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Modular Design to Optimize Product Life Cycle Metrics in a Closed-looped Supply Chain

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Abstract

Growing concerns for the environment demands that product design for the life cycle (DFLC) is considered more carefully. Modularity is seen as a means to incorporate life cycle considerations into product architecture design; however, to date, most modular design methods concentrate on generating highly-modular product architectures but fall short in assessing life cycle consequences of these modules. This paper proposes a methodology to find a robust product modular architecture with minimal life cycle costs and environmental impacts at the design configuration stage. The primary objective of the proposed methodology is not to maximize modularity level, but to adopt life cycle costing and life cycle assessment to identify the most beneficial modular structure. In the case study presented, processing facilities are modeled as a closed-loop supply chain, and their influence on life cycle metrics is evaluated. Using the proposed methodology, a designer can identify not only the most beneficial modular structure during configuration design, but also an optimal supply chain network structure.

Keywords

Design for Life Cycle; Modular Design; Reverse Logistics; Closed-looped Supply Chains

1. Background

Due to growing populations and intensified human activities, the Earth is suffering unprecedented environmental impacts. A sustainable model for development is important and needed. Because of this, design for life cycle (DFLC) has drawn intense attention in recent years. Modular design is a common technique employed to improve DFLC. Many researchers have expanded modularity from a traditional function view to life cycle view. Newcomb et al. [1] stated that a product's architecture determined during the configuration design stage plays an important role in determining its life cycle characteristics. A traditional hypothesis is that the modularity of a product influences its manufacturing cost, ease of service, and effort required to retire/recycle the product. High life cycle modularity can be beneficial across the life cycle. However, determining how much modularity is optimal is still an unanswered question. Currently, there is no clear consensus on the definition of modularity either [2].

Design Structure Matrix (DSM) based methods are most common modular design methods. An essential step of this type of method is to define the relationships between components of a product in a DSM-like form and then apply clustering algorithms to group components into modules. Pimmler and Eppinger [3] defined the interactions between components in four forms, spatial, energy, information, and material and cluster components into functional modules. Due to environmental concerns, researchers also studied modular design not only on functional basis, but also for life cycle considerations. Besides functionality, Newcomb et al. [1] defined the relationship between components for life cycle issues, like recycling, post-life intent, and service frequency and then incorporated them into a modularity measure. They partition a product into modules in DSM using a decomposition algorithm developed by Kusiak and Chow [4] and redesign the product based on the clustered DSM. Gu and Sosale [5] defined the component relationships in more detail for functionality, life cycle characteristics (e.g., assemblability, serviceability, recyclability) and aggregated them into a modularity measure with different weights. Simulated annealing (SA) is used to cluster components into modules in their work. Similarly, Sand et al. [6] proposed using matrices to define functional structure, physical architecture, and life cycle characteristic; then, combining these matrices into one matrix. A clustering algorithm, the modular group algorithm (MGA), is developed to generate modules. Umeda et al. [7] defined the component interactions based on the attributes of product components, constituent materials, physical lifetime, and value lifetime for four life cycle options, recycling, maintenance, reuse, and upgrading. Self-organizing maps (SOM) is used to modularize a product. Unlike previous literature, geometric feasibility is evaluated in their model; however, in practice, the interactions between components in a product can be vague and cannot be described clearly. Thus, some studies introduced fuzzy set theory to define the component interactions. For example, Wang et al. [8] used a fuzzy cluster algorithm to generate product modules for life cycle. Li et al. [9] modeled a product as a fuzzy connected graph and applied fuzzy analytical hierarchy procedure (FAHP) to conduct trade-off analyses among the multiple life cycle objectives. A greedy clustering algorithm is adopted to cluster components into product modules. In summary, the DSM-based methods are applied using numerical matrices whose values are somewhat arbitrary so they can be integrated into different optimization techniques and clustering algorithms for various life cycle purposes. Overall, however, these methods benefit modular structure optimization and cannot specify life cycle benefits. This paper addresses these drawbacks.

2. Problem Description & Proposed Method

Our objective is to find a robust product modular structure through life cycle costing and assessment in a supply chain as well as to examine the influence of the supply chain condition on modular design. To simplify product decomposition, the product architecture is divided into three levels, product, module, and component; and the basic components in a product are predetermined. These components are grouped into modules and a robust product structure, which consists of these modules and has a low life cycle cost and environmental impact, will be identified. The environmental impacts are measured by total energy consumptions (kilowatt hour, kWh) in the supply chain. The product life cycle includes three stages, manufacturing, use, and retirement. At the manufacturing stage, components are assembled into modules, and these modules are assembled into a product. At the use stage, a service task is performed regularly. Failed components/modules are replaced with working ones and then are disposed or returned for module rebuild. At the retirement stage, the product is disassembled into modules, and then an end-of-life option (reuse, or recycling, or disposal) is selected based on life cycle benefit maximization for each module.

The methodology has seven steps (see in Figure 1). First of all, we model a product in a connectivity graph in terms of the components (vertex) and the interactions between the components (edges), and then an initial modular structure is formed using the connectivity graph. Next, a universal supply chain optimization model (SC model) for possible modular structures is constructed so that all possible modular structures can be evaluated in LCC and LCEC of their corresponding supply chain network. To efficiently find a robust modular structure for life cycle benefit, we begin the search with an initial modular structure, which has the minimum number of reusable modules covering all reusable components and the minimum number of recyclable modules covering the remaining recyclable components. Then, the SC model is used to evaluate the initial structure. According to the output of the SC model, a heuristic is used to generate a set of promising modular structures, and then these structures are evaluated by the SC model. If the object value can be improved, we update the current modular structure and then go back to the previous step. We repeat this process until the objective value can not be improved further.

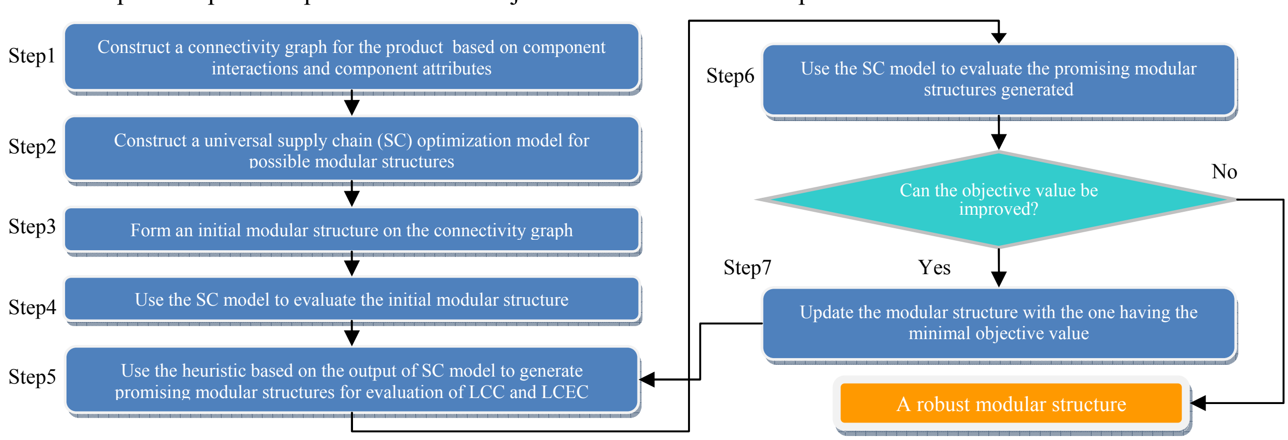


Figure 1. The steps of the methodology

2.1 The Connectivity Graph

The first step is to map a product into a functional model represented by a connectivity graph or DSM. The vertices represent the components and each has its unique attributes, and the edges represent the relationships or interactions between the components.

Component Attributes (Vertices): The component attributes used in the methodology contain weight, cost, energy consumption, etc. as shown in Table 1. The end-of-life (EOL) options include reuse (RU), recycling (RC) and disposal (D). Reuse has a greater potential among EOL options to reduce cost and to increase sustainability; thus, it gets the first priority as an EOL option; recycling and disposal follow respectively.

Component Interactions (Edges): The functional relationships between components are defined using Pimmler and Eppinger's relevant work [3], where functional interactions can be in four forms: spatial, energy, information, and material. If any of these interactions occurs, we score the pairwise component relationship as "1", and "0" otherwise. "1" implies that a connection needs to be established so that the product can work as intended. "0" means no connection needs to be established. Once all functional interactions between components are defined, a DSM (Figure 2) or a connectivity graph (Figure 3) can be used to summarize them. Based on the connectivity graph (or DSM) along with design experience pertaining to analogous products, a designer can then determine a proper joining method to maintain the functional relationship, and hence, the product cost can be also estimated. With a life-cycle viewpoint, a sample component interaction is presented in Table 2.

Table 1. An example of vertex/component attributes

Vertex/ Component	Weight (g)	Mfg. cost ($)	Mfg. energy (kWh)	MTBF (month)	Reuse value ($)	Recycling value ($)	End-of-life option	Service intent
Component A	2693	19.10	8.3	336	19.2	0.78	RU/RC/D	Y/N

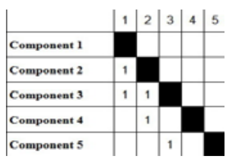


Figure 2. A DSM example

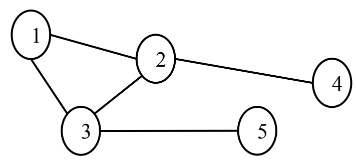


Figure 3. A example of a connectivity graph

Table 2. A sample edge/component interaction along with pertinent information

Edge/Interaction	Function	Manufacturing			Service						Retirement		
		Assembly time (sec)	Assembly cost ($)	Assembly energy (kWh)	Assembly time (sec)	Assembly cost ($)	Assembly energy (kWh)	Disa. time (sec)	Disa. cost ($)	Disa. energy (kWh)	Disa. time (sec)	Disa. cost ($)	Disa. energy (kWh)
Component A-Component B	0/1	20	0.184	0.15	20	0.084	0.07	20	0.084	0.07	20	0.084	0.07

2.2 The Calculation of LCC and LCEC

Once the component attributes and the component interactions are defined as above, the LCC and LCEC of various modular structures can be calculated. The calculation consists of three stages: manufacturing, service, and retirement, as described below. These calculations will be incorporated into the supply chain optimization model as the modular structure-related parameters so that the model may be adapted to various modular structures.

$$C_T = C_M + C_S - R_R \quad (1)$$

Where, C_T is total life cycle cost; C_M is the manufacturing cost; C_S is the service cost; R_R is the retirement revenue.

$$E_T = E_M + E_S - S_R \quad (2)$$

Where, E_T is total life cycle energy consumption; E_M is the manufacturing energy consumption; E_S is the service energy consumption; and S_R is the retirement energy saving.

Manufacturing cost and energy consumption

$$C_M = \sum_{i \in I} C_{ci} + \sum_{i \in I} \sum_{j \in I, i \neq j} C_{aij} \quad (3)$$

Where, i, j are the component indexes; I is the component set of a product; C_{ci} is component cost of component i in a product; and C_{aij} is assembly cost of the component i and j in a product.

$$E_M = \sum_{i \in I} E_{ci} + \sum_{i \in I} \sum_{j \in I, i \neq j} E_{aij} \quad (4)$$

Where, E_{ci} is the manufacturing energy consumption of component *i*; and E_{aij} is the assembly energy consumption of the component *i* and *j* in a product.

Service/maintenance cost and energy consumption

$$C_S = \sum_{k \in S} f_k \sum_{i \in k} \sum_{j \in k, i \neq j} (C_{dij} + C_{aij} + C_{mmi}) \tag{5}$$

Where, C_s is the service cost; *k* is the index of the module for service intent; *S* is the module set for service; f_k is the service frequency of the module *k*; C_{dij} is the disassembly cost to disjoin the failed modules from a product; C_{aij} is the assembly cost to install the working modules; and C_{mmi} is the cost of the working modules *i*.

$$E_S = \sum_{k \in S} f_k \sum_{i \in k} \sum_{j \in k, i \neq j} (E_{dij} + E_{aij} + E_{mmi}) \tag{6}$$

Where, E_s is the service energy consumption; E_{dij} is the disassembly energy consumption of disjoining the failed modules from a product; E_{aij} is the assembly energy consumption of the working modules; and E_{mmi} is the manufacturing energy consumption of the working modules *i*.

Retirement return and energy saving

$$R_R = R_{rem.} + R_{recy.} - C_{disp.} \tag{7}$$

Where, R_R is the total retirement return; R_{rem} is the reuse return of the modules; R_{recy} is the recycling return of the modules; and $C_{disp.}$ is the disposal cost of the modules/materials not reused and recycled.

$$S_R = S_{rem.} + S_{recy.} - E_{disp.} \tag{8}$$

Where, S_R is total retirement energy saving; S_{rem} is the reuse energy saving of the modules; S_{recy} is the recycling energy saving of the modules; E_{disp} is the disposal energy consumption of the modules/materials not reused and recycled.

Reuse/remanufacturing return energy saving

$$R_{rem.} = \sum_{k \in R1} \left[r_{rem.k} - \left(\sum_{i \in k} \sum_{j \notin k} C_{dij} \right) - \sum_{i \in k} C_{rebi} \right] \tag{9}$$

Where, *k* is the index of the module for reuse; *R1* is the module set for reuse; $r_{rem.k}$ is the reuse return of the module *k*; C_{dij} is the disassembly cost of the module for reuse; C_{rebi} is the rebuild cost of the components in the reuse module.

$$S_{rem.} = \sum_{k \in R1} \left[s_{rem.k} - \left(\sum_{i \in k} \sum_{j \notin k} E_{dij} \right) - \sum_{i \in k} E_{rebi} \right] \tag{10}$$

Where, $s_{rem.k}$ is the reuse energy saving of the module *k*; E_{dij} the disassembly energy consumption of the module for reuse; and E_{rebi} is the rebuild energy consumption of the components in the reuse module.

Recycling return and energy saving

$$R_{recy.} = \sum_{k \in R2} \left[r_{recy.k} - \left(\sum_{i \in k} \sum_{j \notin k} C_{dij} \right) - (C_{shk} + C_{spk} + C_{mrk} + C_{disp.k}) \right] \tag{11}$$

Where, k is the index of the module for recycling; R2 is the module set for recycling; $r_{recy.k}$ is the recycling return of the modules k; C_{shk} is the shredding cost of the modules k in a product; C_{spk} is the separation cost of the modules k in a product after shredding; C_{mrk} is the material recovery cost of the modules k in a product; and $C_{disp.k}$ is the disposal cost of the materials not intended for recycling in the modules *k*.

$$S_{recy.} = \sum_{k \in R2} \left[s_{recy.k} - \left(\sum_{i \in k} \sum_{j \notin k} E_{dij} \right) - (E_{shk} + E_{spk} + E_{mrk} + E_{disp.k}) \right] \tag{12}$$

Where, $s_{recy.k}$ is the recycling energy saving of module *k; E_{shk}* is the shredding energy consumption of the modules *k* in a product; E_{spk} is the separation energy consumption of modules *k* in a product after shredding; E_{mrk} is the material recovery energy consumption of modules *k* in a product; and $E_{disp.k}$ the disposal energy consumption of the materials not intended for recycling in modules *k*.

2.3 The Supply Chain Optimization Model of the Modular Structure

The objective of the supply chain model is to minimize LCC and LCEC as shown below.

$$Min \quad Z_{LCC} \ \& \ Min \quad Z_{LCEC} \tag{13}$$

Where, Z_{LCC} is the life cycle cost in the supply chain (\$); Z_{LCEC} is the life cycle energy consumption in the supply chain (kWh).

Constraints

The constraints in the model include forward flow balance, reverse flow balance, and the capacity of facilities. For forward flow balance, we use "Product demand = ∑outbound product flow from the assembly facilities" as the relationship. Similar relationships are used for the reverse flow balance. We also assume that the product demand is fulfilled at 100% level, and hence, only the capacity of the facilities at the reverse flow is discussed. The capacity of the disassembly facilities and rebuild facilities is measured in labor-hours, and the capacity of recycling facilities is measured in weight (ton). The capacity of the disposal facilities is assumed unlimited. Due to the uncertainties of these capacities, eight various supply chain conditions (SC1~SC8) may occur and they are summarized in Table 3.

∑ inbound product flow to the disassembly facilities ≤ ∑ the capacity of disassembly facilities

∑ inbound module flow to the rebuild facilities ≤ ∑ the capacity of rebuild facilities

∑ inbound module flow to the recycling facilities ≤ ∑ the capacity of recycling facilities

Because the change of the modular structure will trigger a change in the related parameters (e.g., module disassembly cost, module weight, etc.), each modular structure transition will result in a different SC model.

Table 3. Various reverse supply chain conditions

SC conditions	Disassembly Capacity	Rebuild Capacity	Recycling Capacity
SC1	Sufficient	Sufficient	Sufficient
SC2			Insufficient
SC3		Insufficient	Sufficient
SC4			Insufficient
SC5	Insufficient	Sufficient	Sufficient
SC6			Insufficient
SC7		Insufficient	Sufficient
SC8			Insufficient

2.4 The Formation of an Initial Modular Structure

The initial modular structure on the connectivity graph denotes a modular structure with minimal number of reusable modules including all reusable components and the minimal number of recyclable modules including the remaining recyclable components. If we do not consider the variance of edge weight in the graph (e.g., disassembly cost, disassembly energy consumption) and the supply chain, this modular structure can bring most of the potential life cycle benefits. This is because all reusable components in a product are included in reuse modules, and can be reused. The remaining recyclable components are included in recycling modules and can be recycled. Besides, the number of the connections between components required to break is minimized because the number of reuse modules and the remaining recycling modules is minimized. To form an initial modular structure, first of all, we select one of reusable components arbitrarily and form a module. We merge all adjacent reusable components into the module until no adjacent reusable component to the module can be found. Next, we find another reusable component among the remaining components and repeat the merging process above. This step is repeated until all reusable components are clustered in modules. Similarly, we repeat these steps for the remaining recyclable and disposal components until all components are clustered into modules. The initial modular structure is used as an initial basis in the successive heuristic to generate other possible modular structures. Because of its good quality of life cycle benefit aforementioned, it can also help avoid many unnecessary graph partitions.

2.5 The Heuristic to Generate Promising Modular Structures for Evaluation

Because all our possible modular structures are based on the connectivity graph, the problem of product modularization becomes a graph partitioning problem. However, unlike the traditional graph partitioning problem, the objective function of the problem in this research depends not only on vertex property and the interactions between vertices, but also the output of the SC model. Thus, the various supply chain conditions needs to be incorporated into the heuristic for graph partitioning. The heuristic includes two stages. Stage 1 focuses on the partitioning of reusable components on the graph, and Stage 2 focuses on recyclable components. This is because reuse can bring us a higher life cycle benefit than recycling. The heuristic is illustrated in Figure 4 in addition to the details provided in steps 5~7 of Figure 1. In the heuristic, the ratio of reuse value to required resources is used at Stage 1 to evaluate whether a reusable component has a potential to improve the objective value of the SC model if it is assigned to the adjacent modules. The reuse value is the reuse return minus the associated disassembly cost. If the disassembly and rebuild capacity in the supply chain is insufficient, the associated resources required for a modular structure is incorporated into the calculation and vice versa. Similarly, the ratio of recycling value to required resources is used at Stage 2. The calculation of these ratios varies with the supply chain conditions and is enumerated in Table 4. The calculation for energy consumption is similar to the calculation for cost. We only need to replace the reuse/recycling return with the reuse/recycling energy saving and replace the disassembly cost with the disassembly energy consumption.

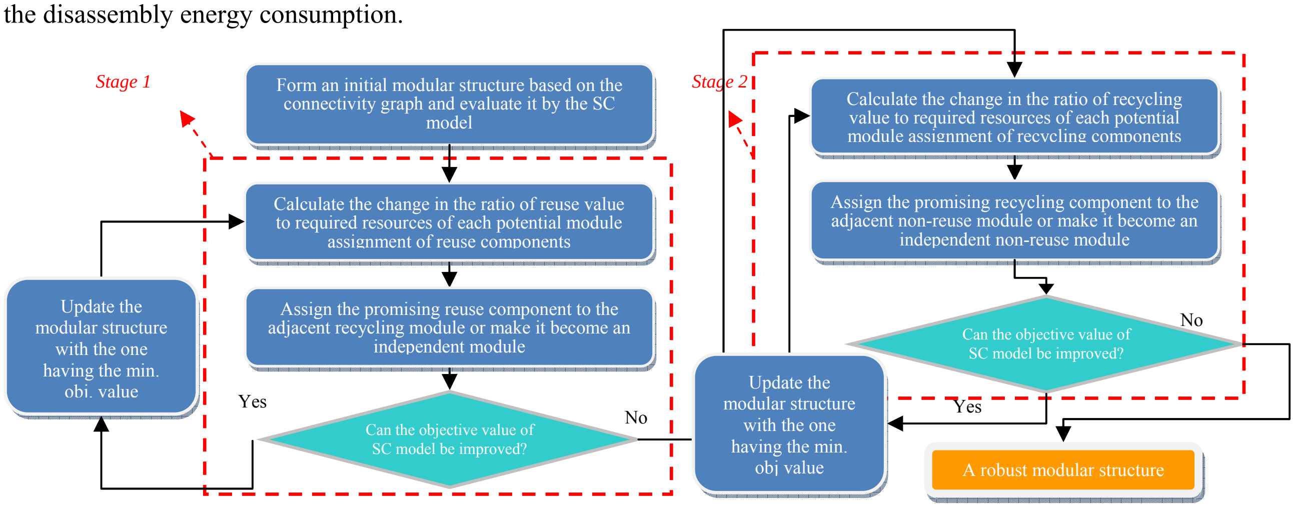


Figure 4. The heuristic to generate new modular structures for evaluation

Table 4. The criteria for evaluating potential modular structures in costs

SC conditions	Stage1: for reuse modules	Stage2: for recycling modules	SC conditions	Stage1: for reuse modules	Stage2: for recycling modules
SC1	$V_{rem.k}=r_{rem.k}-C_{dk}$	$V_{rec.k}=r_{rec.k}-C_{dk}$	SC5	$\frac{V_{rem.k}}{resource}=\frac{r_{rem.k}-C_{dk}}{t_{dk}}$	$V_{rec.k}=r_{rec.k}-C_{dk}$
SC2	$V_{rem.k}=r_{rem.k}-C_{dk}$	$\frac{V_{rec.k}}{resource}=\frac{r_{rec.k}-C_{dk}}{w_{mk}}$	SC6	$\frac{V_{rem.k}}{resource}=\frac{r_{rem.k}-C_{dk}}{t_{dk}}$	$\frac{V_{rec.k}}{resource}=\frac{r_{rec.k}-C_{dk}}{w_{mk}}$
SC3	$\frac{V_{rem.k}}{resource}=\frac{r_{rem.k}-C_{dk}}{t_{reb.k}}$	$V_{rec.k}=r_{rec.k}-C_{dk}$	SC7	$\frac{V_{rem.k}}{resource}=\frac{r_{rem.k}-C_{dk}}{t_{dk}+t_{reb.k}}$	$V_{rec.k}=r_{rec.k}-C_{dk}$
SC4	$\frac{V_{remk}}{resource}=\frac{r_{remk}-C_{dk}}{t_{rebk}}$	$\frac{V_{rec.k}}{resource}=\frac{r_{rec.k}-C_{dk}}{w_{mk}}$	SC8	$\frac{V_{rem.k}}{resource}=\frac{r_{rem.k}-C_{dk}}{t_{dk}+t_{reb.k}}$	$\frac{V_{rec.k}}{resource}=\frac{r_{rec.k}-C_{dk}}{w_{mk}}$

k the index of the module for reuse; $V_{rem.k}$ the reuse value of module k; $r_{rem.k}$ the reuse return of module k;
C_{dk} the disassembly cost of module k; $t_{reb.k}$ the rebuild time for module k; t_{dk} the disassembly time of module k
$V_{rec.k}$ the recycling value of module k; $r_{rec.k}$ the recycling return of module k; w_{mk} the weight of module k for recycling

3. Numerical Example & Analysis of Results

An example of a refrigerator is provided to demonstrate the proposed methodology. Each refrigerator component has a set of attributes as shown in Table 5, where the reusable components are highlighted in grey. Using the information displayed and the methodology aforementioned, we can construct a connectivity graph (Figure 5) and estimate the assembly and disassembly costs. The life cycle processes are categorized in to six types and these processes are performed in the facilities spreading in a supply chain network as shown in Table 6. Facility locations are summarized in Table 7 (adopted from [11]). The proposed methodology is applied to find the robust modular structure. Because we are interested in the influence of various supply chain conditions on modular design, all various supply chain conditions (SC1~SC8) aforementioned are examined and compared.

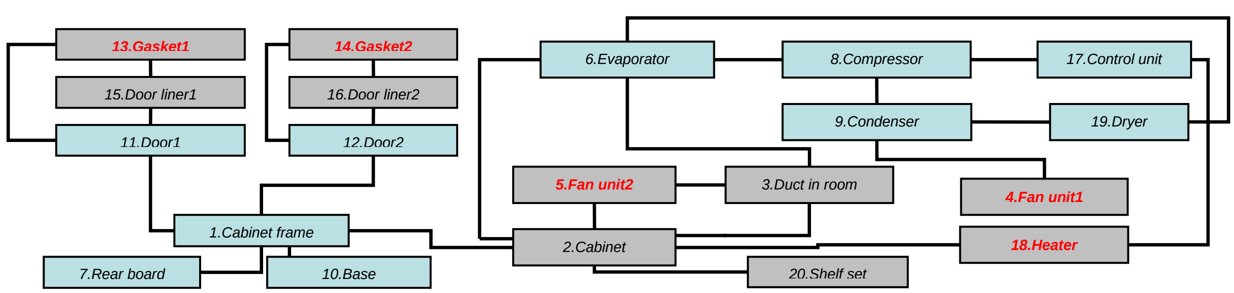


Figure 5. The connectivity graph of the refrigerator

Table 5. The attributes of the components in the refrigerator (Adopted from Umeda et al. [10])

No	Component	Material	Weight (g)	Price ($)	Mfg. cost ($)	Mfg. energy (kWh)	MTBF (month)	End-of-life option	Service intent
1	Cabinet frame	Fe	23606	180	53.13	72.9	312	RU/RC/D	N
2	Cabinet	Plastic	29313	788	243.13	147.7	192	RC/D	N
3	Duct	Plastic	1028	40	12.65	5.2	162	RC/D	N
4	Fan unit1	Fe	483	26	8.51	1.5	108	RC/D	Y
5	Fan unit2	Fe	483	26	8.51	1.5	108	RC/D	Y
6	Evaporator	Al	532	50	14.01	1.6	120	RU/RC/D	N
7	Rear board	Fe	986	27	8.67	3.0	336	RU/RC/D	N
8	Compressor	Fe	7985	80	24.01	24.7	144	RU/RC/D	N
9	Condenser	Fe	2669	40	12.44	8.2	204	RU/RC/D	N
10	Base	Fe	1240	26	8.25	3.8	324	RU/RC/D	N
11	Door1	Fe	2693	60	19.10	8.3	336	RU/RC/D	N
12	Door2	Fe	4331	70	21.88	13.3	348	RU/RC/D	N
13	Gasket1	Plastic	40	6	2	0.2	72	RC/D	Y
14	Gasket2	Plastic	60	9	3	0.3	72	RC/D	Y
15	Door liner1	Plastic	2236	52	16	11	168	RC/D	N
16	Door liner2	Plastic	4472	104	32	22	168	RC/D	N
17	Control unit	Fe/Plastic	4677	332	108.08	16.8	156	RU/RC/D	N
18	Heater	Al	112	42	13.44	0.4	84	RC/D	Y
19	Dryer	Cu	111	13	3.96	0.3	144	RU/RC/D	N
20	Shelf set	Plastic	1266	34	10.5	6.4	252	RC/D	N

Table 6. The life cycle processes in the supply chain

Process	Process description	Location
p1	Product and module assembly	F1, F2, F3
p2	Service (maintenance)	F4, F5
p3	Product collection and disassembly	F6, F7
p4	Module inspection and rebuild	F8, F9
p5	Material recycling	F10, F11
p6	Disposal	D1, D2

Table 7. The distance matrix of the supply chain

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	C1	C2	D1	D2
F1	0														
F2	600	0													
F3	410	490	0												
F4	220	430	200	0											
F5	790	500	470	580	0										
F6	1290	880	1020	1080	510	0									
F7	1070	1340	860	1020	1050	1470	0								
F8	720	1130	690	720	1100	1590	470	0							
F9	1370	1200	970	1160	680	1290	1150	1410	0						
F10	560	670	210	370	520	990	640	630	910	0					
F11	1520	1680	1280	1470	1390	1540	510	990	1250	1080	0				
C1	770	780	400	580	470	860	680	730	690	220	920	0			
C2	480	160	350	290	380	840	1140	1030	1200	520	1560	740	0		
D1	1120	950	720	910	450	430	970	1160	250	680	1140	450	970	0	
D2	1340	850	1100	1130	610	290	1650	1710	680	1110	1830	1070	840	690	0

Symmetric

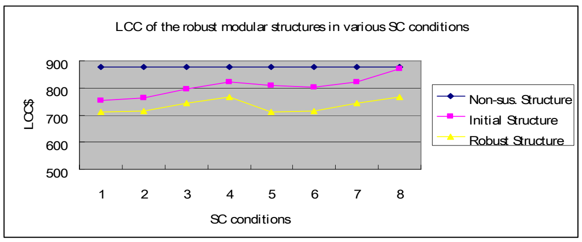
Table 8. The robust modular structure in SC1

Modular structure	Module	Component	End-of-life options		
			Reuse	Recycling	Disposal
Robust structure for LCC	M1	1,7,10,11,12	×	×	×
	M2	6,8,9,17	×	×	×
	M3	13,15		×	×
	M4	14,16		×	×
	M5	2,3,5,18,20		×	×
	M6	4		×	×
	M7	19	×	×	×
Robust structure for LCEC	M1	1,7,11,12	×	×	×
	M2	6,8,9,17,19	×	×	×
	M3	13,15		×	×
	M4	14,16		×	×
	M5	2,3,5,20		×	×
	M6	4		×	×
	M7	10	×	×	×
	M8	18		×	×

The robust modular structures for minimizing LCC and LCEC in the supply chain are found and the robust modular structures in SC1 are shown in Table 8. The LCC and LCEC of the robust modular structures under various supply chain conditions are listed in Table 9 and are plotted in Figure 7. “Non-sus. structure” in Table 9 means the refrigerator is not designed for sustainability and all of its components are disposed. The LCC and LCEC of the initial and robust modular structures under the various supply chain conditions are compared to it and their differences are represented in percentage. Overall, the proposed methodology can find a robust modular structure to reduce at least 13% of LCC and LCEC in various supply chain conditions (LCC: between 13% and 19%; LCEC: between 13% and 17%). The more recovery facilities (disassembly, rebuild, and recycling) in the supply chain are constrained in capacity, the higher LCC and LCEC become, and thus less improvement can be made.

Table 9. The LCC and LCEC of the robust modular structures in the various supply chain conditions

LCC	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8
Non-sus. structure	878.45							
Initial structure	754.57	761.82	795.62	823.57	810.53	802.53	823.00	870.42
	14.1%	13.3%	9.4%	6.2%	7.7%	8.6%	6.3%	0.9%
Robust structure	709.84	714.54	744.86	767.05	711.88	716.21	745.52	767.05
	19.2%	18.7%	17.1%	12.7%	19.0%	18.5%	15.1%	12.7%
LCEC	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8
Non-sus structure	412.15							
Initial structure	365.36	366.29	383.65	384.69	377.07	389.47	383.97	384.72
	11.4%	11.1%	6.9%	6.7%	8.5%	5.5%	6.8%	6.7%
Robust structure	343.61	344.47	358.12	358.78	345.01	345.39	358.12	358.78
	16.6%	16.4%	13.1%	12.9%	16.3%	16.2%	13.1%	12.9%



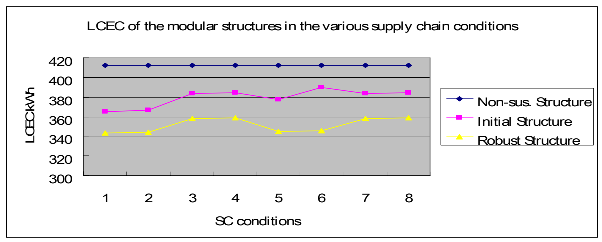


Figure 7. LCC (left) and LCEC (right) of the robust modular structures under various SC conditions

4. Conclusions

Based on the analysis above, the proposed methodology is effective to improve modular structure in the various supply chain conditions. However, further studies are required to handle the uncertainties in reverse logistics. In addition, under the various supply chain conditions, a modular structure performs differently in LCC and LCEC. It shows that the condition of a reverse supply chain does affect the level of benefit the modular structure brings. Thus, it is important to consider it for modular design to minimize the LCC and the LCEC in the supply chain.

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