A Multi-plant Tolerance Allocation Model for Assembled Electronic Products in Green Supply Chain Management

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Abstract – **Due to increased environmental consciousness, customers are aware of the world's environmental problems in the last few decades. The green principles have been expanded to many departments within organization, including supply chain. Green Supply Chain Management (GSCM) covering every stage in manufacturing from the first to the last stage of life cycle has emerged in the last few years. In this research, GSCM is the concept for manufacturing that minimizes waste through product and process design, including the definition of the product construction, production, and recycling. To achieve the concept of GSCM, tolerance allocation for assembling a product needs to consider how a product can be disassembled and recycled before the product is planned to be assembled. In this research, a multi-plant tolerance allocation model for assembled electronic products is presented. Firstly, tolerance allocation model is presented to determine the working tolerance of each of the components. A mathematical programming model is presented to assign the components to the suitable plants with the cost objectives of manufacturing costs and GSCM costs. An example product is tested and illustrated.**

Keywords - **Assembled electronic products; tolerance allocation; green supply chain manufacturing.**

I. INTRODUCTION

With increased environmental concerns in recent years, more customers are conscious of the world's environmental problems such as global warming, toxic substance usage and decreasing in non-replenish resources. Darnall, Jolley and Handfield [1] debated environmental Management Systems (EMS) make less progress in reducing environmental harms. Customers prefer to spend more money rather than buying harmful products. For that reason, environmentally benign manufacturing will become greatest challenges, not only from an engineering perspective, but also from a business and marketing perspective as well. Zhu and Sarkis [2] indicated that since the Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and Eco-design for Energy using Products (EuP) directives were passed by the European Union (EU), Green Supply Chain Management (GSCM) has been emerged as a strategy by leading electronic industry companies. Srivastara and Srivastara [3] and [4] defined GSCM as integrating environment thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, and end-of-life management of the product after its useful life.

To explore the market potential of substituting traditional products with new environmental services in repair, recycling and remanufacturing, there is no doubt in rethinking product and process innovation technology development programs and reducing energy consumption, material intensity and waste design. Green design is an important sub-topic to GSCM. It is about designing a product or a service that encourages environmental awareness. Taleb and Gupta [5] created applied algorithms to design a product recovery system and showed that "core algorithms" and "allocation algorithms" were the scheduling systems that would help reduce waste. In typical electronic products, there are electronic components, electrical components, subassembly and functional modules, printed circuit boards (PCBs), flexible printed circuit boards (FPCBs), mechanical mechanisms, frames, structures, and cases. In the past, the materials can be metal, plastic, glass, rubber, semiconductor, ceramic, and so on without considering environmental effects. Nowadays, electronic industry companies would like to become more competitive, they have to apply green principles to use environmental friendly raw material and perform Reverse Logistics (RL) in their own industry to reduce the waste of non-replenish resources by [6].

A typical process plan for producing an assembled electronic product is to manufacture the components with the required manufacturing operations and then to assemble the components with the required assembly operations. To ensure the electronic functions of the assembled product, a set of blueprint dimensions and tolerances need to be specified for the final product. Since the final product is assembled from a group of components, the set of blueprint tolerances is a result of the accumulated working tolerances of the manufacturing operations of the member components. For an assembled electronic product, the blueprint dimensions and tolerances need to be achieved after the assembly operations are performed and the final product are assembled. This is especially important for modern electronic products in which components are designed with very small or thin sizes and complex shapes. When the components are produced with manufacturing operations, each of the components must be manufactured with the specified working dimensions and working tolerances. Because of the complexity of the different manufacturing operations in an electronic product, there are different levels of working tolerances and they can result in different costs. In some cases, if materials and manufacturing operations of components are different, the same level of working tolerances can cost differently.

Some manufacturing operation may achieve a smaller tolerance with less cost while some manufacturing operation may cost higher to achieve the same level. For example, the manufacturing operation for cutting sheet metal or plastic may cost less. On the other hand, the cutting of certain glass, precious metal, ceramic, and PCBs can cost more. As a result, it may be required to maintain different levels of working tolerances on different types of components manufactured with different materials and various manufacturing operations.

Therefore, given the blueprint dimensions and blueprint tolerances of a designed product, and given the tolerance characteristics of the manufacturing operations, the blueprint tolerances need to be distributed to the components to determine the working tolerance of the manufacturing operation of each component while cost factors are considered. The purpose of a tolerance allocation model is to determine the working tolerances of the components such that the blueprint dimensions and tolerances can be obeyed and to achieve the specified cost objectives.

In a collaborative manufacturing environment of GSCM, each component may be manufactured with the manufacturing operations that are located at different plants. After the components are manufactured, the subassemblies and the final product are assembled with the assembly operations at the assembly plants. For an assembly product, the multi-plant collaborative manufacturing scheme may include several manufacturing plants and assembly plants located at different locations. If different manufacturing operations at the different plants are utilized, the working dimensions and tolerances may be allocated differently. Therefore, a multi-plant tolerance allocation model needs to consider a wider domain of diverse manufacturing operations with different capabilities at the multiple plants.

There are a variety of tolerance allocation methods capable of optimizing tolerance allocation objectives. Reviews of tolerance allocation methods can be found in [9] and [12]. The research by [13] presented a model for optimum tolerance allocation in assembly. Tseng and Terng [17] presented a feature based tolerance allocation model for evaluating a machining part with alternative manufacturing sequences represented with multiple sets of manufacturing features. Bai *et al.* [7] presented a model for optimization of machining datum selection and machining tolerance allocation with genetic algorithms. Zhang *et al.* [18] presented operational dimensioning and tolerance in process planning with setup planning. Chen and Fischer [8] presented a GA method for solving tolerance allocation for a part with multiple processes. Kopardekar and Anand [11] presented tolerance allocation using neural networks. A fuzzy comprehensive evaluation and genetic algorithm method was applied in the research by [10] for solving optimal tolerance allocation. An application of GA method by [14] presented genetic-algorithm-based optimal tolerance allocation using a least-cost model. A research by [16] presented optimum tolerance allocation in mechanical assemblies using an interval method. The continuous ants colony algorithm was applied by [15] to analyze sensitivity-based conceptual design and tolerance allocation. As observed, the previous tolerance allocation models mainly differ in types of products and processes, cost models and objectives, and the solution methods. Although much has been done, the previous research considers only a predefined sequence of manufacturing operations confined in a specified single plant. In addition, considering the GSCM concepts to the characteristics of different components in assembled electronic products have not been discussed.

The purpose of this research is to consider the environmental harms and develop a multi-plant tolerance allocation model for assembled electronic product. A tolerance allocation is developed by considering all the feasible manufacturing operations at the available multiple plants to maximize the cumulative sum of the working tolerances. A mathematical programming model is presented to perform assignment and distribution of components to the most suitable plant with an aim of minimizing multi-plant green manufacturing costs. The green manufacturing costs in GSCM include disassembly cost, recycling cost, and pollution cost.

This paper is organized as follows. Section 2 presents the multi-plant tolerance allocation model. An illustrative and computational example is discussed in Section 3. Finally, conclusions and further research are discussed in Section 4.

II. THE MULTI-PLANT TOLERANCE ALLOCATION MODEL FOR ELECTRONIC PRODUCT

2.1 Notations

i : a component,

j : a manufacturing plant,

r : a manufacturing operation,

x_{ij} : (0, 1) decision variable, a value of 1 indicating component i is manufactured at plant j,

t_i : variable representing working tolerance for component i,

σ_i : standard deviation of the manufacturing operation for component i,

z_{ir} : standard deviation of the feasible manufacturing operation r capable of manufacturing component i,

I : number of components,

J : number of manufacturing plants,

I_S : set of components,

J_S : set of manufacturing plants,

R_i : set of all the feasible manufacturing operations capable of manufacturing component i,

T_B : blueprint tolerance,

D_B : blueprint dimension,

X_i : working dimension for component i,
u_i : directional vector for X_i in a dimensional chain,
A_{ij} : fixed cost parameter for component i at plant j,
B_{ij} : fixed cost parameter for component i at plant j,
k_{ij} : quality loss parameter for component i at plant j,
w_{ij} : unit rework cost for component i at plant j,
d_{ij} : standard deviation of the manufacturing operations for component i at plant j,
C_{ij}^{T} : machining tolerance cost,
C_{ij}^{Q} : quality loss cost,
C_{ij}^{S} : manufacturing setup cost,
C_{ij}^{F} : material handling cost,
C_{ij}^{C} : assembly operation cost,
C_{ij}^{β} : disassembly operation cost,
C_{ij}^{L} : manual operation cost,
C_{ij}^{ω} : recycling cost,
C_{ij}^{α} : pollution cost,
C_{ij}^{P} : transportation cost.

2.2 The tolerance allocation model

The dimensional chain is given as $D_B = \sum_{i=1}^{I} u_i \times X_i$. The primary objective is to maximize the cumulative sum of the working tolerances.

Objective

$$\text{Max} \sum_{i=1}^{I} t_i \tag{1}$$

st.

$$t_i > 2\sigma_i \qquad \forall i \in I_S \tag{2}$$

$$t_i > 0 \tag{3}$$

$$\sigma_i = \underset{r \in R_i}{\text{Min}} \{ z_{ir} \} \qquad \forall i \in I_S \tag{4}$$

$$\sum_{i=1}^{I} t_i \le T_B \tag{5}$$

The objective function $\text{Max} \sum_{i=1}^{I} t_i$ intends to maximize the cumulative sum of the working tolerances. The constraint $t_i > 2\sigma_i$ states that the working tolerance t_i for components i should be larger than double the magnitude of the standard deviation of manufacturing operation for component i.

2.3 Multi-plant component distribution and plant assignment model

The objective is to minimize the sum of multi-plant green manufacturing costs. These costs are related to machining tolerances, quality loss, manufacturing assembly operations, handling, transportation, pollution, manufacturing disassembly operations, manual operations, manufacturing setup and recycling costs.

Objective

$$\begin{aligned}\text{Min } (&\sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{T} + \sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{Q} + \sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{S} + \sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{F} + \\ &\sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{C} + \sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{L} + \sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{\beta} + \\ &\sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{P} + \sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{\alpha} + \sum_{i=1}^{I}\sum_{j=1}^{J} C_{ij}^{\omega})\end{aligned} \tag{6}$$

st.

$$t_i > 2d_{ij} \times x_{ij} \qquad \forall i \in I_S, \forall j \in J_S \tag{7}$$

$$C_{ij}^{T} = \left(A_{ij} + \frac{B_{ij}}{t_i^2} \right) \times x_{ij} \qquad \forall i \in I_S, \forall j \in J_S \tag{8}$$

$$C_{ij}^{Q} = k_{ij} \times d_{ij}^2 \times x_{ij} \qquad \forall i \in I_S, \forall j \in J_S \tag{9}$$

$$k_{ij} = w_{ij} / t_i^2 \qquad \forall i \in I_S, \forall j \in J_S \tag{10}$$

$$x_{ij} = \begin{cases} 0 \\ 1 \end{cases} \qquad \forall i \in I_S, \forall j \in J_S \tag{11}$$

$$\sum_{j=1}^{J} x_{ij} = 1 \qquad \forall i \in I_S \tag{12}$$

The constraint $t_i > 2d_{ij} \times x_{ij}$ ensures that if component i is assigned to plant j, then plant j must be capable of performing the manufacturing operation for manufacturing component i. The constraint $\sum_{j=1}^{J} x_{ij} = 1$ restricts that each component is assigned once to one plant.

III. RESULTS

The presented models were implemented and tested by developing software on a personal computer with a Pentium 2.0 G Hz CPU and 2GB of memory. The optimized solution of the linear programming problem is computed using the Lingo software. The example product P as shown in Fig. 1 is a notebook with seven components. Fig. 2 shows the schematic diagram of the assembled product of the components. The designed blueprint dimensions and tolerances are also listed in Fig. 2. In Table I, the names of the components and the data of the components are listed. To assure proper functions of the final product, there is a required clearance y. The required clearance y is required to prevent noise intervention between the component 2 (LCD Panel) and component 3 (Sensor). The clearance is assigned as $y = D_0 \pm t_0 = 0.50 \pm 0.10$ and used as the blueprint dimension DB of the product. The input data at the first stage for the example product P and the components is shown in Table I. The output of the first stage is shown in Table II. In Table II, the working tolerance t_i is allocated for each component to achieve the maximized objective.

The working tolerance t_i is used as input to the second stage. There are three manufacturing plants, Plant 1, Plant 2, and Plant 3. The numerical data of the cost parameters and the related cost information for the components and the three plants can be input for computation. With the modeling and solution of the models in two stages, the optimized result can be obtained with the lowest multi-plant manufacturing cost. As shown in Table III, the components can be assigned to the suitable plants with the optimized cost objective. The costs are measured with a unit in dollars.

IV. CONCLUSION

The purpose of this research is to perform the concept of GSCM that minimizes waste through product and process design, including the definition of the product construction, production, and recycling. To achieve the concept of GSCM, tolerance allocation for assembling a product needs to consider how a product can be disassembled and recycled before the product is planned to be assembled. In this research, a multi-plant tolerance allocation model for assembled electronic product is presented. Firstly, tolerance allocation model is presented to determine the working tolerance of each of the components. In order to avoid the waste of the usage of petroleum power for manufacturing operation and manufacturing cost, the objective is to allocate the working tolerances as wide as possible by maximizing the cumulative sum of the working tolerances. According to minimize waste and pollution, the components are assigned to the suitable plants to perform the required manufacturing operations. A mathematical programming model is presented to assign the components to the suitable plants with the cost objectives of manufacturing costs and GSCM costs. An example product of an assembled notebook is tested and discussed. It can be generally concluded that with the presented model, the working tolerances can be allocated for the different types of components manufactured with different manufacturing operations to achieve the tolerance objective. In addition, the components can be distributed and manufactured at the suitable plants with an optimized multi-plant green manufacturing cost objective. This research recommends that researchers could focus more towards to extend producer responsibility through increase product life spans and improved after sales provision, followed by upgrading, reuse or recycling.

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Fig. 1. The example product P is a notebook assembled with 7 components.

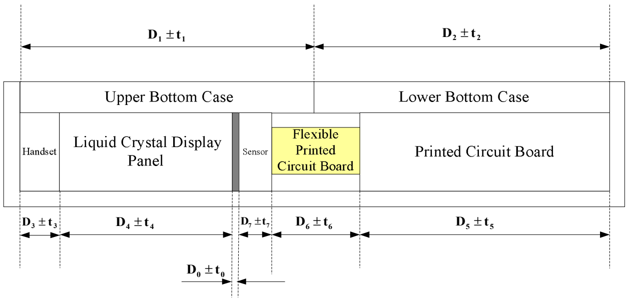

Fig. 2. The components of the example product P and the designed blueprint dimensions and tolerances (unit: mm).

TABLE I
THE LIST OF COMPONENTS AND DATA FOR THE EXAMPLE PRODUCT P (UNIT: mm)

Data Components		Blueprint dimension	Z_{ir}	Value of z_{ir}
1	Upper Bottom Case	98	Z_{11}	0.0200
			Z_{12}	0.0128
2	Liquid Crystal Display Panel	88	Z_{21}	0.0150
			Z_{22}	0.0240
			Z_{23}	0.0195
3	Sensor	4.5	Z_{31}	0.0124
			Z_{32}	0.0080
			Z_{33}	0.0198
			Z_{34}	0.0095
4	Keyboard	40	Z_{41}	0.0251
			Z_{42}	0.0160
			Z_{43}	0.0199
5	Lower Bottom Case	95	Z_{51}	0.0168
			Z_{52}	0.0141
			Z_{53}	0.0205
6	Printed Circuit Board	48	Z_{61}	0.0135
			Z_{62}	0.0022
			Z_{63}	0.0098
7	Flexible Printed Circuit Board	12	Z_{71}	0.0032
			Z_{72}	0.0045
			Z_{73}	0.0018

TABLE II
THE OUTPUT OF THE FIRST STAGE IS THE WORKING TOLERANCE FOR EACH OF THE COMPONENTS FORM THE TOLERANCE ALLOCATION MODEL (UNIT: mm)

Components i	Working tolerance t_i
1	0.0436
2	0.0480
3	0.0180
4	0.0500
5	0.0462
6	0.0224
7	0.0216

TABLE III
THE OUTPUT OF COMPONENT DISTRIBUTION AND PLANT ASSIGNMENT FORM THE MODEL AT THE MODEL AT THE SECOND STAGE (COST UNIT: DOLLAR)

Components i	Plant j	
	Component i is assigned to plant j	Cost for component i at plant j
1	2	190.560
2	3	124.625
3	3	661.251
4	2	100.828
5	2	130.212
6	1	611.002
7	1	587.300
Minimized multi-plant manufacturing cost		2405.778