Fall 2007

Optimal formation of supplier networks for product design and production phases to realize an evolving product family

Padmavathi K. Pakala

Department:

Recommended Citation

Pakala, Padmavathi K., "Optimal formation of supplier networks for product design and production phases to realize an evolving product family" (2007). *Masters Theses*. 4567.
https://scholarsmine.mst.edu/masters_theses/4567

OPTIMAL FORMATION OF SUPPLIER NETWORKS FOR PRODUCT DESIGN AND PRODUCTION PHASES TO REALIZE AN EVOLVING PRODUCT FAMILY

by

PADMAVATHI KRISHNA PAKALA

A THESIS

Presented to the Faculty of the Graduate School of the
UNIVERSITY OF MISSOURI-ROLLA
In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MANUFACTURING ENGINEERING
2007

Approved by

Venkat Allada, Advisor

Frank Liou

Shun Takai

To my parents, sister

and

the significant others.

PUBLICATION THESIS OPTION

This thesis has been prepared in the style as specified by the Journal of Engineering Design.

ABSTRACT

Due to rapid changes in customer requirements and vast improvements in technology, many product development companies have identified strategies like time-to-market (TTM) compression and product family development as critical for attaining success in today's hyper-competitive markets. Compressing the TTM, to a large extent, is dependent on the suppliers and the project execution skills of the integrator companies. This study presents a methodology for selecting suppliers for two significant phases of the product realization process, namely, product design and production. The proposed methodology uses a two-stage approach for supplier selection where suppliers for product design are selected in the first stage and suppliers for production are selected in the second stage. These suppliers cater to the evolving customer requirements over a given planning horizon. Apart from using traditional supplier selection metrics such as cost and time, this study also considers the inter-supplier and supplier-integrator communication effectiveness. The present problem has been solved using a goal programming approach.

ACKNOWLEDGMENTS

I would like to take this opportunity to thank the people who have helped me accomplish this research effort. I am extremely grateful to my advisor, Dr. Venkat Allada, for providing me the opportunity to work in this interesting area, and for his unflinching support, advice and guidance throughout the work. I would like to thank my thesis committee members, Dr. Frank Liou and Dr. Shun Takai, for their insightful comments. I am grateful to the support and encouragement rendered by Abhijit Kumar Choudhury, Smitha Akkinapragada, Kalyani Radha Padma, Aditya Jayam Prabhakar, Mohit Goswami, Shrikant Jarugumilli and Sofia Tan during this work, and also for participating in thought-provoking discussions. I show my gratitude to Dr. C.L. Tseng for providing the Cplex software for solving optimization, and Dr. Ray Luechtefeld for his insightful discussion regarding communication. My thanks to colleagues and friends Rupesh Kumar, Vishnu Borappa, Shivraj Bhandare, Pradeep Tipaji, Deepak Tickoo, Harish Bhagaitkar, and Nandini Balakrishnan, for providing good company. My special thanks to Vicki Hudgins for helping me in formatting the thesis to perfection.

My work would be incomplete without mentioning the efforts, encouragement and trust bestowed in me by my parents, who are a constant source of inspiration, my sister, who is a great companion, and the significant others, who believed in me more than anyone else. I acknowledge my other family members Gayatri lata, Lalitha Bhamidipati, Usha Bhamidipati, Venkat Kolluri, Sundari Nori, Maruthi Nori, and Sita Achanta, who helped me grow to where I am. Special love goes to little angels- Apoorva, Harsha, Nithya, Aneesh, Aditi, Anirudh, and Jaya for keeping me fresh with their cute little talk.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

Optimal formation of supplier networks for product design and production phases to realize and evolving product family

PADMAVATHI K. PAKALA[‡] and VENKAT ALLADA*[‡]

[‡]Sustainable Design Laboratory, Engineering Management Building,
University of Missouri-Rolla, Rolla, MO. 65409. Ph no. (573) 341-4573
*Corresponding Author: 118 Fulton Hall, University of Missouri-Rolla, Rolla,
MO. 65409. Ph no. (573) 341-4141, allada@umr.edu

Abstract

Due to rapid changes in customer requirements and vast improvements in technology, many product development companies have identified strategies like time-to-market (TTM) compression and product family development as critical for attaining success in today's hyper-competitive markets. Compressing the TTM, to a large extent, is dependent on the suppliers and the project execution skills of the integrator companies. This study presents a methodology for selecting suppliers for two significant phases of the product realization process, namely, product design and production. The proposed methodology uses a two-stage approach for supplier selection where suppliers for product design are selected in the first stage and suppliers for production are selected in the second stage. These suppliers cater to the evolving customer requirements over a given planning horizon. Apart from using traditional supplier selection metrics such as cost and time, this study also considers the inter-supplier and supplier-integrator communication effectiveness. The present problem has been solved using a goal programming approach.

Key words: Design suppliers, Production suppliers, Product family, Supplier network, Inter-supplier communication.

1. Introduction

1.1. Overview

High customer expectations, rapid growth in technology, and fierce competition in business are forcing many firms to produce high quality, low cost products in a timely fashion. The product life cycle is considerably shortening, as is evident from the life cycles of products in the consumer electronics, medical equipment, and other industries. As a result, the compression of time-to-market (TTM) of the products has emerged as a weapon for many product realization firms to combat hyper-competition (Carrillo and Franza 2006). For example, a personal computer manufacturer faces a 50-75% loss in sales due to a 6-8-month delay in TTM (Kurawarwala and Matsuo 1993). As depicted in Figure 1, the TTM is composed of time spent in two phases of the product realization process: product design phase (where the time spent is called time for design, TFD), and production phase (where the time spent is called time for production, TFP). Thus, the time spent in both these phases must be minimized to compress TTM.

Another way that firms adopt to attain profits while satisfying the customer needs is by implementing the product development strategy called mass customization (Pine 1993, Willoughby 2006). Large companies like Dell, Boeing, and UPS have adopted mass customization and gained strategic advantage. This strategy can be realized successfully through product platform and product family design (Kulkarni et al. 2005). Product family realization through platform design enables companies to share components, interfaces and processes (design/production, etc.) across the product family, and thereby attain cost and time efficiencies, technological leverage and market power. Thus, a wide variety of product variants with flexible processes can be introduced. For instance, several product manufacturers like Volkswagen, Boeing, Dell and Hewlett-Packard are aggressively implementing platform strategies and producing wide variety of products with few platforms (de Weck et al. 2003).

Besides adopting the product platform strategy, strategic management of the platform and it's portfolio of products is very important. The strategic planning that deals with the development of product platform(s) and management of its product portfolio is called aggregate project planning (Wheelwright and Clark 1992). The planning document used in this strategic planning is called the product family roadmap (Simpson et al. 2006). The product family roadmap provides information on the product variants belonging to different product families that are planned for release, and their time of introduction in a given planning horizon. (Wheelright and Sasser 1989, Meyer and Lehnerd 1997). Gillette has implemented such a product platform roadmap for its razor cartridge and is now overflowing the market with the derivative products from Mach3 (Simpson et al. 2006). The roadmap does not provide all the details of the product platform planning but the major activities that the upper management of a firm must perform in order to reach the expected goals (Gryna et al. 2007).

It is remarkable to mention that, in spite of adopting the product platform strategy, firms continuously face the challenge of sustaining the existing products while investing resources on new product development. Furthermore, USA Today reported on June 14, 2006, that investment of the OEMs in research and development is continuously decreasing, and the federal government is not taking any steps to improve in this direction (Purvis 2006). In this regard, firms began to increase the involvement of suppliers in different phases of the product life-cycle (Lynch 2004, Linder 2004, Calantone and Stanko 2007). By utilizing the capabilities and skills of the suppliers, firms are able to handle the product realization projects at lower costs (Clark 1989, Kessler et al. 2000), shorter lead times (Clark 1989), higher quality (Ragatz et al. 1997, McGinnis and Vallopra 1999), and better manufacturability (Wasti and Liker 1997, Mikkola and Larsen 2003). Other advantages of outsourcing are higher return on investment (ROI), lower staffing requirements, improved flexibility, and access to specialized skill sets and creativity (Chesbrough and Teece 1996, Deutsch 2004, Linder 2004, Lynch 2004).

In the past, supplier involvement in product development projects was confined to production and distribution. By involving suppliers in the production phase, firms can take advantage of the suppliers' manufacturing process capabilities, and high-technology equipment at considerably lower costs. Delivery, commitment to quality, net price, reliability, demographic factors, environmental issues, sourcing strategies, and types of products/services have been given primary importance in most of the works (e.g., Weber et al. 1991, Wilson 1994, Dickson 1996, Hirabuko et al. 1998, Simpson et al. 2002, Humphreys et al. 2003, Sharland et al. 2003, Kamann and Bakker 2004, Goffin et al.

2006, Huang and Keskar 2007, Chopra and Meindel 2007, etc.). Some of these criteria were used as goals while some were used as constraints in solving the supplier selection problem. For successful supplier involvement, the supplier's capabilities must match the firm's requirements. In all these problems, the product design is fixed and the suppliers are selected for the chosen product architecture. Few works adopted the strategy of multiple supplier selection through multi-criteria optimization (Karpak et al. 1999a, Karpak et al. 1999b). Global supplier selection gained emphasis in recent years. Consequently, the criteria for international supplier selection were considered by some researchers (Kaynak 1989, Bowman et al. 2000, Buskens et al. 2003, Choy et al. 2005, Murray et al. 2005).

In recent years, the trend of supplier involvement has spread to product design phase, as is evident in industries like automobiles, aerospace, computers, telecommunications, pharmaceuticals, chemicals, and software (Quinn 2000, Dahan and Hauser 2002, Carson 2007). By involving suppliers in the design phase of the product life cycle, firms are able to release products with less TTM and improved quality. It is to be noted that product design does not involve physical parts of the product. However, it is viewed as a set of design tasks that can be potentially outsourced. The design suppliers can be selected simultaneously while designing the product. In other words, the supplier selection of the design phase is an integrated product design and supplier selection problem. This is a type of Integrated Product and Process design. Here, the factors related to product design and nature of suppliers affects one other in the overall decision. Gupta and Krishnan (1999) attempted to select the components as well as their suppliers simultaneously through a heuristic approach. Their main goal was to minimize the total cost of procurement and usage. Park (2001) developed a comprehensive decision support tool to determine global product strategy and global supply chain configuration simultaneously. Huang et al. (2005) optimized the supply chain network while considering the issues of product platform, manufacturing processes and outsourcing decisions. Heuristic method using Genetic Algorithm has been used to solve the problem. Tenneti and Allada (2005) solved the problem of supplier selection for a planning horizon, while minimizing the total supplier acquisition cost. A hierarchy multiple criteria decision-making model based on fuzzy-sets theory is proposed by Chen et al. (2006) for supplier selection. In this context, it can be mentioned that the suppliers supplying the design of a product must be ‘creative in nature’ (Carson 2007). Examples of companies utilizing the strategy of innovation outsourcing include but not constricted to Dell, Motorola, Hewlett-Packard, GlaxoSmithKline, Eli Lilly, and Procter & Gamble (Calantone and Stanko 2007). In some cases, suppliers who produce design can also manufacture the part.

Some supplier selection problems do not consider the issues of product design and development while selecting the suppliers. These particularly involve the selection of suppliers for clerical and administrative services such as advertising, book-keeping and accounting, legal services, and software and data-processing services (Johnson 1997, Ono 2007). These areas of outsourcing have been considered only during the last few decades. However, these problems are not within the scope of the present study.

As is evident form the above discussion, while an extensive body of research has focused on the supplier selection problem and product design in isolation, simultaneous decision of both product design and supplier network design has not been adequately explored. Furthermore, the suppliers in the selection process have not been explicitly categorized based on various product life-cycle phases, i.e., design, production, distribution, and after-sales service.

The present study emphasizes that communication is an important factor for the successful completion of any project as it has profound effect not only during project planning but also during project monitoring and controlling. The effect of communication takes a higher significance when several suppliers are involved in the project. The importance of communication among the teams in product development projects and the effect of product architecture on this communication have been investigated by several researchers (e.g., Ha and Porteus 1995, Krishnan et al. 1997, Eppinger and Salminen 2001, Yassine and Wissman 2007). Some researchers have studied the effect of product architecture on relationships among buyer and suppliers (Dowlatshahi 1997, McIvor et al. 2000) and the implications of information flow on product development (Graebsch 2005). Vast amount of research has also taken place in the area of buyer-suppliers relationships management alone(e.g., Carr and Pearson 1999, Barut et al. 2002, Prahanski and Benton 2004, Capaldo et al. 2005, Rippa 2005, Amelia and Kaynak 2007). Prahanski and Fan (2007) have gone further in this direction of research on communication/information flow among buyers and suppliers. They have modeled the communication using structural equations and tested it using the data from 138 automotive suppliers. Some works in the literature mention that product-related factors and supplier-related factors affect the supplier selection process (Huang and Keskar 2007). Thus, we identify that though extensive research has been carried out in the areas of buyer-supplier information flow, and the interdependence of product architecture and team interactions separately, there has been no research carried out on developing an operational model for the effectiveness of buyer-supplier communication as a selection criterion for supplier network formation.

From the above discussion, it is evident that there is a pressing need for a methodology for supplier network design that is tailored for design and production phases of a product realization process to cater rapidly changing customer requirements over a given time horizon.

1.2. Methodology contribution

The present methodology is a strategic tool to assist product development firms in their quest to meet the goals of cost, quality and deliverability through supplier involvement. It provides a procedure for selecting the supplier network that is robust to changes in customer requirements and supplier capabilities over a planning horizon. In the present work, the suppliers are categorized based on the phases of the product life cycle namely: concept design, detail design, manufacturing, assembly, logistics and after-sales. The present supplier selection process is illustrated for the two major phases of design and production (which includes manufacturing and assembly) in the product realization process.

In view of the fact that the ultimate goal of any firm is to make profits, we identify several other business parameters, apart from TTM, for selecting suppliers. We consider the work of Smith and Reinertsen (1998) in choosing the supplier selection criteria. They identify four key product development objectives that maximize a company's profitability. They are: market date introduction, product unit cost, product performance, and development project expense. In the present study, the development project expense and the cost of not meeting the desired product performance are included in the total cost of supply. The minimization of total time for design (TFD) aids in meeting the market introduction date. The product unit cost corresponds to the production phase of the product realization process, which is considered in the production phase. In addition to the above selection criteria, we identify that the level of effective communication among the suppliers is a prominent factor in supplier network formation. Thus, three objectives: cost, time and communication effectiveness have been considered to solve the present problem. Uncertainty in demand in terms of both product features and quantity are considered in the present model by showing their variation over a given planning horizon.

The rest of the paper proceeds in this manner: Section 2 equips the reader with the terms and concepts needed to understand the present methodology, along with the assumptions considered. Section 3 provides an overview of the present methodology. This is followed by a detailed explanation of the present case example of insulin delivery device in Section 4. Next, the supplier data provided as input to the methodology is being explained in Section 5. Section 6 elucidates the modeling of the three objectives and the constraints in the present optimization process, along with the discussion on results obtained. Section 7 provides conclusions and future research directions.

2. Terms, concepts, and assumptions

2.1. Terms

1. *Integrator*: The integrator is interpreted as a firm that is responsible for the realization of the final product.
2. *Product life-cycle*: Product life-cycle comprises various phases including market needs identification, concept design, system-level design, detail design, testing, pilot production, manufacturing, assembly, logistics, and after-sales service.
3. *Planning horizon*: The planning horizon is defined as the period of time in the future for which the company makes strategic plans for new product releases.
4. *BOM-Types*: The product features required during the planning horizon are derived based on the product family roadmap provided by the integrator. From this data, the engineering Bill of Materials (EBOM) is developed for the evolving product family. The EBOM is the list of functional parts to be designed for the evolving product family and their corresponding features. EBOM is used in selecting the design suppliers. After the design suppliers provide the detail design of the product variants for the planning horizon to the integrator, the integrator prepares the Manufacturing Bill of Materials (MBOM) and their demand requirements during the given planning horizon. The MBOM consists of the list of parts, the number of parts and their detail design

specifications for a given product(s). The selected production suppliers are provided MBOM information and demand requirements.

5. *Supplier Network*: The group of suppliers and the integrator involved in a project, interconnected among themselves due to the exchange of information or physical goods, is termed as a Supplier Network. It is to be noted that the integrator is also considered as a supplier exchanging product information with other suppliers.

2.2.Concepts

This section introduces two critical concepts used in the present study. They are as follows:

- Supplier categorization based on product life-cycle phases
- Supplier Network Communication effectiveness

Each of these concepts is discussed in detail below.

Supplier categorization based on product life cycle phases: Product life cycle is comprised of all the phases that are responsible for value addition in the product from the view of the customer (Kumar and Krobb 2005). We categorize the suppliers based on the phase during which they are involved in the product life-cycle. The categorization is given in Table 1.

1. *Concept suppliers (CS)*: The suppliers who provide the outsourced product/part's features, functions and corresponding specifications to the integrator, along with careful

analysis of competitors and economic justification of the product/part, (Ulrich and Eppinger 2005) are called concept suppliers. Companies like IDEO, Syncroness, and Novonordisk are examples of concept suppliers.

2. *Design suppliers (DS)*: The suppliers who receive the concept of a product/part and supply its architecture along with complete specifications of the geometry, materials and tolerances, are said to be design suppliers. These suppliers ensure the functionality and manufacturability of the designed parts/products. They perform the tasks of system-level design, detail design, testing and pilot production in the product chain. For example, Calty design research, Inc. is a design supplier that supplies color, trim and wheel design to Toyota cars.

3. *Manufacturing suppliers (MS)*: The suppliers, who have the manufacturing capabilities to provide the parts of required quality and required capacity in the required duration, are called Manufacturing suppliers. These suppliers provide their quotations based on the lot size being delivered. W. W. Williams, Jesco, Crow's Truck Service Inc., and Japan Auto Parts Supply Ltd. are some of the companies that manufacture and supply truck engines.

4. *COTS suppliers (COTSS)*: COTS are the components-off-the-shelf that are available in the market with certain pre-specified specifications. The suppliers that supply such parts to the integrator are called COTS suppliers. As an example, the insulin pen needles are available in the market in certain definite specifications. The companies that manufacture these needles in predetermined specifications are Becton, Dickinson and Company, Ulti-Med, Novo nordisk, etc. They can be called COTS suppliers.

5. *Assembly suppliers (AS)*: The task of integrating/assembling various parts to form a product or a sub-system of the product can also be outsourced. The suppliers who do this job are called assembly suppliers. ProSource Industries, Printed Circuits Corp are examples of assembly suppliers that supply electrical assemblies.

6. *Logistics suppliers (LS):* Certain outsourcing parties take the contract to reach the products to the customers. They provide the logistics part of the product chain. Such suppliers are called Logistics suppliers. UPS, Amazon.com are good examples of logistics suppliers.

7. *After-sales suppliers (ASS):* The after-sales service is a prominent task in some product chains like those of automobiles, home appliances, etc. Thus, the suppliers that provide this task are termed as 'After-sales suppliers'. As an example, PERCEPTA is an after-sales supplier that provides excellent customer care, distributor and retailer support, learning solutions and professional services to automobile customers.

These categories of suppliers can be considered as fundamental. In reality, there exist suppliers that belong to two or more categories. For instance, a supplier can perform the tasks of manufacturing and assembly of a part/sub-assembly. In that case, the supplier is called as a Production supplier (PS). Similarly, the supplier performing the tasks of design, and manufacturing is called as Design and Manufacturing supplier (DMS). Further, in a product development firm, there exist other types of suppliers for market-analysis, administration, maintenance, software services, etc. These types of suppliers are beyond the scope of the present study.

Supplier Network Communication Effectiveness (CE): Effective communication assists in bringing the right information/products to the right place at the right time (Ward, 2007). In the present study, we model the communication among different members in product realization process and term it as '*Supplier Network Communication Effectiveness*'.

Definition of Supplier Network CE: The value addition by a supplier to the project (here, product realization process) through its communication with all other suppliers and the integrator of an organization is defined as the communication effectiveness (CE) of the Supplier. The aggregate sum of Communication Effectiveness (CE) of all the suppliers and the integrator of the project gives the '*Supplier Network Communication Effectiveness*'.

In the present work, the model for supplier network communication effectiveness model has been modified to suit specifically the product design phase and production phase. Figure 2 and Figure 3 provide a snapshot of the supplier network with 2-way communication among suppliers in the two phases of product design and production, respectively. In these figures, the product has n different parts supplied by m different suppliers.

In a product realization process, the communication in the supplier network occurs due to factors related to three perspectives of product realization complexity (Eppinger and Salminen, 2001):

1 product architecture,

2 process task dependency,

3. nature of the organization.

The product architecture view is based on the findings of Sosa (2000) related to the effect of product architecture on the technical communication in product development organizations. In the present study, we observe that the Engineering Bill of Materials (EBOM) plays an important role in supplier network communication effectiveness. The EBOM consists of different design chunks of a product, and the corresponding features. These design chunks are designed on the basis of the functions they satisfy in the product. Based on the product architecture perspective, we model two factors affecting CE: part interaction strength (γ) and part functional importance (θ). The second perspective, process task dependency, implies that the different tasks of the product realization process are dependent on each other for physical goods and/or information. This dependency is captured by the Supplier dependency factor (α). Lastly, the communication among different entities of the product realization process is influenced by the nature of the organization to which each entity belongs. Thus, the factor supplier communication capability index (β) denotes the impact of the nature of organization to which a supplier or the integrator belongs, on the communication among them. The four factors: γ, θ, α, and β are modeled and computed, as described below. It is noteworthy to mention that the model for CE does not consider inter-personal aspects of communication such as selective perception.

Part Interaction Strength (γ): Sosa (2000) observed that 90% of the cases with interactions between the design chunks in a product functional architecture match with the interactions between the respective design teams. Eppinger and Salminen (2001) also predict technical communication in this situation. We use this concept in the present model for supplier network communication effectiveness. We consider that if two design chunks share interactions, the suppliers supplying those two parts have communication between them. Thus, the part which shares more interactions or strong interactions with other parts gets a high part interaction strength value. This conveys that the supplier for such a part/sub-assembly is the *most interconnected* supplier.

In the present paper, the part interaction strength is calculated using the Design Structure Matrix (DSM). In these calculations, we consider four types of interactions among the design chunks of the product (Pimmler and Eppinger 1994). They are as follows: Spatial (S), Material (M), Energy (E), and Information (I). These interactions for different parts are quantified in a matrix called *Parts Interactions matrix*, based on a scale ranging from 0 to 2. This scale (given in Table 2) is obtained by modifying the scale used by Pimmler and Eppinger (1994), such that the interaction strength does not have a negative value. It is because we model the supplier to have communication with other suppliers/integrator whether their part's mutual interaction is beneficial or harmful for the overall product's functionality. Parts interactions matrix for five different parts of a product is illustrated in Table 3. From this matrix, the eigen vectors are calculated for each part (Wind and Saaty 1980, Singh et al. 2006) as shown in Table 4. These are the interaction strengths of each of the parts. It is observed from the last column of Table 4 that Part 3 is most inter-connected in the product. This forces the supplier selection process to select that supplier for this part which has more communication with the other members of the supplier network.

Part Functional Importance (θ): The fractional number of functions of a product that its part/sub-system satisfy is said to be its functional importance. In the present study, the equation for calculating the functional importance of each component/sub-assembly is derived from the principle of value-analysis (Otto and Wood 2004). The part functional importance is based on the number of functions of the product it satisfies. Further, in value analysis, the weight of each function is based on the number of customer needs satisfied by each function. However, we have not harped into the customer needs analysis of the functions. Instead, we grouped the functions of the present product family into primary and secondary functions based on a general view of the product design. Considering the relative importance of primary and secondary functions in a product, they are arbitrarily assigned the importance weights of 0.75 and 0.25, respectively. Table 5 illustrates how different parts in a product satisfy different functions, using five parts of insulin delivery device product family. The part functional importance, θ, is computed using Equation 1.

$$\theta = [(P \times 0.75) + (S \times 0.25)] / N \qquad \ldots (1)$$

where

P denotes the number of primary functions, *S* denotes the number of secondary functions,

N denotes the total number of functions.

The functional importance calculations of each part in the insulin delivery device product family are given in Table 6.

Supplier Dependency Factor (α): The supplier dependency is defined as the dependency of a supplier's task on the tasks of other suppliers or integrator, for information or physical goods to accomplish its own task. This dependency of tasks in a process, which corresponds to dependency of respective organizations involved in the process, has been investigated earlier by Eppinger and Salminen (2001). We quantify the extent of this dependency by a term called the supplier dependency factor. It measures the extent of dependency of a supplier on a scale of 0 to 1. This has been modeled as a logarithmically decreasing function in the present study, for the purpose of illustrating the decay.

We propose two different types of dependencies among suppliers based on the phase in the product realization process they belong to. Accordingly, we model two types of supplier dependency factors: Design supplier dependency factor (α) and Production supplier dependency factor (α'), that affect the communication in design phase and production phase, respectively.

Among design suppliers, the CE is governed by the sequence in which the design chunks of the present product family are being designed. This kind of dependency is called a chain dependency. This is depicted in the design task diagraph shown in Figure 4. In this context, we represent the number of suppliers on which a given supplier is dependent on, by a parameter called supplier task dependency number (*x*). In a chain dependency, the supplier task dependency number of a supplier, denoted by *x*, is equal to the number of design tasks/suppliers on which the supplier is dependent on, including itself. For example, in Figure 2, three different kinds of relationships among design tasks are shown. They are as follows: coupled, sequential or independent (Carrascosa et al., 1998). In Figure 2, the design tasks A and B are sequential. Here, task A is dependent only on itself. So, its dependency number is 1. Task B is dependent on itself and task A. So, its dependency number is 2. The design tasks C and D are coupled. In this case, each of the two tasks are not only dependent on itself, task A, and task B but also on the other task with which they are coupled. Thus, the dependency numbers of task C and task D is 4. The design tasks E and F are independent. Therefore, both their dependency numbers are same as for the coupled tasks. However, they are not dependent on each other. Each of their dependent tasks are tasks A, B, C, D, and itself. Thus, their dependency number is 5.

In the production phase of the product realization process, the suppliers of one tier are dependent on the suppliers of the lower tier for the supply of information and products. We call this kind of dependency as a tier dependency as depicted in the production task diagraph in Figure 5. In Figure 5, all the suppliers of the lowest (here, third) tier are assigned the supplier task dependency number as 1 since they are dependent only on themselves. In the second lower tier, each supplier is dependent on itself and all the suppliers in the lowest (here, third) tier that it needs to produce the component/sub-assembly of required quantity. For example, in Figure 5, the assembly supplier selects two manufacturing suppliers for one of its components and three manufacturing suppliers for the other component, to satisfy the demand of the sub-assembly at maximum communication effectiveness. Hence, the supplier task dependency number of the assembly supplier equals 6 (5 manufacturing suppliers and itself). All the remaining manufacturing suppliers are dependent on themselves for the production of the respective parts of required capacity. So, they have the supplier task dependency number of 1. The tier dependency can be described as a type of chain dependency in which suppliers in the same tier share an independent kind of relationship, while the suppliers in two adjacent tiers share a sequential kind of relationship.

We identify that as the supplier task dependency number increases, the supplier dependency factor decreases. This decrease is attributed to the noise in the system that distracts effective information flow among the suppliers. The noise amplifies as it propagates along the chain of suppliers. This amplification is similar to the popular concept of ‘Bull-whip effect’ usually used in forecast-driven distributed supply chains. In the present study, we modeled the supplier dependency factor as a logarithmically decreasing function of supplier task dependency number, x. The equation formulated for the calculation of supplier dependency factor is given in Equation 2.

$$\alpha = 1, \qquad \text{for } x = h$$
$$= a \times \log_B(b \times (x + c)) + d, \qquad \text{otherwise} \qquad \ldots (2)$$

where

α = Supplier Dependency Factor of a supplier

x = supplier task dependency number

h = threshold number of part types

In the above equation, the values for the constants *a*, *b*, *c*, *d*, and *B* are given in Table 7.

The threshold number of part types, *h*, in Equation 1, can be defined as the maximum number of suppliers which a given supplier/integrator can be dependent on, without decay in the communication effectiveness. This notion is based on the effectiveness of a team leader in managing its team members. The supervisor will be effective to its maximum capability with only a certain number of subordinates under normal conditions. The supervisor becomes less effective either above or below this number. Ouchi and Dowling (1974) call this threshold number of subordinates as the span of control. They also mention its effect on the communication between a supervisor and its subordinates. In the design phase, due to single outsourcing, the threshold number of part types is taken as 1. The incorporation of threshold number of part types in the computation of supplier network communication effectiveness forces the present model to select minimum possible number of suppliers in the network. In other words, it favors supplier base consolidation.

On the other hand, in the production phase, we deal with multiple outsourcing. In this case, we propose that a given supplier can be dependent on twice as many suppliers as there are parts for production, without decay in the communication effectiveness. For example, the assembly supplier in Figure 5 obtains the sub-assembly of required quantity from five manufacturing suppliers. In this case, we set the threshold number of part types for the assembly supplier as twice the number of components its sub-assembly is composed of. Thus, h for this assembly supplier is $2 \times 2 = 4$. There would be decay in the communication effectiveness of the assembly supplier beyond 4 manufacturing suppliers under it. It is noteworthy to mention that the threshold number of part types in the production phase is not dependent on the capacity of each supplier because the capacity of the component/sub-assembly does not play any role on the effectiveness of communication among the suppliers. Whatever may be the quantity of parts the supplier supplies, the flow of knowledge regarding the parts will be the same.

The functions for the computation of supplier dependency factors in the product design phase and production phase are shown graphically in Figure 6 and Figure 7, respectively.

Having obtained the supplier task dependency number as explained earlier, the design supplier dependency factor (α) is calculated as shown in Table 8. Similarly, the production supplier dependency factor (α') is calculated as given in Table 9. It is significant to state here that the supplier dependency factor is constant in the design phase while it changes with changing number of lower tier suppliers over the planning horizon in the production phase.

Supplier communication capability index (β): The factors for supplier communication capability are described by Fynes and Voss (2002). They are provided in Table 10. These factors are not comprehensive but are only selected for the illustration of the methodology. For each pair of members involved in the process, we assign weights to each of the factors on a scale of 0 to 1, on the basis of their past history/knowledge regarding their attitude in communicating with other suppliers. Then a DSM is used for computing supplier communication capability index (β), similar to the calculations in Table 4.

Modeling formula for Communication Effectiveness: We analyze that the *Communication Effectiveness* of a supplier network, in product design phase, is affected by two independent events: the presence of interactions/interfaces among the parts, and the dependency of a supplier in the network. The presence of these events affects the communication among the suppliers. On the other hand, the two other factors - part functional importance and supplier communication capability index (β) help in enhancing the communication among the suppliers, but do not cause communication independently. Based on these inferences, we formulate Design Supplier Communication Effectiveness, using the probability theory of the occurrence of an event due to two independent events as provided in Equation 3.

CE_D = P {(interface strength) U (supplier dependency)}*(functional importance)

*(supplier communication capability index)

$$= (\alpha + \gamma - \alpha \times \gamma) \times \theta \times \beta \quad \ldots (3)$$

The basis for this formulation is depicted in Figure 8. We recognize that the detail design of the parts is provided at the end of the design phase. In this view, the interface issues among the parts do not cause communication among the production suppliers. The main concern of the production suppliers is the delivery of right quantity of the products of the right quality in the right price at the right time. Hence, the part interface strength (γ) does not exist in the formula for production supplier network communication effectiveness (CE_P). The modified formula for CE_P is given in Equation 4 below.

$$CE_P = \alpha \times \theta \times \beta \quad \ldots (4)$$

2.3. Assumptions

The present work on optimal design supplier network selection works with the following assumptions:

1. The methodology is suitable for functional products with incremental innovation. In other words, the evolving product family is obtained from the same technology platform.
2. For the purpose of calculations convenience, the quality loss cost corresponding to each product feature is taken as constant over the planning horizon.

3. A design supplier can design only one part and no multiple sourcing is allowed.
4. The suppliers who supply COTS are design and manufacturing suppliers (DMS) whose cost and time involved in design is assumed to be negligible.
5. The decision of COTS or customized parts for a given design chunk is not considered in this work and is assumed to be implicit.
6. The design suppliers consider the available manufacturing facilities of the pool of manufacturing suppliers while designing the product.

3. Proposed methodology

The present methodology for *optimal selection of supplier networks for product design and production phases to realize an evolving product family* is a two-stage approach in which an optimum design supplier network is selected in the first stage and an optimum production supplier network is selected in the second stage. It is assumed that the tasks of designing and producing the products are not the core competency of the integrator. Hence, they are being outsourced to the suppliers.

Figure 9 depicts the flow diagram for the present method. It is evident form this figure that the inputs given to the first stage are:

1. EBOM (Engineering Bill Of Materials),
2. Integrator’s requirements in terms of product family roadmap,
3. Capabilities of available suppliers.

The integrator prepares a product family roadmap for a given planning horizon. Product design information in terms of the features of a product is obtained from the product architecture details. This is interpreted for all the products variants planned for release in the roadmap, called as the EBOM. Further, the capabilities of the available design suppliers are obtained from their quotations in terms of cost and time. Their communicating attitude with other suppliers is derived from past experience or other sources of information. With this data, the optimization problem is solved for minimum total supplier network cost, minimum total supplier network time and maximum total supplier network communication effectiveness.

As mentioned earlier, the first stage of the present methodology not only selects an optimal design supplier network but also an optimal detail design for each of the product variants of the product family roadmap. The MBOM (Manufacturing Bill of Materials) is derived from the product variant detail designs thus obtained and is fed as input to the next phase. Further, in the production phase, the quantity requirements of each of the product variants play an important role in the supplier selection process. The capabilities of the available supplier pool are also considered. In summary, the inputs provided to second stage are:

1. MBOM
2. Integrator's quantity requirements
3. Suppliers' production capabilities

In this phase, three objectives related to production, namely, production cost, production time and production supplier communication effectiveness, are used to select an optimum production supplier network for the entire planning horizon. It is significant to mention that in the present work, the supplier network in the production phase has two-tiers: one is the supplier network under the integrator and the other is the supplier network under each of the assembly suppliers. The input data corresponding to each of the first-tier assembly suppliers is obtained by solving a localized optimization problem with similar objectives for the manufacturing suppliers under the assembly supplier.

In both the stages, the multiple objectives are solved using mixed-integer linear goal programming approach. The importance weight is assigned to each of the objectives based on the type of product and its market demand. The proposed methodology is highly sensitive to the input data related to product variant requirements and supplier capabilities over the planning horizon. The following sections provide a comprehensive explanation on the inputs to the methodology, solving the optimization problem, and the resultant supplier networks.

4. Insulin delivery devices: case example

The insulin delivery device case example has been chosen in the present study to illustrate the proposed methodology of optimal supplier network selection. A brief introduction to the product, along with information on its use to the end-users is provided in sub-section 4.1. This is followed by a description on how it has been modeled and designed in the present work in sub-section 4.2.

4.1. Product description

Type-1 diabetes is a condition of lack of insulin in the human body that occurs predominantly in children due to various reasons. It is treated by either injecting insulin in the human body, inhaling the insulin, or through pills under medical supervision. Among them, injecting insulin is largely in vogue since last decade. Also, this mode of diabetes treatment is considered reliable and healthy (Burton and Uslan 2006). In the present study, we consider insulin delivery device product families to illustrate the present methodology of optimal design supplier network selection.

The main function of the insulin delivery device is to inject insulin into the human body. The considerations that play a vital role during the design of the product are the following customer requirements:

a. Accurate insulin dose dialing
b. Minimum pain while injecting
c. Portable
d. Cost-effective

It is essential for diabetics to monitor the blood glucose levels continuously as a part of daily diabetes management. Considering this necessity of the customers, some insulin delivery devices attach the device for blood glucose level monitoring, called the glucometer as an additional feature to the insulin delivery device. Some devices are programmed to deliver insulin to the human body based on the current blood glucose level. In addition, several other features can be added to the product to help the diabetics deal with diabetic impairments. For example, senior citizens may have difficulty in remembering the previous insulin dose injected. Hence, some insulin delivery devices provide memory that saves the information regarding the amount of last insulin dose.

The above mentioned characteristics of an insulin delivery device can be continuously improved through different function-technology mappings and product features. In other words, the function-technology mapping is changing and evolving over time. At the same time, the demand of the product during the planning horizon is uncertain due to continuously varying customers' acceptance. However, we model constant demand for a given term in the planning horizon. Thus, according to Lee (2002) it can be concluded that, in the present case, the product is functional with incremental innovation. The processes like manufacturing and assembly capability requirements are changing during the planning horizon, but made constant within each term of the planning horizon. Thus, based on the observations of Lee (2002), the resultant supplier network for such a product meets the customer requirements during the planning horizon at reduced cycle times and with varying objective values across the terms. Accordingly, the supplier network obtained in the present work is both agile and optimal (compromisingly efficient among the three objectives of cost, time and communication effectiveness).

4.2. Product design

The product family roadmap used in the present study is shown in Figure 10. Here, based on the market demand, the products released at different terms in the planning horizon are numbered from 1 to 7 along with the identification of market segment(s). It is to be noted that though the roadmap in the Figure 10 shows the actual products, the detailed information about the product design is not available at this strategic level of the product realization process.

Using the information provided in the product family roadmap, we develop an EBOM (Engineering Bill of Materials) which is common to all products of the present product families. Figure 11 shows this EBOM. It is composed of five design chunks, each associated with attributes describing them. In this context we define a design chunk as the conceptual part that performs primary and/or secondary function(s) of the product. The specifications of the attributes of design chunks vary along the planning horizon based on the product being designed in each term. For example, the variation of the specifications for the design chunk, *the enclosure*, is shown in Table 11.

Each of the attributes of the design chunks is associated with a quality loss cost, based on the modified Taguchi's Quality loss function as described below.

Modified Taguchi's quality-loss function: According to Taguchi's quality loss concept, the integrator incurs loss for not meeting the target specifications of the product derived from customer requirements. This customer satisfaction loss cost is called the quality-loss cost. In this theory, the product features are categorized as follows: 1) Larger the better, 2) Nominal the best, and 3) Smaller the better. However, we identify that there are certain features whose absence incurs some customer satisfaction loss cost. Hence, we have divided the product attributes into four categories based on the requirements of the customers in the product as discussed below:

1. Larger the better: The product features that give greater customer satisfaction by increasing their specification value fall under this category. Examples are needle guage, maximum deliverable dose, and accuracy of dosage. For such features, the customer satisfaction loss cost is computed by the formula given in Equation 5.

$$QLC = k \times (1 \div y)^2 \qquad \ldots (5)$$

2. Nominal the best: The product features that render greater customer satisfaction when their specification value equals a nominal value fall under this category. Examples are insulin reservoir capacity, case weight, and viewed size of dose. For such features, the customer satisfaction loss cost is computed by the formula provided in Equation 6.

$$QLC = k \times (y - m)^2 \qquad \ldots (6)$$

3. Smaller the better: The product features that cause greater customer satisfaction by decreasing their specification value fall under this category. For such features, the customer satisfaction loss cost is computed by the formula given in Equation 7.

$$QLC = k \times y^2 \qquad \ldots (7)$$

4. Feature presence/absence: The product features that provide customer satisfaction by their mere presence fall under this category. Memory storage for the quantity of previous dose is a good example of this category. Customer satisfaction loss cost for such features is a constant, k, specific to a feature, as shown in Equation 8.

$$\begin{aligned} QLC &= k, && \textit{if corresponding feature is present} \\ &= 0, && \textit{otherwise} \end{aligned} \qquad \ldots (8)$$

In all the above formulae (Equations (4) – (8)),

k is customer satisfaction loss constant,

y is product specification value as dictated by the design, and

m is available product specification value

The quality loss cost does not vary over the planning horizon in the present study. Its value for different product features is provided by the integrator's market survey department as shown in Table 12. It is to be noted that the data used here is hypothetical for the purpose of illustration of the methodology.

The quality loss cost of a design chunk varies with the varying specifications. We term the variants of a design chunk, varying in specifications, as instances of the design chunk. We have categorized each design chunk into some instances. Each instance is modeled to be available in some/all terms of the planning horizon. Table 13 shows the instances of each design chunk in the second column and their availability during the planning horizon from third column onwards. The quality loss cost is computed for each instance of the design chunk based on the modified Taguchi's quality loss concept by taking the data pertaining to changing customer requirements from the product family roadmap.

The tasks of designing different instances of design chunks depend on each other for design information. This design task dependency can be observed to be occurring due to two inter-related reasons as listed below:

a) Design task sequence
b) Lag durations

The requirement of specific information from specific design chunk necessitates the occurrence of design tasks in a specific order for the realizing the design of final product. The design task sequence is shown in Figure 12. In addition, all design tasks need not start or finish immediately after the previous task in the sequence finishes or starts. There could be a lag between tasks. Several such aspects of design task dependency are captured in a diagram called the *Design Dependency Diagram*. The design dependency diagram for the present product family is shown in Figure 13.

4.3. Production

The features of all the planned product variants are fixed during the first stage of the proposed methodology. Then, the integrator translates the design chunks into structural parts as shown in Table 14. Here, the five design chunks have been translated into seven structural parts. It has been identified that an *insulin delivery device* comprises of seven parts (including sub-assemblies (SA) and components (C)). Each product variant of the evolving product family of insulin delivery devices is assumed to contain these general parts though their specifications and features vary along the planning horizon. Among the seven parts, two are modeled as sub-assemblies. The cartridge is modeled as a sub-assembly comprising two components: glass tube (C11) and rubber cap (C12). Similarly, the needle sub-assembly comprises needle (C31) and cap (C32). The demand requirements for each of the seven above mentioned general parts of the evolving product family in each term of the production planning horizon is derived from the product variant market demand. If a part appears twice in a product variant corresponding to a term, the demand of that part would be twice as that of the demand of the variant. All these details pertaining to the detail design of the product variants in each term of the planning horizon, is shown in Manufacturing Bill of Materials (MBOM). Table 15 provides MBOM for the evolving product family of insulin delivery devices. It is evident from MBOM that unlike in the product design phase, the parts of the production phase do not have several instances. Based on the customer requirements and optimum design supplier parameters (like total design cost, total design time and design supplier network communication effectiveness), an instance per part has already been selected for each term, during the design phase. The hierarchy of different parts, along with the corresponding capacity requirements of the product variants is depicted in Figure 14. It is notable to mention that the number of product variants planned during the planning horizon may not be equal to the realized product variants during the planning horizon. However, all the market segments whose demand is planned to be met, is met by the realized product variants. Due to this inherent vagueness present in the number of realized product variants, the realized roadmap of product variants in the planning horizon is not illustrated in the present work.

Based on market survey and several forecasting techniques, the demand of the products for the evolving product family is considered for four terms in the planning horizon. This demand is in terms of the quantity of products to be produced in each term of the planning horizon as given in Table 16. For the purpose of supplier selection for each of the parts, the demand has been interpreted for each of the parts as shown in Table 17. In Table 17, the needle sub-assembly appears thrice in the final product. Hence, its demand is thrice the demand of individual products.

5. Stage 1: design supplier network formation

A group of members form a network when they are dependent on each other. In the present study, the members of the group comprising the design suppliers and the integrator depend on each other for product design information. Hence, they are said to form a design supplier network. For the same reason, we model communication among them and employ it as one of the three supplier selection criteria. As explained in the model for CE, one of the factors on which the supplier network CE depends is the nature of the organization to which the supplier belongs. This nature, in terms of willingness to share information, willingness to change, level of quality practices, etc., is captured by the supplier communication capability index (β) factor. Its value is interpreted by the integrator based on past experience or other sources.

Besides CE, the total cost incurred and the total time taken are the important factors for the product realization process. Since the suppliers are involved in the present design process, the cost and time of their supply are provided as quotations for the entire planning horizon. However, the cost of switching a supplier during the planning horizon is assessed by the integrator.

Supplier Network Selection: Multiple suppliers are modeled to be available for each of the instances of the five design chunks of insulin delivery device product families. From this pool of suppliers, the supplier network has to be selected at optimum values of cost, time and CE. This is possible by applying a multi-criteria decision analysis that finds a solution by making trade-offs with the three mutually conflicting objectives. We have solved this problem using a linear mixed-integer goal programming approach. For this purpose, the goals of each of the objectives must be set. We adopted the algorithm for goal setting from Kumar and Shankar (2004). In this algorithm, each of the objectives is solved individually with the respective constraints. The cost and time are minimized and the CE is maximized. The objective function value in each of these cases is set as the goal of the corresponding objective function.

Modeling of each of the objectives, in the present multi-criteria decision analysis, is described in the following sub-sections.

5.1. Design cost

The total design cost of a supplier network for a planning horizon is the aggregate sum of these cost components:

1. Quoted cost of supply,
2. Cost incurred by the integrator due to supplier switch-over,
3. Assessed customer-satisfaction loss cost

The mathematical formulation of the total design cost of supplier network is given by Equation 9.

$$TDC = \sum_{i=1}^{n} \sum_{j=1}^{ni} \sum_{k=1}^{nij} \sum_{t=1}^{4} (\mathrm{DC}_{\mathrm{ijkt}} \times \mathrm{y}_{\mathrm{ijkt}}) + \Sigma(SC_{ijkt,\,t+1} \times y_{sijkt,\,t+1}) \qquad \ldots (9)$$

where

TDC = Total design cost of the supplier network for the given planning horizon

DC_{ijkt} = Design cost quoted by a supplier for an instance of a design chunk

$= PDC_{ijkt} + QLC_{ijkt}$

= (Pure design cost + Quality loss cost) of an instance j of the design chunk i as supplied by a supplier k in term t of the planning horizon.

$SC_{ijkt,t+1}$ = switch-over cost expended by changing supplier k selected in term t, in the next term t+1 for instance j of design chunk i.

y_{ijkt} = binary variable to denote the selection of a supplier k for the instance j of design chunk i in term t of the planning horizon.

$ys_{ijkt,t+1}$ = binary variable to denote the switch-over of a supplier k selected in term t, who gets switched in term t+1 of the planning horizon, for instance j of the design chunk i.

n = number of design chunks of the insulin delivery device

n_i = number of instances for the design chunk i

n_{ij} = number of suppliers available for instance j of the design chunk i

The constraints considered for this objective are as follows:

1. Constraints related to the compatibility among different design chunk instances of the product.

$$\forall t, \quad \sum_{i=1}^{n}\sum_{j=1}^{ni}\sum_{k=1}^{nij} y_{ijk} = 1 \qquad \ldots (10)$$

2. Constraints that restrict the selection of one supplier for a design chunk.

$$\forall t, \ \forall i, \quad \sum_{j=1}^{ni}\sum_{k=1}^{nij} y_{ij} = 1 \qquad \ldots (11)$$

5.2.Design time

The design of each chunk of the insulin delivery device is viewed as an activity and precedence relationships among them are identified. The total design time of a supplier network in the design phase has been modeled based on project management concepts like extended network techniques (lag relationships), early-start-time and early-finish-time relationships, and task sequence. The early-start-time of the first activity is made equal to zero for calculations convenience. Further, for clarity, a dummy activity is used to denote the last design activity in every term of the planning horizon. Thus, the total time taken in the design phase is equal to the time taken by the last activity (here, dummy activity) to reach completion as given in Equation 12.

$$\forall t, \quad TDT = EFT_d \qquad \ldots (12)$$

where

TDT = Total design time of the supplier network

EFT_d = Early Finish Time of the last activity which is a dummy activity.

In addition to the constraints used in the case of total design cost, the present objective regards following time-based constraints:

1. Constraints that force the dummy activity to be the last activity in the sequence.

$$\forall t, \quad EFT_{(d)t} - EST_{(d)t} = 0 \qquad \ldots (13)$$

$$\forall t, \quad \forall l, \ \forall i, \ \ EST_{(d)t} - EFT_{(l)it} \ \geq \ 0 \qquad \ldots (14)$$

2. Constraints on early-start-time, and early-finish-time relationships.

$$\forall t, \ \forall i, \quad \sum_{j=1}^{ni} \sum_{k=1}^{nij} EFT_{ijkt} \ = \ EST_{ijkt} \ + \ d_{ijkt} \times y_{ijkt} \qquad \ldots (15)$$

3. Constraints on the lag relationships among the design tasks.

$$\forall t, \ \ \forall i, \ \forall i', \ \sum_{\mathrm{j=1}}^{\mathrm{ni}} \sum_{\mathrm{k=1}}^{\mathrm{nij}} \ \mathrm{EST}_{\mathrm{ijkt}} - \mathrm{EST}_{\mathrm{i'\,jkt}} \quad \geq \ \mathrm{L}_{\mathrm{i,\,i'}jkt} \qquad \ldots (16)$$

4. Constraint that makes the early-start-time of the first design activity in the design sequence equal to zero.

$$\forall t, \quad EST_{1t} \ = \ 0 \qquad \ldots (17)$$

In the above equations (Eqs. (13) – (17)),

EST = Early start time

EFT = Early finish time

L = Lag duration

d_{ijkt} = time taken by supplier k for designing the instance j of design chunk i in term t of the planning horizon.

l = serial numbers for the last activities in the design sequence.

5.3.Design supplier network CE

The supplier communication effectiveness described in section 2.2 is mathematically formulated for supplier network selection for the entire planning horizon as given by Equation 18.

$$NCE_D = \sum_{i=1}^{n} \sum_{j=1}^{n_i} \sum_{k=1}^{n_{ij}} \sum_{t=1}^{4} \left[\left\{ \left(\alpha_i + \gamma_i - \alpha_i \times \gamma_i \right) \times \theta_i \times \beta_{ijkt} \right\} \times y_{ijkt} \right] \quad \ldots (18)$$

where

α_i = Supplier dependency factor of the design chunk *i*

γ_i = Part interaction strength of the design chunk *i*

θ_i = part functional importance of the design chunk *i*

β_{ijkt} = supplier communication capability index of supplier *k* providing instance *j* of the design chunk *i* during term *t* of the planning horizon.

y_{ijkt} = binary variable to denote the selection of a supplier *k* for the instance *j* of the design chunk *i* in term *t* of the planning horizon.

5.4.Goal programming

In the goal programming approach, the optimization problem is solved by minimizing the sum of deviations of the three objectives from their respective goals (Rardin 1998). But, the three objectives in the present problem are in different units, i.e., the design cost is measured in dollars, the design time is measured in weeks, and CE has no units. Accordingly, their corresponding deviations should not be directly added. So, the three objectives have been scaled to percentage and then their deviations are added (Romero 1991) as shown in Equation 11. Further, solving a multi-objective goal programming involves trade-offs among different mutually-conflicting objectives. In order to reduce the error in optimization and assure efficient points, a small positive multiple of each of the minimization objective functions (here, cost and time) are added, and the same multiple of maximization objective function value (here, CE) is subtracted from the standard deviation objective (Rardin 1998). We denote the small number by the symbol ε, and randomly choose $\varepsilon = 0.95$ in the present study. An importance weight is assigned to each of the objectives on a scale of 0 to 1 based on the relative prominence of the objectives in the supplier network selection process.

We suppose the following:

1) The objective function formulation for cost, time and communication effectiveness are denoted by $f_1(x)$, $f_2(x)$ and $f_3(x)$, respectively,
2) The percentage allowable deviations of each of the objectives are denoted by $\%d_1$, $\%d_2$, and $\%d_3$, respectively,

3) The importance weights of each of the objectives are represented by w_1, w_2, w_3, respectively,
4) The goals obtained by individually solving the objective functions with their corresponding constraints, are given by *a*, *b*, and *c*, respectively.

The formulation for linear mixed-integer goal programming is given by Equation 19, by considering that the cost and time are minimized, and the communication effectiveness is maximized. The system constraints mentioned in Equation 19 refer to the constraints indicated by Equations 10, 11, and 13 to 17.

Minimize

$$[w_1 \times \%d_1] + [w_2 \times \%d_2] + [w_3 \times \%d_3] + \varepsilon[f_1(x) \times 100 / g_1 + f_2(x) \times 100 / g_2 - f_3(x) \times 100 / g_3]$$

Subject to

$$\begin{aligned} &[f_1(x) \times 100 / g_1] - \%d_1 \leq 100 \\ &[f_2(x) \times 100 / g_2] - \%d_2 \leq 100 \\ &[f_3(x) \times 100 / g_3] + \%d_3 \geq 100 \\ &\%d_1 \geq 0 \\ &\%d_2 \geq 0 \\ &\%d_3 \geq 0 \end{aligned}$$

all system constraints … (19)

5.5.Results and discussion

The multi-objective model was run with varying importance assigned to each of the objectives of total cost, total time and total communication effectiveness of a supplier network. ILOG Cplex 4.0 was used to check for the feasibility of the formulation of the optimization problems and the Excel Premium solver platform version 7.0 was used to solve them.

In the goal programming problem, the ranges for importance weights given to each of the objectives vary. In the present problem, it has been identified that the total cost attains most optimum/minimum value at $w_1 = 3.2$. Similarly, total time attains a most optimum/minimum value at $w_2 = 0.3$ and total communication effectiveness of the supplier network attains most optimum/maximum value at $w_3 = 422.2$. The lower limit for all these weights is zero. We call the set (w_1, w_2, w_3) as importance weight triad.

For a set of 10 randomly chosen importance weight triads, we have generated graphs with each of the objective functions on the Y-axis. Table 18 shows the ten importance weight triads. We used MATLAB 7.1.0 to generate the three graphs. Figure 5 shows the graph of varying total cost of the supplier network at different sets of importance weight triads to the objectives. As is evident from the graph, the total cost attains minimum value at the importance weight triad (3.2, 0, 0) in iteration number 9. Similarly, the varying values of optimum total time of the supplier network at different importance weight triads are shown graphically in Figure 16. Here, the total time equals its goal for the first time at the importance weight triad (0, 0.3, 0) in iteration number 1. Figure 17 portrays the graph of varying CE vs. corresponding importance weights triads. This graph shows that the optimum value of the communication effectiveness reaches its goal at the importance weight triad (0, 0,422.2) in iteration number 1. Thus, it is observed that the values of three objectives obtained through optimization are subjective to the relative importance given to each of them, apart from the supplier capabilities and other assumptions in the present paper. However, for the purpose of illustration, we have taken the importance weight triad as (0.8, 0.05, 0.15) corresponding to iteration number 5 as given in Table 16. With these values, the multi-objective optimization is solved to obtain a supplier network that is robust to changing product architecture over the given planning horizon, at optimal cost, time and CE. The results are shown in Tables 19. It is evident from Table 19 that the efficient values deviate from the goals due to the values of the importance weights to each of the objectives. Table 20 demonstrates the supplier network selected for four terms in the planning horizon. It can be observed from this table that the same supplier meets the customer needs of each of the first four design chunks at optimum cost, time and CE for the entire planning horizon However, the supplier supplying the design chunk 'Dose display' had to be switched to another supplier in the last term. In this way, the optimization problem selects suppliers for an extended period so that the total supplier network cost (which includes switch-over cost and quality-loss cost) is minimized, total supplier network time is minimized, and total supplier network CE is maximized compromisingly.

6. Stage 2: production supplier network formation

Corresponding to the production phase, there are three types of production suppliers. They are as follows: assembly suppliers supplying sub-assemblies; manufacturing suppliers supplying components and COTSS (COTS suppliers) supplying COTS (Components-off-the-shelf). Each assembly supplier assembles the components of its sub-assembly, procured from its lower tier manufacturing suppliers. In Figure 14, the components C31 and C32 are COTS because the management decides that the needle of the insulin delivery device can be best obtained as COTS. COTSS are treated as manufacturing suppliers in this stage.

In the present methodology, the discrete supply capabilities are considered for assembly suppliers (as shown in Table 21) and continuous supply capabilities are assumed for manufacturing suppliers As shown in Table 21, in term 1, the assembly supplier AS11 can supply the cartridge sub-assembly in quantities of either 100,000 or 200,000. Table 22 shows supply capabilities of the manufacturing suppliers available for the planning horizon. As seen from Table 22, in term 1, the manufacturing supplier MS21 has the supply capability of 300,000 units. It means that the manufacturing supplier can supply any number of holders up to a maximum of 300,000 units.

Each of the discrete demands of an assembly supplier is called as a demand copy of the assembly supplier. For each such demand copy, there exists a pool of manufacturing suppliers as given in Table 23. Through linear goal-programming approach, the set of manufacturing suppliers that supply the required quantity of components for the sub-assembly configuration at optimum cost, time and communication effectiveness are selected. Thus, having selected the supplier network for the second tier, we proceed with solving the integrator’s problem of selecting the production supplier network, with the same objective functions formulation. The multi-objective optimization problems are solved with goals set by solving each of the following three objectives individually.

6.1. Production cost

The total production cost of supplier network for the production phase is modeled as the sum of assembly supplier's assembly and manufacturing cost, and manufacturing supplier's manufacturing cost. The mathematical formulation for the total supplier network production cost is given by Equation 20.

$$TPC = \sum_{m=1}^{7}\sum_{t=1}^{4}[\sum_{n=1}^{am}(\sum_{p=pl}^{pu}(AUAC_{mtnp} + AUPC_{mtnp}) \times P_{mtn} \times y_{mtnp}) + (UPC_{mtn} \times X_{mtn})] \div D_{mt}$$

$$+ SC_{mnt,\, t+1} \times y_{mnt,\, t+1} \qquad \textbf{...}\ (20)$$

where

TPC = Total production cost of supplier network

y_{mntp}= binary variable to denote the selection of a supplier n providing the discrete demand copy p of part m in term t of the planning horizon.

$AUAC_{mntp}$ = Sum of unit assembly cost and unit defect cost of assembly supplier n for part m, providing the discrete demand copy p.

$ACUP_{mntp}$ = Unit production cost of assembly supplier n for part m, providing the discrete demand copy p.

P_{mnt} = Supply of the supplier n in supplying part m in term t.

D_{mt} = demand of part m in term t of the planning horizon.

UPC_{mnt} = Unit production cost of part m supplied by the supplier n in term t of the planning horizon

X_{mnt} = Supply of the supplier n in supplying part m in term t.

a_m = number of first tier suppliers available for the part m

p_l = minimum amount of capacity in units of a supplier

p_u = maximum amount of capacity in units of a supplier.

$SC_{mnt,t+1}$ = switch-over cost expended by changing supplier n selected in term t, in the next term $t+1$ for part m.

The constraints considered for this objective are listed below:

1. Each assembly supplier can supply not more than one demand copy.

$$\forall m,\ \forall t,\ \forall n,\ \sum_{p=p_l}^{p_u} y = 1 \qquad \dots (21)$$

2. The total supply of each part from multiple assembly suppliers in a term is exactly equal to its demand for that term of planning horizon.

$$\forall m,\ \forall t,\ \forall p,\ \sum_{n=1}^{am} D_{mtnp} \times y_{mtnp} = D_{mtp} \qquad \dots (22)$$

3. The total supply of each part from manufacturing suppliers is exactly equal to its demand.

$$\forall m, \quad \forall t, \quad \sum_{n=1}^{am} \sum_{p=pl}^{pu} X_{mtnp} = D_{mtnp} \qquad \ldots (23)$$

4. The supply of a manufacturing supplier in a term is less than its capacity for that term.

$$\forall t, \ \forall n, \ \forall \mathrm{m}, \ \sum_{p=pl}^{pu} X_{mtnp} \leq C_{mtnp} \qquad \ldots (24)$$

In Equation 24, C_{mtnp} = capacity of supplier n providing part m with capacity p in term t of the planning horizon.

In this stage, the quality loss cost has not been considered since the demand requirements of the customers are assumed to be satisfied through either single or multiple production suppliers.

6.2.Production time

Similar to the total design time model, the total production time depends on the early finish time of the last activity. However, in this stage, all the activities (assembly and production) have finish-to-start relationships without lag. Thus, Equation 25 determines the total production time of the production supplier network.

$$TPT = EFT_I \qquad \ldots (25)$$

where

TPT = Total Production time of supplier network for the given planning horizon

EFT_I = Early finish time of the integrator's task.

Apart from the constraints considered for the total production cost, the following constraints are regarded for this objective.

1. Relations of early start time and early finish time of the various tasks involved.

$$\forall t, \quad EFT_I - EST_I = T_I \qquad \ldots (26)$$

2. Integration starts only after all the assembly and production suppliers finish their tasks.

$$\forall t, \quad \sum_{m=1}^{7} \sum_{n=1}^{am} \sum_{p=pl}^{pu} EST_I - y_{mtnp} \times T_{mtnp} \geq 0 \qquad \ldots (27)$$

In the Equations 26 and 27,

T_I = Time for integration

EST_I = Early start time of integrator for a given term in planning horizon.

T_{mtnp} = Time taken by supplier n with capacity p to provide part m in term t of the planning horizon.

The capacity constraints of different suppliers and constraint on selection of atmost one demand copy of an assembly supplier in each term are imposed along with the lag relationships, early-start-time and early-finish-time relationships for this objective.

6.3.Production supplier network CE

The model for communication effectiveness in the second stage is similar to that in the first stage except for the insignificance of interface strength and modification of supplier dependency number as mentioned in section 2.2.

The net communication effectiveness is mathematically formulated and is given by Equation 28.

$$NCE_P = \sum_{m=1}^{7} \sum_{t=1}^{4} \sum_{n=1}^{a_m} \sum_{p=p_l}^{p_u} (\alpha' \times \theta \times \beta \times y_{mtnp}) \qquad \ldots (28)$$

where

NCE_P = Net communication effectiveness of the production supplier network

α'_m = Design dependency of part i

θ_m = functional importance of the design chunk i

β_{mtnp} = communication capability factor of supplier n providing quantity p of part m during term t of the planning horizon.

y_{mntp} = binary variable to denote the selection of a supplier k for the instance j of the design chunk i in term t of the planning horizon.

a_m = number of first tier suppliers available for the part m

p_l = minimum amount of capacity in units of a supplier

p_u = maximum amount of capacity in units of a supplier.

For solving the optimization problem of communication effectiveness of production supplier network, all constraints that have been considered for the production cost are considered.

6.4. Goal programming

The formulation for the multi-objective optimization in the production phase is similar to that used in the design phase as mentioned in sub-section 5.4. However, in this phase, as can be seen in Figure 5 for production supplier network, there are two tiers of suppliers. Firstly, the goal programming is used on tier-two suppliers to obtain the optimized values of cost, time and communication effectiveness of assembly suppliers. These values are then used to solve the optimization problem of the integrator with a similar approach.

6.5. Results and discussion

The goal programming is run at both the first tier and the second tier of the production supplier network. In the second tier, the manufacturing supplier pool supplying each of the available assembly suppliers is considered. From this pool, an optimal supplier network for each assembly supplier is selected. The importance weights for the three objectives of cost, time and communication effectiveness have been randomly selected as 0.8, 0.05 and 0.15, respectively for showing the results.

The optimal supplier networks for each of the demand copies of the assembly supplier AS11 are shown in Table 24. From these second-tier supplier networks formed, the optimal values of cost and time for these networks are obtained as given in Table 25. However, the communication effectiveness values of these supplier networks are not added to obtain the communication effectiveness of the first tier supplier networks. The number of suppliers in each of these networks is used to estimate the tier dependency and thereby the value of production supplier dependency factor (α'). Thus, the optimized values of cost, time and the number of suppliers selected (obtained from the second tier) are used as input to the optimization problem of the first tier.

Having solved all optimization problems of the second tier and obtained the necessary values for the first tier problem, we solve the cost minimization problem to get an individually optimized value of \$191.90. This is the sum of the unit costs of insulin delivery devices of the four terms of the planning horizon. Similarly, the individually optimized time is 85.38 days and the net communication effectiveness is 7.29. These values are set as goals for the respective objectives and using the formulation for the mixed-integer linear goal programming approach, the efficient objective values are obtained. In the present case, they are same as that of the goals as provided in Table 26.

This may be attributed to the fact that the present constraints are satisfied and the goals are reached without the need for compromise among the objectives. The resultant supplier network is the optimal supplier network for the entire planning horizon. Table 27 depicts the supplier network of the integrator. In Table 27, it can be seen that each part is supplied by multiple assembly/manufacturing suppliers. In some cases, the same supplier supplies the required part in required quantity for two or more terms in the planning horizon. For example, for the part, *cartridge screw*, the supplier *MS1* supplies the required quantity for the entire planning horizon at optimal cost, time, and CE.

7. Conclusions and future work

In this paper, we have proposed a novel two-stage supplier selection methodology for the realization of an evolving product family. In the first stage, the customer requirements are provided as input. They have been used by the integrator to select the detail product design and the design supplier network simultaneously. The supplier network selected in this process is optimal in terms of cost, time, and communication effectiveness. In the next stage, the detail design is used to select the production suppliers. The production supplier network considered in this study is two-tiered. In the first tier, there are assembly suppliers as well as manufacturing suppliers. The manufacturing suppliers supplying the first-tier assembly suppliers are present in the second tier. Thus, in the second stage of the present methodology, the suppliers are selected in a tier-wise fashion. The same optimization formulation is used in the second tier and then in the first tier for supplier network selection.

The present methodology has been illustrated by using the case example of insulin delivery device product family. For each of the two phases of product design and production, the suppliers are selected on the basis of three objectives: total cost, total time, and net communication effectiveness of the supplier network. Mixed integer linear goal programming approach is used to solve the three objectives. As a result, an optimal supplier network is formed for each of the two phases. It can be observed that there is a trade-off among the three mutually conflicting objectives while solving the multi-objective optimization problem. Hence, depending on the importance weights assigned to each of their allowable deviations, the efficient values may/may not deviate from their goals.

In the present methodology for optimal selection of supplier networks, we did not consider an explicit demand model. Further, the supplier communication capability index (β) can be modeled in more detail. A more comprehensive model would be to list different factors of communication capability for different types of suppliers (design suppliers, assembly suppliers, manufacturing suppliers, and COTS suppliers) and the integrator. The compatibility issues among various manufacturing processes can be captured in production supplier network communication effectiveness by introducing a term called Part manufacturing compatibility index (γ'). Consideration of supplier selection criteria like environmental issues, demographic factors, and reliability would make the problem richer. The data quoted by the suppliers can be associated with certain probability. Further, the weights to each of the objectives (supplier selection criteria) can be associated with fuzziness. Additional investigation in these areas would be possible future work in this direction.

Another major extension of the present research is the simultaneous selection of supplier networks for both product design and production phases. Then, the optimization process would select suppliers in both the phases considering the compatibility issues between design and production phases of the product from the view of the capabilities of suppliers.

Similar approach can be used to select suppliers in other phases of the product life-cycle. This assists the product realization firms to select optimal supplier networks at any or all phases of the product life-cycle, thus reducing the cost and time invested in product development projects.

8. References

AMELIA, S.C., and KAYNAK, 2007, Communication methods, information sharing, supplier development and performance: An empirical study of their relationships. International Journal of Operations & Production Management, 27(4), pp. 346-370.

BARUT, M., FAISST, W., and KANET, J., Measuring supply chain coupling: an information system perspective. European Journal of Purchasing and Supply Management, 8(3), pp. 161-171.

BOWMAN, D., FARLEYN, J.U., and SCHMITTLEIN, D.C., 2000, Cross-national empirical generalization in business services buying behavior. Journal of International Business Studies, 31(4), pp.667-85.

BURTON, D., and USLAN, M., 2006, Diabetes and visual impairment: Are insulin pens accessible? Access World: Technology and People with Visual Impairments, 7(4). Available online at http://www.afb.org/afbpress/pub.asp?DocID=aw070403 (Last accessed on 20 August 2007).

BUSKENS, V., BATENBURG, R. S. and WEESIE, J., 2003, Embedded Partner Selection in Relations between Firms. Research in the Sociology of Organizations, 20: pp. 107-133.

CALANTONE, R.J., and STANKO, M.A., 2007, Drivers of outsourced innovation: An Exploratory Study. Journal of Product Innovation, 24(3), pp. 230-241.

CAPALDO G., RAFFA L., and, RIPPA P., 2005, Information flows evaluation enhancing buyer-supplier relationships performance: the case of an e-supply chain portal. EurOMA Conference, June 19-22, Budapest, Hungary (Working paper).

CARR, A.S., and PEARSON, J.N., 1999, Strategically managed buyer-supplier relationships and performance outcomes. Journal of Operations Management, 17(5), pp. 497-519.

CARRASCOSA, M., EPPINGER, S.D., and WHITNEY, D.E., 1998, Using the design structure matrix to estimate product development. ASME Design Engineering Technical Conferences - Design Automation Conference, Atlanta, GA, ASME Paper No. DETC98-6013.

CARRILLO, J.E., and FRANZA, R.M., 2006, Investing in product development and production capabilities: The crucial linkage between time-to-market and ramp-up time. European Journal of Operations Research, 171, pp. 536-556.

CARSON, S.J., 2007, When to give up control of outsourced new product development. Journal of Marketing, 71, pp. 49-66.

CHESBROUGH, H.W., and TEECE, D.J., 1996, When is Virtual Virtuous? Organizing for Innovation. Harvard Business Review, 74(1), pp. 65-71.

CHOPRA, S., and MEINDL, P., 2007, Supply chain management: Strategy, planning and operation, Prentice Hall, Upper Saddle River, NJ, pp. 1-24.

CLARK, K.B., 1989, Project scope and project performance: The effects of parts strategy and supplier involvement on product development. Management Science, 35(10), pp. 1247–1263.

CHEN, C.T., LIN, C.T., and HUANG, S.F., 2006, A fuzzy approach for supplier evaluation and selection in supply chain management. International Journal of Production Economics, 102(2), pp. 289-301.

CHOY, K. L., LEE, W. B., LAU, H. C. W. and CHOY, L. C., 2005, A knowledge-based supplier intelligence retrieval system for outsource manufacturing. Knowledge-Based Systems, 18(1), pp. 1-17.

DAHAN, E., and J. R. HAUSER, 2002, The virtual customer. Journal of Product Innovation Management, 19(5), pp. 332-354.

DEUTSCH, C.H., 2004, Outsourcing Design. New York Times, December 30, C1.

DE WECK, O., SUH., E.S., and CHANG, D., 2003, Product family and platform portfolio optimization. ASME Design Engineering Technical Conferences- Design Automation Conference, Shimada, K. (Ed.), Chicago, IL, ASME, Paper No. DETC2003/DAC-48721.

DICKSON, P.R., 1996, The Static and Dynamic Mechanics of Competition: A Comment on Hunt and Morgan's Comparative Advantage Theory**.** Journal of Marketing, 60(4), pp. 102-106, doi: 10.2307/1251904.

DOWLATSHAHI, S., 1997, The role of product design in designer–buyer–supplier interface. Production Planning and Control, 8(6), pp. 522–532.

EPPINGER, S.D., and SALMINEN, V., 2001, Patterns of product development interactions. International Conference on Engineering Design ICED01, Glasgow, Scotland, ISBN 1860583547, pp. 283-290.

FYNES, B., and VOSS, C., 2002, The moderating effect of buyer-supplier relationships on quality practices and performance. International Journal of Operations & Production Management, 22(6), pp. 589-613.

GOFFIN, K., LEMKE, F., and SZWEJCZEWSKI, M., 2006, An exploratory study of close supplier-manufacturer relationships, Journal of Operations Management, 24, pp. 189-209.

GRAEBSCH, M., 2005, Information and Communication in Lean Product Development (American Edition). Lean Aerospace Institute, MIT.

GRYNA, F.M., CHUA, R.C.H., and DEFEO, 2007, Juran’s quality planning & analysis for enterprise quality. McGraw-Hill, New York, pp. 1-5.

GUPTA, S., and V. KRISHNAN, 1999, Integrated component and supplier selection for a product family. Production and Operations Management, 8(2), pp. 163-181.

HA, A.Y., and, PORTEUS, E.L., 1995, Optimal timing of reviews in concurrent design for manufacturability. Management Science, 41, pp. 1431-1447.

HIRAKUBO, N. and KUBLIN, M., 1998, The relative importance of supplier selection criteria: The case of electronic components procurement in Japan. International Journal of Purchasing and Materials Management, 34(2), pp. 19-24.

HUANG, G.Q., ZHANG, X.Y., and LO, V.H.Y., 2005, Optimal supply chain configuration for platform products: Impacts of commonality demand variability and quantity discount. International Journal of Mass Customization, 1 (1), pp. 107-133.

HUANG, S.H., and KESKAR, H., 2007, Comprehensive and configurable metrics for supplier selection. International journal of production economics, 105(2), pp. 510-523.

HUMPHREYS, P.K., WONG, Y.K., and CHAN, F.T.S., 2003, Integrating environmental criteria into the supplier selection process. Journal of Materials Processing Technology, 138(1/3), pp.349-56.

JOHNSON, M., 1997, Outsourcing in Brief, Butterworth-Heinemann, Linacre House, Jordan Hill, Oxford OX2 8DP, Institute of management, Woburn, MA.

KAMANN, D.-J. F. and BAKKER, E. F., 2004, Changing supplier selection and relationship practices: a contagion process. Journal of Purchasing and Supply Management, 10(2), pp. 55-64.

KARPAK, B., KASUGANTI, R.R., and KUMCU, E., 1999a, Multi-objective decision-making in supplier selection: an application of visual interactive goal programming. Journal of Applied Business Research, 15(2), pp. 57-71.

KARPAK, B., KUMCU, E., and KASUGANTI, R.R., 1999b, An application of visual interactive goal programming: a case in vendor selection decisions. Journal of Multi-criteria Decisions Analysis, 8(2), pp. 93-105.

KAYNAK, E., 1989, How Chinese buyers rate foreign suppliers. Industrial Marketing Management, 18(3): pp. 187-198.

KESSLER, E.H., BIERLY, P.E., and GOPALAKRISHNAN, S., 2000, Internal vs. External Learning in New Product Development: Effects on Speed, Costs, and Competitive Advantage. R&D Management, 30(3), pp. 213-23.

KRISHNAN, V., EPPINGER, S.D., and WHITNEY, D.E., 1997, A Model-based framework to develop product development activities. Management Science, 43(4), pp. 437-451.

KULKARNI, R.S., ALLEN, J.K., and MISTREE, F., 2005, Designing product families for a changing market space. ASME Design Engineering Technical Conferences - Design Theory and Methodology, Long beach, California, ASME Paper No. DETC2005-85164.

KUMAR, M., VRAT, P., and SHANKAR, R., 2004, A fuzzy goal programming approach for vendor selection problem in supply chain. Computer & Industrial Engineering, 46, pp. 69-85.

KUMAR, S., and KROBB, W.A., 2005, Managing product life cycle in a supply chain, Springer, New York, Chap. 2, pp. 11-17.

KURAWARWALA, A.A., and MATSUO, H., 1993, Cost of delay in time to market and capacity restriction. Working paper 93-01-02, University of Texas, Austin.

LEE, H. L., 2002, Aligning supply chain strategies with product uncertainties. California Management Review, 44(3), pp. 105-119.

LINDER, J.C., 2004, Transformational outsourcing. MIT Sloan Management Review, 45(2), pp. 52-58.

LYNCH, C.F., 2004, Why outsource. Supply chain management review, 8(7), pp. 44-51.
MEHTA, M., 2005, Design competitively. Industrial Engineer, 37(11), pp. 26.

McGINNIS, M.A., and VALLOPRA, R., 1999, Purchasing and supplier involvement: Issues and insights regarding new products success. Journal of Supply Chain Management, 35(3), pp. 4–15.

McIVOR, R.T., HUMPHREYS, P.K., and HUANG, G., 2000, Electronic commerce: reengineering the buyer-supplier interface. Business Process Management Journal, 6(2), pp.122-38.

MEYER, M.H., and LEHNERD, A.P., 1997, The Power of Product Platforms: Building Value and Cost Leadership, Free Press, New York, NY.

MIKKOLA, J.H., and LARSEN,S.T., 2003, Early supplier involvement: Implications for new product development, outsourcing and supplier-buyer interdependence. Global Journal of Flexible Systems Management, 4(4), pp. 31-41.

MURRAY, J.Y., KOTABE, M. and ZHOU, J. N., 2005, Strategic alliance-based sourcing and market performance: evidence from foreign firms operating in China. Journal of International Business Studies, 36(2), pp. 187-208.

ONO, Y., 2007, Market thickness and outsourcing services. Regional Science and Urban Economics, 37, pp. 220-238.

OTTO, K.N., and WOOD, K.L., 2001, Product design: Techniques in reverse engineering and new product development. Prentice Hall, NJ, Chap. 7, pp. 297-298.

OUCHI, W.G., and DOWLING, J.B., 1974, Defining the span of control. Administrative Science Quarterly, 19(3), pp. 357-365.

PARK, B.J., 2001, A framework for integrating product platform development with global supply chain configuration. Ph.D. thesis, Georgia Institute of Technology, Atlanta, Georgia.

PIMMLER, T.U., and EPPINGER, S.D., 1994, Integration analysis of product decompositions. ASME Design Engineering Technical Conferences - Design Theory and Methodology, Minneapolis, MN.

PINE, B.J., 1993, Mass Customization: The New Frontier in Business Competition, Harvard Business School, Press, Boston, MA.

PRAHINSKI, C. and W.C. BENTON, 2004, Supplier Evaluations: Communication Strategies to Improve Supplier Performance. Journal of Operations Management 22(1), pp. 39-62.

PRAHINSKI, C., and FAN, Y., 2007, Supplier Evaluations: The Role of Communication Quality. The Journal of Supply Chain Management, 43(3), Summer, pp. 16-28.

PURVIS, D., 2006, Partners for lifecycle. Product design & development, December edition, Advantage Business Media, NJ, USA.

QUINN, J.B., 2000, Outsourcing innovation: The new engine growth. Sloan Management Review, 41 (summer), pp. 13-28.

RAGATZ, G.L., HANDFIELD, R.B., and SCANELL, T.V., 1997, Success factors for integrating suppliers into product development. Journal of Product Innovation Management, 14 (3), pp. 190–203.

RARDIN, R.L., 1998, Optimization in operations research. Prentice Hall, NJ, pp. 389-400.

RIPPA P., 2005, Information Sharing in buyer-supplier relationships in Purchasing and Supply Management: Theory and Practice. 9th and 10th IFPSM Summer School, Salzburg.

ROMERO, C., 1991, Handbook of critical issues in goal programming, Pergamon press, NY, pp. 35-40.

SHARLAND, A., ELTANTAWY, R. A., and GIUNIPERO, L. C., 2003, The impact of cycle time on supplier selection and subsequent performance outcomes. Journal of Supply Chain Management: A Global Review of Purchasing and Supply, 39(3).

SIMPSON, T.W., SIDDIQUE, Z., and Jiao, J.R., 2006, Product platform and product family design: methods and applications. Springer, NY, pp. 73-90, Chap. 5.

SINGH, R.K., KUMAR, S., CHOUDHURY, A.K., and TIWARI, M.K., 2006, Lean tool selection in a die casting unit: A fuzzy-based decision support heuristic. International Journal of Production Research, 44(7), pp. 1399-1429.

SMITH, P.G., and REINERTSEN, D.G., 1998, Developing products in half the time: New rules, new tools. John Wiley & Sons, Inc., NY, pp. 23-24, Chap. 2.

SOSA, M.E., 2000, Analyzing the effects of product architecture on technical communication in product development organizations. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA.

TENNETI, B., 2005, Robust supplier set selection for changing product architectures. Master of Science thesis, University of Missouri-Rolla, Rolla, MO.

ULRICH, K.T., and EPPINGER, S.D., 2005, Product design and development. McGraw-Hill, Inc., New York.

WARD, A.C., 2007, Lean product and process development. Lean Enterprise Institute, Cambridge, MA, USA, Part 2, pp. 29-36.

WASTI, S.N., and LIKER, J.K., 1997, Risky Business or Competitive Power? Supplier Involvement in Japanese Product Design. Journal of Product Innovation Management, 14, pp. 337-355.

WEBER, C., CURRENT, J., and BENTON, W.C., 1991, Vendor Selection Criteria and Methods. European Journal of Operations Research, 50, pp. 2-18.

WHEELWRIGHT, S.C., and K.B. CLARK, 1992, Revolutionizing product development. Free Press, New York, pp. 34-36.

WHEELWRIGHT, S.C., and SASSER, W.E. Jr., 1989, The new product development map, Harvard Business Review, 67(3), pp. 112-125.

WILLOUGHBY, M., 2006, SOA: Enabler of Mass Customization. Available online at: http://www.nextgenerationinsights.com/story.php?id=1206200602 (Last accessed 20 August 2007).

WILSON, E.L., 1994, The relative importance of supplier selection criteria: a review and update. International Journal of Purchasing and Materials Management, Summer, pp. 35-41.

WIND, Y., and SAATY, T.L., 1980, Marketing applications of the analytical hierarchy Process. Management Science, 26(7), pp. 641-658.

YASSINE, A.A., and WISSMANN, L.A., 2007, Implications of Product architecture on the firm. Systems Engineering, 10(2), pp. 118-137.

Table 1. Supplier categories

S no.	**Broad stages in product value chain**	**Type of suppliers**	**Abbreviation**
1	Concept design	Concept suppliers	CS
2	Detail design	Design suppliers	DS
3	Manufacturing	Manufacturing suppliers	MS
		COTS suppliers	DMS
4	Assembly	Assembly suppliers	AS
5	Logistics	Logistics suppliers	LS
6	After-sales	After-sales suppliers	AS

Table 2. Modified scale for DSM

Effect of the presence of interaction	**Scale**
Necessary or detrimental for functionality	2
Beneficial or harmful but not necessary	1
Indifferent (doesn’t affect functionality)	0

Table 3. Part interactions matrix

Parts	**1**	**2**	**3**	**4**	**5**
1	0	S(2)=2	E(2)+S(1)=3	S(2)+M(2)=4	0
2	S(2)=2	0	S(2)=2	0	S(2)=2
3	E(2)+S(1)=3	S(2)=2	0	E(2)=2	S(2)+E(2)=4
4	S(2)+M(2)=4	0	E(2)=2	0	E(2)=2
5	0	S(2)=2	S(2)+E(2)=4	E(2)=2	0

Table 4. Part interface strength calculation

Parts	**1**	**2**	**3**	**4**	**5**	**γ**
1	0	0.33	0.27	0.5	0	0.22
2	0.22	0	0.18	0	0.25	0.13
3	0.33	0.33	0	0.25	0.5	**0.28**
4	0.44	0	0.18	0	0.25	0.175
5	0	0.33	0.36	0.25	0	0.189

Table 5. Parts delivering the various functions of the product family

Primary (P) / Secondary (S)	**Functions**	**Parts providing the functions**
P	Deliver insulin	1, 3, 4
P	Protect needle	2, 4
S	Display dialed units	5
S	Sound click at the delivery of each unit	3
S	Show previous insulin dosage	3, 5
S	Display blood glucose reading	2
S	View the remaining insulin units in the cartridge	2
P	Cause minimum pain during shots	4
S	Provide sales appeal	2
S	Retract the dial knob after dialing	3
P	Protect the insulin from direct sun-light	2
S	Stop dialing when the cartridge is empty	3

Table 6. Functional importance of each part

Part #	**No. of functions the part renders**	**Functional importance of the part**
1	P(1)	0.06
2	P(2), S(3)	0.19
3	P(1), S(4)	0.15
4	P(3)	0.19
5	S(2)	0.04

Table 7. Values of the constants in the logarithmic equation for supplier dependency factor

A	**b**	**c**	**d**	**B**
-0.2	7.8	-1	0.8	7.4

Table 8. Calculation of design supplier dependency factor (α)

Part #	**Supplier dependency number**	**α = a*log(b(x+c))+d**
1	1	1
2	2	0.595
3	4	0.485
4	3	0.525
5	4	0.485

Table 9. Calculation of production supplier dependency factor (α') in two planning horizon terms for 1st tier suppliers

	Month 1			**Month 2**		
Tier -1 Suppliers	Capacity In terms of quantity of parts	Supplier task dependency factor	Supplier dependency factor (α')	Capacity In terms of quantity of parts	Supplier task dependency factor	Supplier dependency factor (α')
AS11	100	2	1	100	2	1
	200	3	1	200	3	1
				300	2	1
AS12	100	2	1	100	2	1
				200	2	1
AS31	300	3	1	300	3	1
	600	6	0.504005	600	5	0.578686
AS32	600	4	1	900	5	0.578686
	900	6	0.504005			

Table 10. Factors for assessing supplier communication capability

Willingness to share information
Willingness to change
Trust
Level of quality practices
Commitment for relational continuity
Familiarity with the present business

Table 11. Changing specifications for the design chunk ‘enclosure’ during the planning horizon

Features/parameters	**Year 1**	**Year 2**	**Year 3**	**Year 4**
Material	Metal	Plastic	Plastic	Plastic
Weight	2.5 ounces	2 ounces	2 ounces	3.5 ounces
Additional features	None	Glucometer	Memory	Glucometer and memory

Table 12.Quality-loss costs for different components

Design chunk	**Features**	**Quality-loss concept**	**k (\$/unit spec^2)**	**Unit quality-loss cost**
Insulin reservoir	Capacity	Nominal-the-best	70	$k(y-m)^2$
	Plastic	Y/N	300	Constant
	Pre-filled	Y/N	500	Constant
Enclosure	Plastic	Y/N	300	Constant
	Weight	Nominal-the-best	480	$k(y-m)^2$
	Glucometer	Y/N	700	constant
Delivery mechanism	Maximum dose	Larger-the-better	500000	$k(1/y)^2$
	Viewed size of dose	Nominal-the-best	30000	$k(y-m)^2$
	Accuracy of dosage	Larger-the-better	200	$k(1/y)^2$
	Retractable	Y/N	310	Constant
	Technology	Y/N	500	Constant
Insulin delivery	Guage	Larger-the-better	70000	$k(1/y)^2$
	Length	Smaller-the-better	4	$k(y)^2$
Dose display	Digital	Y/N	600	Constant
	Memory	Y/N	700	Constant

Table 13. Availability of design chunk instances

DESIGN CHUNK	**INSTANCES**	**YEAR1**	**YEAR2**	**YEAR3**	**YEAR4**
Insulin reservoir	CT1	■	■	■	■
	CT2	■	■	■	■
	CT3	□	□	■	□
Enclosure	CA1	■	■	■	■
	CA2	■	■	■	■
	CA3	□	□	□	■
Delivery mechanism	DM1	■	■	■	■
	DM2	■	■	■	■
	DM3	■	□	□	□
Insulin delivery	ID1	■	■	■	■
	ID2	■	■	■	■
	ID3	□	□	■	□
Dose display	DD1	■	■	■	■
	DD2	■	■	■	■

Notation:

■ Availability in the term

□ Unavailability in the term

Table 14. Translation of design chunks to structural parts

Design chunks	**Corresponding structural part(s)**
Insulin reservoir	Cartridge
Case	Barrel
	Pen cap
	Holder
Delivery mechanism	Cartridge screw
Insulin delivery part	Needle sub-assembly
Dose display	Dial knob

Table 15. Manufacturing bill of materials (MBOM)

Parts	**Features**	**Month 1**	**Month 2**	**Month 3**	**Month 4**
		Specifications			
Cartridge	Capacity	3ml			
	Material	Glass		Plastic	Polypropylene
	Filling	Prefilled		Refill	
Barrel, *Pen cap,* *Holder*	Material	Metal			
	Weight	2.5 ounces	2 ounces		3.5 ounces
	Additional features	None	glucometer	Glucometer and memory	None
Cartridge screw	Maximum dose	80			
	Viewed size of dose	0.1		0.15	0.2
	Accuracy of dosage	2	1		0.5
	Retractibility	Non-retractable		Retractable	Non-adjustable
	Technology	manual			computerized
Needle sub-assembly	Gauge	29		31	31
	Length	5		12.5	5
Dial knob	Type	Analog		Digital	
	Additional features	None			memory

Table 16. Demand of the respective product variant in each term of the production planning horizon

	Month 1	**Month 2**	**Month 3**	**Month 4**
Demand (in thousands of units)	100	200	300	400

Table 17. Capacity requirements of structural parts of insulin delivery device product families for planning horizon

Parts	Month 1	Month 2	Month 3	Month 4
Cartridge	100	200	300	400
Barrel	100	200	300	400
Pen cap	100	200	300	400
Holder	100	200	300	400
Cartridge screw	100	200	300	400
Needle sub-assembly	300	600	900	1200
Dial knob	100	200	300	400

Table 18. Importance weight triads in various iterations

Iteration number	Importance weight triad values		
1	0	0.3	0
2	1	0	0
3	0	1	0
4	0	0	1
5	0.8	0.05	0.15
6	1	1	0
7	0	1	1
8	1	0	1
9	3.2	0	0
10	0	0	422.2

Table 19. Efficient values of design supplier network objectives for the planning horizon

	Goals / Target values	Efficient values
Minimum total Design Cost ($)	46948.00	47305.50
Minimum total Design time (days)	117	123.6
Maximum net Design supplier network communication effectiveness (no units)	1.38	1.09

Table 20. Results - design supplier network

Design chunk	Year 1	Year 2	Year 3	Year 4
Insulin reservoir	DS122			
Case	DS211			
Delivery mechanism	DS312			
Insulin delivery part	DMS412			
Dose display	DS511			DS522

Notation:
DSijk is the k^th^ Design supplier available for j^th^ instance of i^th^ design chunk

Table 21. Available assembly suppliers and their demand copies (in 1000s of units)

Sub-assemblies	Assembly suppliers	Demand copies			
		Month 1	Month 2	Month 3	Month 4
Cartridge	AS11	100	100	100	100
		200	200	200	200
			300	300	300
					400
	AS12	100	100	100	100
			200	200	200
					300
					400
Needle sub-assembly	DMS412	300	300	600	900
		600	600		1200
	AS32	600	900	900	900
		900			

Table 22. Available manufacturing suppliers and their supply capabilities (in 1000s of units)

Parts	**Mfg. suppliers**	**Supply capabilities**			
		Month 1	**Month 2**	**Month 3**	**Month 4**
Holder	MS21	300	300	500	400
	MS22	600	600	500	900
	MS23	100	200	500	600
	MS24	200	700	800	800
Cartridge screw	MS41	100	500	550	600
	MS42	250	250	250	250
	MS43	400	450	500	550
	MS44	50	100	150	200
	MS45	500	500	400	400
Barrel	MS51	200	700	600	600
	MS52	50	50	50	50
	MS53	100	100	400	400
	MS54	50	100	150	200
Dial knob	MS61	400	400	500	600
	MS62	200	300	300	400
	MS63	150	200	700	700
	MS64	50	100	600	600
	MS65	100	150	200	200
Pen cap	MS71	30	100	200	300
	MS72	50	600	700	700
	MS73	300	300	400	400
	MS74	100	500	500	500

Table 23. Second tier suppliers (mfg. suppliers) available for assembly suppliers and their supply capabilities (in 1000s of units)

Sub-assemblies	**As suppliers**	**Parts**	**Mfg. suppliers**	**Supply capabilities**			
				Month 1	**Month 2**	**Month 3**	**Month 4**
Cartridge	AS11	*glass tube*	MS1111	50	100	150	200
			MS1112	200	250	300	350
			MS1113	150	500	550	600
		rubber-cap	MS1121	200	450	550	600
			MS1132	400	400	500	550
			MS1133	400	400	500	550
			MS1134	350	350	450	500
	AS12	*glass tube*	MS1211	600	650	700	750
			MS1212	800	850	900	950
			MS1213	400	450	500	550
		rubber-cap	MS1231	500	550	600	650
			MS1232	350	400	450	500
			MS1233	250	300	350	400
			MS1234	500	550	600	650
Needle sub-assembly	DMS 412	*Needle*	MS3111	200	300	400	500
			MS3112	400	400	300	400
			MS3113	300	400	500	600
			MS3114	100	200	300	500
		Cap	MS3121	200	300	500	700
			MS3122	300	400	500	800
			MS3123	100	200	300	400
			MS3124	300	400	400	600
	AS32	*Needle*	MS3111	300	400	500	500
			MS3112	500	300	400	700
			MS3113	200	300	300	500
			MS3114	400	400	400	600
		Cap	MS3121	300	700	500	700
			MS3122	500	600	600	500
			MS3123	400	500	700	700
			MS3124	300	400	500	600

Table 24. Sample for second tier optimal supplier network

<table>
<tr><th>Assembly supplier</th><th>Demand copies</th><th>Month 1</th><th>Month 2</th><th>Month 3</th><th>Month 4</th></tr>
<tr><td>AS11</td><td>100</td><td colspan="4">MS1113</td></tr>
<tr><td></td><td></td><td colspan="3">MS1121</td><td>MS1123</td></tr>
<tr><td></td><td>200</td><td>MS1111</td><td>---</td><td>---</td><td>---</td></tr>
<tr><td></td><td></td><td colspan="4">MS1113</td></tr>
<tr><td></td><td></td><td>MS1121</td><td>---</td><td>MS1121</td><td>---</td></tr>
<tr><td></td><td></td><td>---</td><td>MS1123</td><td>---</td><td>MS1123</td></tr>
<tr><td></td><td>300</td><td rowspan="3">NA*</td><td colspan="3">MS1113</td></tr>
<tr><td></td><td></td><td>MS1123</td><td>---</td><td>MS23</td></tr>
<tr><td></td><td></td><td>---</td><td>MS1121</td><td>---</td></tr>
<tr><td></td><td>400</td><td rowspan="3">NA*</td><td rowspan="3">NA*</td><td rowspan="3">NA*</td><td>MS1113</td></tr>
<tr><td></td><td></td><td>MS1123</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

* NA denotes not applicable.

Table 25. Sample for efficient values of second tier supplier network

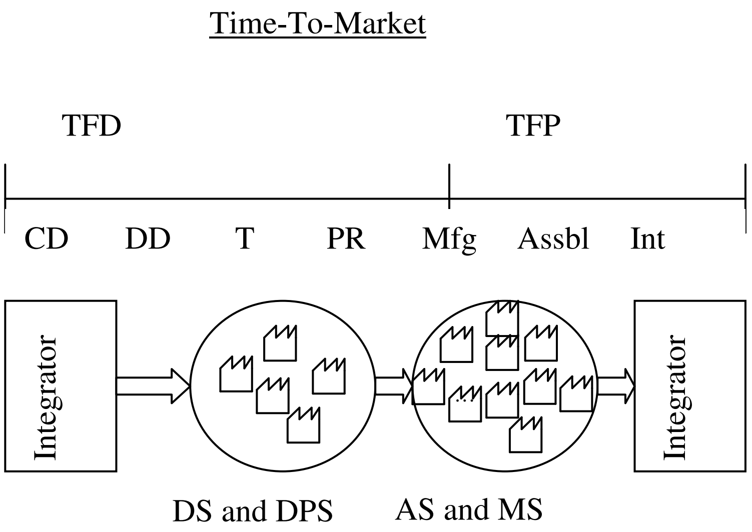
Assembly supplier	**Demand copies**	**Objective values**	**Month 1**	**Month 2**	**Month 3**	**Month 4**
AS11	*100*	*Cost ($)*	2.80	6.0	15.00	21.50
		Time (days)	12	9	11	14
	200	*Cost ($)*	3.50	7.0	15.00	21.50
		Time (days)	16	13	14	17
	300	*Cost ($)*	NA*	7.00	15.00	21.50
		Time (days)	NA*	17	17	20
	400	*Cost ($)*	NA*	NA*	NA*	21.50
		Time (days)	NA*	NA*	NA*	23

Table 26. Efficient values of production supplier network objectives for the planning horizon

	Goals / Target values	**Efficient values**
Minimum total Production Cost ($)	191.90	191.90
Minimum total Production time (days)	85.38	85.38
Maximum net Production supplier network communication effectiveness	7.297	7.297

Table 27. Results - production supplier network

<table>
<tr><th>Part</th><th>Month 1</th><th>Month 2</th><th>Month 3</th><th>Month 4</th></tr>
<tr><td rowspan="2"><i>Cartridge</i></td><td>---</td><td colspan="2">AS11</td><td>AS12</td></tr>
<tr><td colspan="2">AS21</td><td colspan="2">AS22</td></tr>
<tr><td><i>Holder</i></td><td>MS23</td><td colspan="3">MS21</td></tr>
<tr><td><i>Needle sub-assembly</i></td><td>DMS13</td><td>DMS16</td><td colspan="2">AS29</td></tr>
<tr><td><i>Cartridge screw</i></td><td colspan="4">MS41</td></tr>
<tr><td><i>Barrel</i></td><td>MS51</td><td>MS52,MS53, MS54</td><td>MS51</td><td>MS53</td></tr>
<tr><td><i>Dial knob</i></td><td>MS62</td><td colspan="3">MS61</td></tr>
<tr><td><i>Pen cap</i></td><td>MS71, MS72, MS74</td><td>MS73</td><td colspan="2">MS72</td></tr>
</table>



Notation:

TFD: Time for Design
TFP: Time for Production
DS: Design supplier
DPS: Design and Production supplier
AS: Assembly supplier
MS: Manufacturing supplier

CD: Concept design
DD: Detail design
T: Testing
PR: Production ramp-up
Mfg. Manufacturing
Assbl: Assembly
Int: Integration

Figure 1. Product realization process

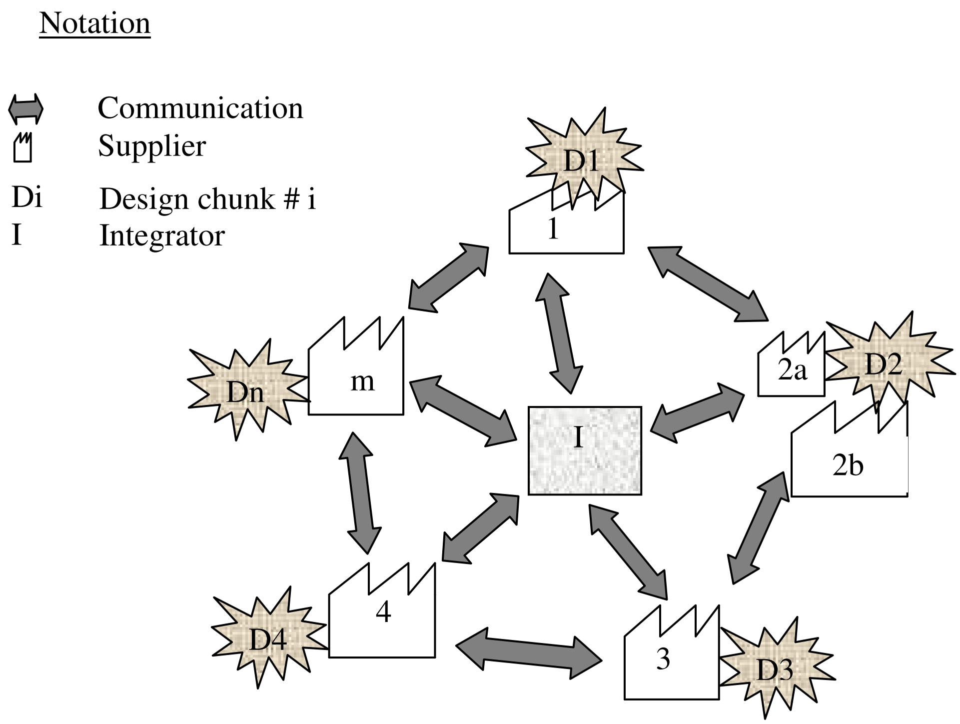


Figure 2. Communication effectiveness (CE) for a design supplier network

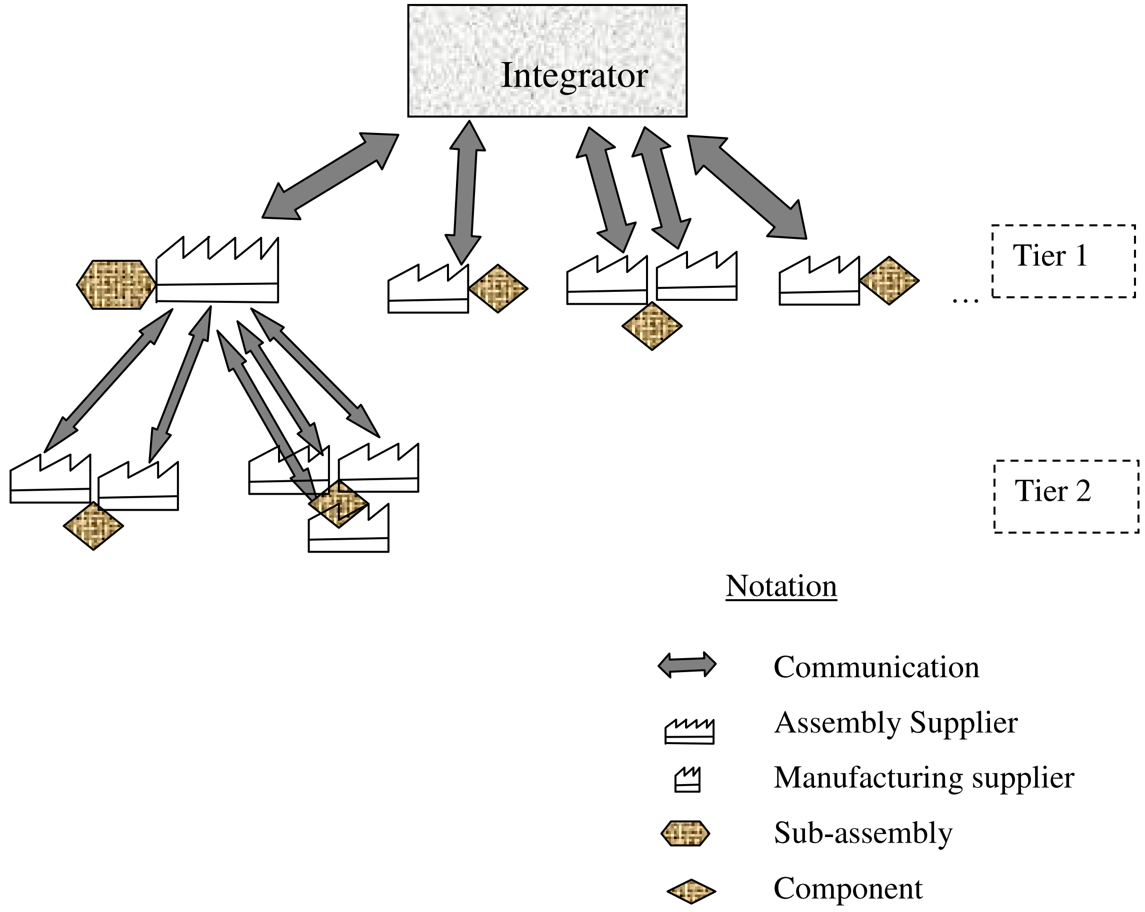


Figure 3. Communication effectiveness (CE) for a production supplier network

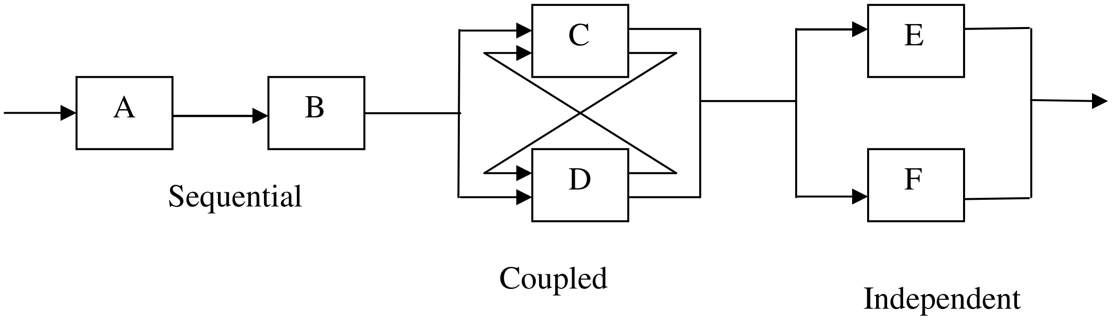
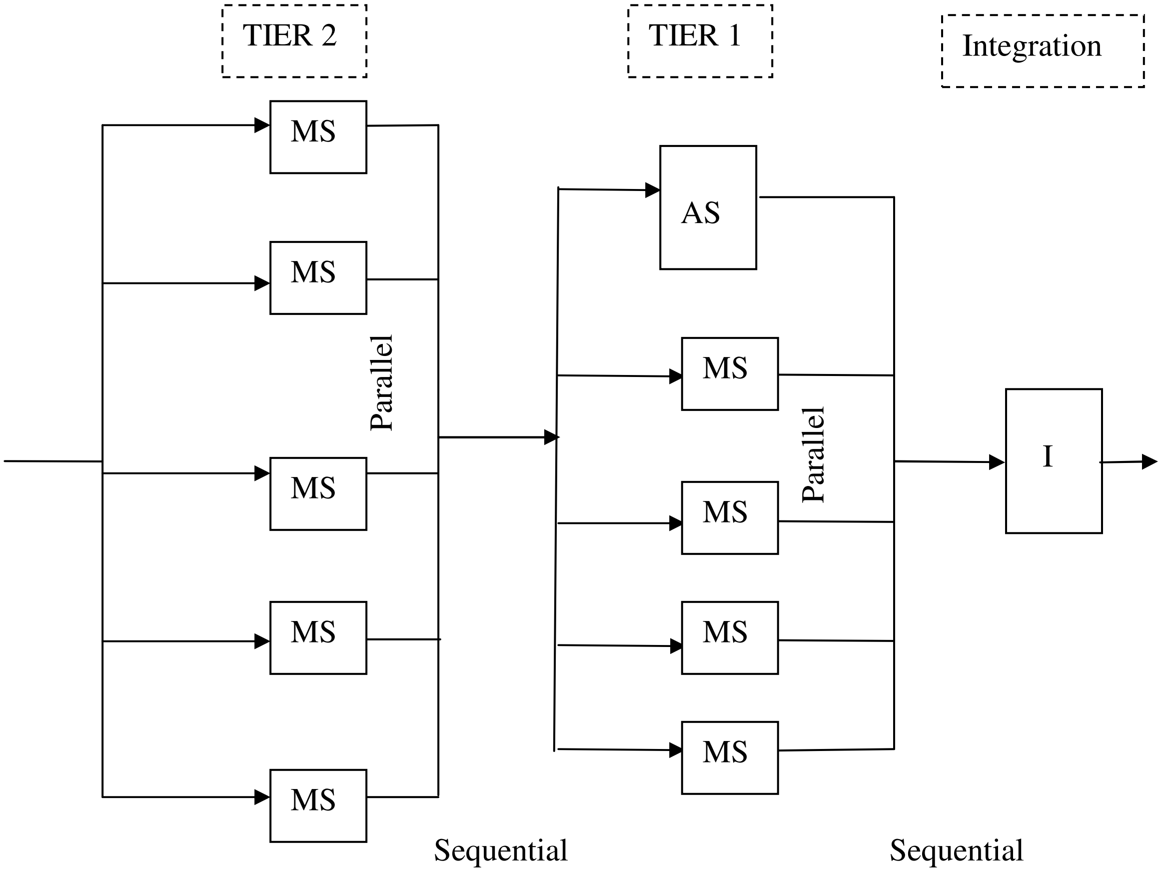
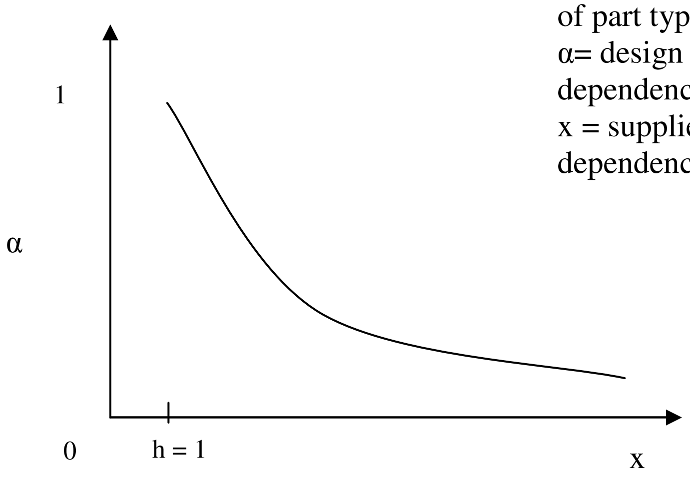


Figure 4. Design task diagraph (chain dependency)



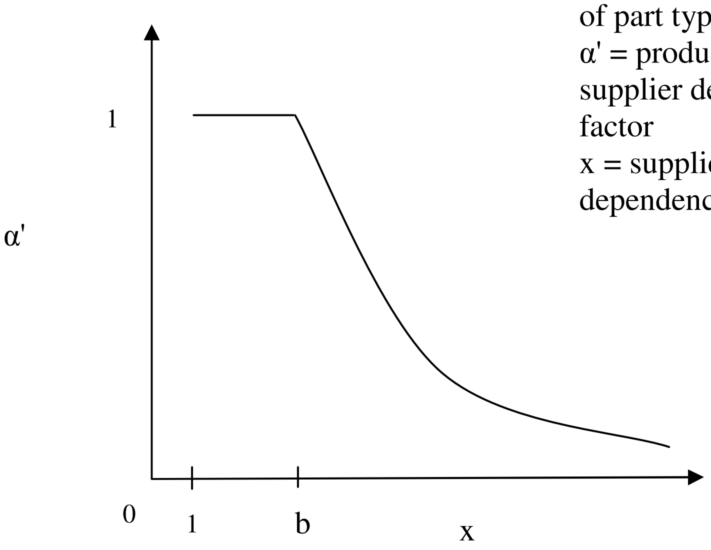
Notation:
AS: Assembly supplier
MS: Manufacturing supplier
I: Integrator

Figure 5. Production task diagraph



Notation:
h = threshold number of part types
α= design supplier dependency factor
x = supplier dependency number

Figure 6. Graph for design supplier dependency factor



Notation:
b = threshold number of part types
α' = production supplier dependency factor
x = supplier dependency number

Figure 7. Graph for production supplier dependency factor

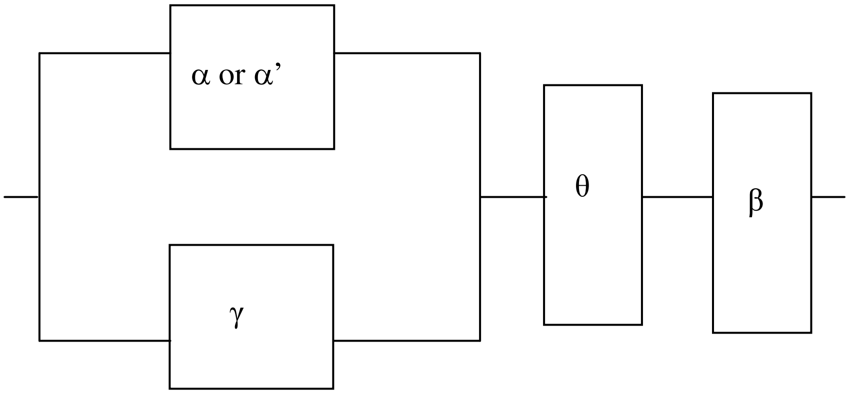


Figure 8. Basis for the formulation of communication effectiveness

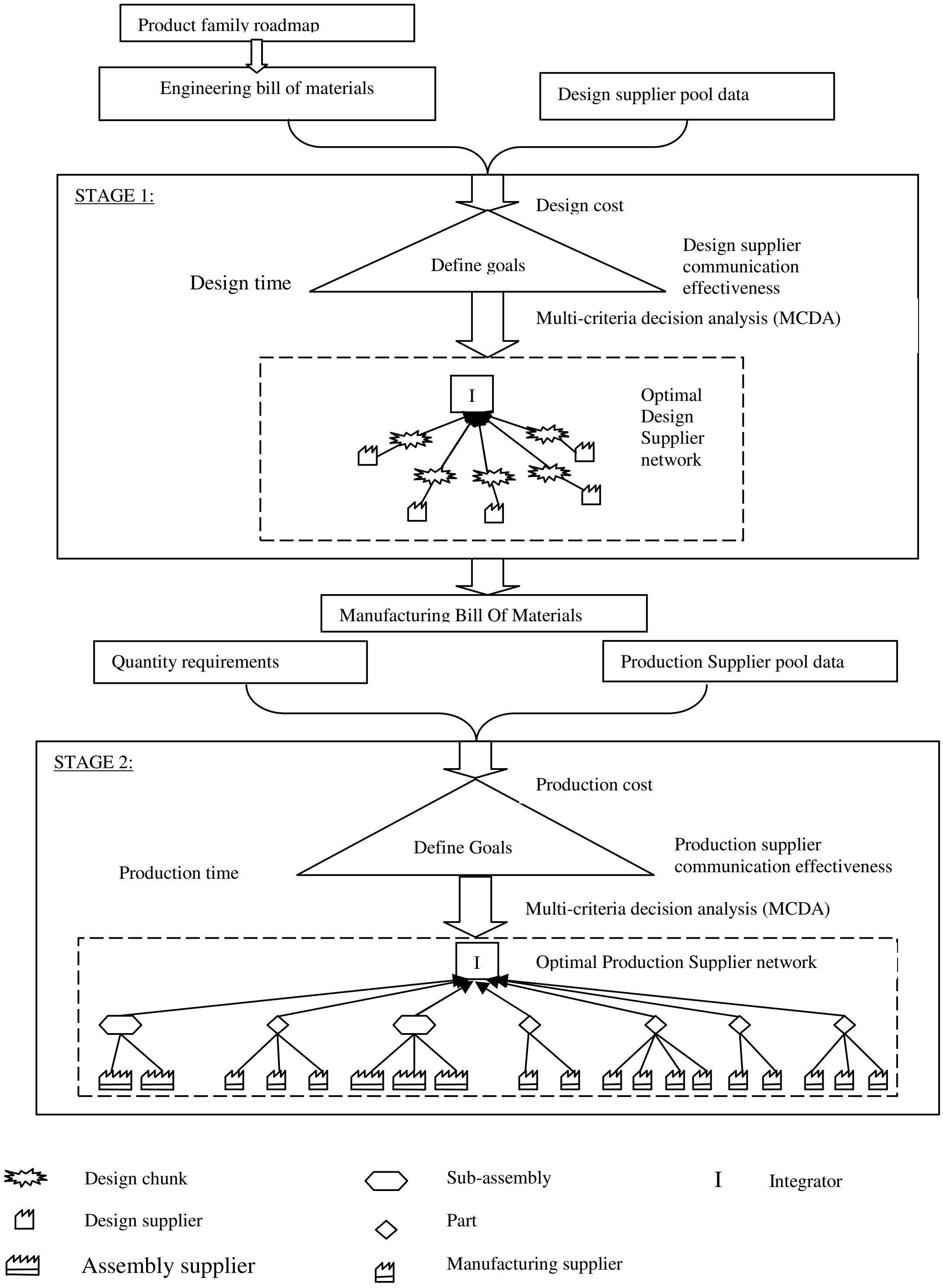
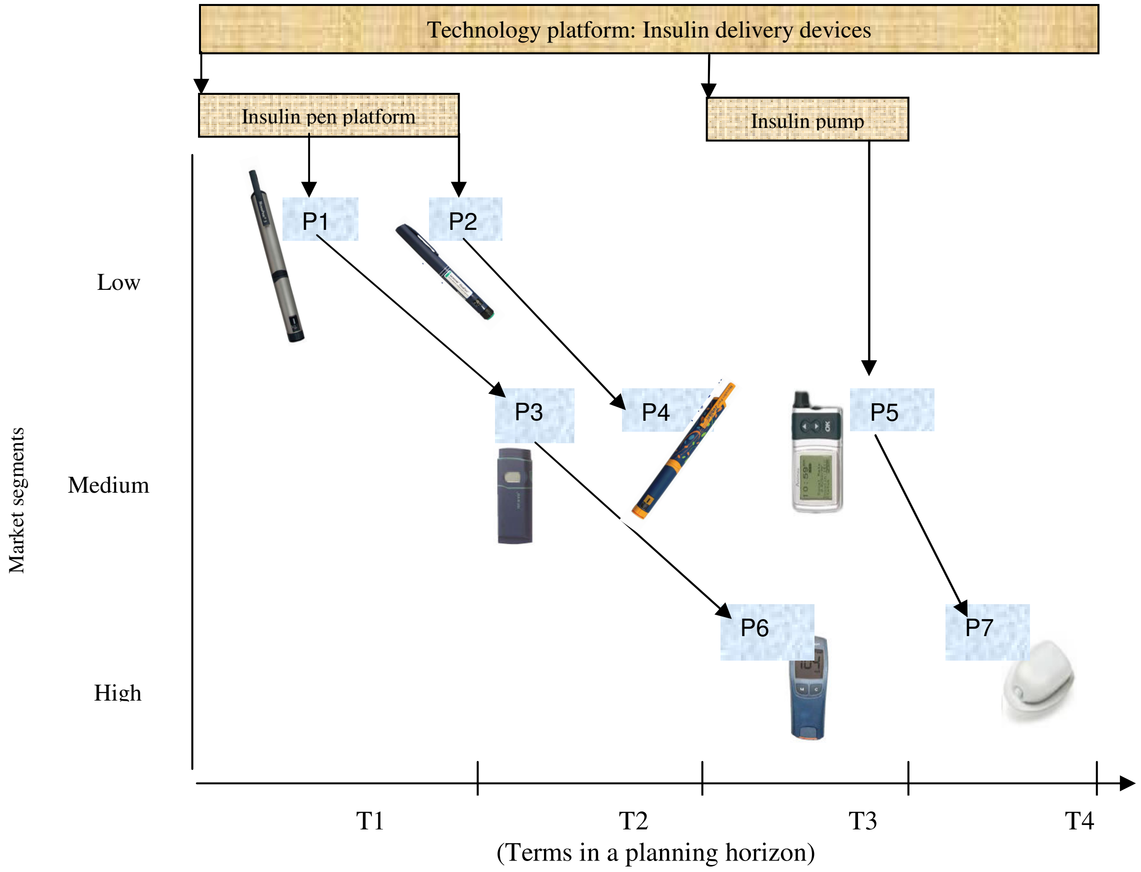


Figure 9: Flow diagram of the methodology



P1: Permanent pen
P2. Temporary pen
P3. Permanent pen with digital dose display
P4. Temporary junior pen
P5. Insulin pump
P6. Permanent pen with attached glucometer
P7. Insulin pump with glucometer and memory

M1: Market for Kids – P2, P3, P7
M2: Market for Middle age – P1, P6
M3: Market for Old age – P4, P5

Figure 10. Product family roadmap for insulin delivery devices

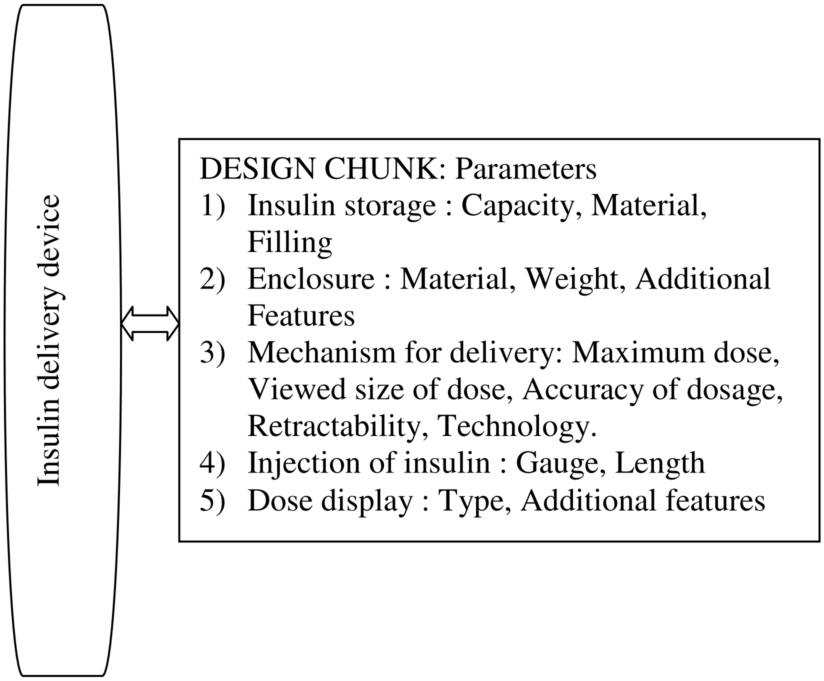
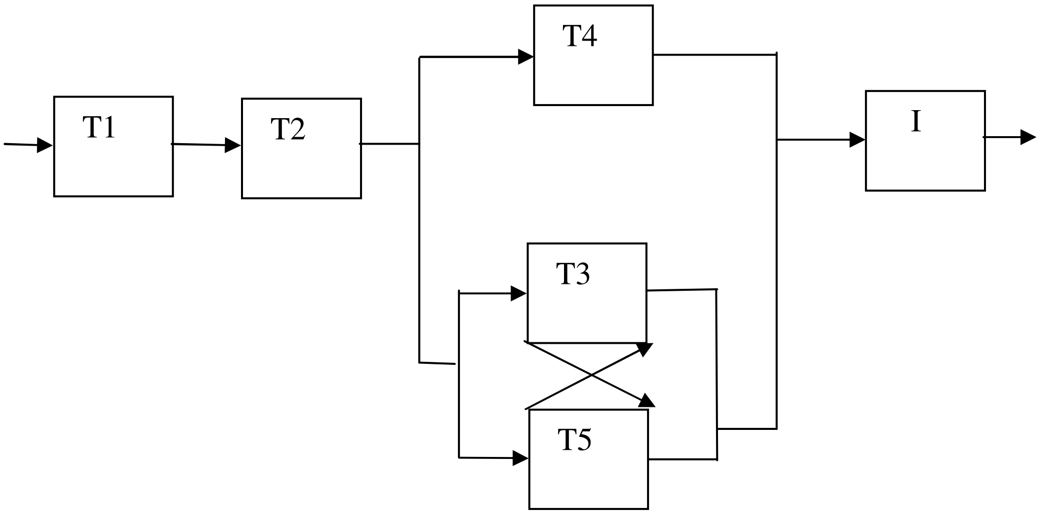


Figure 11. Engineering bill of materials (EBOM) for insulin delivery device product families



Notation:
Ti = Task of designing the design chunk i
I = Integration task

Figure 12. Design task diagraph for an insulin delivery device

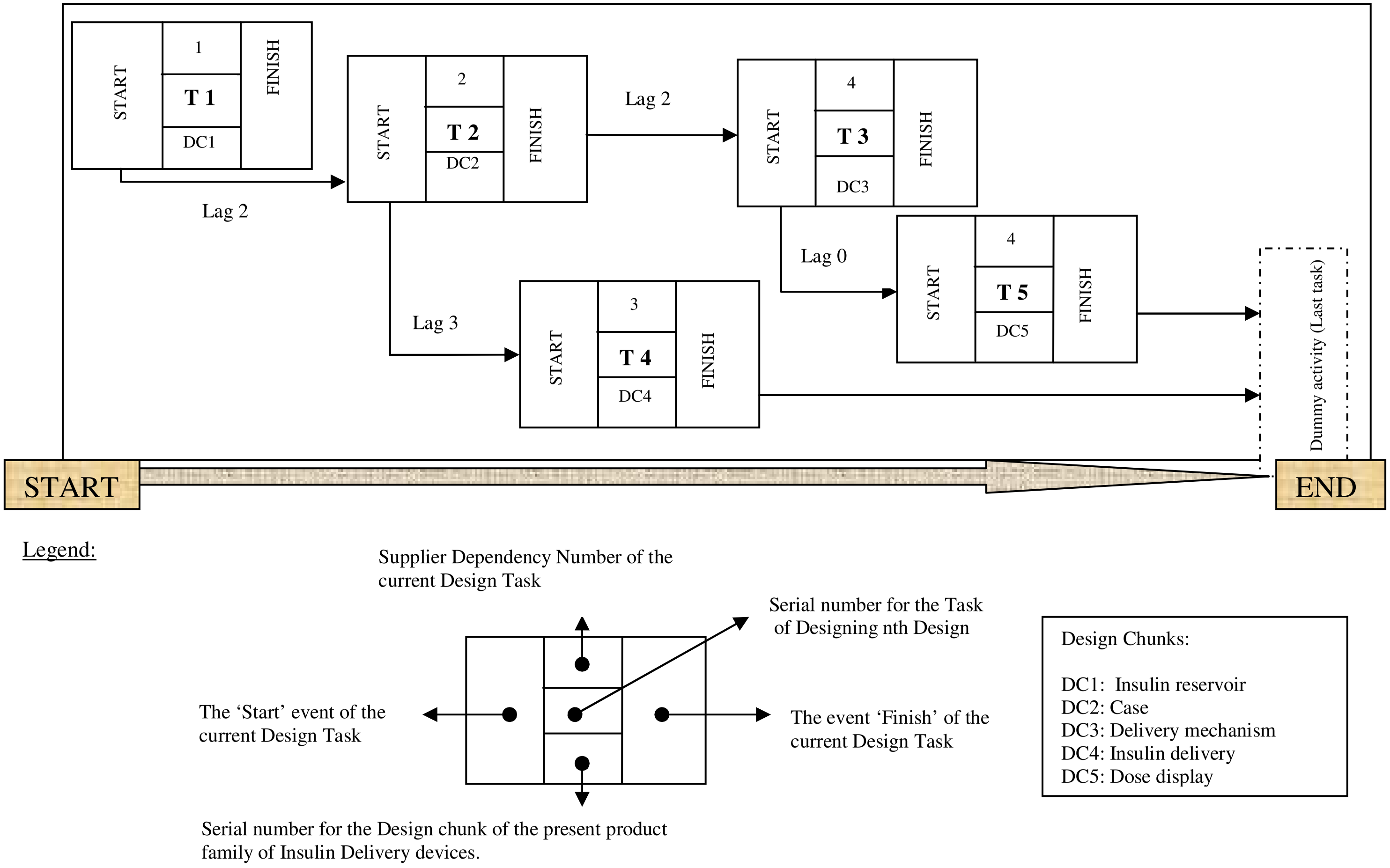


Figure 13. Design dependency diagram for an insulin delivery device

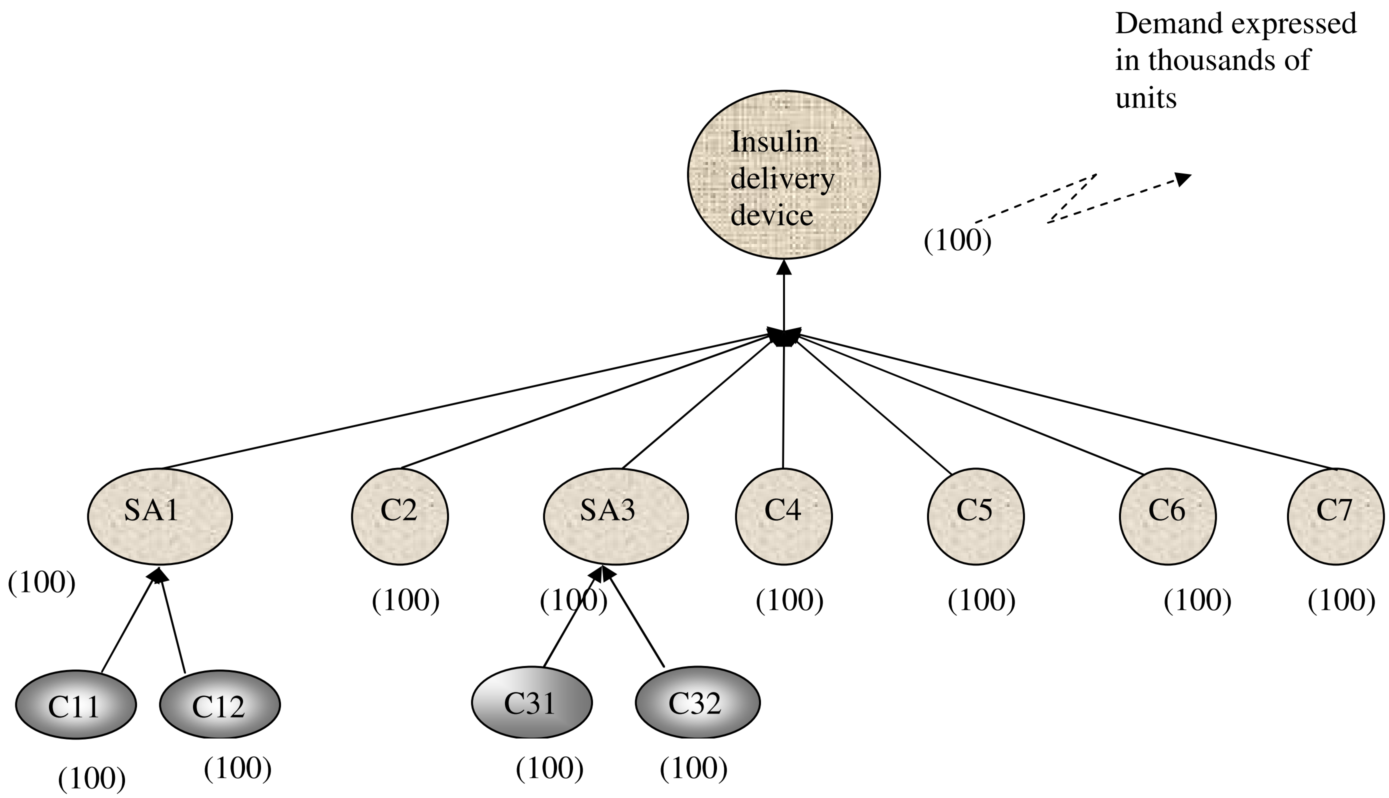


Figure 14. Operational product architecture for an insulin delivery device with quantity requirements for 1st term of the planning horizon

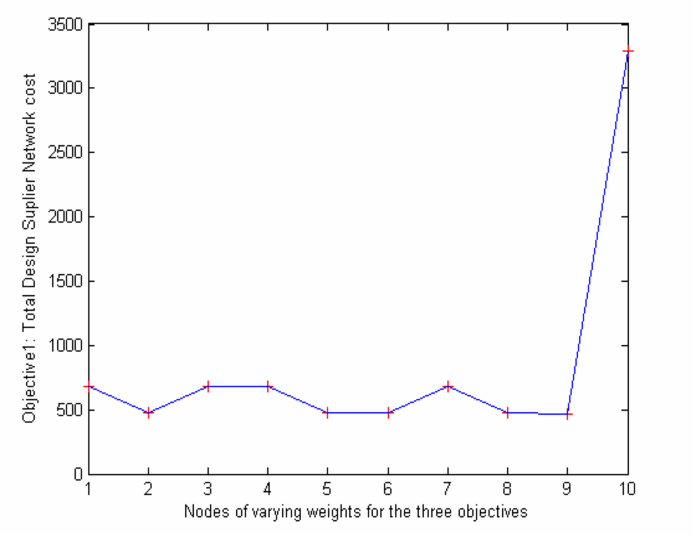


Figure 15. Graph of design cost vs. importance weight triads

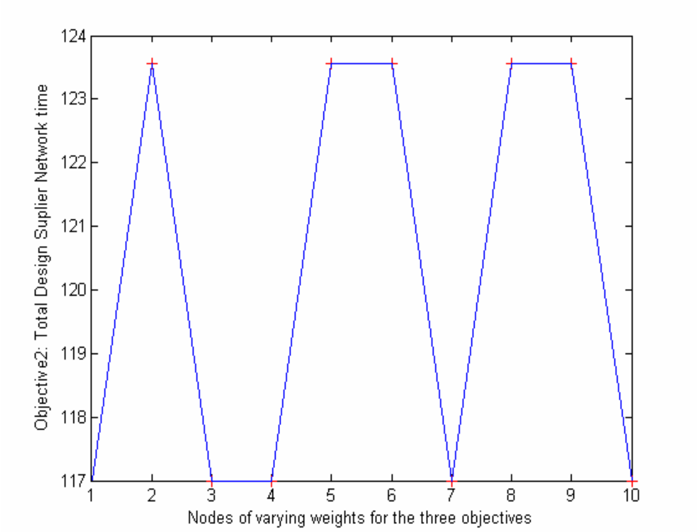


Figure 16. Graph of design time vs. importance weight triads

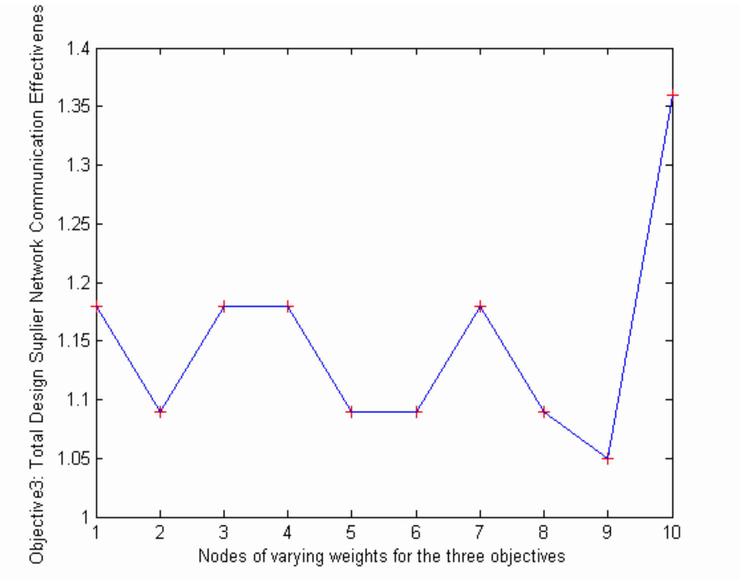


Figure 17. Graph of design CE vs. importance weight triads

VITA

Ms. Padmavathi Krishna Pakala was born on December 18, 1982 in the city of Pithapuram, India. Padma pursued her Bachelors degree in the Mechanical Engineering from one of the top engineering schools in India: Birla Institute of Science & Technology (BITS)- Pilani. During the undergraduation, Padma did several useful projects during undergraduate studies as well as in her intern in ECE Industries Pvt. LTd., and co-op in Intelligroup Asia Ltd. During the intern, she got interested in the activities the company undertakes, including design, manufacturing, quality & inspection, and supplier management. This inspired her to pursue higher studies in manufacturing engineering and attain further technical expertise. She graduated with B.E.(Hons) Mechanical Engineering in May 2005. Then, she joined as a graduate student in University of Missouri-Rolla (UMR), USA for Manufacturing Engineering program in August, 2005. During this period, she worked in Sustainable Design Laboratory (SDL) and handled several projects and attended several conferences. At UMR-SDL, the concept of lean fascinated her as lean implementation is necessary in everything and everywhere. She gained knowledge in Lean implementation in varied environments like product design, manufacturing, supply chain and administration, and also applied practically. She is graduating from University of Missouri-Rolla as a Manufacturing Engineer in December 2007.

Padma is a self-starter and an achiever. Apart from academic life, she pursues interests in music, arts, and nature. She also finds keen interest in socializing and has been known for maintaining a good rapport with her colleagues and peers.