A supply-chain-oriented business process reengineering strategy for on-demand new product development

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Abstract: Various strategies of Business Process Reengineering (BPR) have been developed to improve companies’ entire business process. From a more systematic viewpoint, these systems should be further organised under a unified value-added process, which covers all activities of a supply chain. Based on this understanding, a so-called business process reengineering system (BPRS) was proposed and developed. The BPRS consists of three modules, viz. product conceptualisation module using general sorting and repertory grids, supply chain formation module using the Hopfield neural network, and BPR decision-making module using a location-capacity-based strategy. A case study on cellular phone design was used for system validation.

Keywords: BPR; business process reengineering; supply-chain management; on-demand product conceptualisation; general sorting; repertory grids; Hopfield neural network.


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1 Introduction

In today’s globalised knowledge-based economy, many companies are setting up operations by employing advanced manufacturing technologies to retain competitiveness against their local or international competitors. According to the survey conducted by British Department of Trade and Industry (DTI), companies need to move up the value chain to integrate Computer Numerical Control (CNC), robotics, Flexible Manufacturing Systems (FMS) and computerised management systems in response to this change (Timings and Wilkinson, 2003). In this regard, researchers have attempted their efforts on various approaches, such as reconfigurable manufacturing systems, bottleneck allocation methodology, unified modelling language, open controller architecture, manufacturing cell formation, operation sequencing and tool selection, rapid prototyping, and internet-based information sharing/visualisation (Mehrabi et al., 2000; Plenert, 2000; Bruccoleri et al., 2003; Li et al., 2004; Gancalves and Resende, 2004; Shakeri, 2004; Lan et al., 2004; Zhang et al., 2004). Most of these approaches concentrated on technological perspective of computer-integrated software or hardware.

For manufacturing systems, the ability to react to continuous and unexpected changes in external environment is essential for their market success. Accordingly, companies are driven by shorter time-to-market, higher delivery reliability and cost-efficiency, and more product variety. As a result, a number of innovative activities have been undertaken to optimise manufacturing processes. More specifically, manufacturing cost and cycle time, process planning and scheduling, manufacturing complexity and variety, manufacturing flexibility, manufacturing uncertainty, and constraint-based manufacturing optimisation are typical approaches (Locascio, 2000; Tan and Khoshnevis, 2000; Fujimoto and Ahmed, 2003; Zukin and Dulcol, 2000; Kara and Kayis, 2004; Ioanidis et al., 2004). Hence, it is no longer valid to focus on a single or relatively narrow scope so as to cope with today’s economic challenges. The competition edges for product development have changed tremendously over the past two decades. Several concepts, such as Virtual Enterprise (VE), Customer Relationship Management (CRM), Enterprise Resource Planning (ERP) (Gou et al., 2003; Colombo and Francalanci, 2004; Holsapple and Sena, 2004), have been deployed to incorporate internal and external perspectives as a whole, the external forces of which can assist companies in cohesively cooperating with their suppliers and customers.

Amongst these concepts, a strategy of Business Process Reengineering (BPR) was developed to improve the company’s entire business process in terms of quality, cost, service, lead-time, outcome, flexibility and innovation (Kalpic and Bernus, 2002; Grigori et al., 2004).

Some approaches to BPR were focused on technological perspective, e.g., knowledge management, data mining, groupware, and electronic commerce (Hyun and Kyu, 2000; Kim et al., 2003; Dennis et al., 2003; Hanappi and Kump, 2003). On the other hand, it is equivalently crucial to build up an effective BPR strategy under a uniform framework. Therefore, Kim et al. (2002) developed an iterative algorithm to help manufacturer solve its supply configuration problem. The algorithm takes into account such factors as market demand uncertainty, costs and product characteristics (Kim et al., 2002). To handle such information as customer requirements, business strategies, development projects and idea generation, O’ Sullivan (2002) presented an information architecture and relevant toolset for understanding and managing the process of business development. Vasara et al. (2003) described a fusion of traditional Social Network Analysis (SNA) methods with business strategies in the context of a wider methodology for strategic network analysis. Chouinard et al. (2005) proposed a reverse logistics strategy to recover and process the unused products and redistribute the reusable materials. Nonetheless, from a more systematic viewpoint, these systems should be further organised under a unified value-added process or network, which includes all activities of a supply chain.

For this purpose, a clustered supply chain was investigated to support a heterarchical network of companies and their customers (Frayret et al., 2001). In general, Supply Chain Management (SCM) can be treated as an inter-organisational handling of material flow and value-added chain. Recently, a reference model for SCM was developed by American Supply Chain Council (ASCC), and frequently utilised in academia and industry (Supply-Chain Council, 2001). Intensive research has been focused on supplier selection on the basis of manufacturing issues or logistical processes (Hvolby and Trienekens, 2002; Kreng and Wang, 2005; Govil, 2002; Terzi and Cavallieri, 2004). Hence, various partners rather than manufacturing or logistics service providers frequently exist in a supply chain nowadays. Accordingly, Kärkkäinen et al. (2003) combined product customisation with the quantity and specificity of product-related information for short-term yet complex supply networks. Trappey and Trappey (2004) integrated diverse technologies and methodologies into a Global
Content Management (GCM) services platform, which defines a neutral product content representation for supply-chain purchasing. Yan et al. (2006) incorporated a bidding process into new product development, in which customer requirements were treated as the starting point of a supply-chain formation.

Although SCM has gained increasing attention and numerous problems have been identified and dealt with, there is a lack of systematic approach to tackle these problems at a system level. A supply chain can be viewed as a network of partners, including but not solely restricted to, the suppliers, manufacturers, distributors, retailers, and end customers (Kärkkäinen, 2003). If only partial correlations amongst them are solved like inventory level and production planning, the performance of the whole system is not guaranteed acceptable. Thus, each participant has to process different tasks individually to satisfy the total cost or lead-time of a set of products. In this regard, Chan and Chan (2004) proposed a conception of lean supply chain that could provide a demanding service level at the lowest cost to maximise the value chain amongst participants. Further studied, Chen and Larbani (2005) suggested that the maximum global benefits might be obtained only when all partners formed a seamless alliance, yet the inefficient partners lost significantly in such a union. However, the following issues remain problematic.

- Lack of a systematic approach to comprehensively handle the BPR under a unified supply-chain framework.
- Little research has dealt with uncertainty, ambiguity and variability in supply-chain management effectively.
- The cohesively interacting activities throughout a supply chain have not been effectively integrated with new product development, especially the product conceptualisation stage.
- The factors of partners in a supply chain, e.g., cost, delivery time, competence, location and capacity, have not been well addressed and coordinated.

Based on this understanding, in this work, a so-called Business Process Reengineering System (BPRS) was proposed and developed. The BPRS consists of three modules, viz. a product conceptualisation module, a supply chain formation module, and a BPR decision-making module. Two well-established requirements acquisition techniques, general sorting and repertory grids, were employed and adapted for generating an initial product platform and partner selection criteria, respectively. Based on the initial product platform, a number of initial design options were typically generated. According to each typical design option, partners were preliminarily selected in terms of cost, delivery time and competence using the Hopfield neural network. Consequently, BPR decisions were made based on a location-capacity-based strategy to finalise both product conceptualisation and supply-chain formation. A case study on cellular phone design was used for system validation.

2 Structure of the proposed BPRS

Indisputably, the product conceptualisation stage has a critical impact on the supply chain of a product. It can provide a large number of benefits to a company through incorporating supply chain concerns into product concept. Generally, product conceptualisation is a product life stage in which the product development team determines what functional specifications will satisfy various customer requirements and what enabling technologies, e.g., material allocations and manufacturing capacities, are available for this purpose. In making these decisions, the product development team should collaborate with other partners of a supply chain, including the external suppliers of raw materials and components, as well as such internal participants as research and engineering, manufacturing, operations and logistics engineers. These techniques enable a product development team in determining combinations of functional attributes, manufacturing processes and resource capacities to provide a maximal productivity yet minimal investment.

Figure 1 shows a framework of the proposed BPRS. The system consists of three modules, viz. a product conceptualisation module, a supply-chain formation module, and a BPR decision-making module. It aims to formulate a supply chain in the early stage of product conceptualisation for a company so as to:

- make full utilisation of capacities and resources of existing partners by realising optimal or preferred business collaboration
- respond promptly to on-demand customer requirements in terms of product concept generation.

The anticipated primary business scenario is a progressive process, which is postulated to develop an activity-based supply-chain alliance through selecting preferred participants from on-hand partners of a company via a location-capacity-based strategy. Simultaneously, the process involves product concept initialisation and finalisation with considerations of supply-chain issues. Its use at the early stage of product development should allow the companies to: improve time-to-market by concurrently sharing the information and competence from diverse partners; make full use of the specific capacities and resources of individual participants; develop stronger partnerships as an alliance prior to project launch; and obtain better prices and services via preference selection of partners. Perhaps more importantly, it allows partners to achieve greater business collaboration, rather than simply being treated as independent companies.
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Figure 1 Architecture of the BPRS

A critical factor for the incorporation of product conceptualisation and supply-chain formation is timely evaluation, communication and adoption of design and partner selection criteria and decisions. The BPRS implements this by means of the following procedure (Figure 1):

1. Designers build an initial product platform for a specific product using general sorting – a well-structured knowledge acquisition technique. In parallel, partner selection criteria are solicited by domain experts using repertory grids, which are also a knowledge acquisition technique, for a supply-chain formation.

2. Based on the initial product platform, a number of initial design options are typically generated in relation with different market orientations using morphological configuration, i.e., different combinations of functional attributes elicited by the designers.

3. With respect to each typical design option, the on-hand partners, including suppliers, production units, transportation units, storage units and retailers, are preliminarily selected based on the partner selection criteria, which are further evaluated using the Hopfield neural network. This step aims to reduce the number of initial partners by means of classifying them into two groups, i.e., acceptable and unacceptable partners. Partner selection criteria with regard to typical design options are rated by domain experts and used as inputs to the Hopfield neural network; while its outputs help select acceptable partners.

4. Subsequently, various alternatives of the supply chain can be formed based on the acceptable partners selected. Consequently, the BPR decisions are made upon finalising both product conceptualisation and supply-chain formation. In this step, a location-capacity-based strategy is used as the selection index for a final supply chain, which can be thought of as preference partnering of participants selected from the acceptable partners. Meanwhile, the product concept is further finalised according to the actual capacities and resources obtained from partners.

The details of a knowledge-based BPRS are described in the next section, Section 3.

3 A knowledge-based BPRS

In the proposed BPRS, a variety of technologies have been applied to aid product conceptualisation and supply-chain formation. Typical tasks include establishing the product platform, soliciting the partner selection criteria, and making BPR decisions. As there may exist overlapping or conflicting amongst the functional attributes of a product concept and the interacting activities in a supply chain, uncertainty, ambiguity and variability are unavoidable when product concept and supply chain are formed. Accordingly, the BPRS is also established in the form of a unified knowledge-based framework, which spans from knowledge acquisition, representation and evaluation for the purpose of associating both product conceptualisation and supply-chain formation processes dynamically.

3.1 Product platform generation using general sorting

As early-stage design knowledge possesses ambiguous, uncertain and incompleteness yet innovative and subjective nature, possibly semi-tacit or tacit, recent research efforts of knowledge acquisition have focused on soliciting effective knowledge elicitation techniques within a variety of knowledge acquisition scenarios. However, there exist a number of weaknesses whilst using traditional or ‘non-contrived’ knowledge acquisition techniques, e.g., interview, survey, self-report and observation, such as no single standard form and no systematic descriptions about techniques and their use (Rugg and McGeorge, 1999). Maiden and Rugg (1996) distinguished between two major types of knowledge acquisition techniques, viz. ‘contrived’ techniques, e.g., sorting, laddering and repertory grids, and ‘non-contrived’ techniques. It was claimed that the ‘contrived’ type refers to techniques that are not so heavily dependent on natural language dialogue but good at reducing systematic bias, eliciting implicit knowledge, representing declarative as well as procedural knowledge.

Specifically in this study, general sorting, which was derived from Kelly’s personal construct theory
organised into a hierarchical structure or taxonomic tree. Once the terms have been sorted, they are separated by the reasons or criteria by which experts/designers grouped or can be divided any further. The elicitor then determines the terms used for the specific problem.

**STEP 3:** Once the terms have been sorted, they are organised into a hierarchical structure or taxonomic tree. More than one hierarchy may be required if many terms are used for the specific problem.

Based on the design knowledge acquired, the well-established graphical structures, which can deal in depth with formalisms for representing knowledge and relevant relationships, include hierarchies and networks. Amongst them, conjoint analysis and analytic hierarchy process are usually developed based on hierarchical structures (Chen et al., 2005; Yan et al., 2002), whereas Function–Behaviour–Structure (FBS) method and Design Information Framework (DIF) method are frequently deployed using network structures (Gero, 1990; Lim and Sato, 2003). Thus, a simplified process of graph decomposition for product design approaches (Lim and Sato, 2003; Chen and Occeña, 1999) often tends to transform network structure into hierarchical representation because the network structure has exactly the same psychological force as the hierarchy, and can be transformed to the hierarchy or matrix (Novick and Hurley, 2001). Other advantages of employing hierarchical representation for product platform include simple structure, fast recording, and suitable for quantitative reasoning (Yan et al., 2001).

Figure 2 shows the architecture of a generic product platform or design space for establishing the Design Knowledge Hierarchy (DKH) via general sorting technique. The DKH, which organises the designers’ knowledge registered, comes with a four-level top-down designer-directed architecture for decomposing a specific product concept. In this multilevel taxonomy, each category, which is stemmed from the high-level product concept, can be decomposed into several components, and each component contains several parts. Typical design options can be selected from different combinations of part options derived from different parts to form a specific product family.

Product platform significantly affects the entire supply chain in terms of the cost of operation and efficiency. In other words, the specific partners selected and the number of partners involved in a supply chain may influence:

- the amount of time and cost to deliver a product
- the versatility a supply chain can satisfy forecasted customer demands
- the flexibility of the supply-chain formation.

The responsibility of supply-chain managers is to deal with a trade-off between the expected design options, on one hand, and costs and time durations, on the other hand. As such, the preference selection of partners with respect to a specific design option is critical in forming a supply chain. This is because a high-level customer orientation to a specific design option narrows down the number of design options, and pushes directly downstream through a supply chain containing possible combinations of partners involved.

**3.2 Partner selection criteria solicitation using repertory grids**

External issues, which bring about constraints on the capacities of the activities, e.g., unexpected demands, changes in the strategy of competitors and new types of markets, should be precisely identified by a company for its specific supply chain. If some new demands appear, a company has to adjust the constraints upon the major activities of a supply chain, e.g., procurement, manufacturing, inventory, sales and transportation, which are linked with one another together with bespoke external issues. Further studied, each activity in a supply chain is aligned with product conceptualisation cohesively through partner selection criteria. The inheritance of partner selection criteria lead to a general multiple-variants approach by examining the association under multiple, potentially conflicting attributes and resolutions.

However, the desired methods for partner’s behaviour tend to share such characteristics as decomposable, discrete, deterministic, disembodied and linear, while the real world is convoluted in nonlinear, physically constrained and messy situations (Barton, 1999). This may fully or partially be resolved by using such technique as heuristics for
qualitative or quantitative reasoning. Oftentimes, this brings forth a multivariate method to represent these attributes using matrices and further solicit the overlaps and conflicts within them. Amongst the existing research work, Zukin and Dalcol (2000) proposed such criteria as product variety, lead time, cross-functional team and work-in-process inventory. Hyun and Kyu (2000) focused critically on cost, competitor and demand aspects. Chan and Jiang (2001) emphasised issues of business processes and systems, policies and organisational structures. Govil (2002) postulated several factors, e.g., the cost and competence of participants, involved in a supply chain. However, the comprehensiveness of partner selection criteria has not been well addressed.

Previously, the application of different contrived knowledge acquisition techniques in one approach have been attempted, e.g., integration of ladderings and repertory grids and that of sorting and laddering (Yan et al., 2001, 2002). Although general sorting and repertory grids, i.e., ‘contrived’ types, were derived from Kelly’s personal construct theory (Kelly, 1955), there existed some differences (Rugg and McGeorge, 1999). Compared with general sorting, repertory grids are good at capturing knowledge with ordinal representation, e.g., ratings or rankings, and eliciting salient knowledge of domain concepts. In the classic form, the construction of repertory grid technique involves the following steps (McGeorge and Rugg, 1992).

**STEP 1**: Select a group of elements that represent the relevant aspect of the domain under study.

**STEP 2**: Elicit significant constructs through a triadic elicitation method. This involves presenting sets of three elements and asking how two are similar to each other and thus different from the third. This provides one pole of a construct. The other pole is elicited either by asking in what way the third item was different (difference method) or asking what is the opposite of the pole just elicited (opposite method).

**STEP 3**: Evaluate each item in respect of each of the elicited constructs. Frequently, this evaluation takes the form of a rating value. In this way, a grid is constructed in which the sides are formed by the poles of the constructs and the top by the elements, and where the cell values represent the ratings for each item on each construct. Repertory grids generate a map of the concepts that are important to the respondent in understanding the domain.

As a result, the partner selection criteria can be solicited by domain experts. Using repertory grids, a group of criteria, which are strongly related with supply-chain activities, i.e., procurement, manufacturing, transportation, warehousing and sales, are elicited. These criteria include cost, capacity and location aspects, which are correlated with respective participants, i.e., suppliers, production units, transportation units, storage units and retailers. With respect to each criterion, a number of sub-criteria can be further elicited, for example:

- The **cost** criterion includes such sub-criteria as the direct costs, e.g., prices of resources or raw materials, the running costs, e.g., salaries, maintenance and delivery costs, and the incremental costs, e.g., marketing expenses and customer services.
- The **delivery-time** criterion includes such sub-criteria as the time duration a partner finishes its activity, e.g., prepare raw materials or components, and collaborates with other partners, e.g., provide transportation or storage services amongst different partners.
- The **competence** criterion includes such sub-criteria as the capacity of the existing resources, e.g., upper and lower capacity bound, the competence of partners, e.g., quality of resources or raw materials, financial and technical soundness, willingness to participate in a supply chain, and additional services provided.

This assists domain experts in understanding these criteria more comprehensively and facilitates them in weighting or rating the criteria more precisely. After the qualitative reasoning process, the ratings or weightings towards the criteria are constructed with respect to typical design options generated from the DKH described in Section 3.1. As such, an ordinal or a numerical array, instead of a textual or verbatim one, can be used as an input into a quantitative reasoning technique, i.e., Hopfield network, presented in Section 3.3.

### 3.3 Preliminary partner selection using Hopfield neural network

Knowledge acquisition and representation techniques alone are insufficient to handle the concepts that are fuzzy and have no clear-cut boundaries between sets of objects (Rugg and McGeorge, 1999). Although qualitative reasoning provides a global control over feasible directions of variable adjustments, it cannot completely handle the complicated partner selection criteria alone (Yan et al., 2001). Nevertheless, either precise numerical values or fuzzy intervals, e.g. ratings or weightings towards initial design criteria, can be drawn from limited comparison points and intervals, i.e., level, and landmark values, i.e., range, which provides a feasible way to transfer qualitative reasoning into quantitative reasoning process (Kuiipers, 1994). Based on this notion, a combination of qualitative and quantitative methods would be ideal for preliminary partner selection during product conceptualising process. However, multivariate problems pertaining to an integrated view of multi-facet or multi-attribute evaluation results in the complexity of decision-making. Accordingly, the selection of acceptable partners usually brings about ambiguity due to the subjective nature of preferences in decision criteria, such as the partner selection criteria in this study. Furthermore, these criteria contain overlaps and conflicts with one another, and should be taken into account simultaneously. To tackle these
problems, the Hopfield neural network presents a logical alternative.

(i) Algorithm of the Hopfield network

The Hopfield network (Hopfield, 1982), a specialisation of bidirectional associative memory, is a recurrent autoassociative network consisting of a single layer of fully connected processing neurons or elements. In the network, the output units are fed back to the input units using additional feedback connections, viz., recursive interconnections between them. The advantages of Hopfield networks include:

- The Hopfield network is quite a flexible infrastructure that can be applied for either synchronous or asynchronous network, binary, bipolar or other forms of inputs. As such, it avoids the difficulties encountered in propagating synchronisation throughout the large network, and handling partial or corrupted inputs insensitively.

- As the number of possible network states is finite, the outer product of the patterns automatically computes the weights of the Hopfield network without the need for any learning laws. Hence, the Hebbian learning can be used to create the weight matrix in an alternative way.

- The Hopfield network can be transported by bidirectional edges until a stable state through an energy function so as to harness the theoretical complexities, which relieves the need of requiring that each processing element have global knowledge of the entire network at all times.

For the discrete Hopfield network processing, neurons may apply either bipolar (1/-1) or binary (0/1) values. A pattern of N-dimensional discrete values $y_i$ is constituted for the network, which brings about a state vector for the network. The Hopfield network is fully connected in the form that each processing neuron is connected to every other processing neuron (Figure 3). The weights $w_{ij}$ are symmetric, viz., $w_{ij} = w_{ji}$. Thus, there is no self-recurrent connection between a neuron and itself, viz., $w_{ii} = 0$. A discrete Hopfield network can be described as

$$y_i(n+1) = \text{sgn} \left( \sum_{j=1}^{N} w_{ij} y_j(n) - b_i + x_i(n) \right)$$

where $\text{sgn}$ represents the threshold nonlinearity ($-1$, $1$), $b_i$ is a bias, and $n$ is the sequential number of network iterations or epochs. As a bidirectional autoassociative memory, the input $x_i$ is used as an initial condition for network convergence or relaxation, which eventually turns to disappear from equation (1).

The pattern or state of the network is a vector, which is composed of activation levels of the sequentially ordered yet randomly selected processing neurons. These patterns have an associated energy function $E$, i.e., Lyapunov function (Lakshmikantham, 1990), given by

$$E_i = \frac{1}{2} \sum_{j=1}^{N} \sum_{j=1}^{N} w_{ij} y_i y_j - \sum_{j=1}^{N} b_j x_j + \sum_{j=1}^{N} G(y_j) \forall G(y_j)$$

where $w_{ij}$ is the weight from unit $i$ to unit $j$ and $y_i$ is the output of the $i$th unit in the network. It is provided that the symmetry of weight matrix and sufficient steepness of nonlinearity will result in the constant forms of the second and third terms in equation (2). As an iterative network, neurons are permitted to update, one at a time, until convergence occurs. The network is considered to have converged when a minimum of the energy function has been achieved and no individual neuron is motivated to change state while being activated. It is indicated that the Hopfield network will always converge to a state of minimum energy after being updated in the pre-designed manner. Once such a state is achieved, none of the neurons will change their state.

Figure 3 Illustration of the Hopfield network

In general, the energy topology or distribution is a hyperspace where valid states are represented by bipolar or binary state vectors at corners of a hypercube (Li et al., 1989). The discrete Hopfield memory model is conducted by transferring from one corner to another with lower energy, and eventually ends up at a corner with the lowest energy. Since the Hopfield network is an iterative network and only one neuron is updated at a time, it is sufficient to consider the change in energy $\Delta E_i$ resulting from a single-neuron update. Accordingly, it satisfies the following condition based on a single neuron $i$.

$$\Delta E_i = -\frac{1}{2} \Delta y_i S_i \leq 0 \quad \forall S_i = \sum_{j=1}^{N} y_j w_{ij},$$

where a given neuron updating in the Hopfield model can be defined as a stimulus $S_i$ with regard to the $i$th neuron, which is a sum of products of the resulting output $y_i$ and weights $w_{ij}$.
(ii) Specifying the Hopfield network for a pattern association strategy

The Hopfield network has been applied for the combinatorial and optimisation problems even some NP-complete problems, e.g., the massive parallelism and learning complexity in Hopfield models. More specifically in this study, the Hopfield network is specified as a pattern association or classification strategy for preliminary partner selection, the procedure of which is described as the following steps.

**STEP 1: Network training via fix-point learning algorithm**

The number of processing neurons and stable states or attractors is prescribed. Then, a set of output patterns are defined by the bipolar target vectors. More specifically, these vectors are used as the input patterns, \( x^o \), and then converged at a certain output pattern or stable state \( y \), viz., \( y = x^o \) (i.e., the fix-point learning algorithm where \( m \) is the sequential number of stable states).

**STEP 2: Weight matrix acquisition and stability checking**

Meanwhile, these target vectors are used to find the corresponding weight matrix. In other words, the minima of the Hopfield network correspond to a set of target vectors that are memorised by the network. Suppose there are \( m \)-dimensional target vectors for network training, the weights can be obtained according to the following equation:

\[
w_{ij} = \frac{1}{m} \sum_{k=1}^{m} (2x_{ik} - 1)(2x_{jk} - 1) \quad \forall i \neq j, m = 1, 2, ..., M. \tag{4}
\]

Afterwards, the target vectors are validated whether or not they are indeed stable, that is, checked by returning these target vectors into the Hopfield network and subsequently guaranteeing the targets unchanged.

**STEP 3: Network testing and pattern association**

Exemplar inputs are first used for the established Hopfield network testing to make sure that the network finds the closet memory to those inputs, and thereafter ends up in any of the desired target vectors. Consequently, a set of specific inputs is used for network classification, i.e., pattern association. In occasion, undesired equilibria vectors or points may occur because these vectors are unstable in that any noise will move the network out of them.

Up to this point, the decision-making of preliminary partner selection can be determined. Specifically for each existing partner, the rated three-dimensional criteria, i.e., cost, delivery-time and competence, associated with each typical design option are used as an input sample, whereas two stable states of target vectors are pre-defined for pattern association using the Hopfield network. In details, only those inputs, each of which is activated to one of the pre-determined target vector, are identified as acceptable (others are detected as unacceptable) for further BPR decision-making described in Section 3.4. This helps in reducing the total number and keeping the quality of partners involved, implying that the partners chosen for the next-step evaluation should be those primarily satisfying such selection criteria as cost, capacity and location requirements. Thus, coordination amongst these aspects is considered as a preliminary partner selection strategy. Otherwise, even the highest credit of only one aspect could be an astray towards a supply-chain formation.

3.4 BPR decision-making using a location-capacity-based strategy

The BPR decision-making module is involved in both external environment of the proposed system, i.e., supply-chain development with optimally low cost and high speed, and internal environment, i.e., financially preferred product conceptualisation based on partner selection of a supply chain. In this scenario, the final selection of partners is crucial to a supply chain, and consequently determines the success level of a product or service in the context of cost- and time-efficiency, e.g., order fulfilment and time delivery. An accurate evaluation of activity assignment to partner alternatives should be conducted throughout an entire supply chain, whereas there are quite a few options in this case. Before the final selection of a product concept for a specific customer orientation, the financial perspective of a supply chain, i.e., a supply-chain costing and scheduling, can also be completed to sustain a company’s competitive edges against its competitors in terms of supply-chain formation and product conceptualisation.

Dynamic supply-chain job or activity assignment has been shown to be a Non-deterministic Polynomial hard (NP-hard) problem, where a large number of possibilities, e.g., one-to-one, many-to-one, one-to-many and many-to-many relations or distributions between activities, in which activities can be sequenced (Daganzo, 1999). It is also a stochastic and predictive problem for which analytic simulations have often proven to be inferior without major simplifications. Therefore, traditional job assignment or allocation method does not lend itself to a satisfactory mathematical solution, especially for a complex system like a supply chain of realistic scale (Terzi and Cavallieri, 2004). However, to enhance the performance and allow for further development of a supply chain, a simplified activity-assignmen’t strategy for a supply chain should be resolved. Based on the preliminary partner selection, the factors of location together with capacity of acceptable partners are further considered through setting up a clustered supply chain, which aims to reduce geographical obstacles for the purpose of fast distribution and short delivery-time. As such, a so-called location-capacity-based strategy is proposed in this study, and is described as follows.

**STEP 1:** The sum of distances \( D_p \) between an acceptable partner \( p \) and the others \( d_{pq} \) (with totally \( K \) accepted partners) is calculated according to the location factor...
(shown in equation (5)). The preference selection strategy is: the smaller the value, the more the partner is preferred.

\[ D_{pq} = \sum_{q=1}^{K} d_{pq} \quad \forall p \neq q, p = 1, 2, \ldots, K. \]  

**STEP 2**: The activities of a proposed supply chain (including procurement, manufacturing, transportation, warehousing and sales, viz., \( a = 1, 2, \ldots, 5 \)) are sequenced, whereas the partner alternatives considered acceptable from the preliminary partner selection module (including suppliers, production units, transportation units, storage units and retailers, viz., totally \( K \) accepted partners) are then categorised into relevant activities and ranked in an ascending order of distance sum (totally \( T_a \) for each category).

**STEP 3**: With respect to the capacity factors, once the total capacity \( C^r \) of the first \( t^r \) partners, which are sequentially selected from each category, is more than the predicted quantity \( Q^r \) for a certain activity, these partners are finally selected as preferred ones (presented in equation (6)). Here, it is supposed that the number of accepted partners \( T_a \) is enough for establishing a supply chain regarding a specific design option; otherwise, an effective supply chain cannot be formed.

\[ C^r = \sum_{a=1}^{T_a} C^r_a \geq Q^r \quad \forall t^n \leq T^a, a = 1, 2, \ldots, 5. \]  

As a specific design option is derived from a specific target market or customer segment, different preferred partners may be selected. Referring to equation (6), a preferred supply chain can consequently be formed for a typical design option. The preferred product concept can be obtained, which is finalised based on the actual materials and resources provided by those partners.

## 4 A case study on cellular phone design

A case study on cellular phone design was used to illustrate the performance of the proposed prototype BPRS. With competitive business environment in cellular phone marketplace, such creative conceptions as continuously technology-advanced and environment-focused yet cost-low hardware and software are increasingly applied to cellular phone design. In other words, supply-chain adaptation is frequently becoming technological added-values provided for functional diversity, customer satisfaction and environmental responsibility. In this respect, the competition edges will involve fast technological innovations with environmental-friendly functionality and acceptable performance–price-ratio. Accordingly, product life-cycle of cellular phones becomes shorter, which brings about much higher requirements in fast product conceptualisation and accurate customer orientation. Based on this notion, it is imperative and of great significance for organisations to adopt a novel strategy, e.g., BPRS, for facilitating effective product conceptualisation.

In the BPRS, the initial product platform, i.e., DKH, was elicited and recorded by designers. In so doing, a four-level DKH was used for initial product platform formation using general sorting (Figure 4). It was composed of a number of categories, relevant lower-level components and parts. In addition, the initial design options could be chosen from combinations of various part options. Up to this point, design options were typically generated as the initial alternatives. Table 1 lists three example design options.

![Figure 4 Illustration of a DKH for cellular phone design](image-url)
Table 1: Representation of part options and example design options

<table>
<thead>
<tr>
<th>Part option</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card reader</td>
<td>SIM card</td>
<td>SIM card</td>
<td>Green-smart SIM card</td>
</tr>
<tr>
<td>Keypad</td>
<td>General keypad</td>
<td>General keypad</td>
<td>Lock keypad</td>
</tr>
<tr>
<td>Connector</td>
<td>Infra-red connector</td>
<td>Data cable</td>
<td>Blue-tooth connector</td>
</tr>
<tr>
<td>Radio freq.</td>
<td>Dual-band frequency</td>
<td>Dual-band frequency</td>
<td>Dual-band frequency</td>
</tr>
<tr>
<td>Display unit</td>
<td>LCD</td>
<td>LED</td>
<td>LCD</td>
</tr>
<tr>
<td>(De)compressio n</td>
<td>CODEC portion</td>
<td>CODEC portion</td>
<td>CODEC portion</td>
</tr>
<tr>
<td>DSP/Memory</td>
<td>GSM/SMS/GPRS</td>
<td>GSM/SMS</td>
<td>GSM/SMS/GPRS</td>
</tr>
<tr>
<td>Cover/Case</td>
<td>Small</td>
<td>Medium</td>
<td>Small with recycled materials</td>
</tr>
<tr>
<td>Screen</td>
<td>Medium</td>
<td>Medium</td>
<td>Big</td>
</tr>
<tr>
<td>Button</td>
<td>Button</td>
<td>General button</td>
<td>Smart button</td>
</tr>
<tr>
<td>Antenna</td>
<td>Internal antenna</td>
<td>External antenna</td>
<td>Internal antenna</td>
</tr>
<tr>
<td>Screen display</td>
<td>Full colour</td>
<td>General display</td>
<td>High-resolution full colour</td>
</tr>
<tr>
<td>Microphone</td>
<td>Integrated phone</td>
<td>External phone</td>
<td>Internal phone</td>
</tr>
<tr>
<td>Photo sensor</td>
<td>General sensor</td>
<td>Not included</td>
<td>High-resolution sensor</td>
</tr>
<tr>
<td>Voice sensor</td>
<td>General sensor</td>
<td>Not included</td>
<td>High-performance sensor</td>
</tr>
<tr>
<td>Battery/charger</td>
<td>Low-lead battery</td>
<td>High-performance battery</td>
<td>Low-lead high-performance battery</td>
</tr>
<tr>
<td>Carry case</td>
<td>Not included</td>
<td>Not included</td>
<td>Recycled-material case</td>
</tr>
<tr>
<td>Headset</td>
<td>General-material headset</td>
<td>Not included</td>
<td>Recycled-material headset</td>
</tr>
<tr>
<td>Internet</td>
<td>Included</td>
<td>Not included</td>
<td>Included</td>
</tr>
<tr>
<td>Messaging</td>
<td>SMS/MMS</td>
<td>SMS</td>
<td>SMS/MMS</td>
</tr>
<tr>
<td>Game</td>
<td>Included</td>
<td>Included</td>
<td>Included</td>
</tr>
<tr>
<td>Software</td>
<td>TCP/IP</td>
<td>Not included</td>
<td>TCP/IP/Java/DHTML</td>
</tr>
</tbody>
</table>


The partner selection criteria were then solicited by domain experts regarding cost, delivery-time and competence criteria, and thereafter rated by domain experts with regard to each initial design option. Subsequently, the rating values were scaled within a range from −1 to 1, and then employed as the inputs to the Hopfield network for preliminary partner selection. Especially in this study, the inputs associated with one target vector (1, 1, 1) were chosen for the secondary-level decision-making. In contrast, those activated to the other one (−1, −1, −1) were discarded as unsatisfied. Figure 5 presents the results from Hopfield network pattern association (specifically for Design Option 1). In this case, 27 out of 53 existing partners were considered acceptable for the next-step decision-making. This could assist in narrowing down the existing partner number. It was also found that two undesired equilibria vectors or points occurred because these vectors were unstable so that they were unidentified or uncertain in relation with both states.

Figure 5: Results from Hopfield network pattern association (see online version for colours)

Based on the preliminary partner selection, the factors of location together with capacity of acceptable partners are further considered through setting up a clustered supply chain. The sum of distances between an acceptable partner and the others is first calculated and preceded based on the preference selection strategy that the smaller the value, the more the partner is preferred. Figure 6 illustrates a process of BPR decision-making. The activities of a proposed supply chain, including procurement, manufacturing, transportation, warehousing and sales, are sequenced, whereas the partner alternatives considered acceptable from the preliminary partner selection module, including suppliers, production units, transportation units, storage units and retailers, are then categorised into relevant activities and ranked in an ascending order of distance sum. Once the total capacity of the first several partners is more than the predicted quantity for a certain activity, these partners are finally selected as preferred ones. It should be noted that the number of accepted partners is enough for
establishing a supply chain regarding a specific design option; otherwise, an effective supply chain cannot be formed. Table 2 lists the final results of the selected partners. As a specific design option is derived from a specific target market or customer segment, different preferred partners may be selected. A preferred supply chain can consequently be formed for a typical design option. The preferred product concept can be obtained, which is finalised based on the actual materials and resources provided by those partners.

Figure 6 Illustration of BPR decision-making process (see online version for colours)

Table 2 Statistical results of selected and preferred partners

<table>
<thead>
<tr>
<th>Partner</th>
<th>Example design option</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Option 1</td>
<td>Option 2</td>
<td>Option 3</td>
<td></td>
</tr>
<tr>
<td>Supplier</td>
<td>6 (4)</td>
<td>8 (2)</td>
<td>3 (3)</td>
<td></td>
</tr>
<tr>
<td>Production unit</td>
<td>5 (3)</td>
<td>7 (2)</td>
<td>2 (-)</td>
<td></td>
</tr>
<tr>
<td>Transportation unit</td>
<td>5 (4)</td>
<td>5 (2)</td>
<td>5 (3)</td>
<td></td>
</tr>
<tr>
<td>Storage unit</td>
<td>6 (4)</td>
<td>6 (2)</td>
<td>6 (3)</td>
<td></td>
</tr>
<tr>
<td>Retailer</td>
<td>7 (4)</td>
<td>5 (3)</td>
<td>4 (3)</td>
<td></td>
</tr>
</tbody>
</table>

It was observed from Table 2 that:

1. With respect to each design option, various partners might be selected from the existing partners. In addition, different partner numbers were accepted. For example, 29, 31 and 20 partners were selected from 51 existing partners, according to the preliminary partner selection using Hopfield neural network. This implied that the partner selection criteria were rated in different degrees or levels for each design option in terms of diverse part options.

2. Different preferred partners could be selected regarding three design options due to partner capacity and predicted quantity for each design option. For example, the predicted quantity of Design Option 1 is more than that of Design Option 2, so that totally 19 partners, instead of 11 partners, were selected as preferred partners to form a supply chain.

3. A supply chain in relation with Design Option 3 could not be successfully formed because the total capacity of 2 accepted partners is less than the predicted quantity for production units. In other words, the number of accepted partners is not enough for establishing a supply chain with respect to Design Option 3.

Cross-referencing to Tables 1 and 2, it could be further detected that:

1. A design option, together with its option parts, might bring forth diverse market or customer orientations. For example, Design Options 2 and 3 were emphasised on cost and sustainability issues, respectively, whereas Design Option 1 could be a good choice for its sustainability–cost equivalence. In more detail, most part options selected in terms of physical layer and software components, such as decompression technology and multimedia function, were weakly related to product sustainability features yet strongly relevant to product customisation features.

To implement more customisation features, the product cost is possibly higher yet acceptable in efficiency, such as Design Option 1. Hence, a specific supply chain could be easily formed to satisfy these features. In addition, these features might significantly determine the market share and competition edge of a company, e.g., for the high-consumption group. For instance, it becomes a trend to include the movie, music and internet functionalities for the purpose of preliminary market testing. On the contrary, if a company adopts a relatively conservative marketing strategy so as to maintain the existing market share, such as Design Option 2, design options with higher cost-efficiency and hence lower sustainability-degree might be more preferable.

2. A large number of part options selected in terms of user interface and hardware components, such as card reader and caver/case for Design Option 3, were cohesively related with product sustainability features but possibly with higher cost, such as R&D, supply and recycling cost, in the initial product development stages. For example, the recycled materials were used to replace plastics in case or cover manufacturing. As a result, the supply chain could not be successfully formed in this case. However, product sustainability features, rather than simply considering product price, are accepted by more and more consumers nowadays. Therefore, from product mass production and customisation viewpoint, the product cost could be reduced after successful market launch with increasing production volume and customer acceptance. Accordingly, it is imperative to attract new suppliers so as to enhance the company’s competition edge and bring about a wide acceptance from various customer groups. The following measurements could be...
considered, especially for Design Option 3, in forming a sustainable supply chain.

- High performance of recycle-impacted parts, e.g., low power-consumption yet long use-time accessories, such as various sensors that reduce the frequency of end-of-life reuse, recycling and disposal.
- Innovative design of part substitutions, e.g., blue-tooth or infra-red connector, instead of data cable made of plastics, which is unfriendly to the environment.
- Green quality of parts provided by suppliers and their competence of end-of-life processing, e.g., low-lead battery that is easy for disposal.

5 Conclusions

A BPRS has been proposed and developed in this study. The proposed prototype BPRS consists of three modules, viz. a product conceptualisation module, a supply chain formation module, and a BPR decision-making module. The following summarises the conclusions reached according to two different levels:

(i) From a system level, it has been established that:

1 The BPRS merges the product concept development, supply chain formation and business process reengineering perspectives to make design decision-making more comprehensively.

2 The BPRS is capable of resolving the incomplete, ambiguous, uncertain and subjective nature of sustainable design knowledge at early stage of product conceptualisation.

(ii) From a technological level, it has been established that:

1 The BPRS integrates knowledge acquisition, representation and evaluation processes from qualitative reasoning to quantitative reasoning.

2 The BPRS shares a logical and cohesive linkage under a unified framework and formal scenario, the results from which are more precise. In more detail:

- The general sorting and repertory grids techniques, which possess broad knowledge coverage and ease of use characteristics, are employed in a single approach for different purposes of hierarchical and multi-attribute representation, respectively.
- The Hopfield network is applied to deal with ambiguous, uncertain, incomplete and subjective early-stage sustainable design knowledge, and conduct quantitative reasoning for more clear-cut decision-making.
- The location-capacity-based strategy can be effectively used to finalise both product conceptualisation and supply-chain formation.

The BPRS has been investigated and validated by a case study on cellular phone design. The results are promising and reveal the potential of the proposed prototype system.

Acknowledgements

The research was supported by Shanghai Education Committee Research Project (Project No. 07SG52), Shanghai Science & Technology Committee NSF Project (Project No. 08ZR1409200), and National High-Tech R&D Plan (Project No. 2007AAA04Z105).

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