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Modular design to support green life-cycle engineering

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Abstract

The severe competition in the market has driven enterprises to produce a wider variety of products to meet consumers' needs. However, frequent variation of product specifications causes the assembly and disassembly of components and modules to become more and more complicated. As a result, the issue of product modular design is a problem worthy of concern. In this study, engineering attributes were added to the liaison graph model for the evaluation of part connections. The engineering attributes added, including contact type, combination type, tool type, and accessed direction, serve to offer designers criteria for evaluating the component liaison intensity during the design stage. A grouping genetic algorithm (GGA) is then employed for clustering the components and crossover mechanisms are modified according to the need of modular design. Furthermore, a reasonable green modular design evaluation is conducted using the green material cost analysis. According to the results, adjusted design proposals are suggested and materials that cause less pollution are recommended to replace the components with pollution values higher than those in the module. Finally, the authors use Borland C++ 6.0 to evaluate the system and clustering method. To illustrate the methodology proposed in this study, a table lamp is offered as an example.

Keywords: Modular design; Green life-cycle engineering; Grouping genetic algorithm; Liaison intensity; Green analysis

1. Introduction

Not until recent years have people realized the importance of environmental protection. People pay more attention to the environment they are living in and the way people deal with the limited resources. Among resource disposal methods, recycling and garbage classification are two methods widely applied. These ways, however, are passive methods in the launch, usage and damage of products. Moreover, fierce market competition is shortening the product life cycle and the passive resource recycling approach can no longer cope with the ever-increasing burden current products have on the environment. Therefore, it is important to maximize the usage percentage of resources and minimize the damage to the environment in the early product design stage. This kind of more aggressive design tendency is referred to as green life-cycle engineering design (Otto & Wood, 2001; Tseng & Chen, 2004).

The so-called product life cycle refers to the total amount of time from material, manufacturing, assembly, consumer use, and final disposal or recycle of a product, and green life cycle is mainly determined by the last two stages, product use, disposal or recycle. While the use of a product will affect its life span, the disposal and recycle of a product will definitely affect the environment and the resource availability. To prolong the product's life cycle and to make the most of resources, the end of the product life cycle does not imply the disposal of the components. Instead, we need to solve the problem from the root of the enterprise activities, especially from the R&D of new products (Tseng & Chen, 2004). Many researchers have explored the issue from different points of view, such as design for environment (DFE), design for recycling (DFR), and design for disassembly (DFD) (Güngör

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& Gupta, 1999; Lambert, 2003). Due to the fact that well-designed modular structures can improve product life-cycle activities, modularity plays a more important role than the whole product life-cycle approach. For example, not only will common modules increase the chances of efficient reuse and recycling operation, they also feature ease of upgrade and maintenance, ease of product diagnosis, repair, and disposal, and so on.

Taking green life cycle into consideration, the authors attempted to apply the green modular concept to product design. Advantages for this study are listed as follows (Gu & Sosale, 1999; Otto & Wood, 2001; Zhang & Gershenson, 2003):

(1) Reexamination of product functions and specifications ensures that the goal of environmental protection can be achieved.
(2) Reduction in product assembly time can enhance the efficiency of production.
(3) Products or product components can be recycled, reused and disposed of more easily.
(4) The life-cycle cost estimation enables designers to bring product cost into control.

There are different perspectives with respect to measuring the product modularity. Jose and Tollenaere (2005) had made a comprehensive review regarding the modular design issue. In Section 2, the different viewpoints will be discussed. In the past, most conceptual descriptions have been rendered regarding the green-oriented modular study but a scientific methodology is rarely seen. In our study, a new methodology of green-oriented modular design will be proposed in Section 3. The approach comprises the following three parts:

(1) Clarifying the liaison intensity of components: in addition to clarifying the liaison relationships of components through visualized diagrams, the liaison intensity of components is decided by their engineering attributes.
(2) The clustering algorithm: the goal of clustering is to assign the components whose liaison intensities are stronger in the same module. In this way, the liaison intensities among different modules are relatively weaker, indicating that it is easy to connect the components if they are assigned to the same module.
(3) Green pollution and cost analysis: while changing the design specification, designers need to green pollution take and costs into consideration so that they can work out the proper design ideas in accordance with the material property to fulfill the product functions.

These three parts will be discussed in Sections 4–6 respectively. In Section 7, the design of a table lamp will be used to illustrate the methodology proposed in this study. Finally, conclusions are made in Section 8.

2. Background of product modularity

2.1. Diverse viewpoints

In the descriptive model of product functions, according to Otto and Wood (2001), modules can be defined as the integral physical structures corresponding to specific product functions. Meanwhile, the product function model is closely related to the customer's needs. Therefore, a proper modular design is able to reduce the production cost and assemble components effectively into new products to cope with the rapid change of customer's needs. The approach to meeting the customer's needs and function specifications is called the function-based modular design. In the past, different methods had been proposed to explore the function-based modular design issue; for example, Huang and Kusiak (1998) and Kreng and Lee (2004).

In the assembly-based modular design method, products are generally described by liaison graph proposed by De Fazio and Whitney (1987). Researchers need to deal with modules on the basis of network partition and analysis the subassemblies or modules from the stability viewpoint. Lee (1994) and Tseng, Chang, and Yang (2004) are typical representation for this approach of assembly-based modular design.

In general, the manufacturing-based idea does not cover the algorithm for the formation of product modules. Emphasis is often placed upon smooth connections between the design and manufacturing phases. In this domain, He and Kusiak (1996) and Kahoo and Situmdrang (2003) used manufacturing time as the criteria for efficiency evaluation.

On the other hand, the traditional low-cost and mass production model has difficulty in meeting the requirements of the contemporary era. Mass customization aims to provide customer satisfaction with increasing variety and customization without a corresponding increase in cost and lead time. Enterprises have to cope with the frequent variation of product specifications by a stock strategy of bigger numbers of components and modules in the customized environment. Therefore, the exploration of modular design will help with the production and control of mass customization. In terms of mass customization, Mikkola and Gassmann (2003) and Fujita and Yosshida (2004) offered a valuable evaluation method for this issue.

According to the green life-cycle-based concept, modular design is focused upon the environmental level. Newcomb, Bras, and Rosen (1998) used group techniques to develop modular design; Gu and Sosale (1999) used the simulated annealing algorithms to explore modular design; Qian and Zhang (2003) proposed an environmental analysis model for achieving the modular goal.

2.2. Problem formulation

As mentioned earlier, the paper attempts to focus on the green life cycle of product design. Three different problems should be taken into consideration in green modular design: (1) the descriptive way of product models and the calculation of liaison intensity of components, (2) the clustering method, and (3) the evaluation of the clustering result. Therefore, a new approach is proposed in this paper.

In this study, the liaison graph proposed by De Fazio and Whitney (1987) is employed to describe products. In such graphic models, the relationships between components are clearly presented. Fig. 1 shows an example of the liaison graph in which nodes represent components and arcs represent the liaison intensity between components. Fig. 1a demonstrates the graphic model for a pen and Fig. 1b shows the pen's liaison graph. In the diagram, the Ink–Tube denotes that there is a contact relationship between components and a new idea about the liaison intensity is decided by the engineering attributes of components, which is defined as the component liaison intensity (LI) in this study. A higher LI indicates a more difficult type of combination and a smaller LI means a simpler type of combination.

Secondly, in terms of the clustering methodology, Gu, Hashemian, and Sosale (1997) adopted traditional genetic algorithms (GAs) but the number of modules and the content size should be set previously, which is an evident disadvantage. To deal with such problems, Falkenaur (1998) once proposed using GGAs to solve the clustering problem. In Falkenauer's view, traditional GAs have three limitations regarding clustering problems: (1) the traditional type of encoding wastes redundant space; (2) it is not easy to generate good-quality offspring population through the standard reproduction mechanism such as Roulette wheel; and (3) the standard exchange mechanisms like crossover and mutation tend to spoil the quality of the offspring population.

Thirdly, the authors employed the green pollution index and cost viewpoint to evaluate the clustering output. The results obtained from the pollution and cost analyses can help designers select suitable ideas according to the material property as well as the specific requirements of product functions.

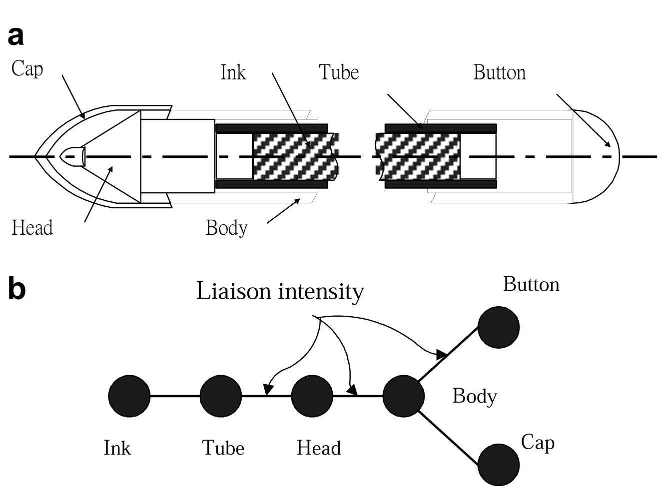

Fig. 1. Liaison graph of a pen.

3. Outline framework and related assumption for green-oriented modular design

The proposed methodology for the green modular design is shown in Fig. 2. The detail procedure is illustrated as follows:

Stage 1: Build up the scoring system:
- Step 1: Evaluate the liaison intensity of product (Section 4.2).
- Step 2: Calculate the liaison intensity (Section 4.3).

Stage 2: Grouping genetic algorithms:
- Step 3: Use the heuristic algorithm as the initial population (Section 5.3).
- Step 4: Reproduction, an optimal rate between 0 and 1 is randomly generated for the use of reproduction. Such a rate serves as the threshold for the selection of chromosome.
- Step 5: Crossover (Section 5.4).
- Step 6: Mutation (Section 5.5).
- Step7: Calculate the fitness value (Section 5.2).

Stage 3: Green material analysis:
- Step 8: Determine the green polluted percentage.
- Step 9: Evaluate the pollution value of each component (Section 6.1).
- Step 10: Product redesign (Section 6.3).
- Step 10-1: Choose alternative material of low pollution and cost (Section 6.2).
- Step 10-2: Improve the liaison intensity of the chosen module and its related modules.
- Step 11: Check if the adjusted design is satisfactory. If not, go back to Step 9, change the polluted percentage or change the liaison intensity in Step 1. If yes, end of the green pollution analytic flow.

Some assumptions for the proposed methodology are listed as follows:

(1) In this study, emphasis is placed on the liaison intensity between parts, and green cost information to help with the designer's decision-making. Whether a strategy is correct depends upon the total product design. While the product design strategy is not considered in the study, it is assumed that during design alteration stage, the right decision can be made by the designer.
(2) For each engineering attribute, the value of liaison intensity is correct and fully represented the tight degree of connection between components.
(3) During the evaluation of modular design, the product design will be unchanged. That is to say, the total number of components and liaisons are fixed.
(4) For the cost estimation, we assume the material cost of component is sensitive to its weight. When the material is modified, it is hypothesized that the unit

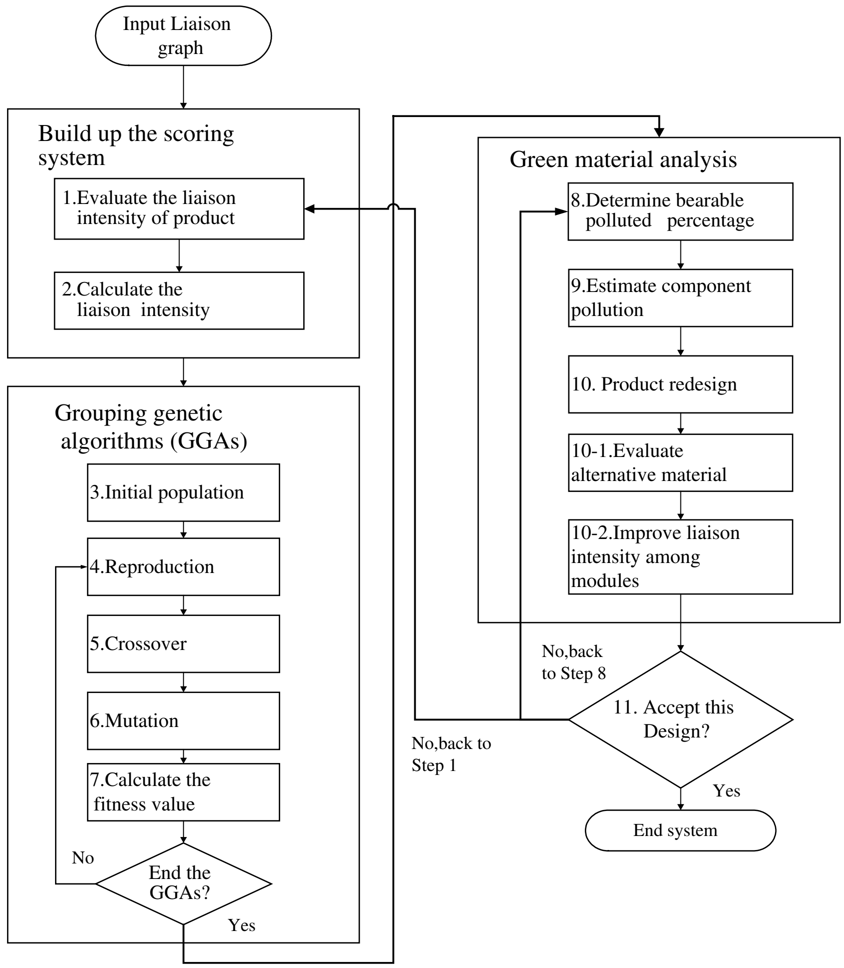

Fig. 2. Proposed flowchart of green modular design process.

material and manufacturing costs are known (Shehab & Abdalla, 2001; Zhang & Gershenson, 2003).

(5) In the assembly and manufacturing cost, the time estimation for assembly and manufacturing is assumed to be known. The assumption is supported by previous research result (Boothroyd, Dewhurst, & Knight, 1994; Zhang & Gershenson, 2003). In practice, the time estimation can be predicted by the methods of time measurement (Tseng & Tang, 2006).

(6) Any component or module produced by methodologies that can be entirely supported by manufacturers and suppliers.

4. Estimation of liaison intensity among components

4.1. Terminology description

The section explains the definitions proposed to deal with modular design. Suppose an assembly product P is composed of a set of elements called components. These components are connected through mechanical links (liaisons). In this non-oriented connected graph $G(C,L)$, C is the set of N_c nodes representing the components of the product, and L is the set of N_l edges symbolizing the links (liaisons) between these components (De Fazio & Whitney, 1987).

Product $P = \{C_i |\ i = 1,2,3,\ldots,N_c\}$
Interconnected by N_l liaisons, then
$L = \{l_{st}|s,\ \ t = 1,2,3,\ldots,N_l,\ \ l_{st}$ represent the liaison between C_s and C_t; s and t represent the component number in Product P, $s \neq t\}$

With the definition of a liaison, it is possible to define a module. A module is a subset of N_m components from P, so that the liaison subgraph generated from the corresponding N_m vertices is connected. If a product P can be decomposed into N_k modules, such a product can be described as follows:

Product $P = \{M_i|i = 1,2,3,\ldots,N_k\}$

4.2. Evaluation items

In this study, a number from 0 to 100 is employed to describe the liaison intensity between components. When the number is bigger, the liaison intensity is higher. The liaison intensity is decided by four engineering attributes of components such as the contact type, combination type, tool type, and accessed direction. This kind of evaluation is similar to the product disassembility evaluation method proposed by Das, Yedlarajiah, and Narendra (2000). While the weight for each engineering attribute can be decided by the managerial division according to the company's policy, the weights of these four attributes used in this study are contact type—30%, combination type—20%, tool type—35%, and accessed direction—15%. These four engineering attributes of components are described below. The higher liaison intensity (LI) score represents the tighter connection degree between components. The values about LI from Tables 1–4 can be reset depending on the designer's domain knowledge.

4.2.1. Contact type

The contact type depicts the contact area and contact point between components. The degree of contact between two components is higher if the number of contact points or the contact area is bigger. Five grades of contact (Table 1) are used in this study: point contact, line contact, single face contact, multi-point contact, and multi-face contact, from which the point contact has the weakest liaison, and the multi-face contact has the strongest liaison.

4.2.2. Combination type

The combination type attribute depends on the tightness of component combination. As shown in Table 2, four types of combination attributes are defined in this study: put on, insert, turn in, deep combine, and not disassemble. Among them, put on is an easy combination type; insert is more difficult than put on; and turn in is the most difficult combination type.

4.2.3. Tool type

This engineering attribute takes the operation difficulty of tools into consideration. As can be seen in Table 3, five categories are used in this study: hand, screwdriver, small tool, special tool, and large tool. The tool type of which the operation difficulty is bigger indicates that it is more difficult to combine the components.

4.2.4. Accessed direction

The accessed direction attribute, as the name suggests, considers the intensity of components from the viewpoint of feasible combination directions. A bigger number of accessed angles indicate that the combined components are less interfered by the other components. In this study, $\pm x$, $\pm y$, and $\pm z$ are employed to describe the accessed direction. The number of accessed angles represents the degree of component intensity. As shown in Table 4, five degrees, from strong to weak, 5, 4, 3, 2 and 1, are defined in this study.

Table 1
Intensity of contact type

Attribute	Liaison intensity	Description
Point contact	6	The contact part is a point
Line contact	12	The contact part is a line
Single face contact	18	The contact part is a face
Multi-point contact	24	Many points will be contacted
Multi-face contact	30	Many faces will be contacted

Table 2
Intensity of combination type

	Attribute	Liaison intensity	Description
Combination type	Put on	4	Two components can be combined only by putting one on the other; precise operation is not necessary
	Insert	8	Precise insertion is needed to combine two components
	Turn in	12	Two components should be combined with tools and precise turning forces
	Deep combine	16	Two components should be combined with tools, and a forceful precise operation
	Not disassemble	20	Two components should be combined with tools and once combined, they will be disassembled only by tearing them down

Table 3
Intensity of tool type

Attribute	Liaison intensity	Description
Hand	7	Two components can be combined by hand
Screwdriver	14	A screwdriver is needed to combine two components
Small tool type	21	A small tool is needed to combine two components
Special tool type	28	A special tool is needed to combine two components
Large tool type	35	A large tool is needed to combine two components

Table 4
Intensity of accessed direction

Attribute	Liaison intensity	Description
5 Angles	3	Two components can be combined from 5 angles
4 Angles	6	Two components can be combined from 4 angles
3 Angles	9	Two components can be combined from 3 angles
2 Angles	12	Two components can be combined from 2 angles
1 Angle	15	Two components can be combined from 1 angle

4.3. Computing intensity

With the liaison intensity in the above four engineering attributes, the total component liaison intensity (LI) between components can be denoted as

$$\mathrm{LI}_i = \mathrm{CT}_i + \mathrm{CB}_i + \mathrm{TL}_i + \mathrm{AD}_i \tag{1}$$

where LI_i represents the total liaison intensity of the ith component; CT_i represents the contact type intensity of the ith component; CB_i represents the combination type intensity of the ith component; TL_i represents the tool type intensity of the ith component; AD_i represents the accessed direction intensity of the ith component.

5. Grouping genetic algorithm (GGA)

5.1. Encoding

The diagram shown in Fig. 3 illustrates the way of coding proposed in this paper, each gene of which stands for a module. Such kind of genetic coding features a flexible length of the chromosome, which is helpful for searching the optimal number of modules. Moreover, it avoids the problem that too long a chromosome will reduce the efficiency. For a chromosome composed of five modules "ABCDE", the number of modules can be expressed as $A = \{1\}$, $B = \{3,6\}$, $C = \{4\}$, $D = \{2\}$, $E = \{5\}$. Each gene can correspond to the relative components. For example, Module B includes Parts 3 and 6.

5.2. Fitness design

If C_l and C_k represent two components in a module M_i, then the liaison intensity between them can be expressed as LI_{lk}, where T_i stands for the accumulated liaison intensity in module M_i. And because the arc in the liaison graph does not have specific directions, the accumulated liaison intensity should be divided by 2, as shown in Formula (2):

$$T_i = \sum_{C_l \in M_i} \sum_{C_k \in M_i} \mathrm{LI}_{lk}/2 \tag{2}$$

Moreover, the accumulated liaison intensity is a constant $\mathrm{LI}_{\mathrm{total}}$, because the total number of liaisons is fixed. The goal of GGA setting is to maximize the liaison intensity within the module ($\mathrm{LI}_{\mathrm{intra}}$) and minimize the liaison intensity between modules ($\mathrm{LI}_{\mathrm{inter}}$). More importantly, a stronger $\mathrm{LI}_{\mathrm{inter}}$ means that the $\mathrm{LI}_{\mathrm{intra}}$ is weaker, indicating that it is easy to assemble and disassemble components in a module. Because the $\mathrm{LI}_{\mathrm{intra}}$and $\mathrm{LI}_{\mathrm{inter}}$ are mutually exclusive, if we subtract the $\mathrm{LI}_{\mathrm{intra}}$ from the total liaison intensity ($\mathrm{LI}_{\mathrm{total}}$), we get the $\mathrm{LI}_{\mathrm{inter}}$ of a module. This is expressed as follows:

$$\mathrm{LI}_{\mathrm{inter}} = \mathrm{LI}_{\mathrm{total}} - \mathrm{LI}_{\mathrm{intra}} \tag{3}$$

And if there are q modules after the clustering task, we need to calculate the sum of the liaison intensity of each module. Therefore, the maximum $\mathrm{LI}_{\mathrm{intra}}$, the biggest liaison intensity in a module, can be denoted as Formula (4):

$$\mathrm{LI}_{\mathrm{intra}} = \sum_{i=1}^{q} T_i \tag{4}$$

5.3. Initial population

In the initial stages of GGA, many chromosome populations should be generated in that the variety of the initial population and better fitness values will effectively improve the evolution efficiency during the searching of the optimal solutions. Ericsson and Erixon (1999) once pointed out a way to look for the ideal number of modules and components (Formula (5)), which is based on the assumption of minimizing the assembly time:

$$\text{Ideal number of modules} \leqslant \sqrt{\text{Component number}} \tag{5}$$

In this study, the upper bound of the number is calculated by Formula (5) and the lower bound of the number of modules is set to be 1. The initial genetic combination of the chromosome is then built up through a random greedy algorithm as listed below:

Step 1: Generate randomly a feasible number of modules under the limit of the maximum number of modules.
Step 2: Assign randomly the first component to any module.
Step 3: In a higher priority, assign the rest of the components to the modules with higher liaison relationships. If there is no proper module to assign, then assign them randomly. Repeat this step until all components are assigned to product modules.

5.4. Crossover

In GGA, the crossover operation is not decided by the crossover rate. In a single-point operation, two parent generations will be selected, each crossover point of which is randomly selected. From the crossover point, new offspring generations will be obtained by exchanging the right side of a parent generation and the left side of another parent generation. Repeating this step can generate a new offspring

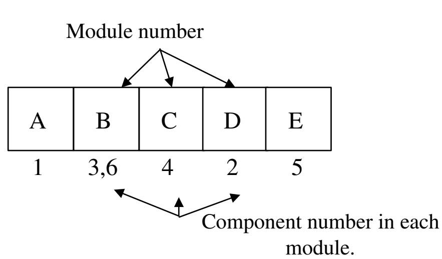

Fig. 3. Encoding for grouping genetic algorithms.

generation. To generate excellent offspring generations, we employ the GGA crossover operation as follows:

Step 1: After a pair of chromosome is chosen, generate randomly two crossover points for each of them to define the exchange range (Fig. 4a).
Step 2: Insert the central site of the second chromosome into the first chromosome (Fig. 4b).
Step 3: Remove the same components and empty modules in the second chromosome and the first chromosome. Pick out the single object left in the module (Fig. 4c and d).
Step 4: Insert the selected single object into the second chromosome.
Step 4-1: Calculate the liaison intensity in the module. New fitness value should be calculated after Steps 1 and 2 (Formula (4)).
Step 4-2: Limits of the maximum number of modules should be checked for the number of modules after the crossover operation. If the outcome does not meet the requirement, insert components or add new modules.
Step 4-3: Calculate the effects the single component may have on the fitness value when it is inserted into every possible module. Assign the rest of the components to other possible modules. If possible modules are not found, then add new modules and assign these components to them.
Step 5: Repeat Steps 2–4 for the first chromosome.

In the above procedure, Step 4 is different from that in the original GGA algorithms (De Lit, Falkenauer, & Delchambre, 2000). There are two principles in the GGA crossover procedure.

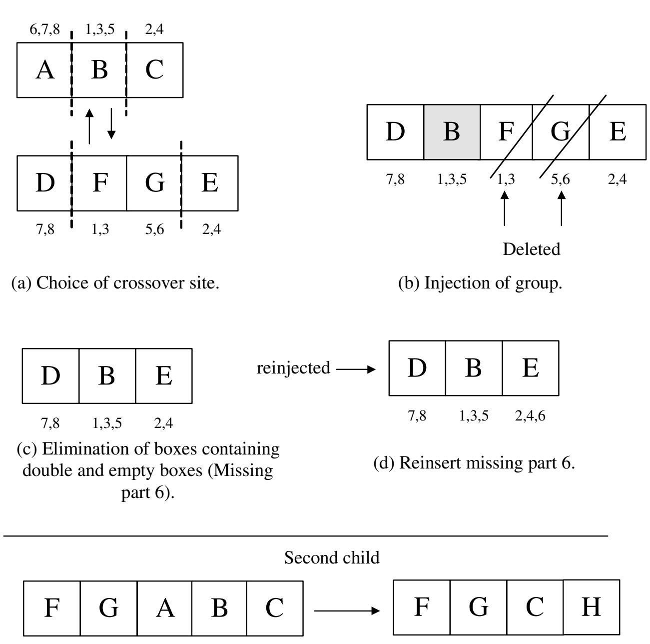

Fig. 4. Crossover for grouping genetic algorithms.

Principles for inserting components: According to the fitness values obtained from Step 4-3, find the optimal insert operation. If the improvement is not evident, insert randomly components into any module.

Principles for adding new modules: Assign the rest of the components into possible modules according to the liaison intensity between components. If no suitable modules are found, assign them randomly to the newly added modules.

5.5. Mutation

De Lit et al. (2000) suggested three strategic considerations in the GGA application: create a new group, delete an existing group, and move the components randomly in a group. If no feasible chromosomes are found, then the heuristic solution can help correct such irrationality. The mutation operation will be executed only when the chromosome's mutation probability is equal to or smaller than a certain value. This kind of mechanism can prevent us from falling in the local optimal value and avoid the early convergence problem.

6. Balance between cost and green design

6.1. Green analysis

The green analysis is conducted in this study according to the pollution value offered by Eco-indicator99 (http://www.pre.nl/). The Eco-indicator refers to the pollution reference value the component material causes to the environment. The higher value means higher injuries for the environment after the product is used. Because weight is used as an investigation unit for Eco-indicator, the estimated pollution value for a component can be represented as Formula (6):

$$\text{Poll} = \text{Weight} \times \text{Indicator} \tag{6}$$

In Formula (6), Poll indicates the pollution value of a component. The value can be regarded as dimensionless figures. For the Eco-indicator point (Pt), 1Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant. Weight denotes the weight of the component (kg); and Indicator represents the unit pollution index of a component.

6.2. Cost analysis

In the perspective of product design estimation, the total cost can be determined by three major cost viewpoints: (1) material cost, (2) manufacturing cost, and (3) assembly cost. Therefore, the total cost can be estimated by Formula (7):

$$\text{TC} = C_{\text{m}} + C_{\text{mpc}} + C_{\text{a}} \tag{7}$$

where TC represents the total cost (NT$). In the year of 2006, 1 US dollar is approximately equal to NT$32.8 and

0.78 Euros. C_m is the cost of material, C_{mpc} is the cost of manufacturing, C_a is the cost of assembly.

The material cost C_m can be defined by Formula (8):

$$C_m = C_{mu} \times W_m \tag{8}$$

where C_{mu} indicates the unit cost of material (NT\$/kg); and W_m indicates the material weight (kg).

The manufacturing cost C_{mpc} can be computed based on the feature methodology developed by Shehab and Abdalla (2001). In their methodology, a feature is defined as a generic shape carrying product information from computer-aided design, or communication between manufacturing and design. The manufacturing cost C_{mpc} can be decided by Formula (9):

$$C_{mpc} = C_{pcu} \times T_{pcu} \tag{9}$$

where C_{pcu} means the unit cost of manufacturing (NT\$/s); T_{pcu} indicates the time for manufacturing (s).

The assembly cost C_a can be decided by Formula (10):

$$C_a = C_{au} \times T_{au} \tag{10}$$

where C_{au} represents the unit assembly cost (NT\$/s), and T_{au} refers to the assembly time (s).

6.3. Design modification and the modular component analysis

In the study, designers can change the design principles according to change of component materials so as to reduce the component liaison intensity between modules. Such design principles are combined into the following five rules:

1. Redesign the product component according to the outcome pollution value or cost evaluation.
2. For the change of material, designers need to evaluate the liaison intensity of the newly added component.
3. When the material is changed, designers need to take into consideration the liaison intensity of the related combined components.
4. When the material is changed, designers need to delete some liaison intensity of the related components.
5. The engineering attributes between modules, including contact type, combination type, tool type, and accessed direction are suggested to change.

With the green pollution value and cost data at hand, designers can choose alternate materials to reduce the pollution value in a module. Furthermore, the intra liaison intensity between modules can be adjusted according to practical needs.

7. A practical example

As shown in Fig. 5a, the table lamp is composed of 22 components and 22 liaisons. First of all, we need to evaluate the liaison intensity of each component in terms of each engineering attribute. The outcome liaison intensity is shown in Table 5. Take liaison 1–2 as an example, it shows the relationship between Components 1 and 2; the single face contact has an intensity of 18 (Table 1); the put on combination type's intensity is 4 (Table 2); the intensity of the hand type of assembly is 7 (Table 3); and the intensity of the accessed direction is 3 for five angles (Table 4). According to Formula (1), the total component liaison intensity $LI_{12} = 18 + 4 + 7 + 3 = 32$. Table 5 serves as input data for the GGA.

In this study, we used Borland C++6.0 to compile the program and the test environment was on a Pentium 2.8 GMHz PC at 512 MB RAM. The operation interface for LI estimation is shown in Fig. 6. In this case, the population number is set at 20; the number of evaluation generations, 100; the mutation rate, 0.1; and crossover rate, 0.8. According to Formula (5), we need to pinpoint the upper bound of the number of components in each module. Therefore, the maximum number of modules is set to be 5 ($\sqrt{\text{Component number}} = \sqrt{22} \cong 4.69$).

When the fitness value reaches 813, an optimal situation can be obtained from the GGAs. The results are {6, 19, 3, 20}{9, 10, 8, 7}{4, 1, 2, 22, 21}{15, 5, 18, 16, 17}{13, 14, 11, 12}, each of which represents a specific module of the table lamp. Each number represents specific components that are shown in Fig. 5b. Then, according to the Eco-indicator99 (Formula (6)), the component material pollution analysis is conducted to check the pollution percentage (Table 6). In Table 6, the total pollution value can be got from the summation for the Poll value. The total pollution value is 183.4 for the lamp example. Then we can calculate the last column percentage (%). For example, the percentage of Component 1 can be worked out as $26.4/183.4 = 14.39\%$. In this study, two redesign cases are further discussed.

7.1. Situation 1: If the current bearable green pollution value is 20%

Because Steps 1–7 have been discussed earlier and are the same for the two situations, only the algorithms after Step 8 are presented here.

Step 8: Component 8's pollution value is the highest (Table 6). Obviously, Component 8 (Soft_pipe) should be improved.

Step 9: In terms of the individual component pollution evaluation, Component 8's specifications are weights = 0.2 kg; pollution unit value = 240; environmental pollution index = 48; and green polluted percentage = 26.17%. The material for Component 8 should be adjusted.

Step 10: The major function of Component 8 is to support the lamp. The pollution value for the material before design modification is 240

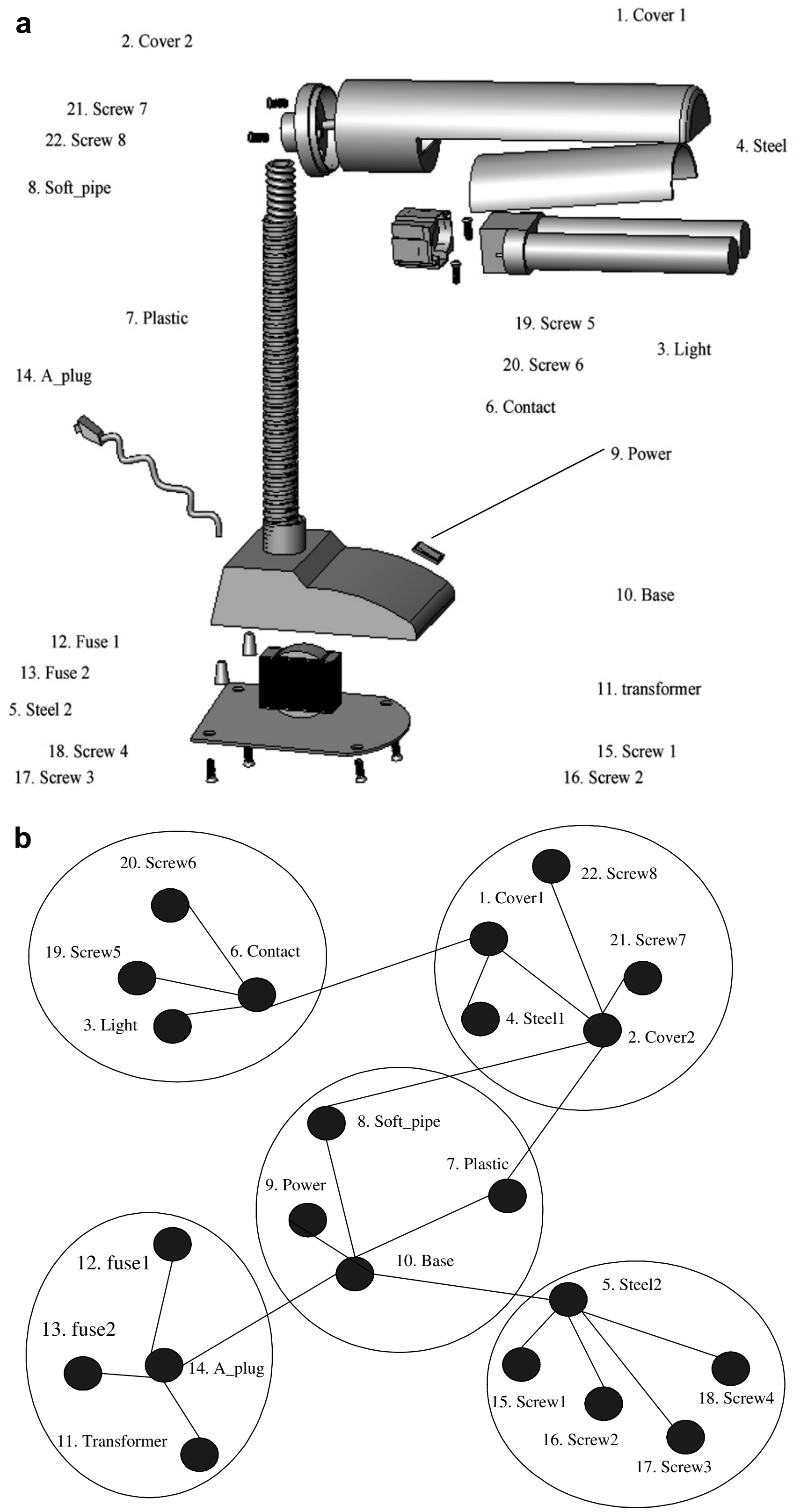

Fig. 5. Case study—table lamp. (a) Part diagram and (b) liaison graph.

(Cast iron). It is suggested to use the Electro Steel because of its lower pollution value of 24.

Step 10-1: The material and manufacturing costs will be changed when the material is changed. The material and manufacturing cost before and

Table 5
Estimate liaison intensity for table lamp

Liaison	Contact type	Combination type	Tool type	Accessed direction	Liaison intensity
1–2	SFC	Put on	Hand	5 Angles	32
1–4	SFC	Insert	Hand	1 Angle	48
1–6	SFC	Put on	Hand	5 Angles	32
2–7	LC	Put on	Hand	5 Angles	26
2–8	LC	Insert	Hand	5 Angles	30
2–21	PC	Turn on	Small tool type	1 Angle	54
2–22	PC	Turn on	Small tool type	1 Angle	54
3–6	MFC	Insert	Hand	1 Angle	60
5–10	SFC	Put on	Hand	5 Angles	32
5–15	PC	Turn on	Small tool type	1 Angle	54
5–16	PC	Turn on	Small tool type	1 Angle	54
5–17	PC	Turn on	Small tool type	1 Angle	54
5–18	PC	Turn on	Small tool type	1 Angle	54
6–19	PC	Turn on	Small tool type	1 Angle	54
6–20	PC	Turn on	Small tool type	1 Angle	54
7–10	LC	Put on	Hand	5 Angles	26
8–10	LC	Insert	Hand	5 Angles	30
9–10	MPC	Insert	Hand	4 Angles	45
10–14	PC	Insert	Hand	1 Angle	36
11–14	PC	Put on	Small tool type	1 Angle	60
12–14	PC	Turn on	Hand	1 Angle	40
13–14	PC	Turn on	Hand	1 Angle	40

PC: point contact; LC: line contact; SFC: single face contact; MPC: multi-point contact; MFC: multi-face contact.

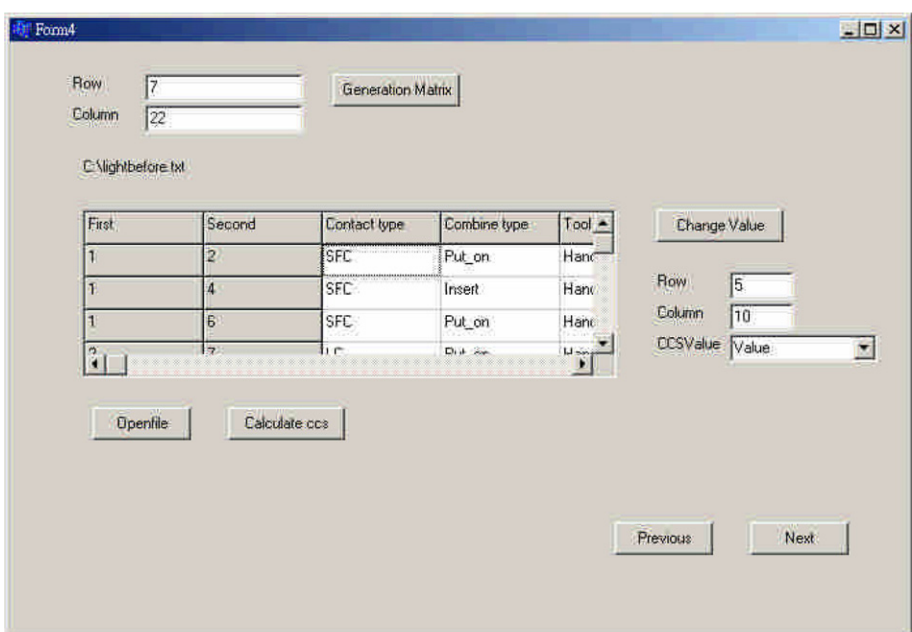

Fig. 6. Interface for liaison intensity estimation.

after modification for Component 8 is shown in Table 7.

Step 10-2: Because Component 8 is a single component, the assembly engineering attribute remains the same. Therefore, the assembly cost stays unchanged.

Step 11: Check whether the design modification is satisfactory. Through green pollution value analysis, it is found that the pollution value is much lower, dropping from 48 to 4.8, and that the cost is estimated to rise from NT$5.32 to NT$5.7.

Table 6
Pollution percentage analysis

Component	Name	Weight	Material	Indicator	Poll	%
1	Cover1	0.08	Plastic	330	26.4	14.39
2	Cover2	0.03	Plastic	330	9.9	5.4
3	Bulb	0.04	Glass	51	2.04	1.11**
4	Steel1	0.01	Steel	86	0.86	0.47
5	Steel2	0.1	Steel	86	8.6	4.69
6	Contact	0.05	Plastic	330	16.5	9**
7	Plastic	0.01	Plastic	330	3.3	1.8
8	Soft_pipe	0.20	Cast iron	240	48	26.17*
9	Power	0.01	Plastic	330	3.3	1.8
10	Base	0.04	Plastic	330	13.2	7.2
11	Transformer	0.30	Steel	86	25.8	14.07
12	Fuse1	0.01	Plastic	330	3.3	1.8
13	Fuse2	0.01	Plastic	330	3.3	1.8
14	A_plug	0.05	Plastic	330	16.5	9
15	Screw1	0.00125	Cast iron	240	0.3	0.16
16	Screw2	0.00125	Cast iron	240	0.3	0.16
17	Screw3	0.00125	Cast iron	240	0.3	0.16
18	Screw4	0.00125	Cast iron	240	0.3	0.16
19	Screw5	0.00125	Cast iron	240	0.3	0.16**
20	Screw6	0.00125	Cast iron	240	0.3	0.16**
21	Screw7	0.00125	Cast iron	240	0.3	0.16
22	Screw8	0.00125	Cast iron	240	0.3	0.16

Notes: The mark "*" indicates the components chosen from 20% bearable polluted percentage, and the mark "**" indicates those chosen from the whole modular concept.

Table 7
Material cost and manufacturing cost change of Component 8

	Before modification			After modification		
	Unit	Weight	Cost	Unit	Weight	Cost
Material cost	C_{mu}	W_m	C_m	C_{mu}	W_m	C_m
	2.8	0.2	0.56	3.0	0.2	0.6
Manufacturing cost	C_{pcu}	T_{pcu}	C_{mpc}	C_{pcu}	T_{pcu}	C_{mpc}
	4.76	1.0	4.76	5.1	1.0	5.1

Table 8
Material evaluation for light bulb module

Component	Before modification		After modification	
	Material	Indicator	Material	Indicator
3	Glass (green)	51	Glass (brown)	50
6	Plastic	330	PVC	240
19	Cast iron	240	Electro Steel	24
20	Cast iron	240	Electro Steel	24

7.2. Situation 2: Designer can replace the whole module according to the bearable green pollution value

In the case of table lamp, light bulb module needs to be improved because it is a consumptive component. Therefore, its pollution value should be considered to improve the total module.

Step 8: Analyze the bearable green pollution percentage.

Step 9: The related components for the light bulb module contain Components 3, 6, 19, and 20. Their pollution values are also shown in Table 6.

Step 10: Major components for the light bulb module are Component 3. Components 19 and 20 connect Components 3, 6 and 1. Because the result of clustering indicates that these four components are of the same module, their pollution values are further analyzed and shown in Table 8.

Table 9
Material cost and manufacturing cost change of light bulb module

Component	Before modification			After modification		
	C_{mu}	W_m	C_m	C_{mu}	W_m	C_m
Material cost						
3	2.5	0.04	0.1000	2.6	0.04	0.1040
6	1.2	0.05	0.5000	1.3	0.05	0.5500
19	2.8	0.00125	0.0035	3.0	0.00125	0.0038
20	2.8	0.00125	0.0035	3.0	0.00125	0.0038
Total cost			0.607			0.6616
	C_{pcu}	T_{pcu}	C_{mpc}	C_{pcu}	T_{pcu}	C_{mpc}
Manufacturing cost						
3	3.25	1.0	3.2500	6.24	1.0	6.24
6	1.8	1.0	1.8000	1.95	1.3	2.54
19	4.76	0.001	0.0048	Combine	Combine	0
20	4.76	0.001	0.0048	Combine	Combine	0
Total cost			5.0596			8.78

Step10-1: A proper decision should be made if the lower pollution material chosen causes the cost to rise. Consequently, the material and manufacturing costs for a module will be changed. The material cost and manufacturing cost of the light bulb module before and after modification are shown in Table 9.

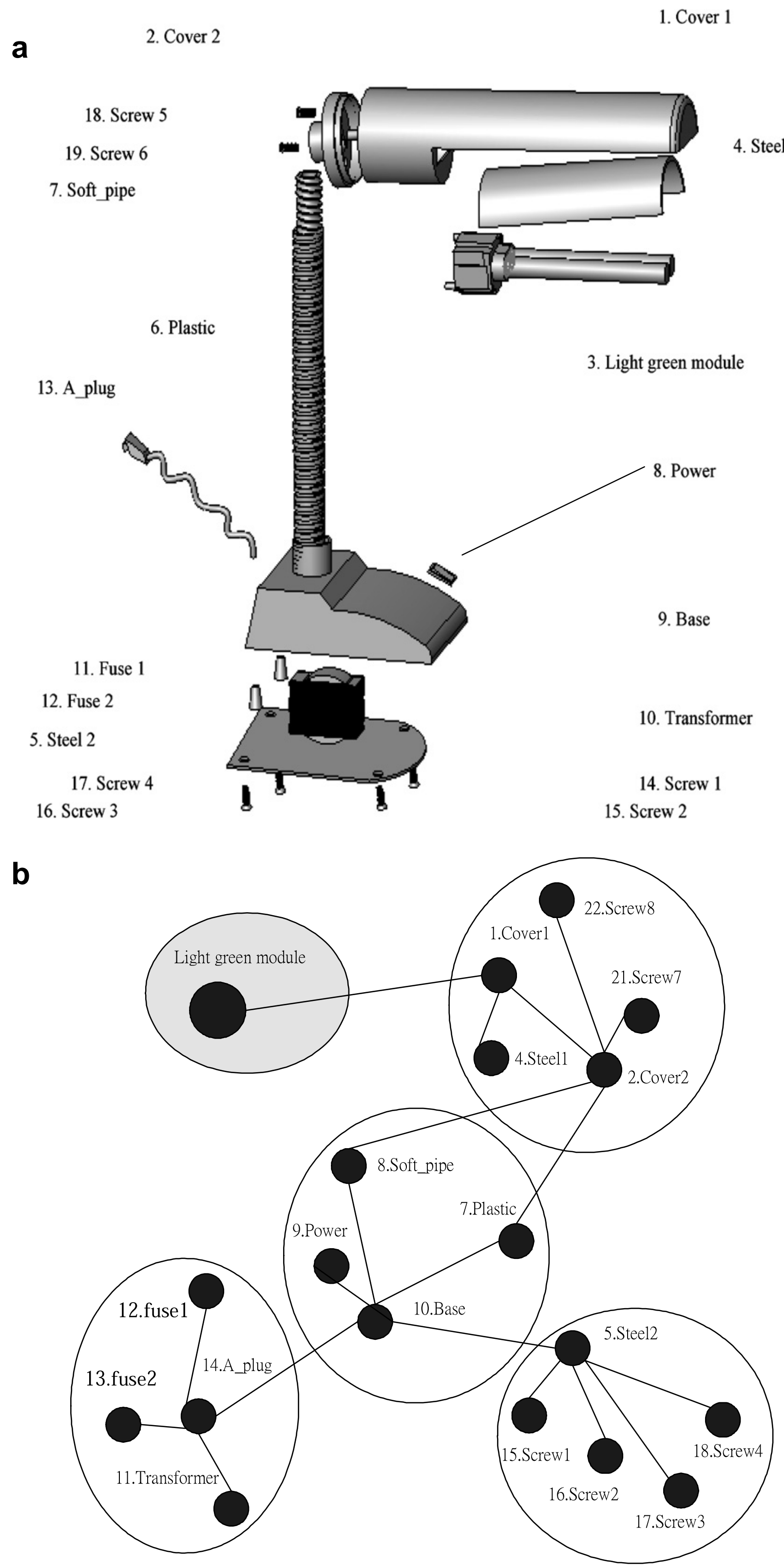

Fig. 7. (a) Revised design for Situation 2 and (b) a revised modular graph for the table lamp.

Table 10
Assembly cost change for light bulb module

Before modification			After modification		
Unit	Time	Cost	Unit	Time	Cost
C_{au}	T_{au}	C_a	C_{au}	T_{au}	C_a
0.049	0.5755	0.0282	0.049	4.2086	0.1974

Step 10-2: In the case of the light bulb, the liaison intensity between modules is suggested to adopt "easy assembly design." It is suggested that the related modules of the light bulb should be integrated to form a new component so as to enhance the convenience in renewing the component. The modified design for Situation 2 is shown in Fig. 7a, and the improved liaison graph is shown in Fig. 7b. We can find that the light bulb modular is an integral design. The new attributes for liaison intensity are "point contact", "insert" combined type, "hand" tool type and "1 angle" assessed direction type. Moreover, the change in assembly cost is listed in Table 10.

Step 11: Check if the outcome satisfies the designer's goal of design modification. Through the green polluted analysis, the pollution value is changed from 19.14 to 14.06, and the total cost will rise from NT$5.69 to NT$9.64.

Two alterative solutions have been generated in Situations 1 and 2. It is also found that the reduction in pollution value brings forth a rise in the cost and that the liaison intensity between components will change with the design modification. Therefore, the final solution will be decided by the R&D division.

The solution to the environmental pollution problem lies in the root of enterprise activities, the product design. It goes without saying that a subtly built environmental standard and complete database will help set up a better modular design. This will also enable designers to find a choice from the balance between conflicts of cost and green consideration. More importantly, enterprises should follow the management standards as ISO9001, ISO14001 and add the concept of green life cycle to their operation of total supply chain (Ammenberg & Sundin, 2005).

8. Conclusions

In this study, new methodologies for evaluating product modularity from the viewpoint of green life cycle are proposed. First, a score system using the liaison graph was adopted to evaluate the liaison intensity between components. Moreover, a GGA was adopted for the clustering of modules. Finally, green pollution and cost analysis was conducted to evaluate the clustering result. When the material of components is changed, the product component design is also modified, and so are the relations of liaison intensity between components. Through a cyclic adjustment procedure of the liaison intensity between components and the design modification, the green modular design can be achieved.

According to the green-oriented product design, it may be the case that the new design will bring forth higher costs. But it is the enterprise's obligation to pay more attention to the environmental protection. In the future, related laws of the environmental protection policy will be drawn up and put into action to regularize the enterprise activities. In addition, enterprises should take responsibility for the increasingly serious environmental pollution problem. The concept of green life cycle should be added in the total supply chain.

It is evident that green-oriented modular design is just a general issue. In the future, focus can be put on the integration of modular design method and other related product development approaches so as to multiple the suggestions of product design. Besides, the green pollution standard and information database should also be established as references for designers. In addition, proper decision-making strategies can be added to help evaluate the liaison intensity between components, making the algorithm more objective and flexible.

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