Int J Adv Manuf Technol (2002) 19:384–391
Ownership and Copyright

The International Journal of Advanced Manufacturing Technology

Partnership Synthesis for Virtual Enterprises

X. N. Chu,[1] S. K. Tso,[2] W. J. Zhang[3] and Q. Li[4]

[1]CIMS Institute, Hefei University of Technology, Hefei City, Anhui Province, PR China, [2]CIDAM (Centre for Intelligent Design, Automation and Manufacturing), City University of Hong Kong; [3]Department of Mechanical Engineering, University of Saskatchewan, Canada; and [4]Department of Mechanical Engineering, University of Adelaide, Adelaide, Australia

The virtual enterprise (VE) concept is one of the most important ways to raise the agility and competitiveness of a manufacturing enterprise. Under this concept a master company develops its products by using the manufacturing resources of external partners. Thus product design and partner selection or partner synthesis become two important issues. In this paper, we propose an integrated product design and partner synthesis process model, and develop an architecture of computer-aided product design and partner synthesis system for the VE (CAPDPS), in which product design and the partner synthesis module and the respective databases are implemented. Partner synthesis activity, in this paper, is divided into two phases: partner type synthesis and partner instance synthesis. In the partner type synthesis phase, group technology (GT) is applied for retrieving and selecting potential partners. In the partner instance synthesis phase, more factors other than the cost are identified, and the analytic hierarchy process (AHP) method is employed to select the best partner from the potential ones. A specific automobile manufacturing group (including master company and its partner factories) and its typical product – automobile steering assembly – are used as a case to verify the feasibility of the proposed approach.

Keywords: Partner synthesis; Multiple-attribute decision making; Product design; Agile manufacturing; Virtual enterprise; Partnership synthesis for virtual enterprises

1. Introduction

Today, with the continuous changes in the global competitive environment and the rapid growth of information technologies, manufacturing is entering a new era, where product life is rapidly decreasing, product structure is more frequently changed and customer-oriented, and all activities related to the product life cycle are being affected by globalisation.

Correspondence and offprint requests to: Professor X.-N. Chu, CIMS Institute, Hefei University of Technology, Hefei City, Anhui Province, PR China, 230009. E-mail: xnchu@mail.hf.ah.cn

In this new manufacturing era, manufacturers have to develop and produce more complex products in less time while still competing in global markets. For many, these requirements are too demanding to allow them to develop and produce a product within a single manufacturing plant. It is increasingly seen that the development and production of a product is becoming a joint venture between suppliers, manufacturers, distributors, and customers. This dispersion of manufacturing functions throughout the globe is a major factor which has led to the development of the extended enterprise [1] or virtual enterprise (VE) [2–4].

VE is attracting increasing attention from both the academic and industrial communities. Extensive programs are being conducted worldwide on relevant issues to propagate the VE concept, to build VE prototypes, and to realise VEs. Many terms and definitions have been proposed for VE, but so far, there is no unified definition. For instance, for the NIIIP project [2]: "A Virtual Enterprise is a temporary consortium or alliance of companies formed to share costs and skills and exploit fast-changing market opportunities". To Walton and Whicker [3]: 'The Virtual Enterprise consists of a series of co-operating "nodes" of core competence which form into a supply chain in order to address a specific opportunity in the market place'. From Song and Nagi [4]: 'A virtual enterprise, different from a traditional enterprise, is constructed by partners from different companies, who collaborate with each other to design and manufacture high quality and customized products. It is product-oriented, team-collaboration styled, and featured as fast and flexible'.

A set of common characteristics can be identified from the various definitions:

1. There is a master company which takes charge of selecting and managing its partner factories.
2. The partner members and organisation structure of a VE is product oriented.
3. The product development and production are distributed among the master company and all partner factories.
4. The partnership of the master company with its partner factories may not be permanent.

It is clear that in a VE, the partner factory selection or synthesis is the basis and premise for building and operating a VE enterprise, and this synthesis process is strongly coupled with the product design process. This makes sense of "design for partnership" for a VE being equivalent to design for manufacturing in conventional manufacturing plants. The partner synthesis and product design as well as their computer implementation in the context of a VE is thus worthy of being studied. In this paper, the emphasis will be placed on the partner synthesis or selection issue.

2. Related Work

Partner synthesis has been addressed by analysis of the information needs in agile manufacturing. Candadai et al. [5] discussed three types of data necessary for product design and partner synthesis. They proposed modelling product data by using the STandard for the Exchange of Product (STEP) model and group technology (GT) codes. Two other types of data about partner factories and technological processes were also described, but no detailed implementation was reported. Zhang [6] identified the complexity in product data and partner data modelling in the global manufacturing environment, and discussed a product conceptual model that is able to describe both product families and product variants in one unified structure.

For partner selection, Zhang et al. [7] discussed some attributes for partner company selection, e.g. the price that a partner company asks for, the delivery date, etc. They have also developed a computational model with these attributes to select partner companies. The attributes proposed by them will be further enriched and improved in our research. Qin et al. [8] presented a computational model to select partner companies with the objective of completing the project in the shortest time while keeping existing project progress unaffected. Starting from the project management viewpoint, their method decomposes a project into tasks that will subsequently be completed by partner companies. The computational model is an optimisation model with the variable time as the objective function. Their approach has considered each task related to a particular part module (of a whole product). However, the effects on product configuration from the partner company selection are not considered. Halevi [9] presented a matrix method to achieve the global optimisation of a manufacturing process. In particular, his work considers the cost or time as the optimisation criterion. The decision-making process when introducing new equipment in a company has also been discussed in his study. Since the new equipment is purchased from other companies, his work implies a methodology to justify why a partner company should be chosen. Mak et al. [10] reported on the design of a system to handle customer orders in geographically different areas, by taking into account the capacity of the manufacturing factories, the schedule and tariff payment, with the overall objective of reducing the costs associated with the transportation, the manufacturing process, stock, early delivery, and late delivery. Mak's work has considered the global manufacturing scenario. However, the manufacturing plant concerned is not organised under the virtual enterprise principle. Tabucanon et al. [11] proposed an approach to the design and development of an intelligent decision-support system for selecting a machine for a flexible manufacturing system. Their method is relevant to this research project. In their approach, the analytic hierarchy process (AHP) and rule-based techniques were applied for multicriteria decision-making in machine selection. A "best" machine can be selected from several potential ones. Tabucanon's work is limited to machine selection, but the VE concept has not been involved.

Ping et al. [12] proposed a framework for an automatic configuration design system, in which the product design activity is represented by configuration design and product data is expressed in STEP format so that a designer can collect mechanical parts from different factories through the network. When designing a new product, the user sends design requirements into the system and the system responds with the required components, by retrieving from the component database in which components have previously been classified and stored. Ping's method can be used directly in the VE scenario. However, the partner synthesis issue has not been directly considered.

From this review, it can be seen that product design and partner synthesis are two important activities for the VE. Current work involves either product design or partner synthesis but has not successfully integrated the two. The combination of these two activities has the potential to improve the partner selection greatly and to lead to better designs from the viewpoint of "design for partnership".

3. The Partner Selection Process

Normally in traditional enterprises, the approach for selecting partner factories is quite cumbersome. First of all, the master company has to find some candidate factories through business relationships or friendly recommendations, and then obtain information from these factories by means of telephone or fax. After initial filtration, some interested factories are left, and the master company will send managers and technicians to these interested partners to investigate on site. After obtaining detailed information and direct impressions, the master company will negotiate with the most promising ones, and finally select the most satisfactory factory and enter into a contract with it. This selection process is very time-consuming and has some critical drawbacks. First, by using traditional methods and communication tools, only a small number of all available partners are reached by the master company. This may not lead to an optimal global selection. Secondly, owing to the lack of a systematic selection approach and the inability to quantify intangible factors, cost has been seen as the safest and the most uncontroversial factor in partner selection. Other factors which may sometimes prove to be important are ignored. Thirdly, partner selection is separated from product design, which may cause more repeated design. A systematic partner selection approach is necessary to help the master company qualify partners by consideration of both tangible and intangible factors.

4. Proposed Approach

Under the VE concept, partner selection is strongly coupled with product design. For this reason, we propose an integrated product design and partner synthesis process model for VE as shown in Fig. 1. In this model, product design and partner synthesis are totally integrated. The distinction between these two types of activity is somewhat blurred, e.g. product component selection and partner type synthesis are carried out simultaneously in the same phase.

Product design activities, based on general design theory [13], are divided into four phases: product requirement analysis, product function design, product layout design and components selection. Product requirement analysis is necessary to analyse, clarify, and define the requirements that the final design has to fulfil. The result is a detailed product requirement (including lead time, cost, quality, quantity, and other constraints) for the product to be designed. Product function design decomposes the overall function of the product to be designed into several subfunctions. The arrangement of the individual functions or the relationships between the overall function and the subfunctions can be expressed with the help of the function structure. In product layout design, some principal solutions are selected from a solution database to match these subfunctions, and then these principal solutions are divided into realisable components or assemblies. These components or assemblies, together with their links (interfaces), form the product layout that is normally represented by a scale drawing in which only component type and parameter value intervals are determined. The final component and its parameter values will be determined in the components selection phase, (or partner type synthesis phase) that will be discussed in the following.

To reduce the complexity of the problem, we divide partner synthesis into two phases: partner type synthesis and partner instance synthesis. These two kinds of synthesis are explained by Li et al. [14] through the following examples:

1. For partner type synthesis, a decision that we often make in the product design process: e.g. "We need a partner company which can produce a telephone handset." (In the case of telephone product development.)

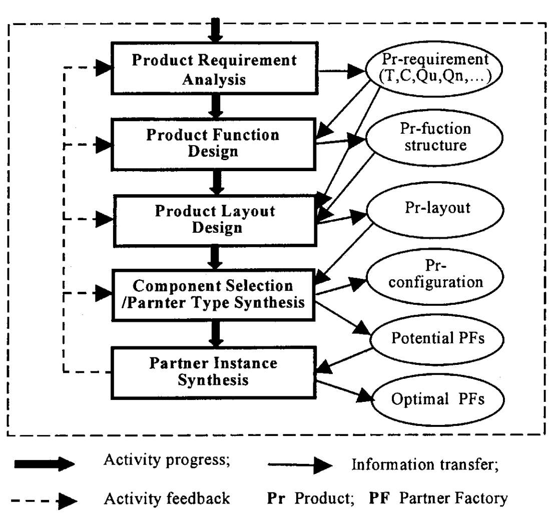

Fig. 1. Integrated product design and partner synthesis process model.

2. For partner instance synthesis, a decision that we often make in product design process: e.g. "There are *n* companies which can produce a telephone handset. We decide to choose company *i*."

In the partner type synthesis phase, apart from the selection of product components, a group of potential partners that can produce these types of components are also determined by using GT technology. In the partner instance synthesis phase, factors other than cost are identified, and such factors are of both tangible and intangible types, e.g. time, quality, and customer service, etc. Thus, this problem becomes a multiple-attribute decision making (MADM) problem. A selected MADM theory, i.e. analytic hierarchary process (AHP), is proposed to determine the best partner from those derived from the partner type synthesis.

Activity feedback has two meanings. First, the feedback from the partner type synthesis to the product layout design or the preceding activities may imply that a prescribed product structure cannot be implemented using the current state-of-the-art of manufacturing technology adopted by any partner factories. There is therefore a request for a modification of a preceding decision on the product structure. Secondly, the feedback from the partner instance synthesis to the partner type synthesis or preceding activities may imply that no partner factory can be found which is commited to the production or delivery of a portion of the product owing to the limits of time, quality, quantity, or cost. This calls for re-activating the type synthesis or the preceding activities. The presence of the activity feedback implies that a concurrent decision process may be needed in pursuance of the global optimisation of a VE system design.

5. System Architecture

Under the methodology aforementioned, we propose an architecture for a computer-aided product design and partner synthesis system for VE (CAPDPS) as shown in Fig. 2, which contains five function modules, and a knowledge base and partners' databases.

The product design module provides the designer with a platform, on which a designer can perform the requirement analysis, the product function design and the layout design with the support of the knowledge base and partners' databases. In the partner synthesis module, the designer selects the component and potential partner factories by using the GT code, and finds the best partner factory for each component by means of the AHP method. The man–machine interface gives the designer a user-friendly interface which interprets the user's commands and displays the intermidiate or final results from the system in human-readable formats. Knowledge acquisition and maintenance tools are employed by the system expert to create and maintain the knowledge stored in the knowledge base. The knowledge base contains (i) knowledge about the product design and the partner synthesis, e.g. the rules for decomposing the product function and matching these functions against principal solutions, the rules for selecting partner synthesis criteria and the criteria weighting methods, (ii) algor-

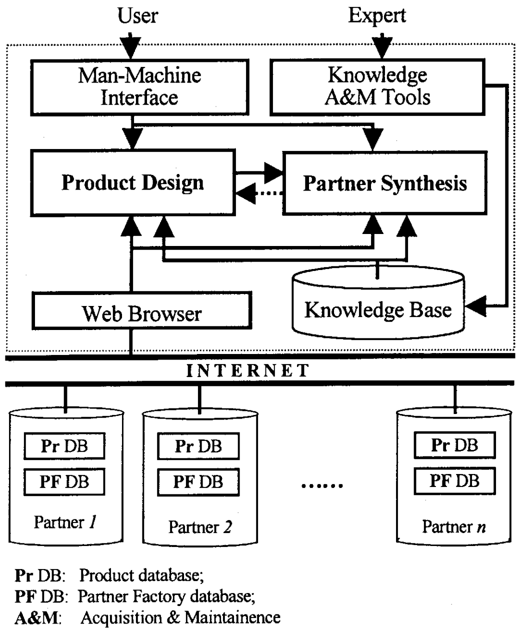

Fig. 2. Architecture of CAPDPS.

ithms, e.g. geometric means algorithm for calculating weights of the criteria. The Web browser is used for browsing, retrieving, and selecting data concerning the product and partner factories from the partners' databases distributed through the Internet. The partners' databases are of two kinds: product database and partner database. The product database stores the detailed information of products that are expressed in STEP format. The partner database contains some information about the factory business, such as factory production capability, track record, types of product that could be delivered, quality, cost and time to delivery, etc.

In the rest of this paper, we will concentrate on the partner synthesis as well as the respective data models. A specific automobile manufacturing group (including the master company and its partner factories) and its typical product – automobile steering assembly – will be used as a case to verify the feasibility of the proposed approach.

5.1 Product Data Model

Two types of product data are critical within the VE environment. Standardised models of part designs, such as STEP, allow firms and suppliers to represent, express, and exchange all useful product information. Furthermore, concise product descriptors, such as GT codes, allow firms to search for and retrieve similar product designs efficiently [5].

STEP is an international standard which provides a complete representation of product data throughout the life cycle of a product. Different STEP models are included within ISO 10303 for the representation and exchange of product data, such as recourse models and application protocols (AP). These models are developed in a formal data specification language called EXPRESS (ISO 10303–11). Each consists of a number of entities whose attributes and relationships describe some portion of the product data. In our work, based on recourse and application protocols, a product data schema model of an automobile steering system is formed and expressed by EXPRESS. Owing to the object-oriented features of EXPRESS, the schema models preserve extensibility and modularity ability, and new types or similar product types are formed by referencing the related schema. Product data are exchanged between the master company and partner factories by means of a neutral file.

Group technology is a manufacturing philosophy that exploits similarities in the design and manufacturing attributes of products. It allows a designer to search for parts which are similar to a candidate design. The implementation of group technology depends upon the GT code, which is a sequence of alphanumeric characters which describe important part attributes. GT coding schemes for mechanical parts include MICLASS and Opitz. These schemes capture critical part characteristics such as main shape, machined feature description, machined feature orientation, dimensions, dimensional accuracy, material and company-specific information such as lot size and raw material shape. For the automobile steering system, we have established a GT coding schema which can describe important attributes of the product.

5.2 Partner Factory Data Model

The partner factory business information such as types of products that could be delivered, quality, capacity, cost, time, and software and hardware production facilities, should be made available through the Internet to increase an individual factory's business opportunities. For each particular factory which adopts the VE concept in its business, a partner factory database must be built. A conceptual model for this database has been proposed by Zhang (see [6] for a more detailed discussion). This model strategically structures the data, focusing on those assemblies and parts related to particular products that a business entity (factory) may deliver. This database aids the type and instance synthesis process in such a way that all relevant partner factories with a particular part stored in the product database can be retrieved straightforwardly, together with detailed production information. With some selection criteria given, the best partner factory can thus be determined.

5.3 Partner Type Synthesis

The flow of partner type synthesis is shown in Fig. 3. Input to partner type synthesis is the result of product layout design, namely, the components file and their assembly relationships file. Partner type synthesis is a two-stage process. Stage 1 requires knowledge about the product catalogue for selecting possible components and their potential partners by matching the component type against the product type in the vendors' (or partners') product databases distributed through the Internet. Stage 2 checks the constraints among all selected components according to their assembly relationships. If there is a conflict, one or more components should be reselected. After these two stages, a final product configuration and their potential partner

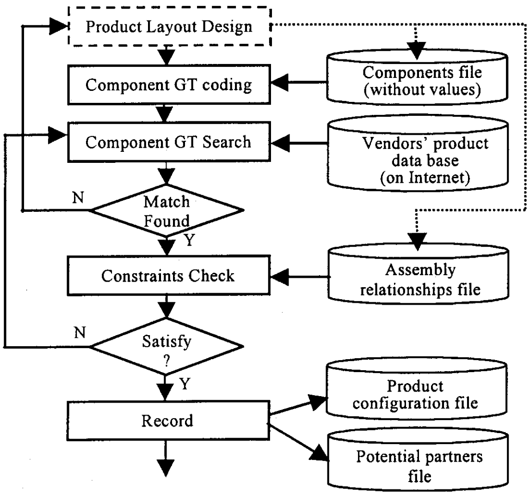

Fig. 3. Partner type synthesis process.

factories are determined. The final partner factories will be determined in the partner instance synthesis phase.

5.3.1 Stage 1. Component GT Search

Before GT component search, a GT code should be assigned to each component from the component file. This task, in our project, is now performed by a human interactively, in accordance with the GT classification and coding system specially designed for the automobile steering system. The GT search, through the Internet, compares the GT code of the component to be designed, with the GT code of products stored in every vendor's product database. If there is a match, there is one (or more) partner factory that can produce this kind of component. If there is no match, with the current state-of-the-art of manufacturing technology, this kind of component cannot be produced by any of the partner factories. Thus, a request for modification of the product layout is fed back to the designer.

5.3.2 Stage 2. Constraints Check

Assembly relationships from the product layout design phase can be expressed by means of a group of constraint equations. Variables in these equations stand for the parameters of different components selected in stage 1. The constraint equations should be satisfied so that the assembly relationships among these components can be guaranteed. A constraints check program has been developed to check whether these equations are satisfied by inputting component parameters. If the equations are not satisfied, one or more components should be reselected in stage 1. If all the equation are satisfied, all these components and corresponding partner factories are stored in two files, respectively: the product configuration file and the potential partner factories file. The latter will be used in partner instance synthesis to determine optimally the final partner factories.

5.4 Partner Instance Synthesis

Partner instance synthesis is required only if partner type synthesis leads to more than one partner factory for each component. The flow of partner instance synthesis is shown in Fig. 4. In this phase, AHP is applied to the selected partner factories to result in a "best partner" for each component. This phase uses the knowledge of experts and the user's preference and judgement. An important feature of this phase is that it could be applied to the selection of any type of partner factory with little modification.

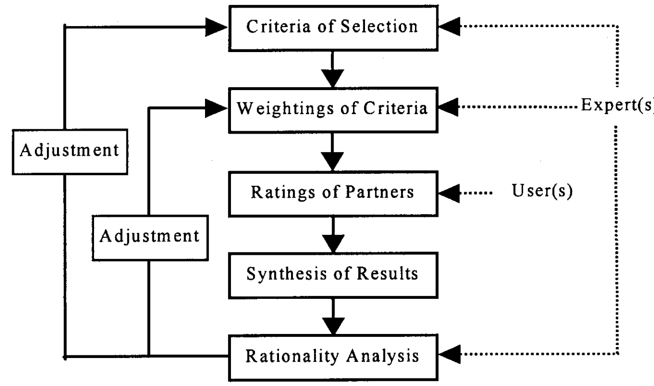

Fig. 4. Partner instance synthesis process.

5.4.1 The Criteria for Partner Selection

The partner selection problem is decomposed in a hierarchy, shown in Fig. 5. The criteria and their levels were obtained from a consensus of experts. Level 1 contains the overall goal, level 2 consists of five main criteria, and level 3 consists of alternatives. The main criteria are cost, time, quality, customer service, and financial stability.

The criterion "cost" is determined by the price asked for by a potential partner factory, which may be composed of manufacturing cost and transportation cost.

The criterion "time" of a partner factory can be justified by the "delivery lead time" (DLT), since DLT of a part will severely affect the production schedule of the master company. We propose to determine each partner factory's time criterion as: $TC = Dx + Dy$, where Dx is the previous actual delivery record of a partner factory, for the part concerned, and Dy is the time offered by the partner factory. TC is related to DLT.

The criterion "quality" of a partner factory can be justified by the "history" of that factory, that is, the previous record of the factory's performance associated with a particular part

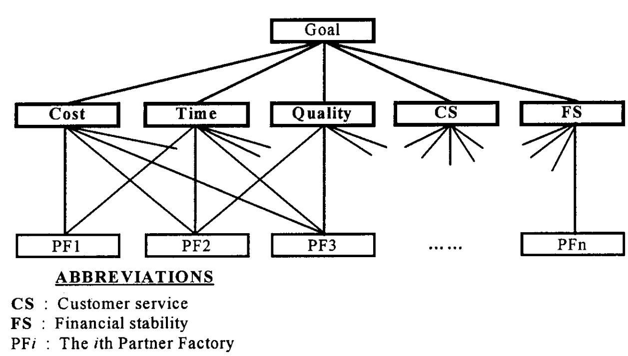

Fig. 5. Hierarchy of partners selection problem in AHP.

which is of interest to the master company. We use the percentage of defective parts in several previous deliveries as an index to evaluate the quality of the partner company, for which a statistical analysis method is employed.

The criterion "customer service" of a partner factory can be measured by the following factors:

1. Delivery delay rate.
2. Average delivery delay time.
3. Average response time to customer inquiry.
4. Time for repairing a product.

The criterion "financial stability" of a partner factory can be described simply by the average percentage profit increase over the last three years, $FS' = \Sigma fs_i/3$, where, fs_i is the percentage profit increase of the ith year. In order to be consistent with other criteria, set $FS = 1/FS'$.

There are two kinds of criteria: objective and subjective. Objective criteria are those that can be modelled mathematically, and those that cannot are treated as subjective criteria. There are cases in which the method of measurement for some of the criteria is stated mathematically (for definition purposes), but the criterion is treated subjectively because of unavailable data, e.g. some " history data" of a partner factory.

It is noted that according to the AHP theory, the criterion values must be normalised to avoid some potential computational problems inherent to the presence of different units associated with the criteria. A method called linear normalisation [15] is chosen.

5.4.2 Weighting of Criteria

The role of weightings serves to express the importance of each attribute relative to the others. Hence, the assignment of weightings plays a key role in the MADM process and may vary from user to user. Weightings should, of course, reflect the purpose of the evaluation. Moreover, the weightings themselves are useful information and are knowledge features. Ranking n criteria at the same time may place a heavy cognitive burden on the user and needs "expertise" knowledge. Therefore, a method by which a complete ranking can be obtained from a set of pairwise judgements is the preferred approach [15] in this paper. The pairwise judgement data are stored in a matrix that is used as an input to a program to calculate the weightings of criteria by using the geometric means approximation method [15].

5.4.3 Rating of Partner Factories

The user may rate "suitable partner factories" on the basis of different criteria. For those criteria defined mathematically, equation calculations are carried out for the determination of the contribution of each alternative. For subjective criteria or for objective criteria in the absence of the required data, a convenient scale is chosen, e.g. a scale of 1–9 (a rating of 1 means the worst while a rating of 9 means the best among the alternatives). Using his judgements and needs, as well as knowledge of partner factory features, the user will rate the partner factories relatively. If the user feels that a criterion is unimportant for his case, he can show no perference (in which case default ratings are used, treating each alternative partner factory the same) or give equal ratings to all alternative partners. The definition and measurement method for the user is the same as for the experts so that uniformity of definition is maintained. This is where the user is expected to use his "expertise" in rating the partner factories. The relative contributions among all the alternatives for every criterion are stored in pairwise comparison matrices.

5.4.4 Synthesis of Results

After inputting weight matrices and comparison matrices at level 3, the system will compute the contribution of each alternative to the overall goal by aggregating the resulting weightings vertically. The overall priority for each alternative is obtained by summing the product of the criteria weight and the contribution of the alternative, with respect to that criterion. The optimal partner factory can then be deduced.

5.4.5 Rationality Analysis on Results

An analysis on the rationality of the results can be carried out by comparing the decision made by the experienced expert with that made by the system. The analysis results can be used as feedback for improving the performance of the system by means of adjustment of the weights and criteria.

6. Test Results

Using the architecture of the CAPDPS system, the partner synthesis module as well as the respective databases have been implemented with Microsoft VB and ACCESS. A specific automobile manufacturing group (including a master company and its partner factories) together with its typical product – an automobile steering shaft assembly as shown in Fig. 6 – is chosen for this case study. The sample product consists of several components, e.g. steering shaft, steering wheel, universal joint, and combination switch, which are made in different partner factories. According to the methodology proposed in this paper, partner synthesis starts with the end of product layout design. Table 1 shows part of the results of layout design which contains a list of components with their name, parameters, and GT code that are added by the designer interactively. In the partner type synthesis phase, a search

Table 1. Components list.

Number	GT code	Name	Parameters
1	520401	Steering shaft	D_1^1, D_2^1, D_3^1, D_4^1, D_5^1, D_6^1, R_1^1, L_1^1
2	520012	Steering wheel	D_1^2, D_2^2, B_1^2, B_2^2
3	520220	Universal joint	D_1^3, R_1^3, D_2^3, D_3^3
4	520311	Combination switch	D_1^4, L_1^4, L_2^4
5	520110	Steering column	D_1^{10}, D_2^{10}, L_1^{10}
6	012000	Bearing	D_1^5, D_2^5, B_1^5
7	012000	Bearing	D_1^6, D_2^6, B_1^6
8	021100	Nut	D_1^7, E_1^7
9	041000	Snap ring	D_1^8, D_2^8, H_1^8
10	041000	Snap ring	D_1^9, D_2^9, H_1^9

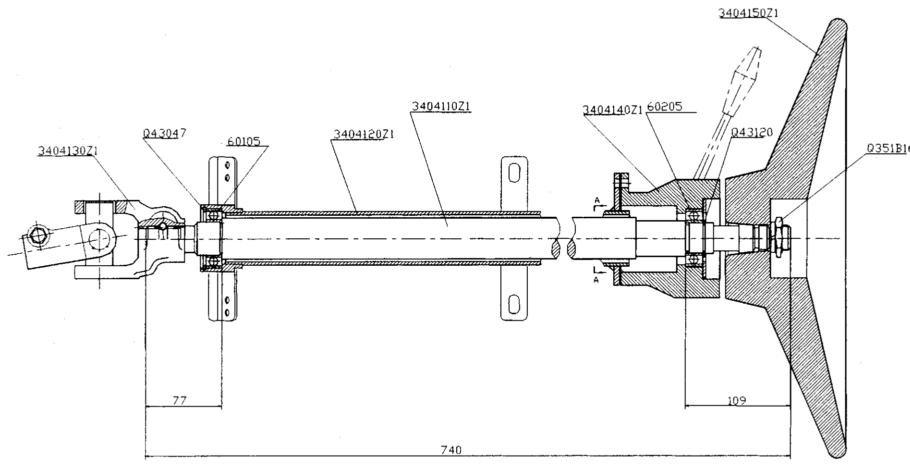

Fig. 6. The layout drawing of a steering shaft assembly.

Table 2. GT search result for component "Universal joint".

Number	ID code	GT code	Name	Parameters	Partner ID codes
1	3404130Z1	520220	Universal joint	$D_1 = 14$; $R_1 = 8$; . . .	101; 102; 105; 107; 110;
2	3404130Z2	520220	Universal joint	$D_1 = 16$; $R_1 = 8.5$; . . .	101; 102; 105; 107;
3	3404130Z3	520220	Universal joint	$D_1 = 20$; $R_1 = 10$; . . .	101; 102; 103;
4	3404130Z4	520220	Universal joint	$D_1 = 22$; $R_1 = 10$; . . .	102; 103; 104; 110;
5	3404130Z5	520220	Universal joint	$D_1 = 24$; $R_1 = 12$; . . .	105; 107;

program is first triggered, in which the GT code of every component listed in Table 1 is compared with the GT code of products stored in every vendor's product database distributed through the Internet. One of the results of the search is shown in Table 2 for the component "Universal joint". In this table, five universal joints, with the same type (GT code) but different parameter values, have been found. Each of them can be produced or delivered by several different partner factories which are identified by their ID codes listed in Table 2. From these five components, the designer could select one as a candidate. In this case, the universal joint with IDcode = 3404130Z2 is selected. For other components listed in Table 1, the search process is the same. The next step in the partner type synthesis phase is to check all the constraints expressed by a group of equations, as shown in Fig. 7 in this case. A VB program has been developed to check whether all these constraint equations are satisfied. If they are not, one or

$$\begin{cases} D_1^1 = D_1^3 \\ D_2^1 = D_1^5 \\ D_3^1 = D_1^6 \\ D_4^1 = D_1^2 \\ D_5^1 = D_1^7 \\ D_6^1 + 3 <= D_1^{10} \\ D_2^6 = D_1^4 \\ \cdot \\ \cdot \\ \cdot \end{cases}$$

Fig. 7. Constraint equations.

Table 3. Weights of criteria.

Cost	Time	Quality	CS	FS
0.385	0.234	0.169	0.148	0.064

more of the components will be reselected until all these constraint equations are satisfied. In the partner instance synthesis phase, taking the universal joint (ID code = 3404130Z2) and its alternative partner factories (ID code = 101, 102, 105, 107) as an example, the designer first determines the weightings of the criteria, as shown in Table 3, by a pairwise judgement method, and rates each alternative partner factory with respect to the different criteria. Table 4 shows the contributions of the four alternative partner factories to the different criteria. The last step in partner instance synthesis is to compute the contribution of each alternative to the overall goal by summing the

Table 4. Contributions of alternative partner factories on different criteria.

Partner factories (ID Code)	Cost	Time	Quality	CS	FS
101	0.232	0.287	0.262	0.231	0.241
102	0.275	0.277	0.271	0.296	0.256
105	0.221	0.211	0.254	0.212	0.266
107	0.272	0.225	0.213	0.261	0.237

product of the criteria weights and the contributions of the alternatives. In this case, the overall contributions are 0.250368, 0.276684, 0.225785, and 0.247163, respectively, for partner factories 101, 102, 105, and 107, Hence, partner factory 105 is selected as the most "satisfactory" partner for the universal joint (ID code = 3404130Z2) component.

The other nine components in Table 1 go through similar processes for selecting their partner factories. Verification is made by comparing the decisions made by an experienced designer with those made by the system for these 10 components, in which 7 are in agreement and 3 are not. A closer examination of these 3 failure cases reveals that:

1. The proper experience and knowledge on criteria weighting and partners rating are still important for obtaining the correct results.
2. Taking more criteria into consideration and accumulating correct "history data" of the partner factory can further improve the performance of the system.

7. Conclusions

The VE concept is one of the most important ways to raise the agility and competitiveness of a manufacturing enterprise. In this paper, after illustrating definitions, we identify the characteristics of VEs, which show that product design and partner synthesis are two important activities for the VE, and these two activities should be strongly coupled with each other. Based on this, we propose an integrated product design and partner synthesis process model, and develop the architecture of a computer-aided product design and partner synthesis system for the VE (CAPDPS), in which the partner synthesis module and the respective databases are both implemented.

Product data and partner factory data are two important types of data for supporting partner synthesis. Concerning product data, STEP has been proposed as a standardised model for representing and exchanging useful product information among factories. The GT code, as a concise product description, is employed for classifying and retrieving product design efficiently. For partner factory data, a conceptual model is proposed, which describes the cost, time, and the types of products the factory can deliver, as well as other general information concerning the partner factory.

For reducing the complexity of the whole problem, we divide the partner synthesis activity into two phases: partner type synthesis and partner instance synthesis. In the partner type synthesis phase, GT is applied for retrieving and selecting potential partners. In the partner instance synthesis phase, more factors other than the cost have been identified, and the AHP method is employed to find the best partner from the potential partners.

The test results show a basic agreement between the system and the experienced designer. In addition, the decision framework and approach employed in this research is generic and could be used for other types of products and factories when different types of partners are added onto the Internet. The performance of the system could be further improved by taking more criteria into consideration and accumulating correct "history data" of the partner factories.

Acknowledgments

The research reported in this article has been jointly supported by the CityU Strategic Research Grant (Grant no. 7000890), the National Natural Science Foundation of China (Grant no. 59775079) and the High Technology Research and Development Program of China (Grant no. 863–511–707–005).

References

1. Mark Davis and David O'Sullivan, "Systems design framework for the extended enterprise", Journal of Production Planning and Control, 10(1), pp. 3–18, 1999.
2. NIIIP, The NIIIP Reference Architecture, www.niiip.org, 1996.
3. J. Walton and L. Whicker, "Virtual enterprise: myth and reality", Journal of Control, pp. 22–25, 1996.
4. Liugen Song and Rakesh Nagi, "Design and implementation of a virtual information system for agile manufacturing", IIE Transactions, **29**, pp. 839–857, 1997.
5. Arun Candadai et al. "Information needs in agile manufacturing", Proceedings of Engineering Database, ASME, pp. 101–108, 1994.
6. W. J. Zhang, "Methodology for designing a conceptual database system to support partner synthesis in virtual enterprises", The Proceedings of the 3rd CIRP Workshop on Design and Implementation of Intelligent Manufacturing System (IMS), Japan, pp. 137–144, 1996.
7. W. J. Zhang, X. Liu and C. A. Van Luttervelt, "On the proposal of a new theory, methodology and computer aided for virtual enterprises manufacturing systems design – in relation to partner factories selection", Proceedings of International Conference of World Manufacturing Congress'97, New Zealand, pp. 61–66, 1997.
8. Ye Qin et al. "Agile-manufacturing-oriented reengineering of enterprise organization", Proceedings of CIRP Symposium'97 vol. 2 (ISBN: 9624421080), Hong Kong, pp. 468–474, August 1997.
9. G. Halevi, "Global optimization of the manufacturing process", Proceedings of CIRP Symposium'97, vol. 2 (ISBN: 9624421080), Hong Kong, pp. 365–372, August 1997.
10. K. L. Mak et al. "Genetic design of integrated production–inventory–distribution system for global manufacturing", Proceedings of CIRP Symposium'97, vol. 2 (ISBN: 9624421080), Hong Kong, pp. 373–380, August 1997.
11. Mario T. Tabucanon, Dentcho N. Batanov and Devendra K. Verma, "Decision support system for multicriteria machine selection for flexible manufacturing systems", Computers in Industry, 25, pp. 131–143, 1994.
12. Yichao Ping and Chouyeh Shen, "A framework of the STEP-based automatic configuration design system", Proceedings of CIRP Symposium'97, vol. 2 (ISBN: 9624421080), Hong Kong, pp. 490–496, August 1997.
13. H. Yoshikawa, "Design philosophy: the state of the art", Annals CIRP, 38(2), pp. 579–586, 1989.
14. Q. Li et al. "Partnership in virtual company: synthesis methodology", Research project proposal, 1997.
15. Yoon K. Paul and Hwang Ching-Lai, "Multiple attributes decision making an introduction", Sage and International Educational and Professional, London, 1995.