

A Study of a Multi-Criteria Assessment Model for Material Substitution Management and Key Performance Indication

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Abstract

Owing to the trend of mass customization, variation of product structure cannot be fixed or unchangeable. Therefore, substitutive materials policy is a popular used method to meet customers' demand expectation. However, the management objectives of material substitution are various and sometimes there are conflicts between different departments. Therefore it needs a systematic analysis to find out the key factors of adopting substitutive materials under management goal. In this research, an assessment model based on Analytic Network Process (ANP) was constructed to connect the relationship of management objectives and cause of substitutive materials. Firstly, an expert questionnaire was used to filter out useful performance matrices, used as the sub-criteria of the ANP model. Then, a real

case was analyzed using the constructed ANP-based assessment model for material substitution management. Finally, this model was also applied to different companies to verify the effectiveness of generalization through collecting questionnaires from them. The both results indicate that product quality, product reliability and product design are the three significant critical factors that influence the decision of adopting substitutive materials. From the previous three factors, it's obvious that the product quality is the most influential factor when making material substitution decision which the same as practical experiences. That is, this proposed ANP-based assessment model is robust and effective for material substitution management.

Keywords: Mass Customization, Analytic Network Process, Material Substitution

1. Introduction

Boyton *et al.* (1993) suggested that vigorous changes in product demand lead to mass customization, and the solution is the mass production of differentiated products and services by a series of fixed modularized processes. To balance the advantage of mass production and the mass customization of customer demand, operational flexibility is a very important factor. Flexibility is the basis of mass customization, and the best way to achieve flexibility is modularization. Modularization is thus the driving force of mass customization. Today's manufacturing industry is faced with rapid and changing customer demand, and thus many companies need to provide diversified products in small quantity in response to market demand. Relatively, the material management becomes more complex and the importance of material substitution has become relatively higher. The product substitution has existed for a long time. Most current studies discuss the impact of product substitution on enterprise profitability and relevant inventory policy (Messner, 2002). However, regarding the development of product substitution policy, there is no academic or practical systematic analysis. As a result, users often develop the material substitution policy based on experience (Lin, 2002). In order to enhance competitiveness, it is necessary to analyze the factors of consideration including the causes, types, time and material substitution management, expected profit, and influence to make overall material substitution management and assessment methods more beneficial. To find out the substitution policy, it is important to understand in detail the causes of material substitution, analyze important factors, understand the importance, and influence on business goals to make good use of beneficial factors and avoid influence factors of material substitution that are not conducive to business goals.

In the event of material substitution, there are many considerations perspectives. Different perspectives on the program will produce different substitution programs. From the product life cycle perspective, the import period's material substitution decision-making may tend to consider the product's features in pursuit of product uniqueness and market competitiveness. The importance of the cost of material substitution is not as great as that in the maturity period. Secondly, for material substitution consideration and decision-making, each department has its own considerations and insistence. For example, R&D department has functional requirements, the production material management department may consider the inventory run out status, the sales department focuses on order delivery date, while the purchasing department has price preferences. Coupled with the conflict and dependence between the goals of various departments, the sales department and the production department often have conflicts in delivery time, quality and cost efficiency. For example, the

sales department may take urgent orders to meet the requirements of the customer, and the production department expects the stable production scheduling, and rejects the urgent orders. Sometimes, the sales department may take small quantity order in response to the customer requirements, while the production department expects orders in large amount. Therefore, it is difficult to find out a material substitution decision making that meets the overall interests of the company. This paper discusses all possible causes of material substitution and determines the substitution programs by importance, in order to clarify the directions of consideration in the development of material substitution policy and provide decision-making model of overall consideration.

2. Literature Review

2.1 Material Substitution Literature Review

Veinott (1965) divided material substitution into hierarchical substitution and non-hierarchical substitution. The hierarchical substitution means that the product substitution is hierarchical. In general, the substitution can be categorized into two types. One is that only products of more excellent grade can replace products of lower grade, which is known as the downward substitution. The other is the opposite, meaning that only products of lower quality grade can replace the products of higher grade, which is known as the upward substitution.

Balakrishnan and Geunes (2000) argued that progress in product manufacturing technology and product design increases bill-of-materials flexibility. They mentioned two substitutions: one is the independent substitution, which means that the substitution of a certain material will not affect the substitution relationship of other materials of the product. The other is interacting substitution, which means that the substitution of a certain material will affect the substitution relationship of other materials of the product. They proposed the definitions of demand substitution and reactive substitution. The former refers to the customer flexibility when the customer finds out the shortage of desired objective; the latter means the producer use other substitutive products to achieve the same service level to satisfy customers when the original plan is found unable to satisfy the original demands of the customer. Chen *et al.* (2002) extended the viewpoints of Balakrishnan and Geunes (2000), and integrated the concepts of demand substitution and reactive substitution to allow customers to choose suppliers and summarize material list before using the material list as the range of substitution in assembly. In this way, the range of material substitution can be reduced and the interference factors are also reduced accordingly.

2.2. Decision-making Analysis Method and Application

Among multi-criteria decision making methods, the traditional *Analytic Hierarchy Process* (AHP) is one of the most suitable methods to solve the problem with multiple assessment criteria. Proposed by Saaty in 1980s, AHP aims to provide decision makers a way of solving the social and economic problems, and it is also widely applied in solving problems such as purchase supplier choice and operational management (Saaty, 1980). Its core is to categorize the problem in hierarchical order, and considers the dominating role of the upper factors only as well as assuming the mutual independence of factors at the same level. However, in many

practical problems, the factors of various criteria are often dependent and the lower level factors often dominate the upper level factors, that is, there is a feedback relationship. The system architecture in this case is like a network, and Analytic Network Process (ANP) is to solve the structural problem of the network system. The main differences and applications of AHP and ANP are: AHP is used to solve the problems of independent programs or criteria; ANP is used to solve the problems of interdependent programs or criteria (Saaty, 1980). ANP application is to set the goals' priority weight, and explicitly define the network architecture relationship and interdependent hierarchical relationship of objectives and criteria, which is the most important function of ANP application. ANP was proposed by Saaty (1996, 2003) and extended from AHP. Saaty added AHP with the feedback mechanism to process the dependence and feedback relationship of the problem. By getting the ratio scale, it can predict all the criteria, objectives, the internal relationship in between programs and even make the optimal decision-making.

The comparison suggests that AHP is a linear relationship without considering the dependence of the same criteria level. ANP with dependence and feedback mechanism complies with the characteristics of interdependence of material substitution factors. If the decision makers can prudentially consider the existing characteristics of ANP, it can better address the multi-criteria decision-making, which can considerably reduce the value cost and get greater profits (Lin *et al.*, 2008; Lin *et al.*, 2009). Meade and Sarkis (1999) used ANP for decision-making analysis to evaluate program and change the organization more flexible, thus improving the enterprise program's specific objectives. Lee and Kim (1999) cited the ANP method of Saaty, and applied 0-1 ZOGP (Zero-One Goal-Programming) model in the choice of information system programs to reflect the dependence of assessment criteria and feasible programs. Hsu (2000) proposed a systematic and multi-criteria feasible assessment model and method by applying ANP in solving the multi-objective and interdependence problems of the system, as well as establishing the assessment model and implementing the system to help the choice of resource planning system. Huang (2006) applied ANP in the construction of supplier assessment model to discuss the interdependence of environmental factors and supplier assessment criteria. Regarding the selection of diary product supplier of a chain supermarket, Huang discussed the implications of business strategy. Liu (2007) applied ANP in the evaluation of the weight relationship of interdependence between factors and programs to provide the sustainable development of cultural assets of multi-attributes. By adjusting the original function and making use of type changes, it provided a reference for the decision making regarding the reuse of Taichung governmental hall.

ANP is mostly applied in the choice of multiple feasible programs, such as the choice of information system, performance measurement method to improve the decision-making reliability of the assessment process. This paper combines the expert opinion to find out the major causes of material substitution, and uses the case company data to establish the ANP material substitution assessment model. This can solve the material substitution conflicts of various departments in the company, develop the material substitution policy, make the internal process smoother, and improve the overall performance of the company.

3. Research Structure and Method

The study is divided into two parts. The first part is literature review for identifying the company performance indicators and the possible causes of material substitution in various departments. Semi-structured questionnaire survey was conducted on the case company, and increased or decreased the previously identified factors accordingly. The selected criteria and factors can better comply with the actual situations of the case company. The second part is to use the factors identified in the first part to construct the ANP-based assessment model. Based on the results of ANP architecture analysis, this study designed the questionnaire content to understand whether the case company can effectively avoid the conflicts generated from the material substitution. Moreover, this study conducted the general verification to provide better options for the industry in developing the substitution policy.

According to Li *et al.* (2006), if the company can surpass other competitors and distinguishes itself from other competitors by the most competitive priority or competitiveness; it is creating performance. The earliest indicators to measure the manufacturing performance proposed by Skinner (1974) include cost, quality, time and flexibility. As pointed out by Ward *et al.* (1998), in most literature on manufacturing strategy, the four manufacturing performance criteria accepted by scholars include cost, quality, time and flexibility. According to Krajewski *et al.* (2007), regarding the performance constructs, cost refers to produce with lowest possible cost; quality refers to the production of high and consistent quality; time refers to the speed of delivery and the timely delivery as well as the speed of new product development; flexibility refers to product design customization, product diversification and the flexible ability in processing great changes in demand. This study thus summarized the production performance indicators relating to material substitution management from four perspectives including cost, quality, time and customer service to establish the ANP architecture of the case company, observe the relationship between desired performance and causes of material substitution, while distinguishing the factors of consideration in case of the different performance indicators.

4. ANP Questionnaire Analysis and Discussion

The case company in this study is a technology company producing wireless multimedia products. In response to the needs of a diversified customer base, after the company was founded in 2004, it has been strengthening the operational capability of a variety of products in small amounts by modularization. However, this practice has led to excessive material substitution of the company. When the company is faced with using material substitution or not, various departments often have conflicts and problems due to differences in objectives. Therefore, the principle and time of using material substitution has gradually become a formatted data better than nothing. The quality of the substitution policy has never been assessed from the overall perspective of the company. Therefore, we applied the ANP architecture to identify the key performance indicators of the operation and analyze the relationship with factors of material substitution. Finally, based on the empirical analysis results, this study provided suggestions on the future direction of material substitution management to ensure the overall effectiveness of the system of material substitution.

4.1 Current Status of Case Company

For many considerations of the various departments of the company, there are many conflicts. The current situation of the case company has been briefly analyzed as follows, and there are four types of conflicts:

- (1) Purchasing department and quality control department conflicts: to achieve the objective of reducing cost, the purchasing department will continuously seek less expensive materials to substitute the original materials. Sometimes, to control the sudden rise in the price of original materials, more inexpensive materials have to be found for substitution. However, in response to the era of high quality and achieve higher quality level, the quality control department has to use materials of higher grade to substitute for the original materials. In general, materials of higher grade usually mean higher cost, and thus it will result in purchasing department and quality control department conflicts.
- (2) Production material management department and R&D department conflicts: to improve the delivery rate, the production material management department will select the substitutive materials of more rapid and convenient assembly to shorten assembly time. By comparison, to improve product performance or upgrade product, R&D department will actively introduce new technology or new materials to ensure the product competitiveness while the introduction of new technology or material will result in the new configuration of the assembly line. Hence, it leads to production material management department and R&D department conflicts.
- (3) Production material management department and sales department conflicts: to improve the delivery rate, the production material management department may choose substitution material to shorten assembly time. The sales department will use materials designated by the customer to re-configure the production line. Hence, it will give rise to the production material management department and sales department conflicts.
- (4) R&D department and purchasing department conflicts: R&D department may introduce new material or technology due to the progress of the times. However, as the new materials or technology is not mature, it may lead to the problem of supply instability. For purchase, it requires the assessment of the supply condition to reduce the time to wait for the material. Therefore, it leads to the R&D department and purchasing department conflicts.

As mentioned above, for material substitution generated from the internal demands of the company, the departments may consider from two perspectives: (1) starting with the benefits of the company; (2) starting with the perspective of the customer. The material substitution from the perspective of the benefits of the company is to control the product production to achieve the purpose of smooth delivery. The material substitution from the customer perspective aims to improve customer satisfaction. These two considerations may result in conflict. However, both of them expect to achieve customer satisfaction and make profits for the company.

4.2 The Establishment of ANP Architecture

This study invited 10 experts from R&D department, purchasing department, production material management department, quality control department and sales department of different companies for questionnaire interview to establish a material substitution ANP architecture. These experts have more than 10 years of working experience, and have a

certain degree of understanding of material substitution. The cause analysis diagram was used to summarize the general causes of material substitution, and the semi-structured expert questionnaire was developed.

R&D department:

1. Design considerations: in response to market demand and customer needs, or because of the introduction of new technology and new material, for the design changes of product upgrade, new materials may be used as they can improve the functionality of the product, and further substitute the original materials.
2. To shorten assembly time: in assembly, for consideration of assembly difficulty, if there is any difficulty in assembly, other materials may be used in substitution to improve the assembly speed and smoothness, and improve the product delivery rate.

Production material management department:

1. Improve delivery rate: to improve delivery rate is the major task of the production material management department. Sometimes, to improve the delivery rate, in case of material shortage, other materials may be used in substitution.
2. Reduce inventory: the replacement speed of electronic products is very fast and component versions may be upgraded. Therefore, too many old-version components in the warehouse may lead to a heavy burden on inventory cost. Therefore, if the old materials can be used in material substitution, it can effectively reduce inventory and lower cost of the company to make it more competitive in the market.

Quality control department:

1. Safety requirements: each country's standards are not the same, even every standard safety requirements are not the same. Therefore, if the product can pass more certification standards, its quality will be better. The common safety certification standards include Underwriter Laboratories Inc., (UL), Canadian Standards Association (CSA), TÜV CERT, VDE (Verband Deutscher Elektrotechniker. V), Certification Body (CB) and China's electronic products. In response to the standards of different regions, different materials will be used for substitution to meet the safety requirements.
2. Environmental directives: due to the rising environmental consciousness in recent years, relevant laws and regulations have been established in various countries. At present, the environmental requirements have a significant impact on the electronics industry, forming the basic threshold of the information and electronics industry. European Union issued WEEE (Waste Electrical and Electronic Equipment) and RoHS (Restriction of Hazardous Substance) 2002/2003, expecting to effectively control the environmental impact of electronic products of various countries. They have become global indicative regulations. Products containing lead, cadmium, mercury, hexavalent chromium and two brominated flame retardants, polybrominated biphenyls and polybrominated diphenyl ethers are not allowed to be imported into any EU member state.
3. Material quality issue: with the advent of high quality era, if the original materials cannot pass the quality control, let alone being accepted by the quality control department, materials of higher grade will be used in substitution to achieve higher quality level.

Purchasing department:

1. Supplier problem: when the supplier cannot handle a large number of orders or there is recurring instability of supply, in consideration of the timeliness of the case, in order to avoid delays in delivery, we will consider purchase from other vendors. When some companies are faced with the materials from different suppliers, it is regarded as material substitution, therefore, supplier is also one of the factors of material substitution.
2. Original material production discontinued: the amount of material production may not be able to achieve the economies of suppliers, causing the discontinued material production and the supply from new suppliers.
3. Raw material prices are too expensive: in a competitive environment, who can reduce the cost is the winner. Under the pressure of reducing cost, the company will constantly search for the less expensive materials to replace the original raw material. Moreover, the sudden rise in prices of the raw materials may lead to cost pressure and the company has to find the less expensive materials for substitution.

Sales department:

1. Customer complaint substitution: when the product is damaged or returned for repairing, the material spare parts may run out of inventory or be unavailable, other materials have to be used in substitution.
2. Improve product reliability: product reliability is the core product strength of competition. It can be interpreted from multiple angles. For users, the product should be durable with long service life and less failure. To business operators, it means improved product image, high sales prices and lower maintenance costs. For designers, it means good product performance and less failure. To professionals, it means the normal use in strict environment without losing the product performance. To improve product reliability, customers may require modifying product patterns, and thus it may lead to material substitution to achieve higher product performance.

Based on the above causes of material substitution, we invited directors and professionals of various departments for open interview. Through the face-to-face guidance and interaction between researchers and interviewees, the interviewees fully describe their experience and viewpoints of the questionnaire problems. The researchers then made detailed records, and summarized the opinions of the interviewees to collect more detailed data as the architecture of ANP questionnaire. According to the preliminary questionnaire distribution results, we established the ANP-based assessment model by selecting causes of material substitution as shown in Figure 1.

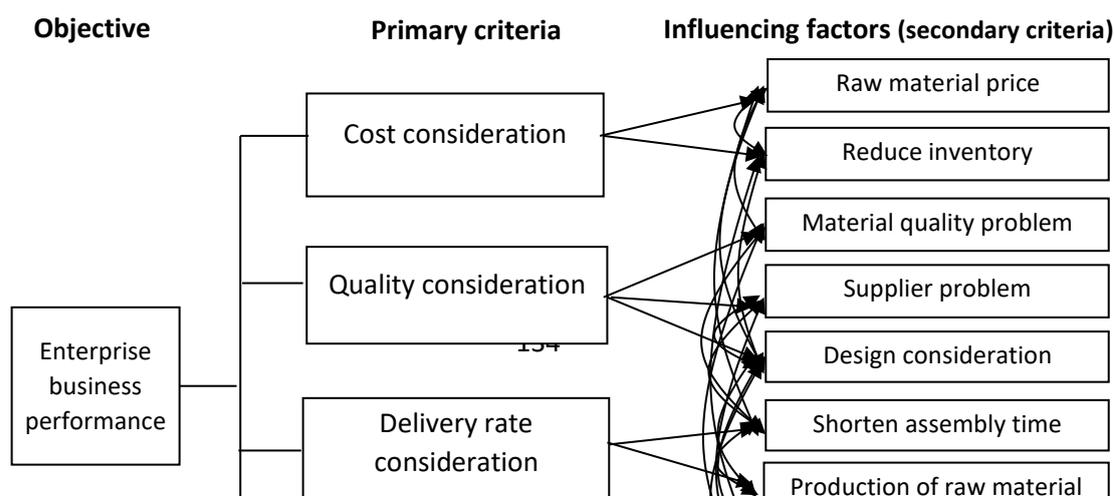


Figure 1: ANP-based assessment model of material substitution

4.3 Assessment of Decision Model

This study used Super Decision software to construct the material substitution assessment model. After the modeling, the geometric mean values of the opinions of 10 experts were integrated and input into the questionnaire model of the decision-making software for the pairwise comparison of criteria. After the integrated assessment, the priority weight values of the interdependent relationships of various assessment criteria can be obtained. By the criteria's priority weight, we can get the importance priority sequence of the impact of the causes of material substitution on business performance. The survey and analysis results are as shown in Table 1.

Table 1: Material substitution factors' priority ranking

Enterprise key performance indicators	Comprehensive importance degree	Ranking
Material quality	0.18325	1
Improve product reliability	0.16333	2
Design considerations	0.12534	3
Supplier problem	0.12280	4
Customer complaint substitution	0.11681	5
Shorten assembly time	0.11483	6
Material production discontinued	0.08922	7
Reduce inventory	0.04998	8

Reduce price	0.03443	9
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The assessment results as shown in Table 1 illustrate the criteria priority ranking. The material quality is the most factor of consideration for material substitution. This suggests that the case company generally believes that material quality is the major factor of consideration in material substitution. The material quality can directly or indirectly affect the overall business performance; followed by “improve product reliability” and “design considerations”. However, the factor of “reduce price” is the least important factor as experts believed.

4.4 Case Company ANP Architecture

This section establishes the ANP assessment model of the case company according to the previous questionnaire. The general questionnaire is used in the case company to determine the key factors for analysis and comparison. By the criteria’s priority weights, this study obtained the importance priority sequence of the impact of causes of material substitution on manufacturing performance. The analysis results are as shown in Table 2.

Table 2: Material substitution factors’ priority ranking

Case company key performance indicators	Comprehensive importance degree	Ranking
Material quality	0.18871	1
Improve product reliability	0.16255	2
Supplier problem	0.12503	3
Customer complaint substitution	0.11537	4
Design considerations	0.11503	5
Shorten assembly time	0.11471	6
Material production discontinued	0.09059	7
Reduce inventory	0.05641	8
Reduce price	0.03160	9

By integrating the material substitution priority ranking results as shown in Table 1 and Table 2, the comparison results are shown in Table 3. The most important two factors are material quality and Improve product reliability. This suggests that the industrial experts or internal experts of the case company have pointed out that the most important factor to improve the case company’s business performance with consideration of material substitution is material quality. It is argued that material quality is the most important factor of consideration in the case of material substitution.

Table 3: Comparison of secondary criteria ranking

Material substitution factor ranking	Enterprise key performance indicators	Case company key performance indicators
1	Material quality	Material quality
2	Improve product reliability	Improve product reliability
3	Design considerations	Supplier problem
4	Supplier problem	Customer complaint substitution
5	Customer complaint substitution	Design considerations
6	Shorten assembly time	Shorten assembly time
7	Material production discontinued	Material production discontinued
8	Reduce inventory	Reduce inventory
9	Reduce price	Reduce price

4.5 Criteria Weight Difference Analysis

For the effective judgment of the analysis results of ANP decision-making, this study discussed whether the priority weight ranking by experts from different fields regarding the causes of material substitution is the same from the perspectives of different departments. As R&D department and quality control department focus on product quality performance, the opinions of experts from these two departments were separated, and we analyzed the opinions of the experts from the rest three departments (production material management, purchase, sales department). As shown in Table 4, even without the opinions of experts from the R&D department and quality control department focusing on quality, other experts believed material quality (0.16627) priority weight is the highest, followed by the factor of "Improve product reliability" (0.14536), "design considerations (0.13654), and "reduce price" (0.03224), which are the same with the analysis results of the opinions of 10 experts. The proposed factors of material substitution are representative and effective. The results of importance ranking of factors of material substitution are consistent. The factor sequence can also deduce that the emphasis on quality by experts is deeply rooted in the minds of the employees regardless of the departmental differences.

Table 4: Material substitution factors' priority ranking

Enterprise key performance indicators	Comprehensive importance degree	Ranking
Material quality	0.16627	1
Improve product reliability	0.14536	2
Design considerations	0.13654	3
Supplier problem	0.13639	4
Customer complaint substitution	0.12054	5
Shorten assembly time	0.10443	6
Material production discontinued	0.10008	7
Reduce inventory	0.05815	8
Reduce price	0.03224	9

5. Conclusions

This study used ANP to construct an assessment model to measure factors of consideration for material substitution decision-making. Moreover, it discussed the key factors of material substitution that affect business operational performance, and conducted an in-depth study by individual interview. In addition to providing a reference model for developing the material substitution policy for the case company, the proposed architecture can be a reference to similar firms interested in establishing the material substitution assessment model, thus reducing the internal conflicts caused by material substitution and speeding up the use of material substitution. Based on the results of expert questionnaire analysis, this study concluded two aspects, the material substitution factors and the manufacturing performance. The suggestions are proposed as follows:

1. Material substitution factor importance assessment: factors of consideration of material substitution management may easily cause conflicts in between departments. This study developed the expert questionnaire accordingly and identified the most important factors of consideration for material substitution of the case company. It was found that, under the requirements of factors of "material quality", "improve product reliability" and "design considerations", "material quality" is most important.
2. Manufacturing performance assessment: this study found that the company should be most concerned about delivery rate as it can affect the customer evaluation of the value of the company. Departments of the company all work hard to improve the delivery rate. However, the most direct impact is from the production material management department. If the delivery rate is affected by shortage of raw materials, the production material management department will consider using material substitution for the smooth delivery of products.

In summary, the major cause of material substitution is poor material quality and material quality is the most factor of consideration. In other words, when the purchasing department is to lower the material cost, the monitoring of material quality and supplier should be more

strictly implemented. The quality control department should fulfill their duties and establish a strict quality inspection system. Comparatively, although timeliness should be pursued by the production material management department, quality is a more important consideration of quality. It is an important basis when measuring the time and quality factors.

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