the first step, we conduct an interface check on the assembled result.

III. *Update assembly information:* the assembly interface that has been used in an assembly operation cannot be utilized any more. These features will be set as inactive.

Assembly sequence

A feasible assembly sequence satisfies both geometric and physical constraints in product assembly, referred to as the precedence relationship [8]. The approach of Disassembly Precedence Matrix (DPM) is used to characterize the spatial relationships among the components to be assembled. In addition, we only consider the component disassembly from the six nominal directions (±X, ±Y, and ±Z) [7]. Each component is moved along a given direction until reaching out of the bounding box of the assembly. The components interfering with the one moving along the path are identified and denoted in the DPM.

Variation of assembly sequence is achieved by two steps. The first step generates different assembly hierarchies. An example consisting of five components is shown in Figure 2. For simplification purposes, we assume that an assembly process only involves two components. There are three different topologies under this assumption. The second step is to arrange the components in each assembly hierarchy. There are n! possible sequences of arrangement for n components.

Component Merge

To merge components is an effective approach to varying product architecture. Here we propose a simplified and semi-automatic method that assists designers to combine components in an assembly and thus leverage this flexibility. The components to be united should satisfy several conditions. First, the material of the components has to be identical. Besides, they need to be adjacent with each other in the assembly. For simplification purposes, we only consider the components with compatible assembly interfaces. Some component features may vanish after the merge and the merged components still need to provide the original design functions.

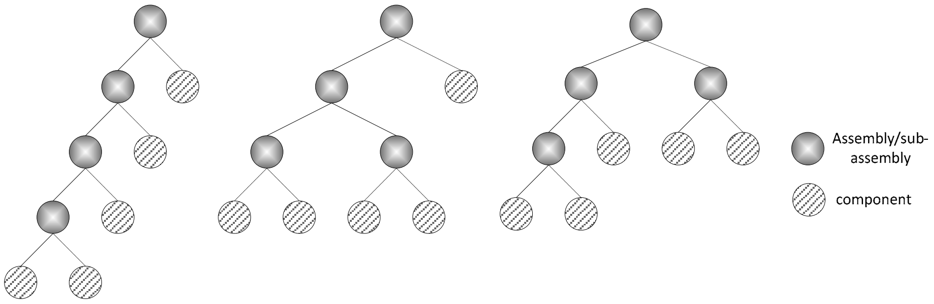

Figure 2: Assembly hierarchies of five components

This condition can be validated based on the function-feature mapping relationship. Lastly, the merged result has a higher geometric complexity, thus decreasing its manufacturability.

The variation procedure of product architecture is shown in Figure 3. The designer is required to provide product design functions, an instance of valid product architecture, and the mapping between features and product functions. The mapping has been manifested during the construction process of component models in SolidWorks™ prior to the procedure. A design of product architecture can result in different BOM's by varying related factors in manufacturing and the supply chain. The later section of optimization framework will explain how to incorporate these factors into the BOM generation process.

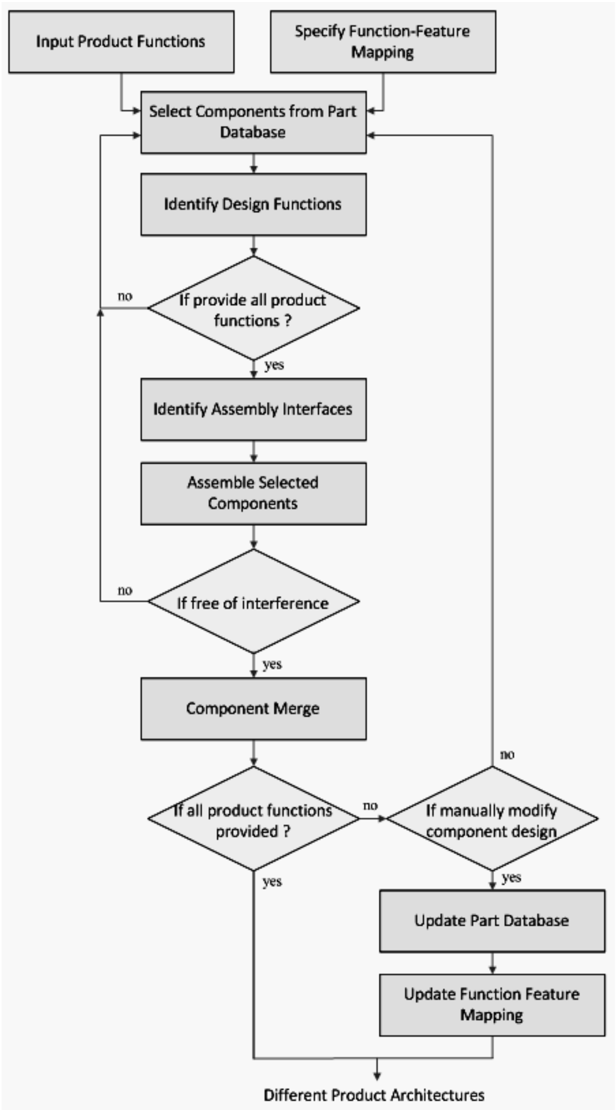

Figure 3: Variation procedure of product architecture

3 LIFE CYCLE ASSESSMENT

In this work, a cradle-to-gate approach is employed to evaluate the environmental impact. It is an assessment of a partial product life cycle. We only consider the impacts of a product in three phases of its lifecycle: preparation of raw materials, manufacturing, and distribution. In addition, the following assumptions are made for each phase. The component suppliers can acquire raw materials from a nearby area and the impact induced by the transportation of raw materials is thus ignored. We only consider the assembly and manufacturing processes of a component. The component material is limited in metals and plastics. They correspond to three manufacturing processes: metal processing, plastic deformation, and injection molding. The possible assembly processes include interference fit, bolt/screw hole, welding, and adhesive bonding. The logistics among the component suppliers and the final assembly plant is our major concern. The transportation of the finished product from the assembly plant to the end customer is not taken into account.

In this work, we adopt DoItPro™ [9] for evaluating the environmental impact of a product during its development process. DoItPro™ was originally developed in 2000 under the support of Ministry of Economic Affairs (MOEA) and the Industrial Technology Research Institute (ITRI) in Taiwan to address the LCA needs of the country. The basic data inventory consists of inputs such as materials, fuel, electrical energy, water, and outputs such as gaseous emissions, water emissions, and solid waste. The major discrepancy between ecological assessment tools and CAD systems is that neither materials nor components result in environmental damage, but only lifecycle activities, like production and transportation. To overcome this problem, we propose the concept of "manufacturing complexity" that links design features and environmental assessment.

4 OPTIMIZATION FRAMEWORK

An optimization framework has been developed to integrate the variation mechanisms described previously and to generate optimal BOM's. Different optimization algorithms are used in the framework to guide those variation mechanisms, as each has different characteristics, problem complexity, and the variation process. For simplification purposes, the following assumptions hold in the optimization. First, the manufacturing and assembly capabilities are known for each supplier. Their individual production capacity is infinite. Second, the outsourcing order of the component manufacturing and assembly cannot be split among multiple suppliers. The batch size in transportation is not considered.

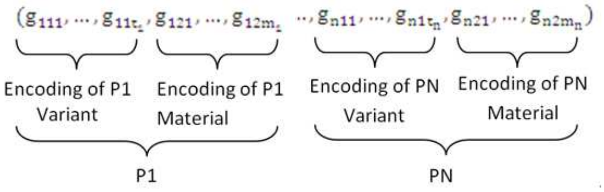

Figure 4: Encoding of chromosome in the GA algorithm

4.1 Genetic Algorithm

A GA-based optimization scheme is adopted for determining the optimal product architecture. Product architecture is represented as a chromosome as shown in figure 4. The fitness value of a chromosome is calculated to determine the probability of its survival during the evolution process. The fitness value consists of four parts corresponding to each major activity in the product development. The probability of the chromosome chosen by the next generation is the inverse of the fitness function. Crossover and mutation operators are used to produce a second generation population in the evolution process. Performing of these operations is determined by the probability values Pc and Pm. A pair of parent chromosomes is selected among the population by the roulette wheel selection mechanism.

4.2 Tabu Search

A Tabu search is applied to determine an optimal assembly sequence in a given assembly hierarchy, which falls into the problem category. A local search procedure is used to iteratively move from the current solution to a new one until reaching a stop criterion. The neighborhood of each solution is modified as the search progresses. The Tabu list is the most critical parameter controlling the search process. It includes the solutions that have been visited in the previous iterations. Tabu Tenure determines the number of previous solutions to be stored. We need to convert the problem (in this case the assembly sequence) into a formulation that would be efficiently processed by a Tabu search. There are n components to be arranged in n slots of an assembly hierarchy, as shown in Figure 8. An assembly sequence π where $\pi(i) \in \{p_1, p_2, \ldots p_n\}$ for i = 1, 2, … n. π is a sequence of component indices. A feasible solution has to satisfy the assembly constraints specified in the DPM. A neighboring solution is generated by a move from the current solution in the search space. In our approach, the move is defined as switching two component indices randomly selected.

4.3 Dynamic Programming

The problem here is to arrange the manufacturing tasks of a given assembly sequence among a group of suppliers subject to individual manufacturing constraints. We assumed that the final product is assembled from n components. n_1 of them are raw parts and $n_2 = n-n_1$ of them are subassembly. A_i is the set that contains the raw parts and subassembly of component i and M_i is the set that contains suppliers who are capable of producing component i. c_{ij} is the environmental impact generated during the manufacturing process when component i is produced by supplier $j \in M_i$. $d_i(j_1, j_2)$ denotes the environmental impact generated when component i is transported from supplier j_1 to supplier j_2.

At each stage of dynamic programming, we evaluate suppliers for one component starting from the first to the nth component. The first component represents the final product. Let $f_i(S_i, X_i) = f_i(S_i, \{X_{k\in A}\})$ be the total environmental impacts for the remaining stages given at stage i component i is produced by supplier S_i. Component k, $k \in A_i$, is produced by the supplier X_k. Given S_i, X_i denotes the value of X_i that minimizes $f_i(S_i, X_i)$ and $f_i^*(S_i)$ is the corresponding minimum value of $f_i(S_i, X_i)$.

$f_i(S_i, X_i) =$ immediate environmental impact (stage i) + minimum future environmental impacts (stage i+1 onward). The immediate environmental impact includes the environmental impact generated during the manufacturing process when component i is produced by supplier S_i or C_{iS_i} and the environmental impact induced by moving raw parts and subassemblies of component i from the locations of their suppliers to the location of S_i. Thus,

$$f_i(S_i, X_i) = C_{iS_i} + \sum_{k\in A_i} d_k(X_k, S_i) + \sum_{k\in A_i} f_k^*(S_k) \qquad (2)$$

If component i is a raw part, A_i is empty. Then

$$f_i\ (S_i) = C_{iS_i} \qquad (3)$$

The objective is to find the minimum environmental impact of the final product, i.e.

$$\min_{S_1} f_1^*(S_1) \qquad (4)$$

Dynamic programming finds the solution by successively searching $f_i^*(S_i)$ for all i as:

$$f_i^*(S_i) = C_{iS_i} + \min_{X_k, k\in A_i} \{\sum_{k\in A_i} d_k(X_k, S_i) + \sum_{k\in A_i} f_k^*(S_k)\} \qquad (5)$$

Recursion is solved by backward induction.

5 IMPLEMENTATION AND TEST RESULT

This work integrates product design and supply chain design for reducing the environmental impact of product development. CAD-related functions are required to ensure that the design solution produced in the search process satisfies the product functional requirements and that the assembly plan is feasible. The proposed methodologies have been implemented using C++ in MS Visual Studio™ 2005. SolidWorks™ 2008 offers a complete set of CAD library in C++ and individual functions can be accessed via DLL calls by external programs. It also contains a simple product data management module, which works as the component database. The ecological data related to the impact assessment is output from the systems into a text file. Proprietary C++ programs have been developed for the optimization schemes based on GA, Tabu search, and dynamic programming.

Figure 5: A test example of bicycle design

An example of bicycle design (see Figure 5) is used to verify the proposed framework. The available materials and variants of individual components are shown in Table 1. Suppose that the bicycle company is developing a new product with a group of suppliers. Some suppliers can only produce certain components due to limitations of their manufacturing capability, as shown in Table 2. Some of them can provide both manufacturing and assembly services. These suppliers are located in different cities in Taiwan. The transportation distances among them are shown in Table 3. The assembly capabilities are listed in Table 4. The LCA data related to CO_2 emission is shown in Table 5. The parameter settings in the GA and Tabu search are shown in Table 6. The search terminates in both algorithms when the maximal number of iterations is reached. The Tabu length is chosen as 7 in the implementation.

Part #	Component name	Material	# of Variants
P1	Grip	PP, PE	2
P2	Pedal	PE, PVC	2
P3	Connection tube	6061 Al, low carbon steel	1
P4	Back frame	6061 Al, gray cast iron	2
P5	Back frame connector	6061 Al, low carbon steel	1
P6	Pedal rod	6061 Al, low carbon steel	2
P7	Handle bar	6061 Al, low carbon steel	2
P8	Main frame	6061 Al, low carbon steel	3
P9	Rim	6061 Al, low carbon steel	2
P10	Seat tube	6061 Al, low carbon steel	1
P11	Rear sprocket	6061 Al, gray cast iron	1
P12	Free wheel	6061 Al, gray cast iron	1
P13	Saddle Connector	6061 Al, gray cast iron	1
P14	Front connector	6061 Al, gray cast iron	2
P15	Suspension	6061 Al, gray cast iron	1
P16	Suspension connector	6061 Al, gray cast iron	1
P17	Front wheel shaft	6061 Al, gray cast iron	1
P18	Front fork	6061 Al, low carbon steel	2
P19	Saddle	PUR flexible foam	1
P20	Tire	synthetic rubber	1

Table 1: Component materials and variants in the bicycle design

	Supplier							
Component name	M1	M2	M3	M4	M5	M6	M7	M8
Grip	V	V						
Pedal	V	V						
Connection tube						V		V
Back frame							V	V
Back frame connector			V		V			
Pedal rod					V	V	V	
Handle bar						V		V
Main frame							V	V
Rim							V	V
Seat tube						V		V
Rear sprocket				V	V			
Free wheel				V	V			
Saddle Connector			V		V			
Front connector			V		V			
Suspension			V	V	V			
Suspension connector			V		V			
Front wheel shaft			V	V	V			
Front fork							V	V
Saddle	V	V						
Tire	V	V						

Table 2: Manufacturing capability of suppliers

distance (km)	M1	M2	M3	M4	M5	M6	M7	M8
	Taichung	Taipei	Yi-Lan	Chunghua	Hsinchu	Chunghua	Pingdong	Yunlin
A1(M3)	440	140	0	480	300	490	900	700
A2(M4)	40	320	480	0	150	20	380	160
A3(M6)	50	330	490	20	90	0	390	130
A4(M7)	600	750	900	380	600	390	0	200
A5	50	300	500	10	150	10	400	150

Table 3: Geographic locations of individual suppliers and their distances

	Grip	Pedal	Connection tube	Back frame	Back frame connector	Pedal rod	Handle bar	Main frame	Rim	Seat tube	Rear sprocket	Free wheel	Saddle Connector	Front connector	Suspension	Suspension connector	Front wheel shaft	Front fork	Saddle	Tire
Grip							A3													
Pedal						A3,A4														
Connection tube								A5						A3,A5				A5		
Back frame					A4,A5			A4,A5		A4	A5	A5								
Back frame connector				A4,A5											A5					
Pedal rod		A3,A4										A5								
Handle bar	A3													A3						
Main frame			A5	A4,A5						A5		A5				A5		A4,A5		
Rim											A5						A5			A4
Seat tube				A4				A5					A5							
Rear sprocket				A5					A5											
Free wheel				A5		A5		A5												
Saddle Connector										A5									A1	
Front connector			A3,A5				A3													
Suspension					A5											A1,A2,A5				
Suspension connector								A5							A1,A2,A5					
Front wheel shaft									A5									A5		
Front fork			A5					A4,A5									A5			
Saddle													A1							
Tire									A4											

Table 4 Assembly capability of suppliers

Preparation of raw materials	unit	CO2 (kg)	density kg/m2	source
PP	kg	1.9	0.89	DoItProTM
PE	kg	1.8	0.917~0.952	DoItProTM
PVC	kg	2.7	1.29~1.30	DoItProTM
gray cast iron	kg	1.5	7.30	DoItProTM
6061 Al	kg	4.5678	2.70	SimaProTM
low carbon steel	kg	0.653	7.80	SimaProTM
synthetic rubber	kg	4.3	1.00	DoItProTM
PUR flexible foam	kg	4.2	0.05	DoItProTM

Manufacturing	unit	CO2 (kg)	source
PVC – Injection molding	kg	0.28	DoItProTM
PP, PE – Injection molding	kg	2.657	DoItProTM
Machining	kg	1.1158	DoItProTM
Sheet metal working	kg	1.3938	DoItProTM

Assembly	unit	CO2 (kg)	source
adhesive	kg/mm2	0.0125	DoItProTM
welding	m	9.03305	SimaProTM
interference fit	per	0.008955	DoItProTM

Table 5: LCA data required by the assessment of environmental impacts

GA	crossover rate	0.5
	mutation rate	0.03
	population size	40
	number of iterations	75
TS	number of iterations	30
	Tabu length	7

Table 6: Parameter setting in the optimization schemes

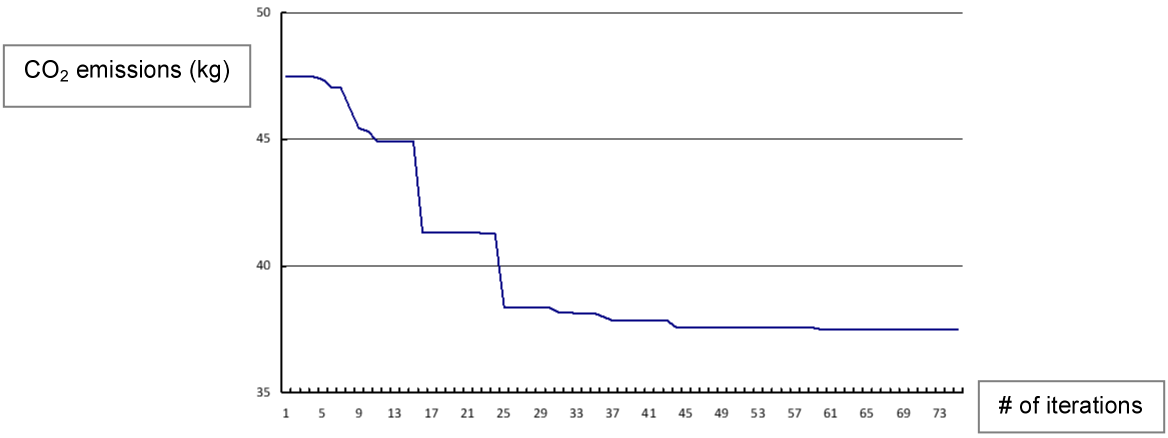

Figure 6: Search process of optimal manufacturing BOM with reduced CO$_2$ emissions

	raw material preparation	manufacturing	assembly	supply chain	total
CO$_2$ emission (kg)	26.28	2.32	0.018	5.55	34.17
CO$_2$ emission (percentage)	76.9%	6.8%	0.05%	16.2%	

Table 7: Breakdown of CO$_2$ emission for the optimal manufacturing BOM

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
variant	b	b	a	a	a	b	b	c	b	a
material	PE	PVC	steel	CI	steel	steel	steel	steel	Al	steel
supplier	M1	M2	M6	M8	M5	M6	M6	M8	M8	M6
	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
variant	a	a	a	b	a	a	a	a	a	a
material	Al	CI	CI	CI	CI	CI	CI	Al	foam	rubber
supplier	M4	M5	M3	M5	M5	M5	M5	M8	M2	M1

Table 8: Optimal product design and supplier selection

The search process of optimal manufacturing BOM in terms of reduced CO_2 emission is shown in Figure 6. The improvement becomes less significant after 60 iterations in the GA algorithm. The best solution after 75 iterations generates 34.17-kg CO_2 emission. As shown in Table 7, the breakdown of the result indicates that raw material preparation dominates the environmental impact of product development. This conclusion is similar to most LCA practices and previous analysis. The logistics in the supply chain also consumes a larger portion of CO_2 and outweighs the manufacturing or assembly activities. The corresponding results of product design and manufacturing supplier selection are summarized in Table 8. The optimal assembly sequence is shown in Figure 7.

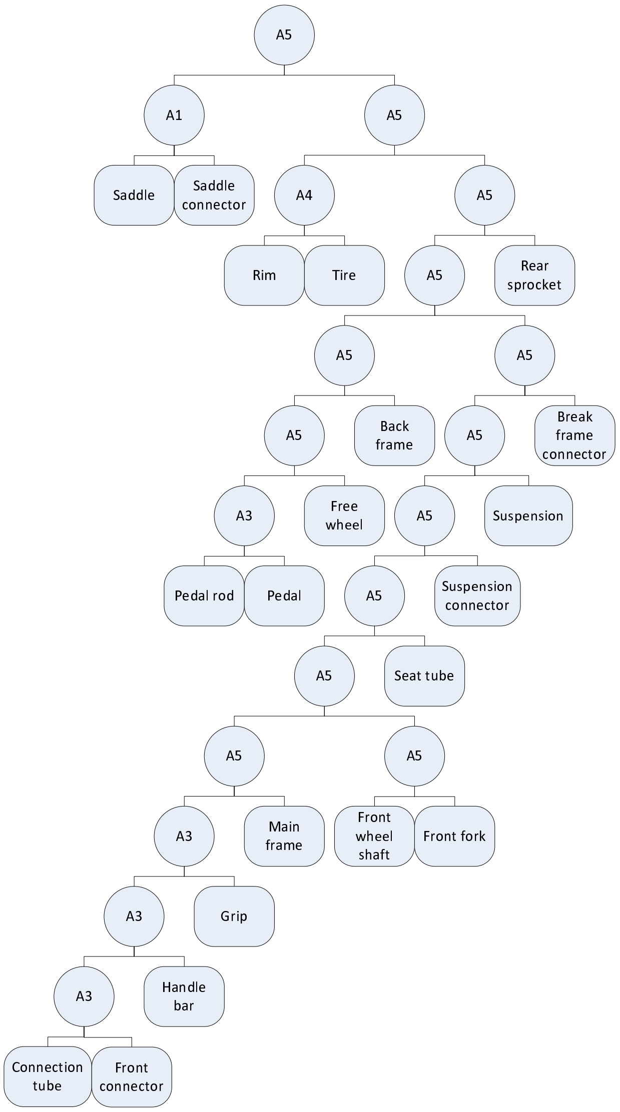

Figure 7 Optimal assembly sequence

6 CONCLUSION

Sustainable product development becomes an imperative for modern manufacturers and consumers all over the world. Product design is considered the critical stage involving decisions that concern environmental impact most. Most design for environment methodologies only facilitate decision making in the detail design stage. The supply chain activities need to be incorporated early in the design process to provide the greatest improvement in sustainability. This paper presented an integrated framework for product designers to make environmentally friendly decisions in consideration of the product design, manufacturing, and the supply chain simultaneously. It incorporates a number of factors into the system design stage that ecologically influence the product development activities. These factors, including component selection, assembly sequencing, assembly method, component merge, and supplier selection, allow automatic variation of manufacturing BOM's. The variation result is guaranteed to provide all product functions and to be interference-free during assembly. LCA was conducted to estimate the amount of CO_2 emissions for raw material production, part assembly/manufacturing, and the supply chain. Three optimization schemes were applied to search for better BOM's with minimized CO_2 emissions. An example of bicycle design was tested to demonstrate the capability of the proposed framework. The test results show that the system design stage offers a feasible means to significantly improve the environmental impact of product development. This research can be improved by incorporating probability-based optimization to account for the uncertainty in estimation of environmental impact.

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