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A Decision Support System to Estimate the Carbon Emission and Cost of Product Designs

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Due to the rising awareness of environmental protection, environmental impact of a product becomes an important design criterion. However, most companies do not have sufficient tools to evaluate the environmental impact of their designs. In this paper, a system to evaluate the carbon emission and cost of product designs is developed to help company determine which design to adopt. For a given design, the assembly structure, assembly sequence, and the supply chain configuration are optimized to minimize the carbon emission. An evolution based genetic algorithm is developed to search the assembly structure and sequence. A dynamic programming based algorithm is developed to optimize the supply chain configuration. To estimate the carbon emission, from cradle to gate life cycle assessment approach is adopted. A real world computer chair examples are used to illustrate the system.

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1. Introduction

People pay more and more attention to environmental issues due to rising awareness of environmental protection. Many environmental related regulations and guidelines are announced in response to people's concern such as the Kyoto Protocol, Montreal Convention, and WEEE, RoHS and EuP Directive of EU. On top of that, the demands of green products are also growing. Therefore, the environmental impact of a product becomes an important design criterion (Pezzoli, 1997).

However, most companies do not have sufficient tools to evaluate the environmental impact of their designs. There are two main reasons make this evaluation difficult. First, to accurately estimate the environmental impact, many activities from extraction of raw materials, manufacturing of parts, and assembling and distribution of the products have to be considered. It requires a lot of accounting efforts and standards to make such estimation meaningful. Second, even the variant and material of parts are given in the design, the environmental impact still varies depends on how these parts are assembled and how the supply chain is configured. To properly and fairly evaluate the environmental impact of a given design, this design's assembly structure, assembly sequence, and supply chain configuration have to be optimized.

In this paper, we develop a decision support system to evaluate the carbon emission and cost of a design and to help company determine which design should be adopted. An evolution based generic algorithm is developed to search the optimal assembly structure and sequence. A dynamic programming based algorithm is developed to optimize the supply chain configuration. The carbon emissions and costs of the designs are evaluated based on cradle-to-gate life cycle assessment (LCA) approach.

The rest of the article is organized as follows. In Section 2, relative literature is reviewed. The input and output of the decision support system are described in Section 3. Section 4 presents the mathematical models and solution approaches required to optimize the assembly structure, assembly sequence, and supply chain configuration. In Section 5, results and analysis based on a real world computer chair case are discussed. Section 6 summarizes the paper with conclusion and future research.

2. Literature Review

Many researchers focus on evaluating environmental impact in early concept design stage (Kang and et al., 2010, and Ahn, 2011). Based on digraph and matrix, Anand and Wani (2010) presented a product life cycle design procedure at the conceptual stage. Bohm et al. (2010) studied the impact of adopting life cycle assessment in the conceptual phase of design. They found that the product architecture given in the system design stage has significant impact on environmental performance. Many papers studied how various product architecture impact the ease of assembly and disassembly (Fixson, 2005 and Kwak et al., 2009). However, the main reason why product architecture has profound influence on environmental impact is because it links product design and supply chain activities together (Fixon, 2005, Chu et al., 2009). Therefore, supply chain configuration should be considered when evaluating the environmental impact of a product (O'Donnell et al., 2009). However, fewer methods integrate supply chain configuration optimization into conceptual design stage when the environmental impact of designs is evaluated.

Most researches focus on the environmental impact of detail design does not take into account the impact of assembly structure, assembly sequence and supply chain configuration neither (Leibrecht, 2005). Grote et al. (2007) developed a method that facilitates design engineers to comply with Eup directive. Feldmann et al. (1999) proposed a scoring system based on multi-attribute value theory called Green Design Advisor (GDA) to evaluate environmental impact of a product according to product's materials and recyclability. Using feature modelling techniques, Mascle and Zhao (2008) estimated environmental impact for parts, assembly, and operation during material extraction and processing, manufacturing, product usage and disposal. In this paper, we develop an evaluation system that will optimize the assembly structure, assembly sequence, and supply chain configuration of product designs. Therefore, these designs can be properly and fairly evaluated.

3. Inputs and Outputs of the Evauation System

In this section, the detail information regarding the inputs and outputs of the decision support system is described.

3.1 Inputs

3.1.1 Variant and Material of All Parts

In a given design, the designer has to specify material variant and material of all the parts consisting of the product. Different material influences the carbon emission 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.

Parts can be designed into different variants. Figure 1 shows three design variants of the arm rest. We use lower case English letter to identify part variants. If there are three part variants available, we call the first variant a, the second one b, and the third one c.

3.1.2 Assembly Feature of Parts

Each part in the design is given an assembly feature. Assembly feature represent those features that are required to attach to the other component. Take the arm rest component in Figure 2 as an example, *plane02* and *hole01* are assembly features to attach arm rest to the seat cushion. In other word, the assembly feature specifies whether two parts has proper interface to assemble to each other which is required in a feasible assembly sequence.

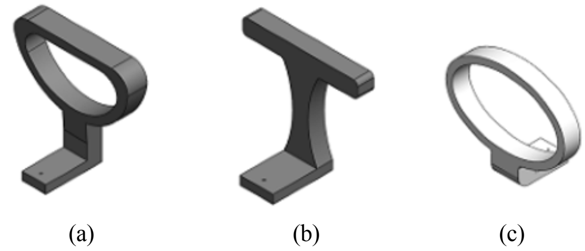


Fig. 1 Three Variants of Arm Rest

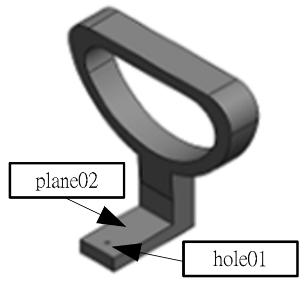


Fig. 2 Features of Arm Rest Component

3.1.3 Geographic Location and Manufacturing Capability of Suppliers

The geographic location of suppliers will determine the transportation distance between suppliers. It has great impact on how the supply chain should be configured and on the transportation carbon emission. Not all suppliers have manufacturing capability to produce all the parts or the capability to produce all materials. Supplier's capability has to be given before supply chain configuration can be optimized. This information in general is easy to access.

3.1.4 Carbon Emission and Cost Parameters

Unit carbon emission parameters for different material, different manufacturing process, and transportation have to be given. Unit carbon emissions for material and manufacturing process are given in Kilogram of CO2 per Kilogram of material used or product produced by the manufacturing process. Unit carbon emission for transportation is given in Kilogram of CO2 per Ton-Kilometer.

Life cycle inventory (LCI) approach which quantifies the natural resources a production system consumes and generates is used to estimate these parameters. 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 adopt DoItPro^{TM} for evaluating the environmental impact of a product during the product development process, including carbon emission of manufacturing processes and electricity carbon emission. DoItPro^{TM} was originally developed in 2000 under the support of Ministry of Economic Affairs (MOEA) in Taiwan to support the LCA needs of the country. The data inventory of this system consists of inputs such as material, fuel, electrical energy, water, and outputs such as gaseous emission, water emission, and solid waste. Notice that the yield rate of component manufacturing is not considered in this work. Data that is not available in DoItPro™ is acquired from SimaPro 7™. SimaPro 7™ is developed by University of Leiden in Dutch.

Unit cost parameters of different materials, different manufacturing process, and transportation are given. Unit cost for material and manufacturing process are given in dollar amount per Kilogram of material used or product produced by the manufacturing process. Unit cost for transportation is given in dollar amount per Ton-Kilometer. This information in general is easy to access.

3.2 Outputs

To properly and fairly evaluate the environmental impact of a given design, this design's assembly structure, assembly sequence, and supply chain configuration have to be optimized. Therefore the output of the decision support system, not only include the carbon emission and cost of the given designs, but also the optimal assembly structure, assembly sequence, and supply chain configuration of the design.

3.2.1 Assembly Structures

Different assembly structures will result in different supply chain configuration and yield different carbon emission and cost. In this paper, we assume each time only two parts or sub-assembly will be assembled. This is not a very strict assumption, because we are not assuming no more than two parts can be assembled together. If 3 parts need to be assembled together, we can assemble two parts first, and attach the third one to the sub-assembly. Figure 3 shows three assembly structures for a product consists of five components.

3.2.2 Assembly Sequences

Similarly, different Assembly sequence will result in different supply chain configuration and yield different carbon emission as well. Figure 4 shows four sequences with a product consisting of four components. The assembly structures are identical, but the sequences to assemble the components are different.

Not all sequences are feasible. A feasible sequence should satisfied two constraints.

The first constraint is the interface constraint. Namely, parts assembled to each other should have proper interface. The assembly feature specified for each part will be used to exam this constraint. Second, a feasible sequence has to take into account the geometry and physical limitations. Figure 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 cartridge is assembled.

To check the feasibility of the second constraint, 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. (2001). Detail procedure can be found in Su, Chu, and Wang (2011).

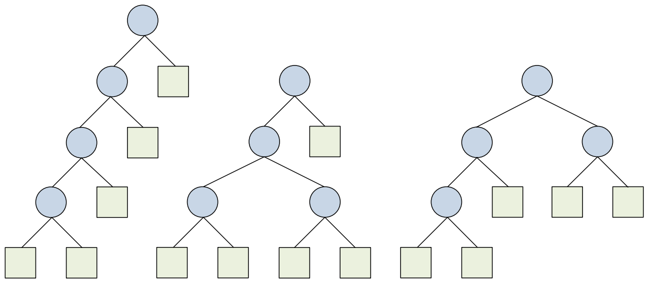


Fig. 3 Assembly Structures for Five Components

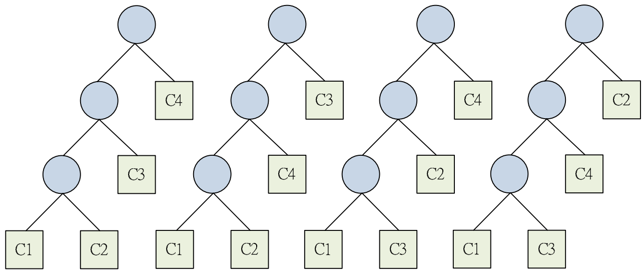


Fig. 4 Four Assembly Sequences with the Same Assembly Structure

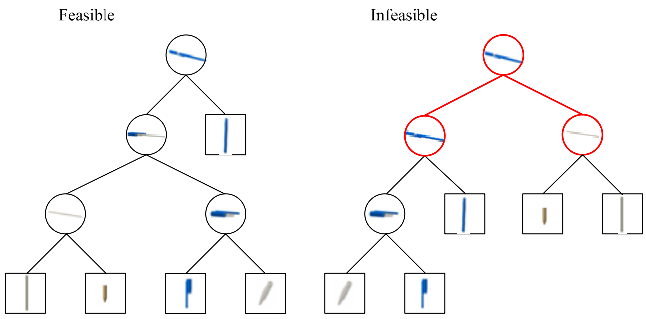


Fig. 5 Feasible and Infeasible Assembly Sequence of a Ball Point Pen

3.2.3 Supply Chain Configuration

The decisions made in supply chain configuration including which supplier to manufacture which part or to assemble which subassembly as well as how these work-in-process are transported in the supply chain. The distance between suppliers and supplier's capability are considered. For each assembly structure and sequence, a dynamic programming algorithm is used to solve for the optimal supply chain configuration. The detail procedure of the dynamic programming algorithm is described in Section 4.2.

3.2.4 Carbon Emission and Cost

Eventually, the carbon emission and cost of the designs will be evaluated. In this paper, we adopt Life Cycle Assessment (LCA) approach to evaluate the carbon emission. LCA is used to evaluate the environmental impact of a product through its life cycle (Ilgin and Gupta 2010). 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., 1995), 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. Similarly, the total cost includes material, manufacturing and transportation costs.

4. Methodology

To fairly evaluate product designs, a bi-level optimization procedure is developed. At the top layer, possible combinations of assembly structure and sequence will be searched according to the evolutionary base GA algorithm. At the bottom layer, for each combination of assembly structure and sequence under evaluation in GA, the corresponding supply chain structure is optimized by dynamic programming.

4.1 Algorithm to Search Assembly Structure and Sequence

According to Su, Chu, and Wang (2012), if there are N parts, the number of available structures is $f(N)=\sum_{i=1}^{\left\lfloor \frac{N}{2} \right\rfloor}\left[f(N-i)\times f(i)\right]$ $\forall\, N\geq 2$. If there are M parts and subassemblies in the structure, the total number of possible sequences is $M!$. When the design is complex and total number of part count is large, the number of assembly structures remains manageable but the number of possible sequences increases exponentially. It will take computer a very long time to find the optimal assembly sequence by complete enumeration. Therefore, we enumerate all structures and develop an evolution based genetic algorithm to search a good assembly sequence in a reasonable time.

Given number of parts and subassemblies M, each assembly sequence is represented as a chromosome as shown in the following:

$$\Bigl(\underbrace{L_1, L_2, \cdots, L_M}_{Sequence}\Bigr)$$

L_i represent the part or subassembly i's location in a sequence. The GA based evolution process is conducted as follows:

Step 1: Initialize the process. Randomly generate N_{pop} chromosomes. N_{pop} is the number of population in each generation and an even number. Evaluate the cost for each chromosome. The minimum value of cost and its corresponding sequence is recorded as best sequence.

Step 2: Calculate p_ς for each chromosomes in the population. Use roulette wheel selection mechanism to select N_{pop} chromosomes from the population. The higher the p_ς, the higher the chance is for a chromosome to be selected. A chromosome can be selected for multiple times. For the ς^{th} chromosome

$$p_\varsigma=\frac{\dfrac{1}{Fit(\varsigma)}}{\sum_{\upsilon=1}^{N_p}\dfrac{1}{Fit(\upsilon)}}$$

Where $Fit(\varsigma)$ is the total cost for ς^{th} chromosome. The higher the total cost, the lower the p_ς is.

Step 3: Randomly from $N_{pop}/2$ pairs of parents. The first chromosome in the pair is called the father, and the second chromosome is called the mother.

Step 4: Generate son and daughter chromosomes by duplicating the genes values from father and mother with respectively. There are $N_{pop}/2$ families now. In each family, there are father, mother, son, and daughter. In total, there are $2N_{pop}$ chromosomes.

Step 5: This step performs the crossover operation. Position based crossover is used. For the son (daughter), randomly select a set of positions. Copy the values of these positions from mother (father) into the corresponding positions of the son (daughter) to change the gene value. Delete the duplicate values from son (daughter). Place the missing values of the sequence into son's (daughter's) chromosome from left to right in an ascending order

Step 6: This step performs the mutation operation. Inversion mutation is used. For each son and daughter chromosome, randomly generate two positions. The genes between these two positions will form a subset. Invert the sequence of the subset.

Step 7: Check the engineering feasibility of the son and daughter chromosome. If any of them is infeasible, use crossover and mutation process to generate new offspring until all of them are feasible.

Step 8: Evaluate the cost of each chromosome. Select two best chromosomes in terms of cost from each family. N_{pop} chromosomes will be selected. Update the best design if a better design is identified.

Step 9: Check if the stop criterion is reached, the maximal iterations in this case. If yes, stop the search; otherwise go to Step 2.

4.2 Dynamic Programming for Supply Chain Configuration

Given an assembly structure and sequence, two supply chain decisions are made to minimize cost. 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. A dynamic programming based algorithm is developed to optimize the supply chain performance. Use tree network to represent the assembly structure and sequence given by the genetic algorithm. Each node represents a work-in-process which is either a part or a sub-assembly. The parent and children relationship indicates that the parent work-in-process is assembled from the children work-in-processes. Therefore, the children have to be manufactured or assembled before the parent. Assume there are N work-in-processes in a design. The end nodes represent work-in-processes that don't have any child. E is the set of end nodes. Let i be the index of work-in-process, i = 1, 2, … , N. A_i is the set that contain the children of work-in-process i and Γ_i is the set that contain suppliers who are capable of producing work-in-process i. The elements in A_i and Γ_i are ranked in an increasing order according to the value of their index. Ai is empty if $i\in E$. For example, in Figure 6, A_5={n-1, n}. We number the nodes from the root to the leaves. The final product is represented by the first node. An instance of the tree network is shown in Figure 6.

Let j be the Index of supplier, j = 1, 2, …, J. c_{ij} is the cost

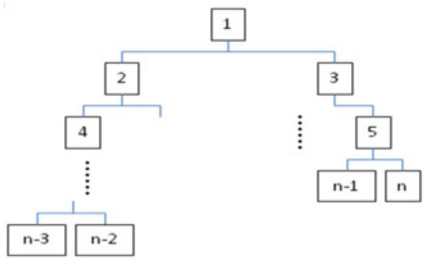


Fig. 6 Tree Network of a Design with *N* Work-in-Process

generated if work-in-process i is produced or assembled by supplier $j \in \Gamma_i$. $d_i(j_1, j_2)$ is the cost generated if component i is transported from supplier j_1 to supplier j_2. We formulate this problem as a dynamic programming problem to determine which supplier should manufacture or assemble which work-in-process to minimize the total cost.

At each stage in the dynamic programming algorithm, we evaluate suppliers for one work-in-process starting from the first one to the N^{th} work-in-process. Therefore, the index of stage is the same as the index of work-in-process. Decision variable vector at stage i is $X_i = \{X_{k \in A_i}\}$ where X_k is the supplier of work-in-process k. State Variable S_i represent the supplier of work-in-process i at stage i.

Let $f_i(S_i, X_i) = f_i(S_i, \{X_{k \in A_i}\})$ be the total cost for the remaining stage given at stage i, work-in-process i is produced by supplier S_i and work-in-process k, $k \in A_i$, is produced by the supplier X_k. Given S_i, let X_i^* denote the value of X_i that minimize $f_i(S_i, X_i)$ and let $f_i^*(S_i)$ be the corresponding minimum value of $f_i(S_i, X_i)$. Thus

$$f_i^*(S_i) = \min_{X_i} f_i(S_i, X_i) = f_i(S_i, X_i^*)$$

Where

$f_i(S_i, X_i)$ = immediate cost (stage i) + minimum future cost associated with component i (stage $k \in A_i$).

The immediate cost include two items. The first one is the cost generated during the manufacturing process when work-in-process i is produced by supplier S_i or c_{iS_i}. The second one is the cost generated by transporting children of work-in-process i from the locations of their suppliers to the location of S_i. Therefore

$$f_i(S_i, X_i) = c_{iS_i} + \sum_{k \in A_i} d_k(X_k, S_i) + \sum_{k \in A_i} f_k^*(S_k) \tag{1}$$

If $i \in E$, A_i is empty. Then

$$f_i(S_i) = c_{iS_i}. \tag{2}$$

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

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

Dynamic programming finds it by successively finding $f_i^*(S_i)$ for all i using the following equation.

$$f_i^*(S_i) = c_{iS_i} + \min_{X_k, k \in A_i} \left\{ \sum_{k \in A_i} d_k(X_k, S_i) + \sum_{k \in A_i} f_k^*(S_k) \right\} \tag{3}$$

If $i \in E$, A_i is empty. Then

$$f_i^*(S_i) = c_{iS_i} \tag{4}$$

The problem is solved by backward induction start with i=N. Because work-in-process $N \in E$. From equation (4), $f_N{}^*(S_N) = c_{NS_N}$. $f_{N-1}{}^*(S_{N-1})$ can be evaluated by either equation (3) or equation (4) depends on whether work-in-process $N-1 \in E$. Similarly $f_{N-2}{}^*(S_{N-2})$, $f_{N-3}{}^*(S_{N-3})$, $\cdots$ $f_2^*(S_2)$, and $f_1^*(S_1)$ can be found by the same procedure.

5. Case Study

We use a real world computer chair example to illustrate the evaluation system. This study use Dev C++^{TM} as programming tool and Solid Works 2008^{TM} as three-dimensional modeling tool. The case company has two existing designs. The part name, part variant, and materials of these two designs are given in Table 1 and Table 2. Once the part variant is specified, the assembly feature can be accessed from part database. Table 3 show the manufacturing capability of each supplier. There are 5 manufacturers who manufacture parts and 3 assemblers who assemble the subassembly. In this particular case, all assembler can assemble all subassembly. Geographic locations of suppliers are shown in Figure 7. Table 4 shows the distance between suppliers based on their geographic locations. The unit carbon emission and unit cost of material, manufacturing, and transportation are given in Table 5 and Table 6. Table 7 shows the density of materials which is used to convert volume specified in Table 1 into weight. The company want to evaluate the carbon emission and cost of these two designs while the assembly structure, assembly sequence, and supply chain configuration are optimized so that it can determine which design to adopt.

The optimal assembly structure, assembly sequence and supply chain configuration for these two designs are shown in Figs. 8 and 9. The total carbon emission and total cost of these two designs are summarized in Table 8.

The major difference between Design 1 and Design 2 is that Design 1 uses cast iron for mechanism 2 (C6) and 3 (C7) while Design 2 uses low carbon steel. Since low carbon steel has higher cost and lower carbon emission than that of the cast iron, one would expect that Design 2 has higher cost and lower carbon emission. However, the results show that Design 2 has higher cost and higher carbon emission and therefore is dominated by Design 1.

The reasons why Design 1 has lower carbon emission are two folds. First, some of the parts in Design 1 have smaller volume. For example, the volume of C8, C9, C10, and C11 of Design 1 are much smaller than that of Design 2. Hence, the material and manufacturing carbon emission of Design 1 is smaller than those of Design 2. Second and more importantly, due to the supplier capability limitation, Design 2's supplier are scattered everywhere in Taiwan. However, Design 1 is able to use suppliers only in the central and south part of Taiwan. Therefore, the transportation carbon emission and cost of Design 1 are smaller than those of Design 2. The impact of supply chain configuration will be more significant if the products evaluated are heavier.

Table 1 Design 1 of Computer Chair

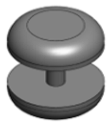
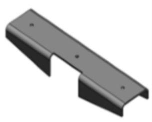
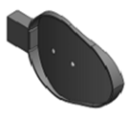
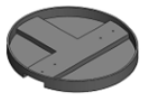
Part Name	Part Variant		Volume (cm^3)	Material
C1 Wheel	a		133.70 (26.74x 5 pieces)	PP
C2 Wheel Caster	a		82.39 (16.48* 5 pieces)	PP
C3 Five Fingernails	a		787.50	PP
C4 Armrest	b		289.62 (144.81* 2 pieces)	PP
C5 Mechanism 1	a		87.51	Cast Iron
C6 Mechanism 2	a		102.01	Cast Iron
C7 Mechanism 3	c		99.56	Cast Iron
C8 Back Cushion Cover	b		1031.70	PP
C9 Seat Cushion Cover	b		1354.63	PP
C10 Back Cushion	b		5886.44	PUR Flexible Foam
C11 Seat Cushion	b		9950.14	PUR Flexible Foam

Table 2 Design 2 of Computer Chair

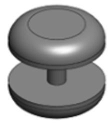
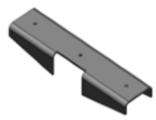
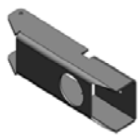
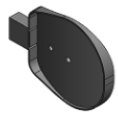
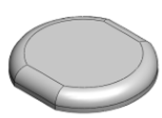
Part Name	Part Variant		Volume (cm^3)	Material
C1 Wheel	a		133.70 (26.74* 5 pieces)	PP
C2 Wheel Caster	c		114.03 (22.81* 5 pieces)	PP
C3 Five Fingernails	c		1840.46	PP
C4 Armrest	a		377.71 (188.86* 2 pieces)	PP
C5 Mechanism 1	a		87.51	Cast Iron
C6 Mechanism 2	a		102.01	Low Carbon Steel
C7 Mechanism 3	c		99.56	Low Carbon Steel
C8 Back Cushion Cover	c		1258.75	PP
C9 Seat Cushion Cover	c		1675.59	PP
C10 Back Cushion	c		7275.51	PUR Flexible Foam
C11 Seat Cushion	c		12346.23	PUR Flexible Foam

Table 3 Manufacturing Capability of Suppliers

Manufacturing Capability (1 means capable)	Suppliers				
Part Name	M1	M2	M3	M4	M5
C1 Wheel	1		1	1	
C2 Wheel Caster	1		1		1
C3 Five Fingernails		1	1	1	
C4 Armrest	1		1		1
C5 Mechanism 1	1			1	1
C6 Mechanism 2	1			1	1
C7 Mechanism 3	1			1	1
C8 Back Cushion Cover		1			1
C9 Seat Cushion Cover	1		1	1	
C10 Back Cushion		1	1	1	
C11 Seat Cushion		1		1	
Material	M1	M2	M3	M4	M5
PP	1	1	1	1	1
PE	1	1	1	1	1
PVC	1	1	1	1	1
Cast Iron	1			1	1
Low Carbon Steel	1			1	1
PUR Flexible Foam		1		1	

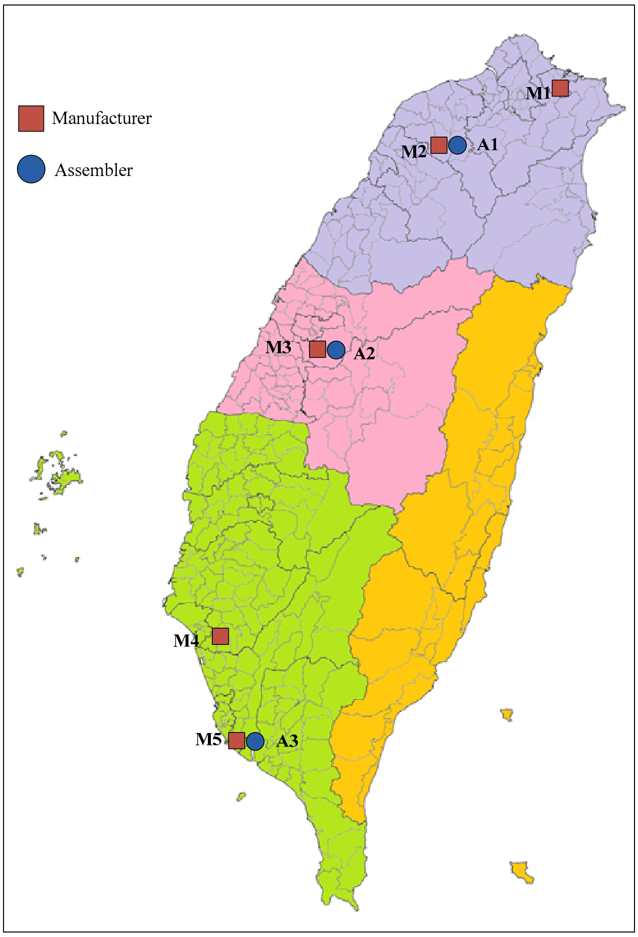


Fig. 7 Geographic Location of Suppliers

Table 4 Distances between Suppliers

Transportation Distance (KM)	M1	M2	M3	M4	M5	A1	A2	A3
A1	70	5	140	280	330	0	140	330
A2	210	140	5	140	190	140	0	190
A3	400	330	190	50	5	330	190	0

Table 5 Unit Carbon Emission

Material	CO2 Emission (Kg/Kg)	Source
PP	1.9	DoItPro™
PE	1.8	DoItPro™
PVC	2.7	DoItPro™
Cast Iron	1.5	DoItPro™
Low Carbon Steel	0.653	SimaPro 7™
PUR Flexible Foam	4.2	DoItPro™
Manufacturing	CO2 Emission (Kg/Kg)	Source
PVC Injection Molding	0.28	SimaPro 7™
PP, PE Injection Molding	2.657	SimaPro 7™
Machining	1.1158	SimaPro 7™
Sheet Metal Working	1.3938	SimaPro 7™
Transportation	CO2 Emission (Kg/Ton-KM)	Source
Truck (Smaller than 3.5 tons)	1.5438	DoItPro™

Table 6 Unit Cost

Material	Cost (NTD/Kg)
PP	55
PE	64
PVC	36
Cast Iron	20
Low Carbon Steel	30
PUR Flexible Foam	24
Manufacturing	Cost (NTD/Kg)
PVC Injection Molding	10
PP, PE Injection Molding	19
Machining	15
Sheet Metal Working	14
Transportation	Cost (NTD/Ton-KM)
Truck (Smaller than 3.5 tons)	10

Table 7 Density of Materials

Material	Density (Kg/M^3)
PP	0.89
PE	0.93
PVC	1.3
Cast Iron	7.3
Low Carbon Steel	7.8
PUR Flexible Foam	0.05

This research is not just a case study. We develop a system to fairly compare different product designs in terms of costs and carbon emission. The purposes of this case study are two folds. First, we try to illustrate the system and to show that the system is capable of handling a real world size problem. Second, by observing the results of this case study, we high light that even though the material and part variant of the design is given, it is not trivial to evaluate the cost and carbon emission of given designs.

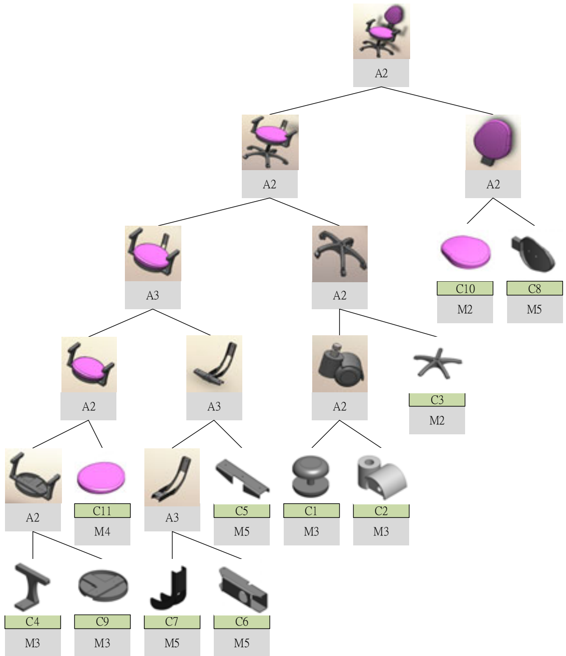


Fig. 8 Optimal Assembly Structure, Sequence, and Suppliers for Design 1

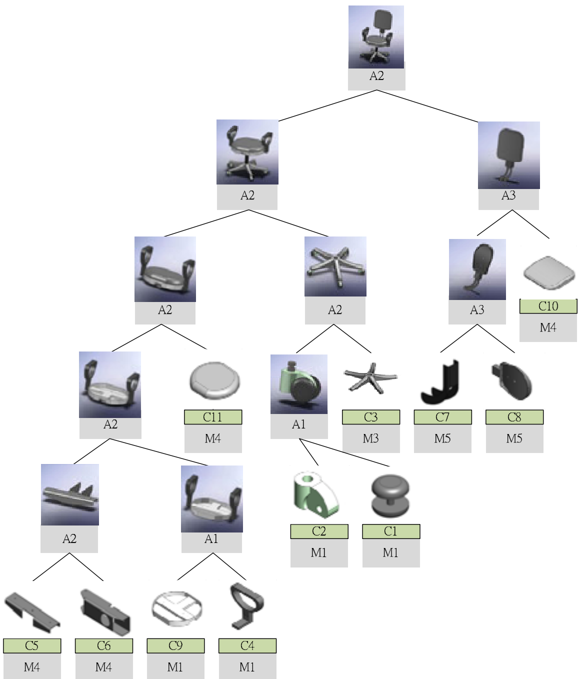


Fig. 9 Optimal Assembly Structure, Sequence, and Suppliers for Design 2

Table 8 Total Carbon Emission and Cost of Design 1 and 2

	Design 1	Design 2
Material Cost	241.33	347.83
Manufacturing Cost	43.45	61.50
Transportation Cost	5.52	11.83
Total Cost	290.3	421.16
Material Carbon Emission	12.71	15.24
Manufacturing Carbon Emission	10.02	12.85
Transportation Carbon Emission	0.88	1.89
Total Carbon Emission	23.61	29.98

6. Conclusion and Future Research

Due to customer's rising awareness of environmental protection and government's stringent environmental regulation, environmental impact becomes one of the most important design criteria. In this paper, we develop a decision support system to help company estimate the carbon emission and cost of product designs and to determine which design to adopt. To properly and fairly evaluate the design, the assembly structure, assembly sequence, and supply chain configuration have to be optimized. A bi-level optimization procedure is developed. At the top layer, an evolution based generic algorithm is developed to search the optimal assembly structures and sequences. At the bottom layer, a dynamic programming based algorithm is developed to optimize the supply chain configuration. To illustrate the decision support system, a real world computer chair example is used. The results show that it is not trivial for a company to identify the design with low carbon emission and low cost.

There are limitations in this paper and many potential future researches. First, 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. Second, in our paper, we only evaluate one product at a time. In the future, this assumption can be relaxed to explore the benefit of process commonality.

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