The framework for an expert system to generate alternative products in concurrent engineering design

San Myint a,*, M.T. Tabucanon b,1

a Sirindhorn International Institute of Technology, P.O. Box 22, Thammasat Rangsit Post Office, Patumthani, 12121, Bangkok, Thailand
b Industrial Systems and Manufacturing Program, School of Advanced Technologies, Asian Institute of Technology, GPO Box 2754, Bangkok, Thailand

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Abstract
This paper presents the framework and development of an expert system to generating alternative products based on the information of customers’ needs and existing products derived from the product realization model [S. Myint, M.T. Tabucanon, A multi-attribute approach to product realization, Proc. of Pacific Conference on Manufacturing, 1994, pp. 553–560]. Depending on the specific design, the primitive parts and attributes are derived and stored in a database. The generation of alternative products is based on the combination of primitive parts stored in the database, rules developed from the expert system and the weights of the customers’ needs. When deriving alternatives, there can be many possible alternatives and thus, the final selection to narrow down all possible alternatives is done by functional grammar approach. The gearbox design is represented as illustrated example.

Keywords: Concurrent engineering; Object-oriented product design; Rule-based expert system

1. Introduction

Due to shorter product life cycle and competitive manufacturing world, concurrent engineering (CE) concept becomes very important, especially, in the product design. The development of new products can be viewed as alternative products generating from the customers’ needs and existing parts. The generation of new products is the major feature of complex design under pressure of time and budget constraints and, thus, the cost of errors is the highest at this stage. There have been many attempts over the recent years to produce computer-based systems which support the generation of alternative products. Typically, these involve the use of checklists, decision trees, and other algorithmic methods such as XCON, MAPLE, COSSACK, PIPPA [3]. Classical rule-based expert systems have been more successful, although knowledge maintenance has been shown to be a problem because previous or existing design on part-designs provides a stimulus for developing a new configuration structure. Then, alternative configurations are evaluated where possible, and carefully trade off a number of possibly configuring factors, such as efficiency, cost complexity, and reuse of existing components to reduce design and
tooling cost. The product related knowledge can be grouped into four categories: (1) knowledge about components; (2) knowledge about relations between components; (3) constraints on properties of materials involving part formation; and (4) relations between components and user preferences [3]. Based on the product knowledge with the customer’s needs, the alternative product configuration can be generated by using an expert system.

The paper discusses with approaches for generation of alternatives by referring with some past research works. Based on the literature review, the framework of an expert system development is illustrated with figure. After proposing the framework, rules for gearbox design are defined. Then, two-staged gearbox design is illustrated as an example for applying the proposed method.

2. Approaches for generation of alternatives

Alternative generation is the most distinctive functional demand posed in design problem. Generation methods vary in the extent to employ reasoned analysis, experiential knowledge, and creative imagination. There are some analytical strategies for generating alternatives in artificial intelligence (AI) and these are transformation method, constraint satisfaction techniques and case-based reasoning. However, the first two methods are vulnerable to charges that alternative spaces are too large and unstructured to be sufficiently explored and that requirements cannot be prostrated. It is now accepted that often solutions will be imagined before the corresponding problem is articulated. Therefore, it is necessary to lie in domain knowledge rather than analytical generation methods. Moreover, experiential knowledge of previous problems, processes, and solutions can be used to generate the alternatives. Generation of alternatives should be based on design goals (needs), bounded with physical constraints such as ability to assemble. If it is possible, it allows the user to give some initial, possible alternatives based on his experience. Thus, it is required to develop user-interactive procedure in generating design alternatives [6]. To develop an expert system to generate product’s options based on its physical attributes related with design goals and constraints, it should include the ability to store, recall and reuse partial or complete configurations. Then, each product and decision processes are stored in knowledge bases. Moreover, the knowledge base should store that information about parts and relations between components.

3. Model development

From the product realization model [4], the modifiable parts and related attributes due to customer’s needs of these parts and assembly index for measuring the relationship due to assemble are identified and derived. Considering information of modifiable

![Fig. 1. The framework of an expert system for generating alternatives.](#)
parts and related attributes based on customers’ needs, knowledge engineering approach with the help of database can be applied to generate the product alternatives’ configurations for product optimization. The concepts of decomposition–composition technique of Liu and Lee [2] and constructive–deductive approach [7] are adopted for developing knowledge-based system. At the first stage, the existing product is decomposed as parts level and each part can be represented as physical functional attributes and non-physical attributes. The assembly constraints and indices become the rules for composition. Liu and Lee’s [2] idea of Design Language, that is, ‘‘every part may be or not be its own functional attribute (paradigmatic series)’’, is adopted. However, it must have related functional attributes when it relates to other parts (syntagmatic). Thus, based on paradigmatic series concept, parts of the existing product

![Diagram of expert system development]

Fig. 2. The structure of expert system development.
can be decomposed and the most modifiable group of parts can be derived. The composition for generating product alternatives based on the results of the product realization model is applied. However, the generation of alternatives based on decomposition—composition could give too many alternatives which can be difficult to handle. On the other hand, if the generated alternatives are too few, the good design alternative may not be captured. Hence, it is advisable to firstly allow generation of all possible alternatives based on the modifiable parts. From this set, the number of alternatives can be reduced using a rule-based system that is derived from past experience and having user interface with a CAD package. The user is allowed to judge on possible alternatives derived by the expert system. If the user selects an alternative, this goes to the database for updating. The model is illustrated in Figs. 1 and 2.

3.1. Measuring manufacturability

It is necessary to measure the manufacturability of the new parts based on the existing part constraints with the existing facility. If the new parts are not manufacturable in the existing facility, the additional facility is required. Thus, the manufacturability indices for new parts also need to be derived. Manufacturability index is defined based on the existing product and facilities. It is assumed that the product is composed of parts and parts are produced by machining. Although parts’ design variables are still unclear in the early stage of design, some general guidelines can be derived and become rules for the expert system. Some general rules are to: (1) minimize the number of parts to be used; (2) maximize the use of standard parts; and (3) maximize the use of modular parts. Some processes and parameters can be estimated in early design stage. (Arimoto et al.’s [1] MEM method.) Since it is impossible to obtain dimensions of the parts in the early stage of product design, it is very difficult to estimate the manufacturing cost and time for the new product. Moreover, manufacturability is a relative and comparative concept. Hence, the introduction of indices seems logical. Resource similarity index (RS) which measures the degree of similarity of resource requirements between two products and manufacturability-process similarity index (MS) to measure the degree of similarity of processes between two products are introduced in this paper.

3.1.1. Resource similarity index

The concept of defining a similarity index is an inspiration from group technology. The proposed index is defined as follows:

\[
RS_{ij} = 2 \left( \frac{N_{ij}}{N_i + N_j} \right) \quad 0 \leq RS_{ij} \leq 1
\]

where, \( N_{ij} \) = number of resource types required by both parts (or products) \( i \) and \( j \); \( N_i \) = number of resource types required by part (or product) \( i \); \( N_j \) = number of resource types required by part (or product) \( j \).

In this index, multiplication with 2 is used to obtain the unity value if all processes are the same in both product \( i \) and \( j \). It means, if \( N_i = N_j = N_{ij} \), then, \( RS_{ij} = 1 \). If both parts have the same resources, \( RS_{ij} = 1 \) and if both parts do not have the same resources, \( RS_{ij} = 0 \).

3.1.2. Manufacturability-process similarity index

After defining the resource similarity, it is also necessary to define process similarity taking into account the process plan. The possible processes required for producing a product (or part) are defined as \( P_i \) and the possible processes for a new part (or modified part) can be also estimated and defined as \( M_j \). Then, if there are similar processes between

<table>
<thead>
<tr>
<th>Process</th>
<th>Type of gears</th>
<th>Spur</th>
<th>Helical</th>
<th>Straight bevel</th>
<th>Spiral bevel</th>
<th>Worm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milling</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Hobbing</td>
<td>4</td>
<td>4</td>
<td>×</td>
<td>×</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Shaping</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Shearing</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>×</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Broaching</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

5 = the cheapest; 1 = the most expensive. Legend: × stands for ‘incompatible to manufacture.’
Table 2
Weights of gear processes based on time*

<table>
<thead>
<tr>
<th>Process</th>
<th>Type of gears</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spur</td>
</tr>
<tr>
<td>Milling</td>
<td>1</td>
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<tr>
<td>Hobbing</td>
<td>2</td>
</tr>
<tr>
<td>Shaping</td>
<td>3</td>
</tr>
<tr>
<td>Shearing</td>
<td>4</td>
</tr>
<tr>
<td>Broaching</td>
<td>5</td>
</tr>
</tbody>
</table>

5 = the fastest process; 1 = the slowest process. Legend: × stands for ‘incompatible to manufacture.’

these two parts, the cost incurred for manufacturing could not be too different; the difference is merely due to dimension. For this difference, the cost and time criteria in optimization can be compensated.

\[ MS_{ij} = 2 \left( \frac{P_i \cap M_j}{P_i + M_j} \right) \]

where \( P_i \cap M_j \) = number of common processes between part \( i \) and part \( j \); \( P_i \) = number of processes required to produce part \( i \); \( M_j \) = number of processes required to produce part \( j \).

If this index value tends to approach 1, both parts \( i \) and \( j \) have the same processes, and it can be said that both parts are compatible in processes. For idle case of \( P_i = M_j = P_i \cap M_j \), \( MS_{ij} \) becomes the value of 1 by multiplication with 2. It can be applied for gear manufacturing and the general processes used for cutting are milling, hobbing, shaping, shear cutting, broaching. Among these processes, the cutting time and cost vary based on the type of gear, number of teeth to be cut and type of materials to be used. However, the cost and time based on type of gear and type of processes can be estimated as shown in Tables 1 and 2.

4. Expert system implementation

For specific application or characterization of the product, it is necessary to define the basic alternative parts attached with the corresponding attributes and rules for the expert system module. Most of the rules are generated based on a specific type of product. In the illustrative example, a gear box is composed of gears, shafts, bearing and housing. The product realization derived the modifiable parts as gears and the assembly constraints dictate to change parts. Therefore, the generation of alternatives begins with the most important parts—gears.

Before generating alternative parts, it is necessary to store the information concerning these parts in the database. Most information related with gear design and gear trains is taken from Dudley’s *Handbook of Gear Design*, and the machining data can be obtained from the *Machine Design Data Handbook*. A gear can be either external or internal depending on the type of teeth. The form of teeth can also classify a gear as spur, helical, straight bevel, spiral bevel and worm gear. An essential consideration is that gears in contact must mesh each other to achieve the required power transmission. For example, the spur pinion must mesh with the spur gear, and the helical gear must mesh with the helical pinion. The following notations are used for each pair of gear set, for generating alternatives.

- \( S_e \) external spur gear
- \( H_e \) external helical gear
- \( B_{1e} \) external straight bevel gear
- \( B_{2e} \) external spiral bevel gear
- \( W_e \) external worm gear
- \( S_i \) internal spur gear
- \( H_i \) internal helical gear
- \( B_{1i} \) internal straight bevel gear (mostly not use)
- \( B_{2i} \) internal spiral bevel gear (mostly not use)
- \( W_i \) internal worm gear

By using these notations, the arrangement of the gears can be represented and other arrangement combinations can also be generated. This approach is called expansion of the design attributes or decomposition technique [2]. There is also the property that both meshing gears must be of the same type. The spur gear set, including external and internal gear type can generate only two alternatives—\( S_S \) and \( S_S \). There are generally five gear types used in real situation and all these are to be used in this study. Thus, the possible number of alternatives is \( \sum^2 2 = 10 \) by taking a pair from each gear type such as \( S_S S_e, S_e S_e, S_e H_e, H_e S_e, B_{1e} S_e, B_{1e} B_{1e}, B_{2e} B_{2e}, B_{2e} W_e, W_e W_e \). After decomposition, it is necessary to eliminate infeasible arrangements due to the geometric constraints and the physical properties using the rules. According to the relationship of gear
axes, gear pairs can be screened out with the following feasibility rules.

4.1. Rules for feasibility

Rule 1: Every external gear must mesh with the same type of gear.

Rule 2: Every internal gear must mesh with the same type of external gear.

There remain four basic gear units after applying the above mentioned rules and these can be seen in Fig. 3a. The axis arrangement can be also considered and developed with the following rules and are illustrated in Fig. 3b.

4.2. Rules for axis arrangement

Rule 1: All spur and helical gears give the parallel shaft arrangement, not incline.

Rule 2: All bevel gears give intersection shaft arrangement.

Rule 3: All worm gears give skew shaft perpendicular arrangement.

The above rules can eliminate technically impossible arrangements. In the illustrative example, the number of alternatives is 10 sets. Then, the alternatives are checked against the desired needs according to the weights given from the product realization model. For example, for speed reduction need, the following rules are applied.

4.3. Rules for speed reduction need

Rule 1: When gear train is spur $S_1S_2$, then $SR = 5$, where $SR =$ speed reduction. When gear train is spur $S_1S_2$, then $SR = 7$. When gear train is helical $H_1H_2$, or $H_1H_2$, then $SR = 10$. When gear train is straight bevel $B_1B_1$, or $B_2B_2$, then $SR = 8$. When gear train is worm gear $W_1W_2$, then $SR = 100$.

Rule 2: When $SR < \text{given }$, check Rule 1. When satisfied, use single train or single stage. When not satisfied, number of stages is $(SR_{\text{given}})/SR$ for all type of gears. Then, generate alternatives up to the number of stages.

Rule 3: When multiple speed need, generate alternatives up to the number of stages for speed reduction desired.

For example, if there are two stages for speed reduction, the number of alternatives become 20 by multiplying with 2 due to positional situation with 10 alternatives derived. For multiple reduction case, it needs to account the layout effect on the arrangement. For a two-stage case, there are $2^{(2-1)}$ alternatives. The number of alternatives that can generally be derived based on the number of speed reduction stages desired (not including planetary gear train) is:

$$\text{No. of generated alternatives} = 2^{(\text{no. of stages} - 1)} \left( \prod_{i=1}^{\text{no. of stages}} 10 \right)$$ (3)

For generating of alternatives for planetary gear train, it is considered as the extension case of two gears set. There are two gear set trains and both have a common gear in both sets. For example, the first gear set $S_1S_2$ and the second gear set $S_3S_4$ can be arranged to become planetary trains. However, the last gear of the first one must be the same as the first gear of the second gear train. Then, the planetary train becomes $S_1S_2S_3S_4$. Similarly, $S_1S_2$ gear train and $S_3S_4$ gear train derived external, internal and external, internal trains. For generating alternatives of
planetary trains, the kinematics graph method developed by Yan and Hsieh [8] is applicable. The characteristics of planetary gear trains are as follows:

1. The number of revolute pairs \( J_r \) is the number of links \( N \) minus one.
2. The relationship among the number of gear pairs \( J_g \), the number of links \( N \), and the degree of freedom \( F \) is: \( J_g = N - (F + 1) \).
3. The relationship among the number of joints, the number of links, and the degrees of freedom \( F \) is: \( J = 2N - (F + 1) \).
4. All members are incident to at least one revolute pair.
5. The sub graph obtained by deleting the gear edges is a tree.
6. A fundamental circuit is formed by adding a gear edge to the tree.
7. The number of fundamental circuits is equal to the number of gear pairs.
8. Each revolute pair edge can be labeled by a level which identifies the location of its axis space.
9. There exists a transfer link (carrier) which contains two revolute pairs with different levels in each fundamental circuit.

Rules for design constraints are established as follows.

4.4. Rules for design constraints

Rule 1: When \( S_S_S \) combination is derived, then it is a simple planetary.
Rule 2: A planetary gear has at least two gear pairs to avoid degeneration.
Rule 3: There are \( (N - 1) \) revolute pairs for \( N \) joint links.

Fig. 4. (a) Speed arrangement 1. (b) Speed arrangement 2. (c) Speed arrangement 3. (d) Speed arrangement 4. (e) Speed arrangement 5. (f) Speed arrangement 6.
Rule 4: There are \((N - 3)\) gear pairs for \(N\) joint links.

Rule 5: Any joint incident to the carrier must be a revolute pair. Any joint incident to the frame must be a revolute pair.

In simple planetary arrangement, the variable speeds can be obtained by arranging the gears; these are the sun gear stationary, planet gear stationary, internal gear stationary, rotate opposite direction with input and output, free all gears. These speed arrangements can be tabulated and illustrated as shown in Fig. 4a through f. Rules can be generated based on specific need. Some of these are as follows:

Rule 1: When \(S_1S_1\), max. power = 2240 kW with efficiency \(= 0.98\).

Rule 2: When \(H_1H_1\), max. power = 22400 kW with efficiency \(= 0.98\).

Rule 3: When \(B_1B_1\), max. power = 370 kW with efficiency \(= 0.98\).

Rule 4: When \(B_2B_2\), max power = 3730 kW with efficiency \(= 0.95\).

Rule 5: When \(W_1W_1\), max power = 560 kW with efficiency \(= 0.95\).

4.5. Rules for single stage

Rule 1: When for spur gears and single stage, the speed ratio could not be greater than 5. When speed ratio is greater than 5:1, the no. of stages = integer value of \((\text{speed ratio}/5)\).

Rule 2: When for helical gears and single stage, the speed ratio could not be greater than 7. When speed ratio is greater than 7:1, the no. of stages = integer value of \((\text{speed ratio}/7)\).

Rule 3: When for straight bevel gears and single stage, the speed ratio could not be greater than 8. When speed ratio is greater than 8:1, the no. of stages = integer value of \((\text{speed ratio}/8)\).

Rule 4: When for spiral gears and single stage, the speed ratio could not be greater than 8. When speed ratio is greater than 8:1, the no. of stages = integer value of \((\text{speed ratio}/8)\).

Rule 5: When for worm gears and single stage, the speed ratio could not be greater than 100. When speed ratio is greater than 100:1, the no. of stages = integer value of \((\text{speed ratio}/100)\).

4.6. Rules for input output arrangement

Rule 1: When for concentric input and output with single step speed ratio, select spur or helical gears with the same speed ratio at each speed reduction stage and even number of stages; each stage speed ratio = \((\text{total speed ratio})^{1/\text{no. of stages}}\).

Rule 2: When for right-angle shafts with intersecting axes, select bevel or worm gears.

4.7. Rules for selecting gear materials

Rule 1: Cast iron as a gear material is used where the stress conditions are light in nature.

Rule 2: Structural steels and steel castings are meant for light to medium duty gears.

Rule 3: When the stress demands are high, hardened and tempered steels as well as case-hardened steels should be used.

For application, all rules mentioned above are written with AutoLISP under AutoCAD environment. All gear information is stored in a database. According to the rules, the request data and attributes are derived by using the database query language. The concept is implemented into a DBASE software. For user interface and software interfacing, visual BASIC is used due to its power of compatibility with the AutoCAD interface under a window environment.

5. Illustrative example

To generate the alternatives for the illustrative example, the modifiable parts are taken from the product realization model [4]. These are gear parts and shafts changing of the orientation. Among these, gear parts are selected according to the important weight derived from the customers’ needs. Using Eq. (3), the total number of alternatives is \((10 \times 10)^2 - 1 = 200\). These alternatives are described in symbolic form as shown in Table 3 by combinations of first stage and second stages. In the first stage, the number of alternatives generated is 100. The second stage also generates 100 alternatives. Thus, total number of alternatives is 200. The coaxial input output arrangement narrows down these alternatives into four (using external spur and helical gear types only). Moreover, the speed ratio request from the customer is 15 and this could not be satisfied with...
Table 3
Possible alternatives for illustrative example

<table>
<thead>
<tr>
<th>First stage</th>
<th>Second stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S, S, S</td>
<td>S, S, S</td>
</tr>
<tr>
<td>S, S, or S, S</td>
<td>S, S, or S, S</td>
</tr>
<tr>
<td>H, H, H</td>
<td>H, H, H</td>
</tr>
<tr>
<td>H, H, H</td>
<td>H, H, H</td>
</tr>
<tr>
<td>B1, B1, B1</td>
<td>B1, B1, B1</td>
</tr>
<tr>
<td>B1, B1, B1</td>
<td>B1, B1, B1</td>
</tr>
</tbody>
</table>

Fig. 5. Helical gear input, helical gear output alternative.

Fig. 6. Spur gear input, helical output alternative.

The spur gear arrangement. Thus, the number of solution for modifying gears narrow down to only three. The final arrangements can be illustrated in Figs. 5 and 6. The last one has the same configuration as in Fig. 6; the only change is with S, H, S. After considering two gear sets for gear train generation, three gear sets can also be considered for alternative generation.

Only planetary train (special case of three gears set train) is considered due to its power of high speed ratio with small size and light weight. If the small weight or size is the most important criterion, it is necessary to consider planetary driver set in the alternative generations. It could be noticed from the product realization model that the size need is the second important needs of the customers and, therefore, the simple planetary train is considered as the third alternative. Although, the simple planetary train is considered as the third alternative, it is driven out by the general rule of minimum parts in the product.

The simple planetary arrangement needs four planetary gears and, based on power transmission, there should be an even number of planets in the train. The two remaining alternatives are (1) the existing system using helical gear train in both stages; and (2) the first stage uses spur gears and the second stage uses helical gear. After screening the selected alternatives among the generated alternatives, it is necessary to use the manufacturability indices called the resource similarity index and manufacturing process similarity index. Then, the ranking of the alternatives can be done based on these indices. For the illustrative example, the first alternative is the existing product design and therefore, the $RS_{alt1} = 1$ and $MS_{alt1} = 1$. For the second alternative, as shown in Fig. 6, the first stage uses spur gear train and the second stage uses helical gear train. Although the gear type is changed from helical to spur, the resources and processes are the same. Therefore, $RS_{alt2}$ and $MS_{alt2}$ also become 1. Therefore, the manufacturability index is not effective for these two alternatives. Thus, these two alternatives are carried on to the product optimization model. All detailed implementation was done with AutoLISP in AutoCAD environment and it can be found in details in Ref. [5].

6. Conclusion

In developing an expert system for alternative generation, it is, sometimes, quite difficult to handle many alternatives based on the combination of the existing parts and related attributes derived from the customer needs. This generation of alternatives is
called as decomposition approach. For example, there are 200 alternatives generated in the first step of the illustrative example. Therefore, a rule-based expert system is developed to screen out technically infeasible alternatives. This screening approach is known as composition. The combined approach of decomposition and composition is called decomposition–composition approach. If there are many alternatives remaining after applying the rule-based expert system for screening, it is necessary to apply selection procedures based on customers’ needs and their importance. The user can input more information related with the product to narrow down the number of alternatives. In the illustrative example, the input output arrangement derived feasible alternatives to just two. It has been demonstrated that the decomposition–composition technique can be effectively applied to generating alternative products by changing the primitive parts of this product. The expert system developed and described can be extended for power transmission system by adding new primitive structure of power transmission system such as belt, chain, together with corresponding rules for screening infeasibility. In addition, the proposed framework can be extended to apply genetic algorithms (GAs) for automatic generation of product alternatives. The authors are extending the research work with genetic algorithms for implementation of automatic generation on alternatives.

References


San Myint is assistant professor of Sirindhorn International Institute of Technology. He received his M.S. and Ph.D. in industrial engineering and manufacturing system engineering from the Asian Institute of Technology (AIT) in 1991 and 1995, respectively. He is a member of Society of Manufacturing Engineering (SME), Institute of Industrial Engineering (IIE) and American Society of Mechanical Engineering (ASME). His research interests include Concurrent Engineering (CE), product development, evolutionary design development, multiple criteria decision making, genetic algorithm, CAD/CAM and internet design development.

M.T. Tabucanon is Dean of the School of Advanced Technologies and Professor of Industrial Systems Engineering, Asian Institute of Technology. He has many years of experience in postgraduate education with an outstanding record of research achievements. He is credited with over 100 publications in the form of books, chapters of books, refereed journal articles, conference proceedings, and working papers. A high proportion of his publications are in reputed international refereed journals. One of his well known book publication, among the few in the field, is Multiple Criteria Decision Making in Industry published by Elsevier. Professor Tabucanon is Editor of the International Journal of Production Economics, Associate Editor of the Journal of Manufacturing Systems, Area Editor on Industrial Management of the International Journal of Information and Management Sciences, a founding member of the International Advisory Board of the International Journal of Operations and Quantitative Management, and a member of the Editorial Boards of the International Journal of Computers and Industrial Engineering, the Journal of Operations Management, the Journal of Prioritization and Decision Making, the Journal of Engineering Valuation and Cost Analysis, and the Engineering Design and Automation Journal, among others. He has served as Guest Editor of Special Issues/Volumes and a paper reviewer of several other international journals.