Fall 2007

Integrated product and its extended enterprise network design using lean principles

Abhijit K. Choudhury

INTEGRATED PRODUCT AND ITS EXTENDED ENTERPRISE NETWORK DESIGN USING LEAN PRINCIPLES

by

ABHIJIT KUMAR CHOUDHURY

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 ENGINEERING MANAGEMENT

2007

Approved by

Venkat Allada, Advisor

Cihan Dagli

Robert B. Stone

To my parents, brother

and

my mentor and friends.

PUBLICATION THESIS OPTION

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

ABSTRACT

Recently, many system integration companies have begun to intensely focus on suppliers' involvement in the product realization process to enhance their competitiveness. The product architecture has a huge impact on the efficiency of the integrator's supplier network. One of the ways to enhance efficiency is to implement the lean principles while creating a collaborative design/manufacturing/supply chain environment. In this study, two distinct stages of the product realization process, namely, design stage and production stage are considered for determining the design and production supplier networks. A distinction is made between different types of suppliers involved in the product realization process, such as design suppliers, and assembly and production suppliers in the production stage. Apart from using parameters such as development time and development cost for evaluating the product realization process, the concept of communication effectiveness has been formalized to form the supplier networks. A goal programming based approach is used to determine the optimal supplier network. The effect of part count reduction strategy as a lean tool to enhance the "leanness" of a supplier network has been studied using a case example of a power drill.

ACKNOWLEDGMENTS

At this important juncture, I would like to take the opportunity to acknowledge the people who have been part of my research and also life at UMR. I would like to thank my advisor, Dr. Venkat Allada, who has always shown confidence in me and worked tirelessly honing me towards perfection. He not only introduced me to this interesting research topic but also maintained the tempo so I remained focused. I would like to thank my thesis committee members, Dr. Cihan Dagli and Dr. Robert Stone, for their insightful comments. I can't imagine my research and personal life without the help and support of my wonderful friends. I would specially mention the name of Padmavathi Krishna Pakala, who has always been my research mate in different projects and has always been the source of my inspiration. Long and protracted discussions on different topics with her have been the hallmark of the present research. I am grateful to the support and encouragement rendered by Mohit Goswami, Pradeep Tipaji, Deepak Tickoo, Sofia Tan, Rahul Rai, Rupesh Kumar, Maneesh Kumar, and Shrikant Jarugumilli during this work, and also for participating in thought-provoking discussions.

I would like to thank some of the people whose importance in my life can't be expressed in words and have been an important source of inspiration for the present work. First I would like to acknowledge my parents and brother, who are a constant source of inspiration who have always showed confidence in me. I would also like to acknowledge my Guruji, Prof. M. K. Tiwari and Usha Aunty, without whose support I would never achieved what I am today. I would also like acknowledge a few of my friends like Maneesh, Rohit, Niraj, Prakash, Raj, Anand, Alok, Yogi, Rahul Sir, Srinivas Sir and the list continues. I would also like to acknowledge my other family members.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

Table Page

Integrated product and its extended enterprise network design using lean principles

Abhijit K. Choudhury* and Venkat Allada**

*Sustainable Design Laboratory, Engineering Management Building, University of Missouri-Rolla, Rolla, MO. 65409. Ph no. (573) 341- 4573

Corresponding Author: 119 Fulton Hall, University of Missouri-Rolla, Rolla, MO 65409 Ph no. (573) 341-4573, allada@umr.edu**

Abstract

Recently, many system integration companies have begun to intensely focus on suppliers' involvement in the product realization process to enhance their competitiveness. The product architecture has a huge impact on the efficiency of the integrator's supplier network. One of the ways to enhance efficiency is to implement the lean principles while creating a collaborative design/manufacturing/supply chain environment. In this study, two distinct stages of the product realization process, namely, design stage and production stage are considered for determining the design and production supplier networks. A distinction is made between different types of suppliers involved in the product realization process, such as design suppliers, and assembly and production suppliers in the production stage. Apart from using parameters such as development time and development cost for evaluating the product realization process, the concept of communication effectiveness has been formalized to form the supplier networks. A goal programming based approach is used to determine the optimal supplier network. The effect of part count reduction strategy as a lean tool to enhance the "leanness" of a supplier network has been studied using a case example of a power drill.

Keywords**:** Product Architecture, Supplier Network, Lean Principles, Communication Effectiveness

1. Introduction

Recently, many companies have begun to focus on the efficient design and management of the extended enterprise network that involves the integrator company and its suppliers and customers along the value chain. The focus has shifted from individual efficiency of the collaborators involved in the value chain to the overall efficiency of the entire value chain. Theories like transaction cost analysis (TCA) have been utilized by researchers to analyze various issues like the impact of outsourcing and insourcing decisions on the organizational efficiency (Calantone and Stanko 2007). Although, outsourcing has been a key business process for the past decade, it has not been well-managed by the firms (Tompkins 2005). Sometimes, the presence of adversarial relationships among the collaborators of the value chain and reliance on past industry practices like "arm's length relationships" has driven the costs up to unprecedented levels. One recent study of the U. S. food industry estimated that poor coordination among supply chain partners leads to wastage of $30 billion annually (Fisher 1997). Clark (1989) and Sako and Helper (1995) in their pioneering work on the impact of supplier relationships on the performance of the various auto companies in Europe, Japan, and USA emphasized the importance of collaborative and sustained relationships for efficient value chain of the product. Similar observations have been noted by Cusumano and Takeishi (1991) and Clark (1989) where they observed that longer and healthier supplier relationships of the Japanese auto makers helped them to introduce new products quickly in the marketplace.

Product design and architecture influences strategic actions such as make/buy decisions, supplier network configuration, decisions determining supplier network configuration, and design of the designer-supplier interfaces (Huang *et al.* 2005, Novak and Eppinger 2001, Gupta and Krishnan 1999, Wissmann and Yassine 2004, Simchi Levi *et al.* 2004, Fisher 1997, Lee 2002, Dowlatshahi 1997, Cottrill 2006). For example, during the planning phases of the Microsoft's XBox 360, the supply chain managers and designers focused on developing an optimum design considering all facets of the product realization process. Issues such as modular or integral product architecture, the complexity of the product architecture and its influence on insourcing/outsourcing decisions, and communication requirements among the suppliers and the integrators were considered (Novak and Eppinger 2001). By adopting similar practices, BMW has efficiently managed its Model 7 product line consisting of 90 exterior colors and 175 interior equipment options (Cottrill 2006). Fisher (1997) developed a framework to show the impact of the type of products on the nature of supply chain. Products were classified in two types, namely, functional products and innovative products. Fisher (1997) used different case studies to conclude that the "effectiveness" of the supply chain is the key measure for functional products and the "responsiveness" is the key measure for innovative products.

Many companies have formulated strategies for designing their supply chain network. For example, Motorola purchases complete designs for its lower-priced phones, Procter & Gamble has set a limit of outsourcing 50% of the design of new products by

2010 (Calantone and Stanko 2007). Monckza *et al.* (1997) identified various drivers of supplier integration for new product development. They are as follows: cost reduction, design and development time reduction, technology improvement, and quality improvement. Krishnan and Gupta (1999) noted the importance of early supplier involvement for the product platform development.

There are only a few works in the literature that deal simultaneously with problems of product design and supplier network formation. Krishnan and Gupta (1999) developed a mathematical framework to simultaneously select the modules and the suppliers for a family of products. They contend that integrating the supplier capabilities in the design process can reduce the number of unique suppliers and procurement costs. Hadnijicola and Kumar (1997) considered international factors like tariffs/import cost, exchange rate, and unit savings derived from economies of scale while making decisions to offer customized or standardized products, and centralized/decentralized manufacturing. Park (2001) solved the simultaneous problem of the product platform design and its global supply chain configuration for a single echelon of suppliers. Choudhury and Allada (2006) attempted a similar problem of integrated product design and supplier selection. The aim was to integrate the supplier capabilities at the system level design stage to determine the amount of Module-off-the Shelf (MOTS) and Product-specific modules (PSM) in the product architecture.

In this study, we aim to solve a simultaneous problem of product and extended enterprise network design. Although, we use the term “extended enterprise network” in this study, our focus is on the design and production phases of the product realization process.

In our literature survey, we have identified the following research gaps:

a) Most literature such as Krishnan and Gupta (1999), Hadnijicola and Kumar (1997), Park (2001), Choudhury and Allada (2006) deals with the involvement of the suppliers in the design phase of the product development. These studies did not consider the explicit distinction between different types of suppliers.

b) Hadnijicola and Kumar (1997) and Choudhury and Allada (2006) have addressed the product composition problem along with the supplier selection problem in the literature. The product composition is defined as the amount of COTS/MOTS or product specific modules (PSM) used in the product architecture. Although Choudhury and Allada (2006) solved the integrated problem of product composition and supplier selection problem, they failed to distinguish between the different types of product-specific modules. This distinction in the product specific modules arises due to different types of relationships shared between the suppliers and the main integrator, i.e., black box part suppliers and detailed controlled part suppliers.

c) The literature pertaining to the simultaneous problem of product design and supplier selection does not evaluate the effectiveness of the resultant supplier network. In this study, we investigate the impact of lean product design/development principles to enhance the efficiency of the extended enterprise network. In order to implement lean principles in a typical product development process, there are two different approaches applied by the practitioners and researchers. They are as follows:-

1. **Lean product design process improvement** – This is a process view of the entire product develop process using the value stream mapping techniques. Unnecessary

and non-value added activities are pruned using this approach. It is akin to the lean manufacturing value stream maps.

2. **Lean product development tools** – Some of the popular lean product development tools include Design Structure Matrix (DSM) (Pimmler and Eppinger 1995), Product Platform Approach (Meyer and Lehnerd 1997), Design for Manufacturing and Assembly (DFMA) (www.dfma.com), Module Function Deployment (MFD) (Ericsson and Erixon 1999).

2. Scope of the problem

In this paper, we aim to solve the simultaneous problem of product composition and supplier selection. After the supplier selection problems are solved the supplier network effectiveness is evaluated using the lean principles.

2.1. *Simultaneous design of product and its extended enterprise*

In this paper, the product design problem has been addressed in two dimensions:– (1) Product composition problem, and (2) Product redesign problem. In the product composition problem, we ascertain the percentage of off-the shelf (COTS/MOTS) and product specific modules (PSM). The decision to use a COTS/MOTS or PSM parts is based on the supplier capabilities available before the integrator. We use the categorization of different types of product specific modules based on the supplier relationships with the integrator, i.e., black box parts and the detailed controlled parts. Different criteria have been developed to ascertain the integrated product composition and supplier selection problem. These criteria have been detailed in the later stages of the paper. The second dimension relating to product redesign problem pertains to the redesign of the existing design in order to to enhance the efficiency of the extended enterprise network formed for a particular product. An example of product redesign, is clubbing of the two discrete functional modules into one. Although, we do the product consolidation (redesign) in this paper, no specific heuristic has been developed to arrive at the decision. The level of detail of the bill of material is different for various stages of the product development, i.e., details gets finer from the conceptual design stage till the production/assembly stage (Hundal 1998).

Smith and Reinertsen (1998) identified four primary factors that affect the success of the product. They are as follows: (1) Market Introduction date (2) Product Unit Cost (3) Product Performance (4) Development project expense. In this paper, we contend that these above factors critically affect the integrated product design and supplier selection problem. However, we contend that the factors like product unit cost, product performance and development project expense can be summed and termed as total product cost. For example, total product unit cost has two dimensions, i.e. unit functional chunk design cost and unit production/assembly cost of a component/sub assembly. Design feature loss cost not provided by the designer is estimated using the Taguchi quality loss function. Similarly, in the production phase the defects in the components per lot are translated back into defect loss cost per component. Thus, in this paper we have focused on factors listed by Smith and Reinerstein (1998) into two major categories, i.e., market introduction time and total unit cost.

The market introduction date or total time to market is a key factor in deciding the product's success in the market (Smith and Reinertsen 1998).As shown in Figure 1, we have sub-divided the total time to market domain in two components: (1) design and development time period and (2) production time period. With the design specifications frozen for the different design chunks in the design phase, the suppliers are selected for the production and logistics time horizon.

2.1.1. Product design and development time period

In this time horizon, the suppliers are involved early in the product realization process. The integrator prepares the Design-Bill of Material (D-BOM) of the concerned product. The D-BOM can be a system level or a conceptual architecture depending on the type of the product. For example, the design suppliers are selected to design a system level architecture in case of a functional product, whereas in the case of incremental or innovative products, the D-BOM is the conceptual architecture of the product. Since, we are dealing with a functional product in this paper we will elaborate only the system architecture (Ulrich and Eppinger 2003). In this paper, we have considered a modular system architecture, which comprises bunch of system modules and interfaces. The performance characteristics of the various design chunks and types of interfaces among the design chunks are elicited by the integrator for the subsequent design supplier selection. We have considered two types of performance characteristics defined for a design chunk, i.e., (1) Presence/absence of a design feature and (2) Scale-based parameters. For example, presence/absence of a LED is a binary decision, whereas attributes such as size, shape, and mass of a product are typically scale based parameters. In this paper, we have utilized the Taguchi's Quality Loss Function for determining the quality loss in the scale based parameters. Suppliers express their capability by providing different levels of possible performance characteristics for each design chunk. Based on their capability, the final specifications of the design chunks are decided.

Clark (1989), Fisher *et al.* (1999), and Hsuan (1999) emphasize the importance of parts strategy in the product design and development time horizon. It has affect on the supplier relationships of the integrator with its suppliers. These relationships can be classified as follows: Arm's Length relationship, and Strategic relationships. Typically arm's length relationships are found predominantly in the case of carryover parts or component/module-of-the shelf (COTS/MOTS), whereas, strategic relationships are found in the case of more customized components. In this paper, we have termed them as Product Specific Modules/Components (PSM/PSC). Both these types of components have their own advantages or disadvantages. For example, COTS/MOTS do not require engineering hours to develop them, but on other hand they can not be customized to meet every customer's requirements. On the other hand, PSM as name suggests are developed to meet variety and is typically associated with a development cost. Based on the work by Clark (1989), Zirger and Hartley (1996), Hartley *et al.* (1997), we have differentiated the product specific modules in two types: (1) Black Box parts (2) Detailed Controlled Parts. Based on the above mentioned parts classification, we have distinct supplier-buyer relationships and hence we have three distinct types of suppliers. They are as follows: **a)** COTS/MOTS suppliers, **b)** Black Box parts suppliers, **c)** Detailed Controlled parts suppliers. Further, as we mentioned earlier the black box parts suppliers typically require more time than the detailed controlled parts suppliers to design or develop a part or a component. However, based on the strategic and healthy relationships maintained by the concerned supplier this time can be minimized. In the later section, we will interpret our understanding of “healthy” relationships to derive a relationship between the development time period of black box parts suppliers and the detailed controlled parts suppliers.

Interfaces/Interactions play a crucial role in the design time horizon. Browning and Eppinger (2002) and Joglekar *et al.* (2001) considered the importance of interfaces in deciding the product development time line and the product development cost. Similarly, Sosa (2000), Eppinger and Salminen (2001), Dowlatshahi (1997) and Allen (1997) considered the impact of interfaces on the design team interactions. In this paper, we have developed an explicit model to depict the design team interactions and extended it to supplier-supplier-integrator relationships. We have termed it as the “Communication Effectiveness” of the enterprise network. The same will be detailed later in this section.

Thus, the design problem solved in this horizon is to determine the type of modules, i.e., COTS/Black Box parts/Detailed Controlled parts from a group of available modules for that particular design chunk. These modules are selected based on the capabilities of the suppliers quoting them. Based on the above discussion, we introduce the various criterion used in the integrated product design and supplier selection problem. Each supplier’s capability is judged based on these factors and thus optimal supplier network is formed.

a) Total product development time – The total time to develop/design a product is termed as the total product development time. Based on the work of Carrascosa *et al.* (1998) and Joglekar *et al.*(2001), we have identified four types of task dependencies in the product development project. A task is defined as the design and development of each design chunk. In addition, we have also defined the lag relationships based on the concepts of PERT/CPM from project management techniques.

Figure 2 represents the various types of product development task dependencies found in the litertaure.

Suppliers quote the time to design each design chunk. Based on the time quoted by the different suppliers, the aim is to select such suppliers that minimize the total product development time period. In this paper, we have considered the product development time period for each COTS/MOTS part type is negligible. However, for product specific components/modules the design suppliers provide their respective module development time period. Later, in this section we will develop an expression to determine the effective product development time for the black box part suppliers. This expression takes into account the communication effectiveness of each supplier and based on that determines the module development time for each black box parts suppliers.

b) Total design cost – The total cost to design the product is termed as the total design cost for each unit of product. This cost includes the following elements:

(1) Module development cost quoted by each supplier for a design chunk, (2) Performance Loss Cost of a module designed by a supplier, (3) Supplier development

cost to develop a supplier for designing a module of a redesigned chunk, (4) Switch over cost.

Module development cost quoted by each supplier for a design chunk – As we mentioned above, each design chunk has a certain module/part type options category, i.e. COTS/MOTS, Black Box parts, and Detailed Controlled parts. Different suppliers falling in each category provide their respective cost quotes to design/develop a unit of module. It is important to mention that there is no design and development cost for each COTS/MOTS module options for each design chunk.

Performance loss cost of a module designed by a supplier - As the requirements of each design chunk can be met by three different types of module options category, i.e. COTS/MOTS, Black Box parts and Detailed Controlled parts, we have developed an expression to calculate the performance loss cost based on Taguchi Loss function (Rai and Allada 2003). We have segregated the different performance requirements of each design chunk in two classes, viz., basic performance characteristics and additional performance characteristics. These costs will be appended to the design cost provided by the respective suppliers for each module options falling in different module category for each design chunk. It is postulated that the almost all the basic performance requirements are met by the COTS items, however for some of the additional features the product specific modules need to be developed. However, all this depends on the importance of that particular feature and the customer loss cost associated with the same.

Supplier development cost to develop a supplier for designing a module of a redesigned chunk – We are interested in redesigning the original product architecture by consolidating two or more functionally discrete design chunks into one. Therefore, the supplier selected for the previous unconsolidated design chunks may or may not be technically capable to provide the modules for these consolidated design chunks. Thus, we include the supplier development cost in the present paper to map the cost incurred by the integrator to develop that particular supplier which was selected for the original design (Goffin *et al.* 1997). However, for the original design stage there will be no supplier development cost as these suppliers are selected for the first time in the enterprise network formed for a given product.

Switch over cost **–** Since we are redesigning the product architecture, therefore the earlier suppliers may or may not be selected in the revised environment. However, this transition happens at a certain cost, i.e., Supplier switchover Cost (Tenetti and Allada 2005).

Based on the total design cost of a module pertaining to each module type (COTS/MOTS, Blackbox parts, Detailed Controlled parts) for a design chunk, we select the supplier providing the same. In this paper, we have considered the module compatibility constraints among the various module options for a given design chunk. This compatibility may arise due to the factors like working principle, technology, interfaces, etc.

2.1.2. Production time period

In this time horizon, the integrator prepares the Manufacturing/Assembly Bill of material of the concerned product architecture after the detailed design phase (Ulrich and Eppinger 2003). Similar, to the design dependency in the design and development time horizon, we have the assembly and manufacturing dependency among the different parts for the product. There are two types of components in the assembly, i.e., singleton components and the sub-assemblies. As the name suggests, singleton components comprises only one component and the sub-assemblies consists of many singleton components. Based on the types of components, we have two types of suppliers for an integrator: (i) Production Supplier (ii) Assembly suppliers. Production suppliers depend on their capacity to supply items to the integrator or the assembly supplier. On the other hand, assembly suppliers depend on their capacity to supply items to the integrator. Based on the demand of the components, we select the multiple suppliers to meet the same (Hong and Hayya 1992). Since, we wish to develop the supplier network of the integrator, we are also interested in the production suppliers of the assembly suppliers. Hence, we solve the selection problem of the assembly suppliers as well. The parameters used for the production and the assembly supplier selection are similar to the criteria used in the design supplier selection. They are as follows:

a) Production and the logistics lead time – It refers to the total time required to get all the components/sub assemblies for the final assembly at the integrator's place. Different assembly and production suppliers provide their manufacturing as well logistics lead time to deliver all the component demand allocated to them.

b) Unit cost of the production/assembly – The total unit production cost of the product is defined as sum of all the unit production cost of the components/subassemblies. This cost includes: (1) Unit production/assembly cost (2) Defect loss cost/unit of each component for each supplier (3) Supplier development cost (4) Supplier switch over cost.

2.1.3. Development of communication effectiveness model for simultaneous design of product and its extended enterprise

In addition to the usual parameters used for the integrated product design and supplier selection problem, we have developed a concept termed as the communication effectiveness of the enterprise network. In any product realization process, the level of communication present among the suppliers plays a key role in deciding an extended enterprise network's effectiveness in accomplishing its task. This is attributed to the presence of varying levels of interdependency among tasks in a product development process. In other words, a supplier network is said to be robust if its overall communication effectiveness is high. Hence, we select the suppliers that yield maximum communication effectiveness in a network. Maximizing the communication effectiveness can be seen as minimizing the supplier risk in the product realization process (Easterman and Ishii 2001).

Webster Online Dictionary defines the Communication Effectiveness as 'the ***actual*** *level of information exchanged between individuals through a common system of exchange of information.*' In the present study, we interpret this definition to mean the information exchange among different suppliers and the integrator in product development projects. It is an aggregate sum of the communication among all the possible pairs of candidates in the network. The factors affecting the communication effectiveness are identified as follows: (a) design chunk interaction strength, and (b) supplier dependency (c) functional importance of a part, and (d) supplier communication capability index.

a) Design chunk interaction strength (γ): Sosa (2000) mentioned that the presence of interfaces among the parts increases the probability of having interactions between the respective design teams. Similar work has been done by Eppinger and Salminen (2001) where they relate the component interactions to the development organization interactions. They found that there is a strong correlation between the product architecture interactions and the development team interactions. In this paper, interactions between the design chunks as determined by the product architecture are assumed to cause communication among the suppliers. For example, if two design chunks share interactions, the suppliers supplying those two chunks should have communication between them. Based on their work, we have considered that the design chunks which shares more interactions or strong interactions with other chunks their corresponding design teams or design suppliers also have the high interaction strength value. The interaction strength is calculated based on the modified Design Structure Matrix (DSM) (Pimmler and Eppinger, 1995). The modification has been done to make negative scales as absolute in the original DSM. This is done to consider at par the harmful/detrimental impacts among the two components to have a similar effect on the communication among the design teams as the necessary/beneficial interactions. Table 1 presents the revised scores for the DSM matrix to be used in the paper. We have used a revised scale to represent the four types of interactions among the components/design chunks. They are as follows: Spatial (S), Energy (E), Information (I), and Materials (M) Interactions.

Based on the revised scales of the DSM, we assign notations for the three types of interactions considered in this research. Table 2 lists the notations for the different types of interactions based on the revised scale.

b) Supplier dependency factor (α): The supplier dependency is defined as the dependency of a supplier on the other suppliers/integrator, whether for information exchange or physical exchange of parts, for accomplishing its own task. We quantity this extent of dependency by a term called the Supplier Dependency Factor (α). The supplier dependency factor measures the extent of dependency of a supplier on a scale of 0 to 1. In a way it measures the overall effectiveness of the organization in terms of its effectiveness. It is noteworthy to mention that in the extended enterprise network selection process, the supplier network that has more communication effectiveness is selected. There is a need for a factor that caters to the negative effect of higher supplier dependency. The communication effectiveness of a dependent supplier decays as the number of supplier increases beyond a certain limit (Johnson and Johnson, 1994). We will utilize this concept to minimize the part number as well as the supplier base in the present model. We argue that in the design and production stage, the task dependency is dictated by the product design, and hence, to enhance the communication effectiveness there is a need to redesign the product as well as minimize the number of suppliers. In this paper, we put forth two types of supplier dependencies existing in design and production and logistics phase. The two dependencies are as follows: (1) Chain dependency (2) Flat structure dependency. Figure 3 represents the two types of supplier dependencies. Referring to the literature on interpersonal communication, there is a communication decay/distortion in a chain dependency type situation (Johnson and Johnson 1994). Common factors like leveling the details, sharpening the focus, and assimilation memory of the message, etc., are some of the factors behind the distortion/decay of the message in chain kind of dependency. This kind of dependency is usually found in the design stage where the dependencies are more sequential in nature.

On the other hand, the flat structure dependencies are found more in assembly/product kind of scenarios. This type of dependencies are similar to the supervisor/worker kind of communication channels or commonly known as span of control in the communication literature (Ouchi and Dowling 1974). The span of control deals with the efficiency of the system in a typical manager/subordinate kind of environment. If the number of subordinates increases beyond a certain point then it leads to the decrease in the efficiency in the supervisor. Similar environment exists in a manufacturing environment, where the integrator or an assembly supplier depends on the lower tier suppliers for the parts to complete their assembly. If the number of suppliers increases beyond a certain limit then it leads to increase in the complexity of the system and decreases the efficiency. Figure 3 represents the two types of supplier dependencies in the design and production stage.

c) **Functional importance of the design chunk (θ) –** The fractional number of functions of a product that a component/sub-system satisfy is said to be functional importance of the design chunk. It is denoted by 'θ' in the present paper. The functional importance of the design chunk portrays how much the integrator wishes to give importance to the supplier communication. For example, the communication of a supplier providing low value component like a screw will have very low importance in the eyes of the integrator (Ward 2007). On the other hand, a communication pertaining to a critical component like an engine in a car will have more importance in the eyes of an integrator.

d) Supplier communication capability index (*β*) –This is determined based on a supplier's plausible communication capability with other suppliers and the integrator. It is also a factor which is measured between 0 and 1. The supplier's communication capability is decided based on the potential possible quality of interaction with other suppliers and the integrator. This communication could be cooperative, competitive, and co-opetitive (Wu and Choi, 2005). However, in this work, we have only considered the co-operative communication among the suppliers and the integrator. By co-operative communication, we mean the communication that exists among the firms through which they achieve their mutual goals (Anderson and Narus, 1990). Our aim is to gauge the effectiveness of the co-operative communication of a supplier with the other suppliers and the integrator. This communication is judged based on factors like willingness to share information, willingness to change, trust, level of quality practices, etc. These factors have been selected based on the importance of the supplier-buyer relationships on the overall quality of the products introduced in the market (Forker 1997). To compute the supplier communication capability index (β) for n-1 suppliers and one integrator, we develop a $n \times n$ matrix to represent the communication quality of a supplier with all other suppliers including integrator. For example in Table 3, the first row represents the quality of the communication of the Supplier 1 with other suppliers and the integrator. The cumulative or the overall communication effectiveness of the supplier (β) is determined based on a method similar to AHP (Saaty, 1980).

Unified model for the communication of the enterprise network - In computation of the 'Communication Effectiveness' of a supplier network, we first develop an expression to enumerate the communication effectiveness of a design chunk. We have used a reliability based model to develop the expression for the same. For example, for technical communication to occur either two design chunks/parts need to share the interactions or there should be existing dependency on other suppliers. The functional importance of the design chunk/part plays a role of amplifier of the communication. The supplier communication capability index is also included in series with the functional importance of the design chunk/part. Therefore, a supplier having a low supplier communication capability index will lead to decrease in the communication effectiveness of the supplier network. Figure 4 shows the relation between different factors of the communication effectiveness model.

We formulated the expression of CE for a design chunk or part as follows:

CE = P{(interface strength) ∪ (supplier dependency)}*(functional importance of the design chunk/part) * (supplier communication capability index)

$$CE = [\alpha + \gamma - \alpha*\gamma] * \theta*\beta \quad \ldots(1)$$

The supplier's communication capability has an impact on the determination for the effective design and development time required by a black box supplier (Mikkola 2000). In this paper, we have developed a model to enumerate the effective time of design chunk development by a black box supplier. Theoretically, a black box supplier may require more or less time with respect to a detailed controlled part supplier. We postulate that a supplier having higher supplier communication capability index will require less time than a detailed controlled parts supplier or vice versa. Figure 5 has been adapted using the concepts of "learning curve". It shows that with the increase in β, the time to develop the black box parts decreases.

On the basis of the above mentioned objectives, viz. cost, time, and the communication effectiveness of the supplier network, the extended enterprise network is formed for the design and production phase.

2.2. *Development of the metrics for evaluating the efficiency of the extended enterprise network*

In order to judge the effectiveness of the extended enterprise network in the design and production phase, we need to develop a phase-based metrics to evaluate the same. Womack and Jones (1996) and Ward (2007) highlighted the importance of improving the "value" of the flow. Therefore, it is important to identify the different types of flow relates to case of the design and production phases. For example in the design phase, flow relates to design information, and hence there is a need to look at the effectiveness of the information sharing among the suppliers. On the other hand, inventory/material flows in the production phase. Therefore, there is a need to improve the value by improving the speed of the inventory in the network. Goffin *et al.* (1997) and Donovan (1999) presented the importance of supplier base consolidation and argued that it leads to better communication effectiveness among the suppliers and the integrator in the design phase and leads to minimization of the inventory holding cost and the total logistics time. For example, Schonberger (2006) argued that an increase in the number of suppliers leads to an increase in the inventory turnover ratio of the supply chain which in turn leads to an leads to appreciation in the inventory holding cost. Thus, we have classified our metrics to judge the effectiveness of the enterprise in two phases. They are as follows:

- Communication effectiveness of the enterprise network in the design phase
- Inventory holding cost in the production and logistics phase

The inventory holding cost is directly proportional to the number of suppliers in the production phase. We assume that each supplier and the integrator/sub-assembly supplier keep a safety stock of 5 days of inventory of an item with themselves to meet the uncertainty or any undesired eventuality.

In order to do so, we conduct the part redesign (part count minimization) to enhance the effectiveness of the extended enterprise network. By reducing the part count in the product architecture, we wish to minimize the number of suppliers in the design and production and logistics phase.

2.3. *Overall solution methodology*

The overall aim of the paper is develop an efficient extended enterprise for a product. It can be seen from Figure 6 that we develop an extended enterprise network for a given Design bill of material (D-BOM) and Manufacturing Bill of Material (M-BOM) in both design and production phase. In addition, to the development of extended enterprise network, we also solve the product composition problem in the design phase of the product realization stage. After developing the extended enterprise network, we evaluate the network using the metrics developed to gauge the effectiveness. Based on the value of the metrics, we redesign the D-BOM and again solve the simultaneous product and the extended enterprise network design problem. We present the overall scope of the paper in Figure 6.

a) Product design and development time period

- D-BOM (number of design chunks, design dependency diagram, functional importance of each design chunk, lag relationships among the design chunks based on the design information required between each design chunk).
- Types of module availability for each design chunk, i.e., whether COTS/MOTS exists in the market.
- The set of modules options along with their types (i.e. COTS/Black box parts/Detailed controlled parts) and features.
- The set of potential suppliers for each module option along with their capabilities in terms of development cost, development time, communication capability with other suppliers and the integrator.

b) Production time period

- M-BOM (Assembly relationships, Number of parts per sub-assembly required, number of sub-assemblies, number of singleton components/parts).
- Demand of the product.

- Supplier capability/capacity in terms of production/assembly & logistics cost, production/assembly & logistics time, supplier communication capability with other suppliers and the integrator.

Given this input, our decision model offers answers to the following questions:

a) Product design and development time period

- Which modules options should be selected for a given design chunk?
- Which design chunks should be outsourced to whom?
- What is the total design time, total design cost, communication effectiveness of the entire design supplier network?

b) Production time period

- How many suppliers should be selected for each sub-assembly/singleton components?
- What are the product unit cost, total production time, and communication effectiveness of the production supplier network?

Based on the answers to the above questions, we develop the extended enterprise network for both the D-BOM's and M-BOM's, and subsequently answer the following questions:

- Which is more effective extend enterprise network based on metrics such as communication effectiveness of the design supplier network and total inventory held up in the extended enterprise network?

- What is the cost incurred for the benefit in terms of enhancement in the communication effectiveness in the design phase and reduction in the inventory cost?

3. Example Problem

In this paper, we have considered a case study problem of a power drill for our analysis. Although, a typical power drill has around 40 parts, however, for our analysis we have considered only few major modules in design and production phases of the product realization process. Later, we redesign the product by minimizing the design chunks as well as the parts to be manufactured or assembled in the product design. This is done with a view to "leanize" the extended enterprise network for a given product design.

3.1. *Original power drill*

In this sub-section, we describe the development of the objective functions and constraints for the original design of a power drill for both the design and production phases of the product realization process.

3.1.1. Product design and development time period

Prior to the development of the objective function and constraints of the original design in the design phase, we present the design sequence of the various design chunks. Figure 7 presents the original design sequence of a power drill. The design sequence starts with the design of the most important design chunk from the functional point of view. We have considered the “tool bit” as the starting design chunk.

We refereed to different websites of various power drill manufacturers and developed the specifications for each design chunk (www.black&decker.com, www.makita.com, www.dewalt.com). Based on the specifications of the different parts/components, we classified the performance characteristics associated with each design chunks and classified them as follows: (a) basic performance characteristics (b) additional performance characteristics. Based on the market study and the various websites of the manufacturers/organizations of these components, we have developed the module availability information for each design chunk. The availability of modules have been classified into three groups: COTS/MOTS, Black box parts (BBP), and Detailed Controlled parts (DCP). Thus, the suppliers providing them have also been classified in three groups, i.e., COTS/MOTS suppliers, BBP suppliers, and DCP suppliers.

Table 4 lists the different types of module options for each design chunk. The module options for the different module types are around 1-4 per design chunk. In this paper, we have assumed around 3-4 suppliers for each module. We have also considered the module compatibility constraints among the different module options for each design chunk. Further, only one design supplier is selected for a design chunk, i.e., the problem aims to select the best module option and its corresponding supplier.

a) Design and development time - The different suppliers provide their design and development time for the different module options they wish to provide. It is important to note that there is no design and development time period for the COTS/MOTS suppliers. As mentioned in the previous section, the effective time taken by the black box suppliers can be more or less based on the supplier communication capability index β. Therefore, for $\beta \geq 0.5$ the effective factor '*b*' has value equal to 0.75 and for $\beta \leq 0.5$, b = 1.5. However, we can change the values of the parameter *b*. Based on the above discussion, we utilize the formula as follows:

$$T' = t^b \qquad \ldots(2)$$

where *T'* is the effective time to design and develop a Black Box part and *t* is the amount of time used to develop a Detailed Controlled part for a given functional chunk.

Based on the design dependency diagram, we draw a CPM diagram of the design and development time period of the original design of the power drill. Figure 7 represents the design and development diagram along with the supplier dependency diagram. The dotted boxes represent that only COTS/MOTS modules are available for these design chunks.

b) Total design cost – As mentioned in Section 2, we have considered four costs in the design and development horizon.

$$\begin{aligned} \textit{Total Design Cost (TDC)} = {} & \textit{Design cost of a module quoted by the supplier} + \\ & \textit{Performance loss cost associated with a module} + \\ & \textit{Supplier development cost for a design chunk} \\ & + \textit{Switchover cost of the supplier for} \\ & \textit{a design chunk} \end{aligned} \qquad \ldots(3)$$

The Total design cost, TDC_{ijk}, is enumerated for each module supplied by a supplier, where *i, j*, *k* denotes the design chunk, module option, and supplier respectively. From now onwards, we further differentiate the notation for *j*, i.e., j^1stands for COTS/MOTS module options, j^2 stands for black box parts, and j^3 stands for detailed controlled parts respectively. The design cost of module designed/developed is represented as 'DC_{ijk}'. However, DC_{ij^1k} is zero as this corresponds to a COTS module.

The performance loss cost (PLC_{ijk}) is computed for each module option *j* of each design chunk *i* supplied by the supplier *k*. The performance loss cost is on the module options and hence those suppliers supplying the same module option will have same performance loss cost. The performance characteristics considers two types Yes/NO binomial feature loss '$PLC^B{}_{ijk}$' and scale-based feature loss $PLC^S{}_{ijk}$. All the scale-based performance loss functions are calculated using the "Nominal the better" performance characteristic case.

$$PLC_{ijk} = \sum_{n}^{N_j} PLC_{ijk}^{B^n} + \sum_{m}^{M_j} PLC_{ijk}^{S^m} \qquad i, j \; \forall \; k \qquad \ldots(4)$$

Each binary $PLC^B{}_{ijk}$ is defined as follows:

$$PLC_{ijk}^{B^n} = \begin{cases} K_n & \textit{if performance characteristic is absent in module j supplied by supplier k} \\ 0 & \textit{if performance characteristic is present in module j supplied by supplier k} \end{cases} \qquad \ldots(5)$$

Where K_n is the performance loss when the feature *n* is absent in the design chunk *i* for module option *j*.

Similarly, $PLC^{S}{}_{ijk}$ is defined as follows:

$$PLC_{ijk}^{S^m} = \begin{cases} L_m (y-t)^2 & if\ |t| \geq y \\ 0 & if\ |t| = y \\ \infty & if\ |t| \leq y \end{cases} \qquad \ldots(6)$$

Where y and t is the level of performance of variable m, respectively

Since we are selecting the design and production suppliers for the first time, we do not have the supplier development cost (SDC_{ijk}), i.e. the switchover cost (SWC_{ijk}). Table 5 and Table 6 present the various performance characteristics of the different design chunks sought by the integrator and the sample cost model for total design cost enumeration.

c) Communication effectiveness of the design enterprise network

Four factors were identified in the design phase that affects the communication. They are described below.

i) Design chunk interaction strength (γ): This relates to the presence of the interactions among the design chunks, which results into communication requirements among the suppliers supplying them. We have developed a revised Design Structure Matrix (R-DSM) to determine the concept of most interconnected supplier in any product architecture by determining the most interconnected design chunk. Table 7 lists the aggregate scores of the various types of interactions among the different design chunks using the revised scale developed in Table 2. It can be seen from Table 8 that the keyless chuck has the highest interaction strength among the different design chunks. This is due to the different types of interactions especially the spatial and energy interaction shared by the keyless chuck with other design chunks. The next design chunk is *the housing*, which shares the spatial interactions with almost all the design chunks. Based on Table 7, we have determined the 'γ 'for the original design of the power drill case example by determining the Eigen vector of the matrix. This exercise is similar to the weights determination in the Analytical Hierarchy Process (AHP) (Saaty, 1980).

ii) Supplier dependency factor (α): The supplier dependency factor in the design and development phase as mentioned before depends on the design dependency diagram during the product development time horizon. As we increase the dependency among the different supplier/design chunks to complete the design of the final product, the supplier dependency factor α will decrease due to the chain dependency. Figure 8 represents the design dependency diagram of the original design of the power drill case example. It can be observed from Figure 8 that tool bit has the design dependency number of 1, this is done to achieve some positive number for each design chunk. Further, the design dependency of gears and switch assembly is 3. This is due to the parallel dependency between these two tasks after the design of the motor starts. Further, there is a start-start lag between the motor assembly and the switch assembly. This is due to the overlap in the design of both the chunks. For example, after determining the voltage and amperage requirement of the motor, the design of the switch assembly can start, i.e. it should not wait till end to get the motor assembly designed. Similar case prevails in the design of the motor assembly and gear design. We have assigned a dependency number (d) to each design task. Based on this dependency number, we determine the supplier dependency factor α by using a logarithmic function.

$$\alpha_i = -0.2 * \left(\log_{7.4} 7.8 * (d_i - 1)\right) + 0.8 \qquad \ldots(7)$$

The logarithmic declining function used here caters to the requirement of having supplier dependency factor as 1 for the dependency number 1. Further, it also depicts the decline in the supplier dependency factor as we increase the supplier dependency number. Figure 8 represents the relationship between the supplier dependency factor (α) and the supplier dependency number (d). Table 9 presents the supplier dependency factor for the different design chunks in the original power drill case example.

iii) Functional importance of the part (θ) – The functional importance plays an important role in determining the importance of the communication among the suppliers-suppliers and supplier-integrator. Table 10 lists the functional importance of the various design chunks. The functional importance of the different components has been developed based on the number of primary and secondary functions satisfied by each design chunk (Otto and Wood 2001) in the system level architecture. From the working point of view, the maximum number of primary functions satisfied in the power drill is the motor assembly and, hence, it has the highest functional importance in the architecture.

iv) Supplier communication capability index (β) – As discussed above**,** the supplier communication capability index is determined by considering the communication of the supplier with the other suppliers and the integrator. We determine the supplier communication capability index of the different suppliers of the pool for the original design and also redesigned power drill.

3.1.2. Production time period

In this phase, we aim to select the supplier for frozen product architecture. The selection of the suppliers is done for M-BOM. The original M-BOM of the power drill example is depicted in Figure 10. Figure 10 also represents the various types of suppliers involved for the producing those components.

In Figure 10, we have 6 singleton components and one sub-assembly. For example, the switch sub-assembly comprises trigger switch, electrical wires, power cords, and tapping screws to be assembled before it is delivered to main integrator's facility with other parts. We are considering the multiple supplier scenarios, where each supplier has its own capacity constraints associated with them. Thus, for a given demand of these components, multiple suppliers are selected based on three objectives, viz., the unit production cost, production time, and communication effectiveness of each supplier. Typically, for each component, we have around 3-4 suppliers and for a sub-assembly. We have considered 3 assembly suppliers.

Based on the above three objectives, we aim to develop the supplier network for the production phase. As can be observed from Figure 10, there are two different supplier selection problems to be solved in the production phase, i.e. one at the integrator level and the other at the assembly supplier level. The assembly supplier (AS) first selects the suppliers for its sub-assembly and based on that selection sends a quote to the integrator. Similarly, the problem is solved by the integrator for the various singleton components and sub-assembly parts. The demand for the power drill is assumed to be constant and is known *a priori* to the integrator. The demand for the various components is a function of number of components required for the final assembly and the demand of that particular product. Table 10 lists the demand for the various components.

a) Total production time – The total time to complete the required demand of the product is termed as the total production time of the product. The assembler and the integrator select such suppliers that minimizes the total production time. This also includes the logistics time required in transporting the materials from the physical facility of the supplier to the integrator/sub-assembler. It is assumed that the production/assembly supplier is responsible for the transportation of the material from one place to another.

b) Total production cost – This cost signifies the total production cost of the product. The total unit production cost comprises unit production/assembly cost and the production quality loss cost for a supplier supplying the component. The unit production cost is applicable in the case of singleton component. On the other hand, for the sub-assemblies, the assembler includes its assembly cost to the sum of unit cost of the components it receives from its suppliers. The production quality loss is determined from the capability index of the suppliers, i.e., the number of defective pieces in the lots which is converted in terms of dollars. Based on the above discussion, we classify the different cost models for various types of suppliers.

Production suppliers

Total Production Cost (TPC) = Unit production cost (UPC) + Unit defect loss cost (UDLC)

Assembly suppliers …(8)

Total Production Cost (TPC) = Unit cost of the components from its suppliers (UCCS) +Unit Assembly Cost (UAC) + Unit defect loss cost

Table 11 and Table 12 lists the sample total production cost and capacity information for each Tier 1 and Tier 2 suppliers.

c) Communication effectiveness of the extended enterprise network – The communication effectiveness is used as a selection criterion for the suppliers in the production stage. However, the model to calculate the communication effectiveness of each supplier is bit different with the model explained in the design stage. For example, we do not consider the interface strength γ in the production stage and the supplier dependency number (*d*) assumes a value of 1 for all the singleton components suppliers at Tier 1 and singleton suppliers at Tier 2. This is done in order to avoid the value zero while selecting the singleton component suppliers for an assembly supplier. For the assembly suppliers, we have assumed that if the supplier dependency number *d* is equal to the number components in the sub-assembly then the value of α is 1. This represents a situation where each part is fully sourced from an individual supplier. However, for *d* more than the part numbers, the efficiency of the assembly supplier decreases. For the original design part number is 4, whereas, for the redesigned product architecture it is assumed to be 2. The functional importance (θ) and supplier communication capability index (β) has the same connotation as in the design phase. For the production phase, the supplier dependency factor (α) mentioned in Eq. (7) has been modified. The revised equation is as follows:

$$\alpha_i = -0.2 * \left(\log_{6.4} 7.8 * (d_i - part\ \ number)\right) + 0.8 \qquad \ldots(9)$$

3.2 *Redesigned power drill*

3.2.1. Product design and development time period

We have consolidated various design chunks in the original product architecture. Since, we redesigned the product, we assume that most of the design are new to the industry and thus are product specific in nature. Here, we solve the module selection problem along with the supplier selection. The basis behind the determination of total design cost, design time, and the communication effectiveness remains the same. Utilizing Eq. 3-6, we determine the total design cost, performance loss cost of each module option, effective development time of black box part by a supplier, supplier dependency factor, etc. In the cost model, however, we have included the supplier development cost for those suppliers who were selected in the last product design and changeover cost for the new suppliers. The design sequence diagram for the revised product architecture is given in Figure 11.

Based on the design sequence diagram, we develop the design and the development diagram and also the supplier dependency diagram. We have retained the same supplier pool used in the earlier phase to have the identical supplier communication capability index (β) to show cause the enhancement in the communication effectiveness.

3.2.2. Production time period

The analysis remains the same here as in the previous production and logistics time horizon and all the equation used to derive the total unit production cost of the product remains the same. The M-BOM is changed to suit according to the new design. The revised assembly and supplier diagram is depicted in Figure 12.

The capacity and the cost offered by the suppliers are on the same scale to the previous case to show the effect of supplier minimization in the production phase.

3.3. *Evaluating the effectiveness of the extended enterprise network*

The metric to judge the effectiveness of a design supplier network is to measure the total communication effectiveness. Both the design supplier network corresponding to each D-BOM is evaluated using the same measure.

In evaluating the production supplier network, we enlist the number of singleton and assembly suppliers in the network. Considering each of them as a node in the graph, we develop a supplier network consisting of different suppliers. Assuming that each lower tier supplier keeps an inventory of 5 days, the higher level or Tier 1 assembly supplier or integrator keeps an inventory of 5 days for the same item, i.e., for a group of same part suppliers, the assembly supplier or integrator keeps an inventory of 5 days.

4. Solution methodology

After the formulation of the objective function and the constraints for the both the design and production phase, we develop a goal programming model to solve the multi-objective formulations. It is important to mention that integrated product design and supplier selection problem for both the designs presented in the Section 3 are the same, hence, the formulation developed for one holds for the other one also.

4.1. *Development of the objective function for the design and development time period*

4.1.1. Total design cost objective model

We aim to minimize the total design cost (*TDC*) of all the design chunks subject to module compatibility constraints and one module and supplier per design chunk constraint, i.e.,

$$TDC = \sum_{i=1}^{I} TDC_{ijk} \qquad \text{….(10)}$$

Where, *I* is the total number of parts

Based on Eq. 3, we have

$$\text{Minimize } TDC = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{K=1}^{K} TDC_{ijk} * x_{ijk} \qquad \text{…(11)}$$

Where x_{ijk} is a 0,1 binary variable., i.e. whether for part *i*, module *j*, and supplier *k* is selected or not. The aim is to minimize the total design cost.

Module compatibility constraints

The module compatibility constraints is represented as follows:

$$\sum x_{ijk} \leq 1 \qquad \text{…(12)}$$

According to Eq. 12 some *i*,*j*,*k* one or none of the module may be selected.

One module and supplier per design chunk constraint

According to this constraint, only one module option and supplier should be selected for a design chunk *i*.

$$\sum_{j=1}^{J}\sum_{k=1}^{K} x_{ijk} = 1 \quad \forall i \qquad \ldots(13)$$

4.1.2. Total communication effectiveness

$$TCE = \sum_{i=1}^{I} CE_{ijk} \qquad \ldots(14)$$

$$\text{Maximize } TCE = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{K=1}^{K} CE_{ijk} * x_{ijk} \qquad \ldots(15)$$

Where TCE is the total communication effectiveness of the design network and CE_{ijk} is the communication effectiveness of supplier k for module option j of part i. CE_{ijk} is calculated using Eq. 1. The module compatibility constraints and one module and supplier per design chunk constraint remains the same for this objective function .

4.1.3. Total time to design

The aim is to select such suppliers and the module options such that the total design and development time period is minimized. From Figure 7, suppose EF_L is the early finish of the last activity and the early Start of the first activity is ES_1. Therefore, the objective function is as follows:

Minimize EF_L - ES_1 …(16)

Subject to:

- Early start and Early finish activities of all the design chunk
- Lag relationships among all the activities
- Module compatibility constraints
- One module and supplier per design chunk

The mathematical formulation for the CPM based constraints has been adapted from Winston (1993).

4.2. *Development of the objective functions for the production time period*

Based on Section 3, we solve two types of optimization problem in this horizon. One is for the assembly supplier and other is for the integrator. We first develop the objective formulation for the assembly supplier. It includes total unit production cost of the components supplied by the production suppliers and its unit assembly unit cost, total communication effectiveness of its production suppliers, and the time required by its production supplier to produce the total demand of the various components and its own assembly time. It is important to mention that we have discretized the total assembly capacity of the assembly suppliers. This is done keeping in view that demand portion of the integrator allocated to a particular supplier is unknown to the assembly supplier. Hence, it is hard to solve the simultaneous selection of the assembly supplier and its production suppliers. In order to address such a problem, we have discretized the total assembly capacity of the assembly supplier. Table 13 lists the demand discretization of an assembly supplier.

Thus, from Table 13, we can gauge that although a supplier has a capacity of 5000 units, it's capacity is discretized in steps of 1000. For each demand breakup, we solve the multi-objective formulation comprising total production cost, communication effectiveness, and production time. Thus, for each demand copy an AS will have a unique assembly cost and manufacturing and logistics cost to produce that particular lot.

The objectives of a copy of the AS are formulated as described in sub sections 4.2.1, 4.2.2, and 4.2.3.

4.2.1 Total production cost

$$\text{Minimize} \sum_{i=1}^{I} \sum_{k=1}^{K} \frac{UPC_{ik} * x_{ik}}{D_i} + UAC_{AS_t} \qquad \ldots(17)$$

Where I is the total number of parts in the sub-assembly, D_i is the total demand of the component i in the sub-assembly and k is the index for the supplier of part i. UAC_{AS_t} is the unit assembly cost of the assembly supplier t. x_{ik} is the volume of the components purchased and UPC_{ik} is unit production cost of the part i supplied by supplier k.

Subject to:

Demand constraint of each part in the sub-assembly:

$$\sum_{k=1}^{K} x_{ik} \geq D_i$$

Capacity constraint of each production supplier

$$\sum_{k=1}^{K} x_{ik} \leq C_{ik} * Y_{ik}$$

Where C_{ik} is the capacity of the supplier *k* supplying part *i*.

4.2.2. Total communication effectiveness

Maximize $$\sum_{i=1}^{I}\sum_{k=1}^{K}\frac{CE_{ik} * x_{ik}}{D_i} \qquad \ldots(18)$$

CE_{ik} is the communication effectiveness of the supplier *k* supplying part *i*.

Subject to:

Demand constraint of each part in the sub-assembly:

$$\sum_{k=1}^{K} x_{ik} \geq D_i$$

Capacity constraint of each production supplier

$$\sum_{k=1}^{K} x_{ik} \leq C_{ik} * Y_{ik}$$

Where C_{ik} is the capacity of the supplier *k* supplying part *i*.

4.2.3. Total production time to assemble a demand copy

Minimize EF_{AS_t} …(19)

Where EF_{AS_t} is the early finish time of all the assembly activity for a demand copy of Assembly supplier *t*.

Subject to:

$$ES_{AS_t} = \max(d_{ik})$$

ES_{AS_t} is the early start of the activity for Assembly supplier *t* and d_{ik} is the time required by the production supplier *k* to meet the demand of part *i*.

Demand Constraint of each part in the sub-assembly:

$$\sum_{k=1}^{K} x_{ik} \geq D_i$$

Capacity constraint of each production supplier

$$\sum_{k=1}^{K} x_{ik} \leq C_{ik} * Y_{ik}$$

Where C_{ik} is the capacity of the supplier *k* supplying part *i*.

A similar formulation exists for the integrator. However, in case of the assembly supplier, the assembly supplier selects one copy of the demand at a time.

4.3.*Goal programming*

Based on the above mentioned three objectives, we develop a multi-objective goal programming formulation in both the design and production phases for the both the product architectures. In a weighted sum goal programming approach, a multi-objective optimization problem is solved by minimizing the sum of deviations of the three objectives from their respective goals (Rardin, 1998). However, the three objectives in the present problem have different units, i.e., the design/production cost is measured in terms of dollars, the design/production time is measured in terms of weeks, and CE has no units. It is imperative that their corresponding deviations should not be directly added. So, the three objectives have been scaled to percentage and then their deviations are added (Romero, 1990), as shown in Equation 20. 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.

Then, the formulation for linear mixed-integer goal programming is given in Equation 20, considering the fact that cost is minimized, time is minimized and communication effectiveness is maximized.

Minimize

$$w_1 \times \%d_1 + w_2 \times \%d_2 + w_3 \times \%d_3$$

Subject to:

$$f_1(x) \times 100 / g_1 - \%d_1 \leq F_1(x) * 100 / g_1$$
$$f_2(x) \times 100 / g_2 - \%d_2 \leq F_2(x) \times 100 / g_2$$
$$f_3(x) \times 100 / g_3 + \%d_3 \geq F_3(x) \times 100 / g_3$$
$$\%d_1 \geq 0$$
$$\%d_2 \geq 0$$
$$\%d_3 \geq 0$$

all system constraints …(20)

where $f_1(x)$, $f_2(x)$ and $f_3(x)$ denotes the time, cost, and communication effectiveness objectives functions and $\%d_1$, $\%d_2$, and $\%d_3$ are its percentage allowable deviations. Similarly, w_1, w_2, and w_3 are the importance weights of each of the objectives and $F_1(x)$, $F_2(x)$, and $F_3(x)$ are the goals of each of objectives, which are determined as the best value of each of the objectives when solved individually.

5. Results and the discussion

For both the product architectures, we have used cost, time, and communication effectiveness of the suppliers to develop the extended enterprise network. In both the phases, the problem is equivalent to a Mixed-Integer problem (MIP). We considered a multi-objective goal programming approach and solved using the Cplex version 9.1 software.

As we utilized the multi-objective goal programming approach, the weights to the different objectives play a critical role in changing the solution to the above problems. A sensitivity analysis has been performed for the original product architecture's development and production phases. Later, for a given set of weights the final results of the evaluation metrics (i.e. Total CE of the extended enterprise network and total inventory held up in the production phase of the extended enterprise network) for the product architectures are compared.

After conducting the sensitivity analysis considering the tradeoffs between the design cost, design time, and CE of the design supplier network, we observed that at vector values (w_1 =1, w_2 = 0, w_3 = 0), we achieved the targeted design cost as obtained from the individual optimization of the design cost objective. Similarly, for the weights (0,1,0) and (0,0,1), targets of design time and CE are also achieved. It is observed that for relatively small values of the weights, this objective's desired values are achieved. This is due to commonality in the set of suppliers selected for each of these individual objectives. On the other hand, for the production phase, none of the desired level is achieved for any of the objectives except the CE.

Based on the extensive simulation and also our requirement for the different phases, we assigned (0.2, 0.1, 0.7) to total design cost, total design time, and total communication effectiveness, respectively, in the design phase whereas in the production and logistics phase we assigned 0.4 to the total production cost, 0.2 to the Production time, and 0.4 to the communication effectiveness. The requirement was to give more importance to the communication effectiveness in the design phase and equal weights to cost and communication effectiveness in the production and logistics phase. Table 14 compares the various metrics we developed in Section 2 for the two designs.

It is seen from Table 14 that with the inclusion of the supplier development and supplier switchover cost the total design cost has increased in the design phase but the communication effectiveness of the supplier network has enhanced by 9.17%. However, this was achieved by investing a sum of 3.3 million dollars in the supplier development and switchover cost. It is assumed that the development cost of the various modules remain the same across two designs. Similarly, in the production phase assuming that $50,000 inventory holding cost/day, the inventory cost decreased by 44.2%. However, an extra expenditure of $22, 5000 was incurred in supplier development and supplier switchover cost. If we consider both holding and supplier development cost in the redesign phase there is a 41.2% decrease in the total cost. These figures are sensitive to many factors like supplier development and switchover cost, holding cost etc. in the production and logistics phase. In the design phase the nature of the logarithmic curve used for determining supplier dependency factor has a significant impact on the communication effectiveness. For example, a gentle slope may lead to no change in the communication effectiveness or vice versa. In future, more different types of curves will need to be tested.

6. Conclusion and future work

In this paper, we proposed a methodology for integrated product design and supplier selection problem. We extended the problem of supplier selection in tow two phases, i.e., design and production phases. Further, we have considered the importance of product composition problem in the design phase along with the supplier selection problem. We have developed a model to distinguish between the black box and detailed controlled suppliers. An important contribution of the paper is to consider total communication effectiveness of the extended enterprise network for the integrated problem of product design and supplier selection problem. We have developed an analytical model to map the causes of the communication among the suppliers. This includes the product architecture elements like functional importance of the design chunks/components, interface strength among the components, design/supplier dependency diagram etc. We have classified the supplier dependency diagram for design and production phases.

After the extended enterprise network for the given product architecture is developed, its effectiveness is checked using some metrics. We have developed the metrics to evaluate the effectiveness of the network formed for both production and design phase. In order to leanize the extended enterprise, we minimize the part count by redesigning the product architecture. The results obtained suggests that there is an increase in the communication effectiveness in the design phase and there is decrease in the inventory holding cost and total logistics and manufacturing time.

The future extension of this work would include:

a. Effect of product obsolensce on the component consolidation strategies.

b. Effect of the demand uncertainty on the integrated product and supplier selection problem.

c. Change in the capability of the suppliers' overtime will be considered in the problem.

d. Effect of Bullwhip in the production will considered during the supplier selection problem in the logistics phase.

Geographical factors need to be considered during the supplier selection so that the effect of part count minimization on the sourcing strategies can be considered.

Terms and Definitions

Types of suppliers

a) **Design suppliers (DS)** – These suppliers provide design services to the main integrator of the product. Companies such as IDEO and Bressler to provide design solutions to the various companies like Kodak, Motorola, HP, etc.

b) **Production suppliers (PS)** – These suppliers are primarily responsible for the production phase of the product life cycle. They do not indulge in the design phase of the product and simply produce and assemble the products according to the specifications provided by the main integrator or the design supplier. Examples of production suppliers are suppliers who produce Components/Modules-off–the-shelf (COTS/MOTS) parts.

c) **Design and production suppliers (DPS)** – These suppliers are responsible for both the design and production activities. There are two types of design and production suppliers (Clark 1989, Mikkola 2000):

- **Detailed controlled parts suppliers :-** These suppliers design and produce new-to-the firm chunks. The functional specifications and detail design and specifications are provided by the integrator. The supplier has the choice to select the appropriate manufacturing/assembly process as well as make any subsequent outsourcing decisions.

- **Black box parts suppliers :-** These new-to-the firm part functional specifications are provided by the integrator. The supplier handles the function-technology mapping, detail design, manufacturing or subsequent outsourcing decisions for the lower tiers. The selection of black box parts typically leads to an increase in the product development time due to the increased technical communication complexity. However, this can be compensated by healthy long-term relationships maintained between the integrator-supplier and supplier-supplier triadic relationships (Mikkola 2000).

Types of bill of materials

a) **Design bill of material (D-BOM)** – This is a list of the functional chunks to be designed in the product. It includes the overall function of the chunk and sub functions. This bill of material is more at a higher level of detail and also includes the design dependency of each design chunk on others.

b) **Manufacturing/assembly bill of material (M-BOM**) **–** The American Production and Inventory Control Society (APICS) defines a bill of material as a "a listing of all the subassemblies, intermediates, parts, and raw materials that go into making the parent assembly showing the quantities of each required to make an assembly" (Chang *et al.* 1991). This bill of material is defined on a more conventional terms and is used for manufacturing the components.

Types of product development dependencies

a) **Parallel product development** – This type of product development occurs when there no information is exchanged between the two tasks. In this case, there exist no precedence relationships among the tasks.

b) **Concurrent product development** – This type of product development occurs when the two or more design activities are highly coupled, i.e., the design information is exchanged both ways. In this case, they have the same early start (ES) and early finish (EF) timeline, i.e., typically these design tasks are constrained by same Start-to-Start and Finish-to-Finish relationships.

c) **Sequential product development** – This type of product development occurs when the flow of information is unidirectional in nature, i.e. frozen information from design activity is passed on to the next design task. These tasks typically have Finish-to-Start relationships with or without lag time period.

d) **Overlapping product development** – This type of product development is a special case of concurrent product development, i.e., after the certain completion of the earlier design task, next design task can start by gathering few vital data for its initiation. After latter's initiation, both the design activities are conducted in parallel. These tasks are normally constrained by start-to-start relationships with or without lag time period.

Extended enterprise network - An extended enterprise network is defined as "all of the entities along an organization's value chain, from its customer's customers to its supplier's suppliers, that are involved with the design, development, manufacture certification, distribution, and support of a product or family of products" (Murman, *et al.* 2002).

Targeted objective design cost – This cost is optimal for the total design of all the chunks for a given a supplier pool and system constraints. This acts as a goal during the multi-objective optimization problem.

Targeted objective design time – This time is optimal for the total design of all the chunks for a given a supplier pool and system constraints. This acts as a goal during the multi-objective optimization problem.

Targeted objective design CE - This CE is optimal for the total design of all the chunks for a given a supplier pool and system constraints. This acts as a goal during the multi-objective optimization problem.

Targeted objective production cost – This cost is optimal for the total production/assembly of all the components/sub-assemblies for a given a supplier pool and system constraints. This acts as a goal during the multi-objective optimization problem.

Targeted objective production time – This time is optimal for the total production/assembly of all the components/sub-assemblies for a given a supplier pool and system constraints. This acts as a goal during the multi-objective optimization problem.

Targeted objective production CE - This CE is optimal for the total production/assembly of all the production/assembly for a given a supplier pool and system constraints. This acts as a goal during the multi-objective optimization problem.

7. References

ALLEN T. J., *Architecture and Communication Among Product Development Engineers*, Sloan School of Management, MIT, Sloan Working Paper, #3983, 1997.

ANDERSON J.C. and NARUS J.A., *A Model of Distributor Firm and Manufacturer Firm Working Partnerships,* Journal of Marketing, Jan. 1990, Vol. 54, No. 1, pp. 42-58

BROWNING T.R., and EPPINGER S.D., *Modeling Impacts of Process Architecture on Cost and Schedule Risk in Product Development*, IEEE Transactions on Engineering Management, Vol. 49, No. 4, Nov. 2002.

CALANTONE R.J. and STANKO M.A., *Drivers of Outsourced Innovation: An Exploratory Study*, Journal of Product Innovation, 2007, Vol. 24, pp. 230-241.

CARRASCOSA M., EPPINGER S.D., and WHITNEY D.E., *Using the design Structure Matrix to Estimate Product Development Time*, Proceedings of ASME Design Engineering technical Conferences, Sep. 1998, Atlanta, Georgia, DETC98-6013.

CHOUDHURY A.K., and ALLADA V., *Product Configuration Selection Problem: A Fuzzy-Goal Programming Approach*, Proceedings of ASME International Mechanical Engineering Congress and Exposition, Nov. 2006, Chicago, Illinois, IMECE2006-15059

CLARK K.B., *Project Scope and Project Performance: The Effect of Parts Strategy and Supplier Involvement on Product Development*, Management Science, Vol. 35, No. 10, Oct. 1989, pp. 1247-1263.

COTTRILL K., *Supply Chain Experts Get Their Say on Product Design*, Supply Chain Strategy, Feb. 2006, Harvard Business School.

CUSUMANO M.A., and TAKEISHI A., *Supplier Relations and Management: A Survey of Japanese, Japanese-Transplant, and U.S. Auto plants*, 1991, Working paper #3256-91/BPS, MIT Sloan School of Management.

DONOVAN D., *The dawn of the mega-supplier*, Business Report, 1999, Bain and Company, Boston, MA.

DOWLATSHAHI S., *The Role of Product design in designer-Buyer-Supplier Interface*, Production Planning and Control, 1997, Vol. 8, No. 6, pp. 522-532.

EPPINGER S.D., and SALMINEN V., *Patterns of product Development Interactions*, International Conference on Engineering Design, ICED 01 Glasgow, Aug. 2001, pp. 283-290.

ERICSSON A. and ERIXON G., *Controlling Design Variants: Modular Product Platforms,* 1999, New York: ASME.

ESTERMAN M. and ISHII K., *Concurrent product development across the supply chain: Development of integrators/supplier risk and coupling indices*, ASME DETC-CIE Conference, 2001, Pittsburgh, PA, Paper No. DETC2001/DFM-21192.

FISHER M., RAMDAS K., and ULRICH K., *Component Sharing in the Management of Product Variety: A Study of Automotive braking Systems*, Management Science, Vol. 45, No. 3, March 1999, pp. 297-299.

FISHER, MARSHALL L., *What is the right Supply Chain for Your Product?*, Harvard Business Review, March-April, 1997, pp. 105-116.

FORKER L.B., *Factors affecting supplier quality performance*, Journal of Operations Management, Nov. 1997, Volume 15, Number 4, pp. 243-269.

GOFFIN K., SZWEJCZEWSKI M., and NEW C., *Managing Suppliers: When Fewer Can Mean More*, International Journal of Physical, Distribution & Logistics Management, Vol. 27, No. 7, 1997, pp. 422-436.

GUPTA S., and KRISHNAN V., *Integrated Component and Supplier Selection for a Product Family*, Production and Operations Management, 1999, Vol. 8, No. 2, pp. 291-308.

HADJINICOLA G.C., and KUMAR K.R., *Factors Affecting International Product Design*, Journal of the Operational Research Society, 1997, Vol. 48, No.11, pp. 1131-1143.

HARTLEY J.L., MEREDITH J. R., MCCUTCHEON D. and KAMATH R.R., *Suppliers' Contributions to Product Development: An Exploratory Study,* IEEE Transactions on Engineering Management, 1997, Vol. 44, No. 3, pp. 258-267.

HELPER, S., SAKO, M., U.S. and Japanese supply systems: are they converging? Sloan Management Review, 1995, 96 (3), pp.105-113.

HONG J.D., and HAYYA J.C., *Just-In-Time Purchasing: Single or Multiple Sourcing?*, International Journal of Production Economics 27, 1992, pp. 175-181.

HSUAN, J., Impacts of supplier-buyer relationships on modularization in new product development. *European Journal of Purchasing and Supply Management*, 1999, 5, pp. 197-209.

HUANG G.Q., ZHANG X.Y., and LO V.H.Y., *Optimal Supply Chain Configuration for platform Products: Impacts of Commonality demand Variability and Quantity Discount*, International Journal of Mass Customization, Vol.1, No.1, 2005, pp. 107-133.

HUNDAL M.S., *Time-driven Product Development. In: Usher, J.M., Roy, U. and Parsaei, H.R.*, Editors, Integrated Product Development Process, 1998, John Wiley & Sons, New York, pp. 59-84.

JOGLEKAR N.R., YASSINE A.A., EPPINGER S.D., and Whitney D.E., *Performance of Coupled Product Development Activities with a Deadline*, Management Science, 2001, Vol. 47, Dec. 2001, pp. 1605-1620.

JOHNSON D.W. and JOHNSON F.P., *Joining together: Group theory and group skills*, 1994, Boston: Allyn and Bacon, pp. 159.

LEE H. L., *Aligning Supply Chain Strategies with Product Uncertainties*, California Management Review, 2002, Vol. 44, No. 3, Spring 2002, pp. 105-119..

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

MIKKOLA J.H., *Modularization assessment of product architecture,* Working Paper No. 00-4, Danish Research Unit for Industrial Dynamics, Copenhagen Business School, Denmark.

MONCZKA R. RAGATZ G., HANDFIELD R. TREND R. and D. FRAYER, *Supplier Integration into New Product Development: A Strategy for Competitive Advantage,* Working Paper, 1997, The Global Procurement and Supply Chain Benchmarking Initiative, Michigan State University, The Eil Broad Graduate School of Management, East Lansing, Michigan.

MURMAN E., ALLEN T. J., BOZDOGAN K., CUTCHER-GERSHENFELD J., MCMANUS H., NIGHTINGALE D., REBENTISCH E., SHIELDS T., STAHL F., WALTON M., WARMKESSEL J., WEISS S., and WIDNALL S., *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative*, 2002, Palgrave Macmillan.

OTTO K.N. and Wood K.L., *Product Design: Techniques in Reverse Engineering and New Product Development*. 2001, Upper Saddle River, NJ: Prentice Hall.

NOVAK S., and EPPINGER S.D., *Sourcing By Design: Product Complexity and the Supply Chain*, Management Science, Vol. 47, No. 1, Jan. 2001, pp. 189-204.

OUCHI W.G. and DOWLING J.B., *Defining the Span of Control*, Administrative Science Quarterly, Sep. 1974, Vol. 19, No. 3. pp. 357-365.

PARK B.J., *A Framework for Integrating Product Platform development with Global Supply Chain Configuration*, Thesis, July 2001, Georgia Institute of Technology.

PIMMLER T. U. and EPPINGER S. D., *Integration Analysis of Product Decompositions,* Proceedings of the ASME Design Theory and Methodology Conference (DTM' 94), 1994, DE-Vol. 68, pp. 343-351.

RAI R. and Allada V., *Modular product families design: agent-based Pareto-optimization and quality loss function-based post-optimal analysis*, International Journal Production Research, 2003, Vol. 41, No. 17, pp. 4075-4098.

RARDIN R., *Optimization in Operations Research,* 1998, Prentice Hall, Englewood Cliffs, NJ.

ROMERO C., *Handbook of Critical Issues in Goal Programming*, 1991, Pergamon Press, Oxford.

SAATY T.L., *The Analytical Hierarchy Process*, 1980, New York: Mc Graw Hill. USA.

SCHONBERGER R.J., *Supply Chains: Tightening the Link*, Manufacturing Engineering Magazine, Sep. 2006, pp. 77-92.

SIMCHI-LEVI D., KAMINSKY P. and SIMCHI-LEVI E., *Managing the supply chain: The Definitive Guide for the Business*, 2003, McGraw-Hill, New York.

SMITH P.G., and REINERTSEN D.G., *Developing Products in Half the Time*, Second Edition, 1998, John Wiley & Sons, New York.

SONMEZ M., *A Review and Critique of Supplier Selection Process and Practices*, 2006, Working paper #2006:1, Loughborough University.

Sosa, M. E. *Analyzing the Effects of Product Architecture on Technical Communication in Product Development Organizations*, 2000, Ph.D. Thesis in Mechanical Engineering, Massachusetts Institute of Technology.

TENNETI B. and ALLADA V., *Robust Supplier Selection for Changing Product Architectures*, Proceedings of IMECE, 2005 ASME International Mechanical Engineering Congress And Exposition, November 5-11, 2005, Orlando, Florida USA, Paper No. IMECE2005-81179.

TOMPKINS J., *Logistics and Manufacturing Outsourcing: Harness your Core Competencies*, 2005, Tompkins Press, Raleigh, N.C.

Trent, R. and Monczka, R., Achieving excellence in global sourcing, *MIT Sloan Management Review*, 2005, Vol. 47, No.1, pp. 24-32.

ULRICH K.T., and EPPINGER S.D., *Product Design and Development*, 2003, Tata McGraw-Hill, New Delhi.

WANG G., HUANG S. H, and DISMUKES J.P., *Product Driven Supply Chain Selection Using Integrated Multi-Criteria Decision-Making Methodology*, International Journal of Production Economics 2004, Vol. 91, pp. 1-15.

WARD A.C., *Lean Product and Process Development*, 2007, The Lean Enterprise Institute, Cambridge, MA.

WINSTON W.L., *Operations Research: Applications and Algorithms*, Third Edition, 1994, Duxbury Press, California.

WISSMANN L. A. and YASSINE A.A., *Product Architecture and the Firm*, 2004, Working Paper, Product Development Research Laboratory, Department of General Engineering, University of Illinois at Urbana-Champaign, IL.

WOMACK J. and JONES D., *Lean Thinking: Banish Waste and Create Wealth in Your Organization,* 1996, Rawson Associates, New York.

WU Z. and CHOI T., *Supplier-supplier relationships in the buyer-supplier triad: Building theories from eight case studies,* 2005, Journal of Operations Management, Vol. 24, pp. 27-52.

ZIRGER B.J. and HARTLEY J. L., *The effect of acceleration techniques on Product Development Time,* IEEE Transactions on Engineering Management, May 1996, Vol. 43, No. 2., pp. 146-152.

Available online at: http://www.blackanddecker.com, last accessed on 08/20/2007.

Available online at: http://www.makita.com/ last accessed on 08/20/2007.

Available online at: http://www.dewalt.com/ last accessed on 08/20/2007.

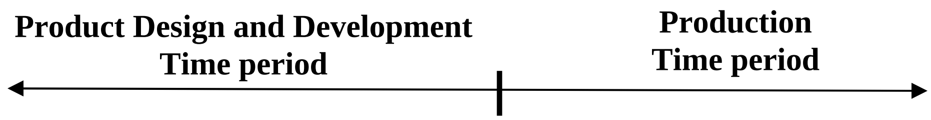


Figure 1: Two major time domains introducing a product to the market

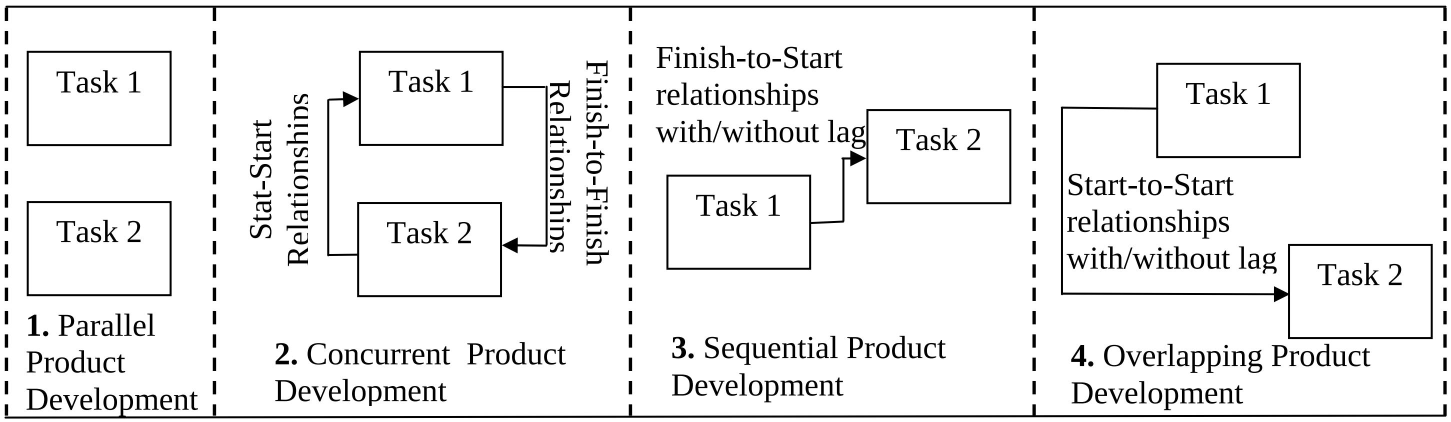


Figure 2: Different types of product development task dependencies

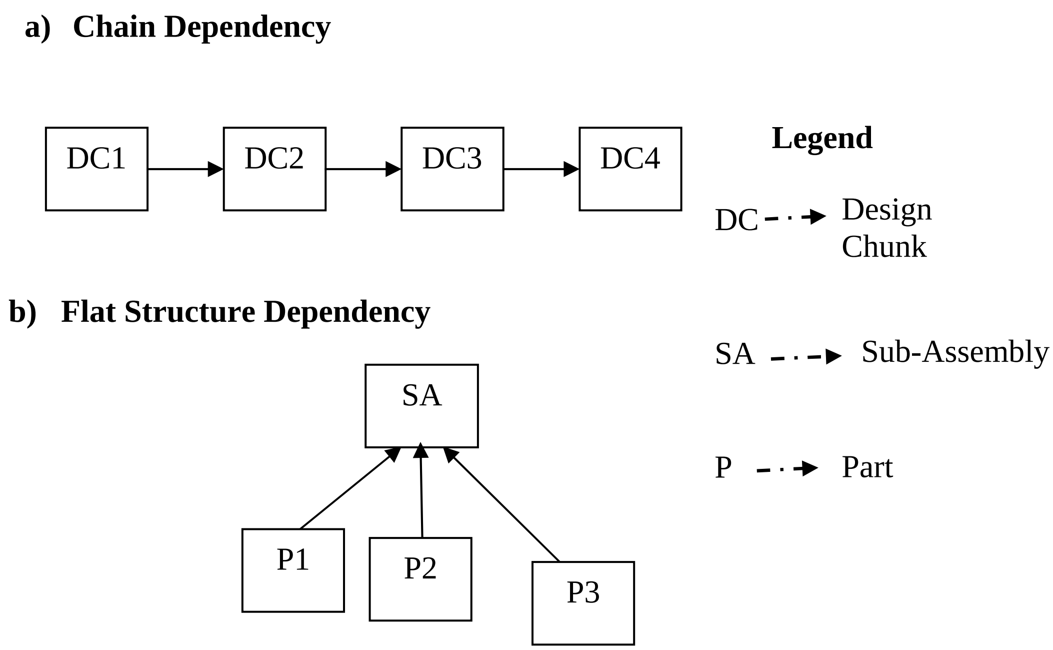


Figure 3: Types of dependencies present in the supplier network

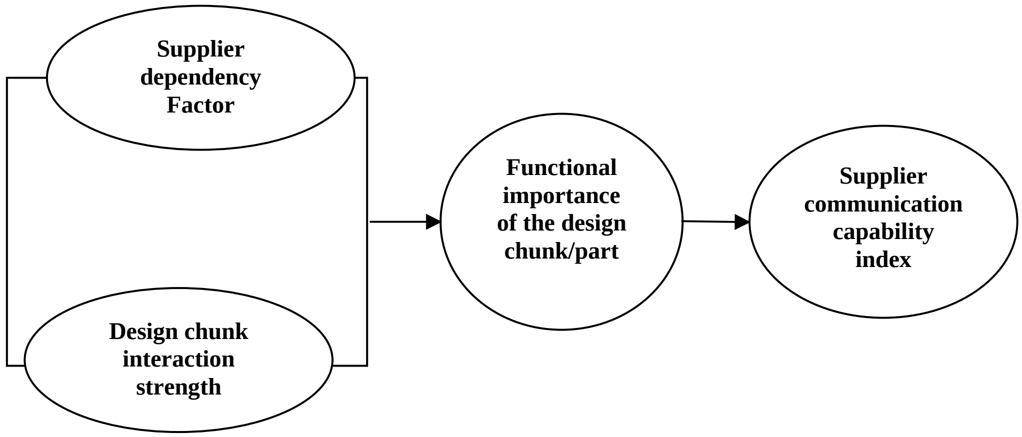


Figure 4: Reliability theory based model to depict the communication effectiveness of the supplier network

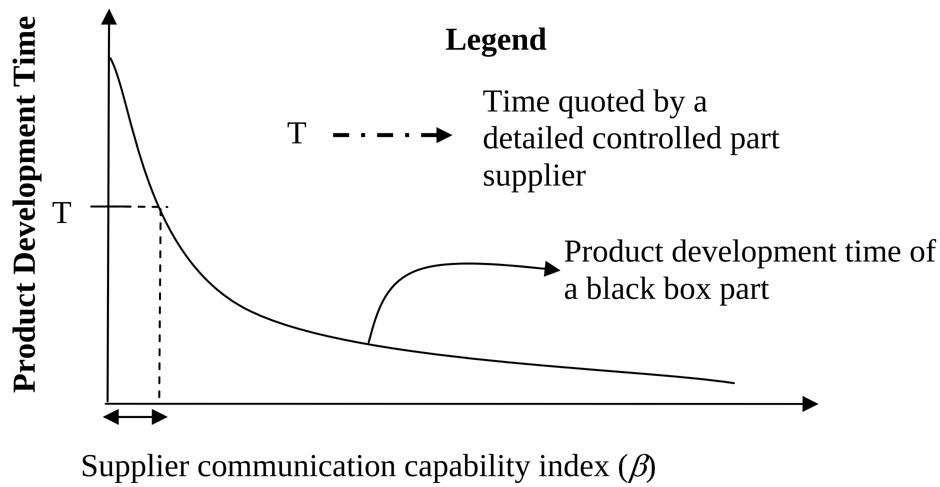


Figure 5: Relationship between the product development time and the supplier communication capability index for black box part

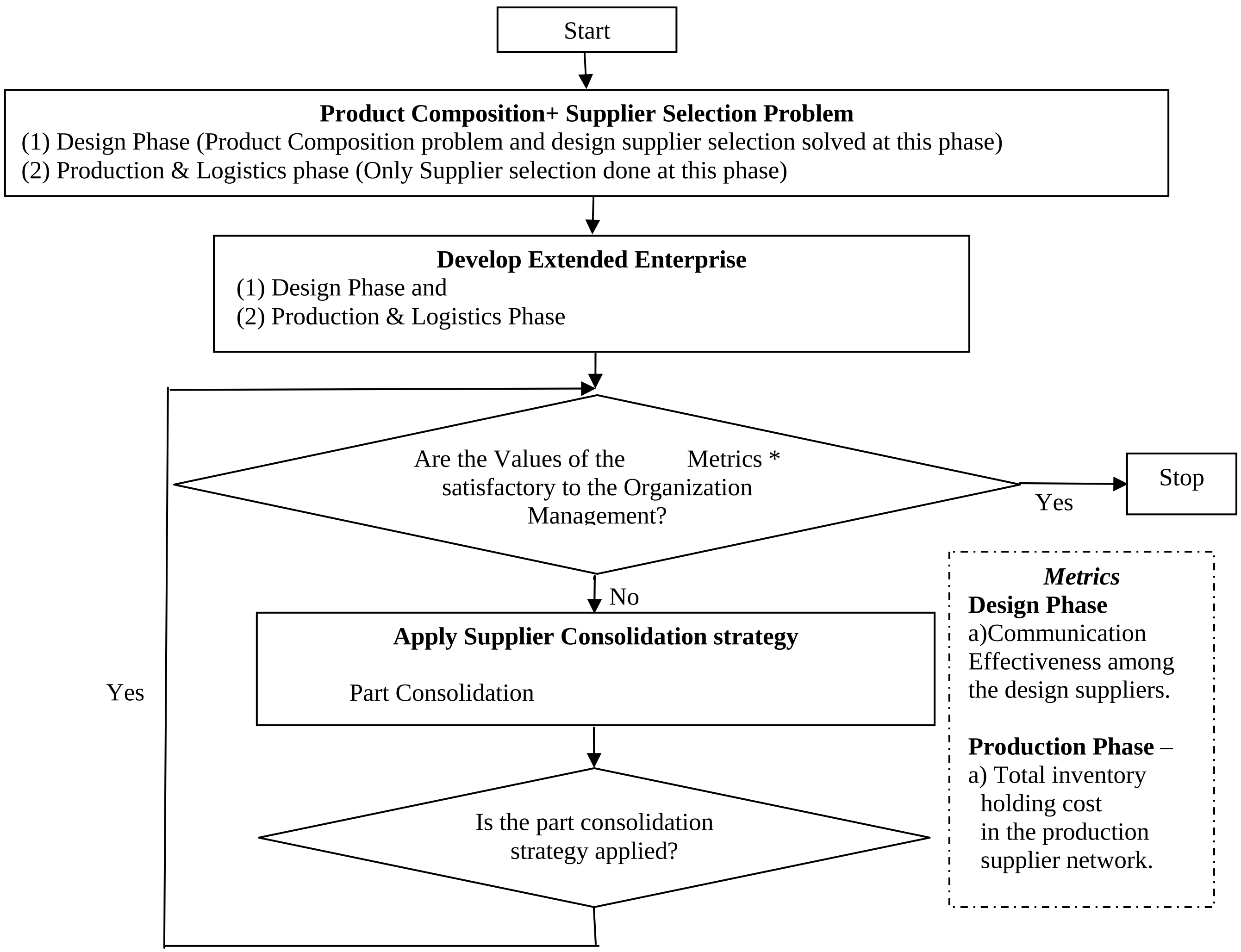
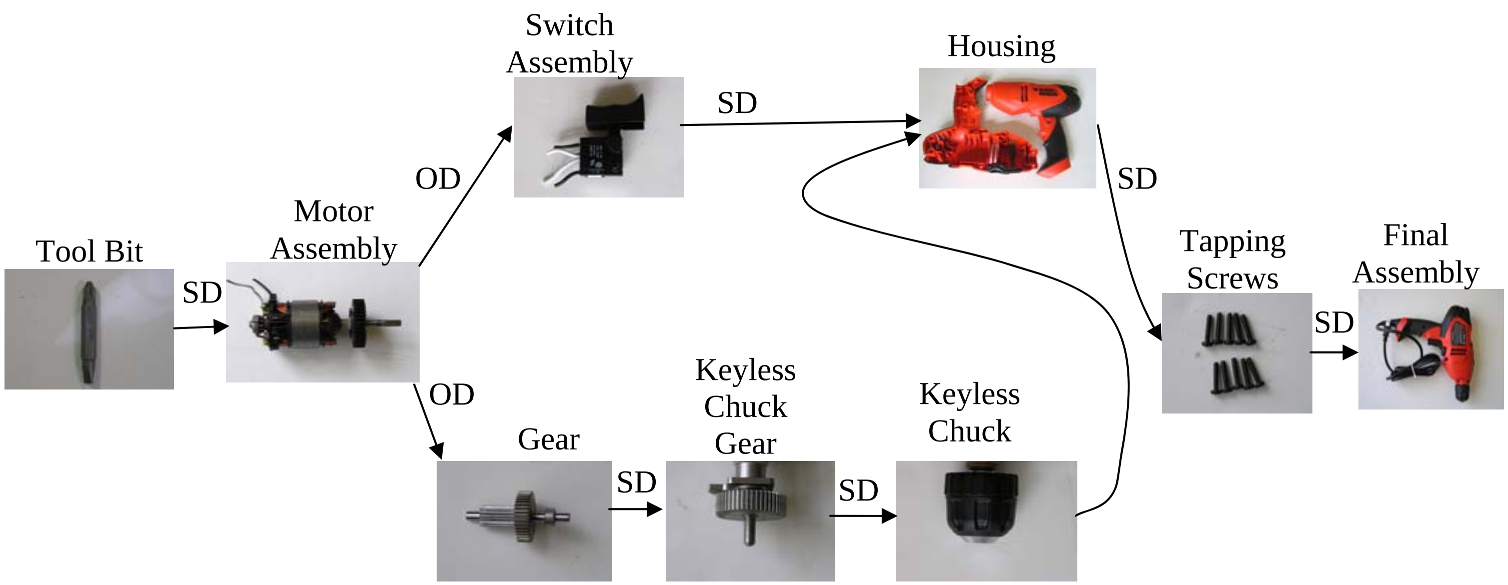


Figure 6: Overall scope of the paper



Legend for design dependencies among the different design chunks
Sequential Design Dependency – SD
Overlapped Design Dependency – OD
Parallel Design Dependency - PD

D-BOM – (1) Drill Bits (2) Motor Assembly (3) Switch Assembly (4) Housing (5) Gears (6) Chuck (7) Key less Chucks (8) Tapping Screws

Figure 7: Design sequence and D-BOM of the original design for a power drill

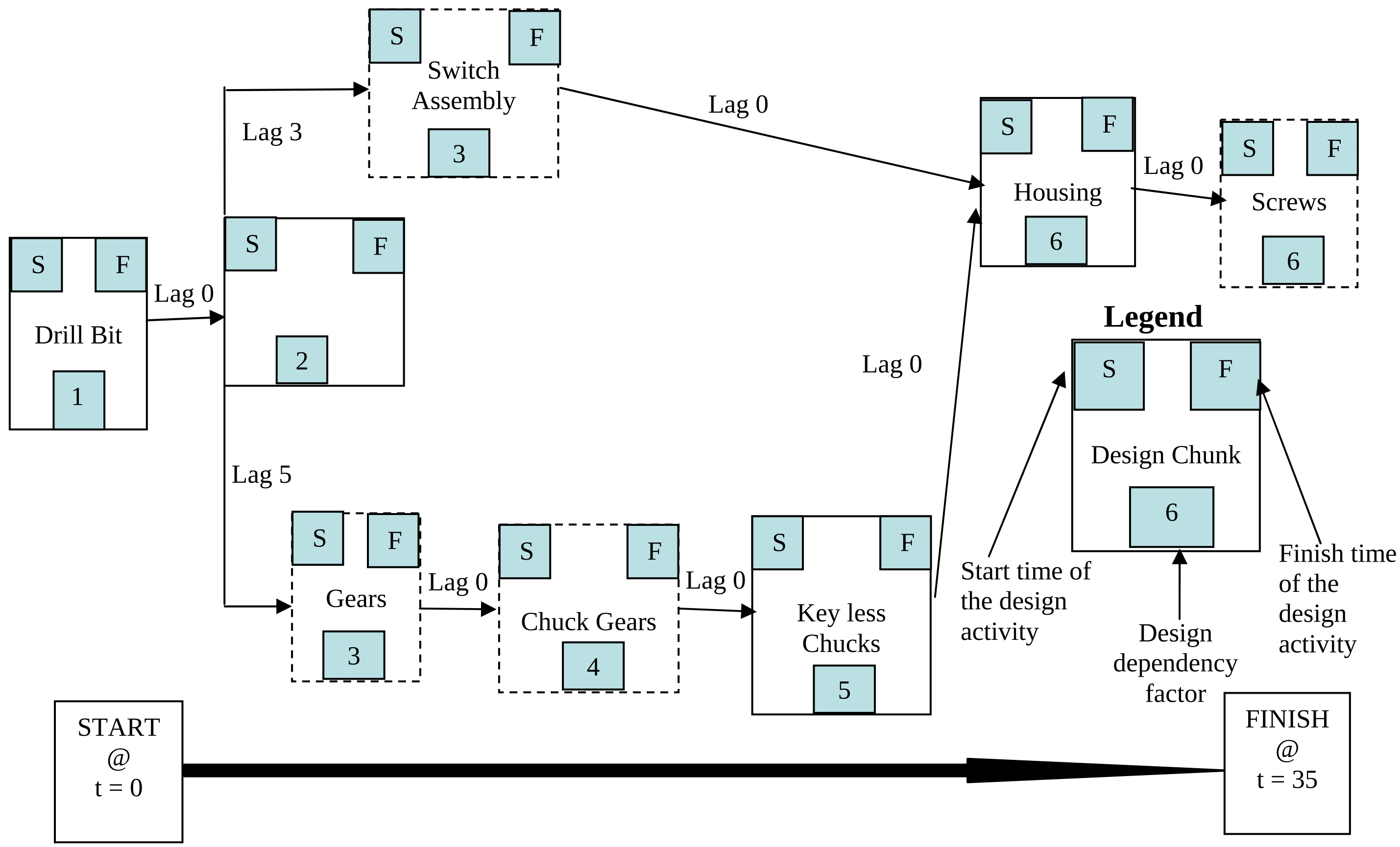


Figure 8: Design dependency and task diagram of the original power drill case example problem

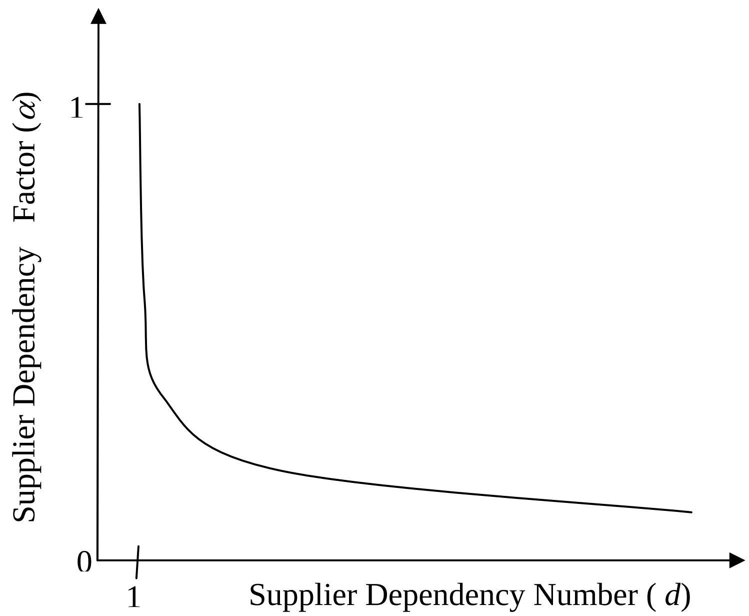


Figure 9: Relationship between the supplier dependency factor and supplier dependency number

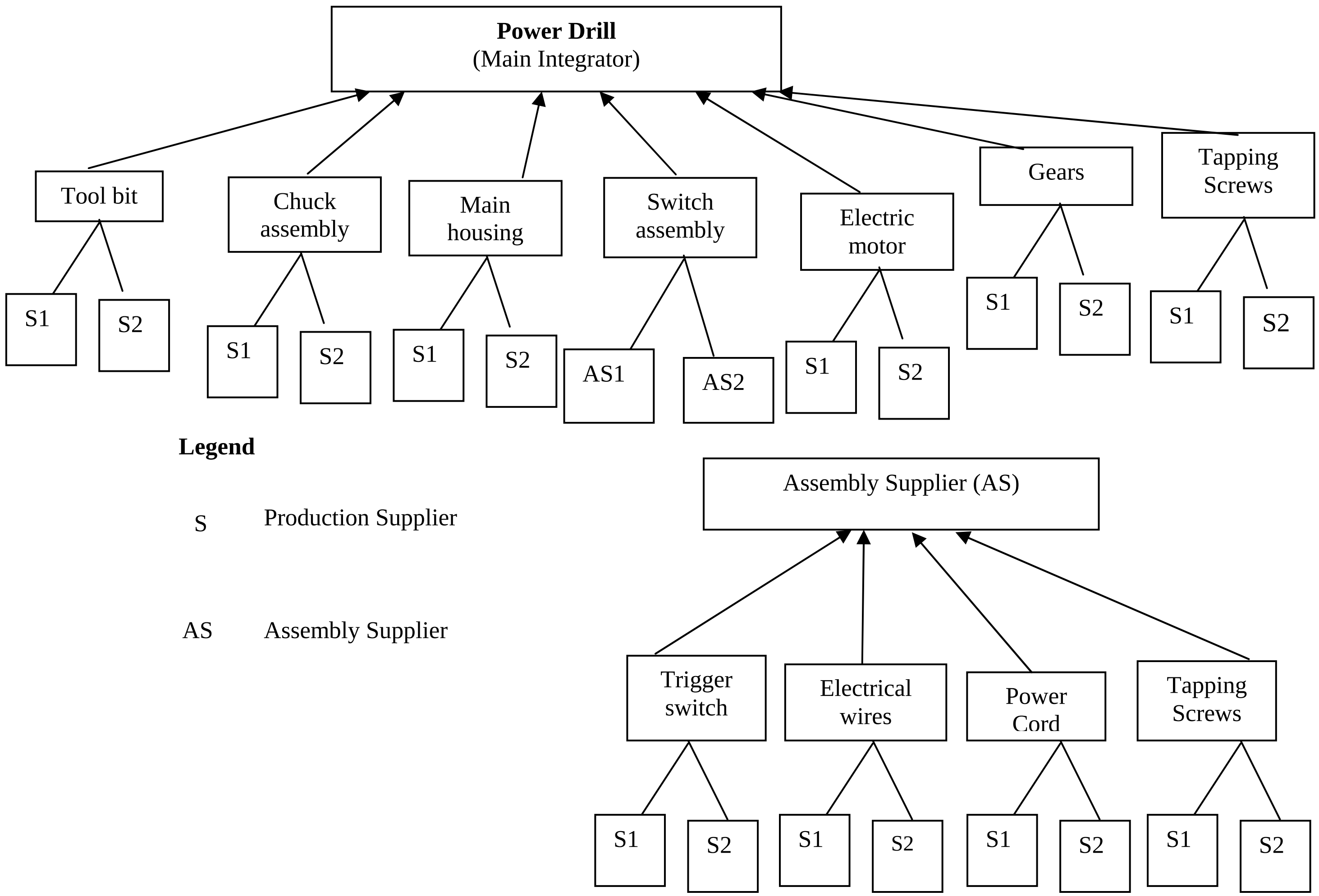
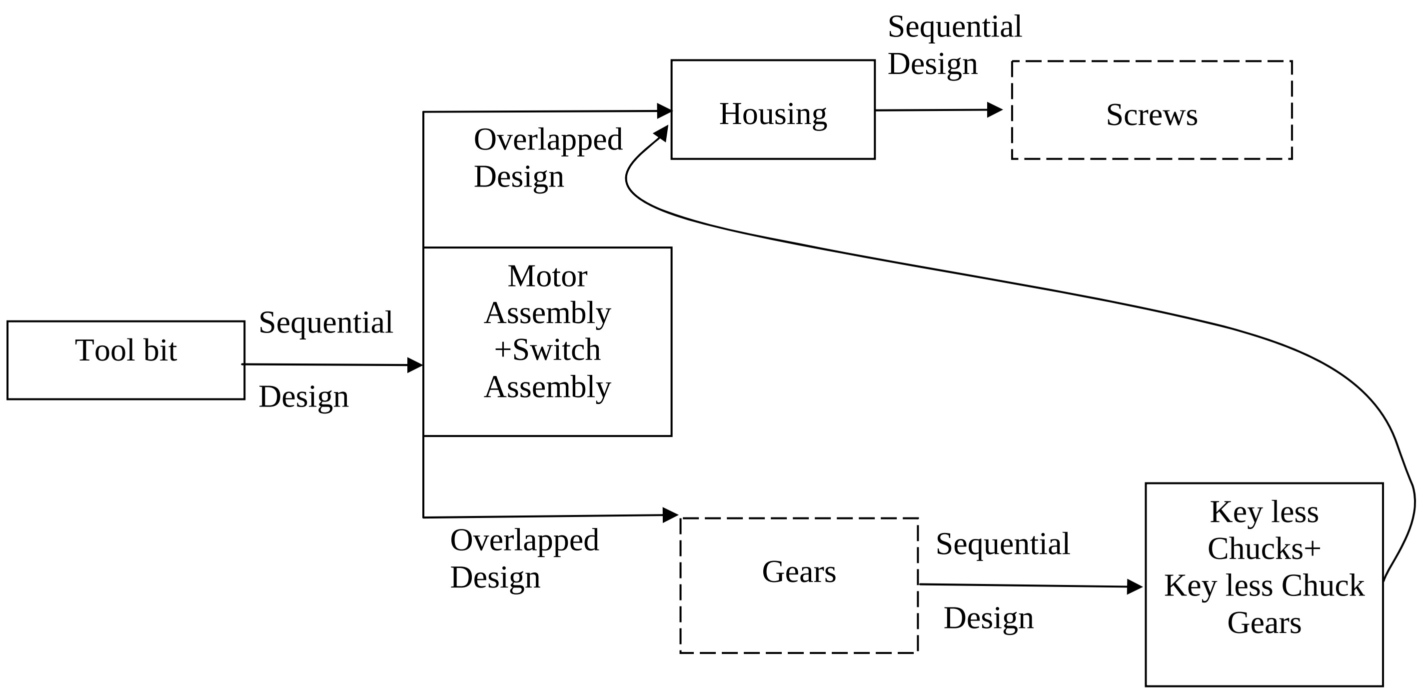


Figure 10: Hypothetical supplier diagram of the power drill case example



D-BOM – (1) Motor Assembly+ Switch Assembly (2) Housing (3) Gears (4) Chuck Gears + Key less Chucks (5) Drill Bits (6) Screws

Figure 11: Redesigned design sequence and D-BOM for power drill example

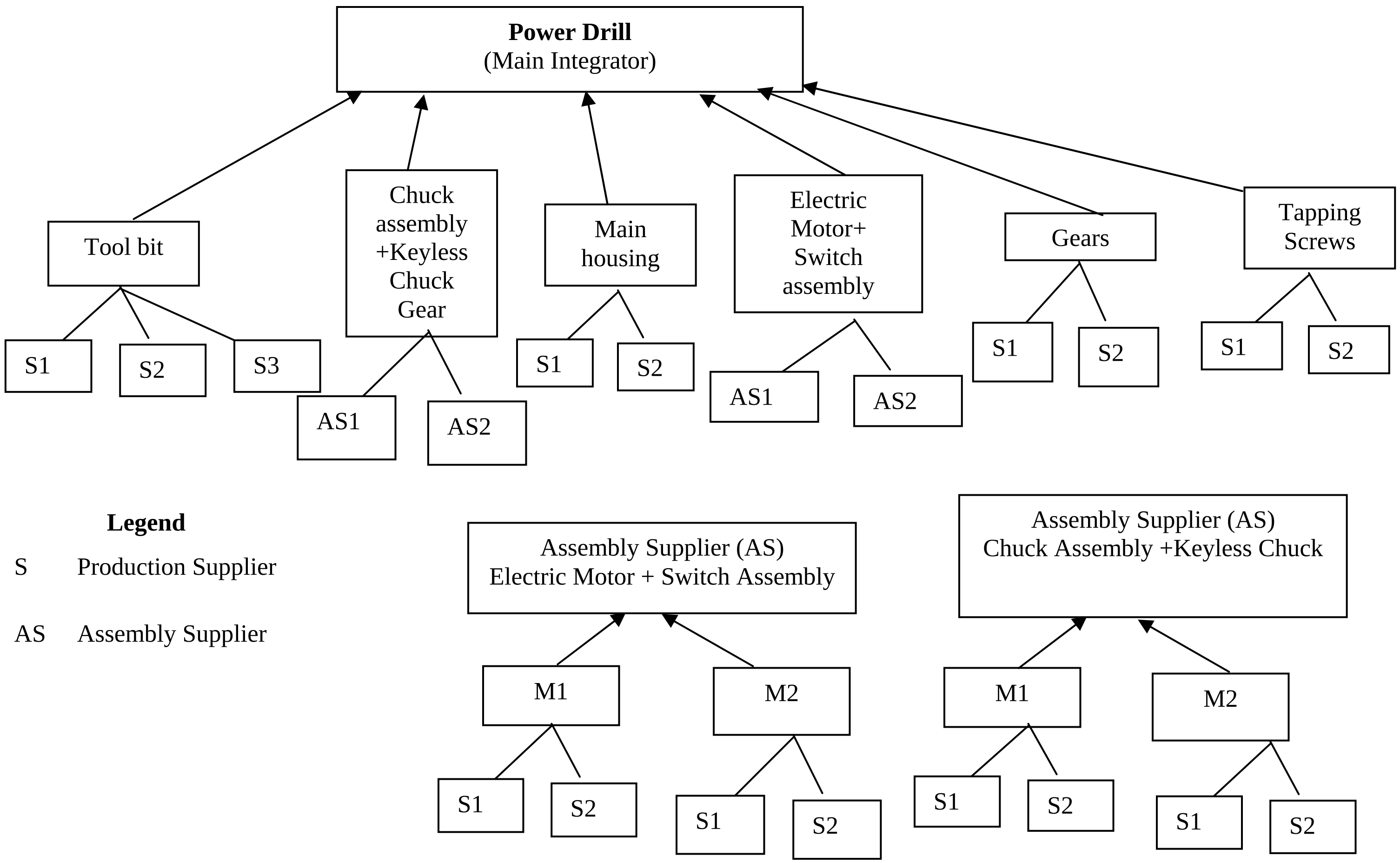


Figure 12: Hypothetical part-supplier diagram of the power drill case example

Table 1: Revised scores for the different types of interactions between the components

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

Table 2: Revised denotation of the various types of interactions

Type of Interactions	Notations	Effect of the presence of interaction
Spatial	S2	Physical adjacency is required or prevented for functionality.
	S1	Physical adjacency is beneficial but not absolutely necessary for functionality or Physical adjacency causes negative effects but does not prevent functionality.
Energy	E2	Energy transfer/exchange between two chunks is required or prevented for functionality.
	E1	Energy transfer/exchange between two chunks is beneficial but not absolutely necessary for functionality or Energy transfer/exchange between two chunks causes negative effects but does not prevent functionality.
Material	M2	Material exchange between two chunks is required or prevented for functionality.
	M1	Material exchange between two chunks is beneficial but not absolutely necessary for functionality or Material exchange between two chunks causes negative effects but does not prevent functionality.

Table 3: Quality of communication among the pool of suppliers and the integrator

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Integrator
Supplier 1	1	0.8	0.6	0.3	0.9
Supplier 2	0.8	1	0.4	0.6	0.8
Supplier 3	0.6	0.4	1	0.3	0.3
Supplier 4	0.3	0.6	0.3	1	0.6
Integrator	0.9	0.8	0.3	0.6	1

Table 4: Different types of module options for the design chunks

Sl. No.	Part Description	Type of modules/Components	Type of product specific modules
1	Tool bit	COTS/PSC	Detailed controlled parts
2	Chuck Assembly	MOTS/PSM	Black box parts/Detailed controlled parts
3	Main Housing	PSM	Black box parts/Detailed controlled parts
4	Switch Assembly	MOTS	-
5	Electric Motor	MOTS/PSM	Black box parts/Detailed controlled parts
6	Gears	COTS	-
7	Tapping Screws	COTS	-
8	Chuck Gears	COTS	-

Table 5: Performance characteristic requirements of the various design chunks

Design Chunks	Basic Features					Additional Features							
	Feature 1	**Feature 2**	**Feature 3**	**Feature 4**	**Feature 5**	**Feature 1**	**Feature 2**	**Feature 3**	**Feature 4**	**Feature 5**	**Feature 6**	**Feature 7**	**Weight**
Tool bit	Different sizes of drill bits	-	-	-	-	Titanium nitride coating	Surface Hardness greater than 80	Drilling in plastics	Drilling in plastics, Metals,	Special casing for the tool bit	Ambidextrous	-	5 grams for each tool bit
Chuck Assembly	3/8 Chuck key	Shank Size 1/4	Key Less	-	-	Reconditionin g services	Reduced head height	Provision of LED to illuminate the drill	Locking system	Color selection features for sleeve	-	-	902 grams
Main Housing	Rubber remodele d	-	-	-	-	Anti-slip gripping	Soft gripping	Work at low temperature	Shock absorben t	Electric insulation	Specific Company Logo	Slot for Leveler	300 gram
Switch Assembly	It should provide the power	Multi-speed trigger switch	Dust Resistant	2 pin plug	Reversible in nature	-	-	-	-	-	-	-	34 gram

Table 5: Performance characteristic requirements of the various design chunks (Contd…)

Design Chunks	Basic Features							Additional Features	
	Feature 1	**Feature 2**	**Feature 3**	**Feature 4**	**Feature 5**	**Feature 6**	**Feature 7**	**Feature 1**	**Weight**
Tapping Screws	BT 4*25	-	-	-	-	-	-	-	4*3 grams
Chuck Gears	Double gear reduction	Bevel gear with heat treated material	-	-	-	-	-	-	180 grams
Motor	6 Ampere Motor	50/60 Hz	1/6-1/4 HP	RPM (0-2200)	Universal Electric Motors	230 V	2:1 gear reduction	Brush system for protecting the Motor Assembly	628 grams

Table 6: Sample total design cost calculation for a design chunk *Electric Motor*

	Basic Features				**Additional Features**	**Different Cost factors**					
	Feature 1	**Feature 2**	**Feature 3**	**Feature 4**	**Feature 1**	**Weight (Grams)**	**Performance Loss Cost($)**	**Design Cost ($)**	**Switchover Cost/Unit ($)**	**Supplier Development Cost/Unit ($)**	**Final Cost ($)**
Suppliers	6 Ampere Motor	50/60 Hz	1/6-1/4 HP	RPM (0-2200)	Brush system for protecting the Motor Assembly	628					
S1	1	1	1	0-2200	1	633	11500	500000	0	0	**511500**
S2	1	1	1	0-2200	1	633	11500	565000	0	0	**576500**
S3	1	1	1	0-2200	1	633	11500	456000	0	0	**467500**
S4	1	1	1	0-2200	1	633	11500	512500	0	0	**524000**

Table 7: Revised-DSM for the power drill case example

	Motor	**Switch**	**Cover set**	**Gears**	**Keyless Chuck Gears**	**Key Less Chucks**	**Drill Bits**	**Screws**
Motor	0	(E2,S2) = 4	(E1,S2) =3	(E2, S2) = 4	0	0	0	0
Switch	-	0	(S1) = 1	0	0	0	0	0
Main Housing	-	-	0	(S1) = 1	(S1)=1	(S2) = 2	0	(S2) = 2
Gears	-	-	-	0	(E2,S2) = 4	(S1) = 1	0	0
Chuck Gears	-	-	-	-	0	(E2,S2) = 4	0	0
Key Less Chucks	-	-	-	-	-	0	(E2,S2) = 4	0
Tool bit	-	-	-	-	-	-	0	0
Screws	-	-	-	-	-	-	-	0

Table 8: Design chunk interaction strength (γ)

Motor	**Switch**	**Main Housing**	**Gears**	**Chuck Gears**	**Key Less Chucks**	**Tool bit**	**Screws**
0.18	0.04	0.22	0.11	0.12	0.24	0.04	0.02

Table 9: Enumeration of supplier dependency factor (α)

Design Chunks	d_i	α_i
Motor	2	0.59
Switch	3	0.52
Main Housing	6	0.43
Gears	3	0.52
Chuck Gears	4	0.48
Key Less Chucks	5	0.45
Tool bit	1	1
Screws	7	0.41

Table 10: Functional importance of the different design chunks

Design Chunks	θ_i
Motor	0.23
Switch	0.10
Main Housing	0.07
Gears	0.10
Chuck Gears	0.10
Key Less Chucks	0.20
Tool bit	0.17
Screws	0.03

Table 11: Sample total production cost and capacity information about tier 1 supplier for original product design

		Production/ Assembly Cost ($)	Defect Loss Cost ($)	Switchover Cost	Supplier Development Cost	Total Cost ($)	Capacity of each supplier
Electric Motor	Supplier 1	50	10	0	0	60.00	4000.00
	Supplier 2	60	11	0	0	71.00	1000.00
	Supplier 3	70	12	0	0	82.00	500.00
	Supplier 4	80	13	0	0	93.00	3000.00
Drill Bit	Supplier 1	30	9	0	0	39.00	2000.00
	Supplier 2	32	8	0	0	40.00	4000.00
	Supplier 3	37	7	0	0	44.00	400.00
	Supplier 4	45	7	0	0	52.00	3500.00
Screws	Supplier 1	0.5	5	0	0	5.50	30000.00
	Supplier 2	1	8	0	0	9.00	40000.00
	Supplier 3	0.75	9	0	0	9.75	50000.00
	Supplier 4	1.25	11	0	0	12.25	450000.00
Gear	Supplier 1	5	21	0	0	26.00	1200.00
	Supplier 2	6	11	0	0	17.00	1000.00
	Supplier 3	7	10	0	0	17.00	200.00
Keyless Chuck Gear	Supplier 1	3	8	0	0	11.00	4500.00
	Supplier 2	4	5	0	0	9.00	3400.00
	Supplier 3	5	6	0	0	11.00	2000.00
Chuck	Supplier 1	20	0	0	0	20.00	6000.00
	Supplier 2	25	1	0	0	26.00	4500.00
	Supplier 3	30	2	0	0	32.00	5400.00
	Supplier 4	24	4	0	0	28.00	900.00
Cover Set	Supplier 1	15	5	0	0	20.00	5000.00
	Supplier 2	18	7	0	0	25.00	1800.00
	Supplier 3	12	8	0	0	20.00	1400.00
	Supplier 4	13	9	0	0	22.00	700.00
Switch Assembly	Assembly Supplier1	2	11	0	0	13.00	1000.00
	Assembly Supplier2	3	12	0	0	15.00	5000.00
	Assembly Supplier3	4	13	0	0	17.00	3000.00

Table 12: Sample total production cost and capacity information about tier 2 suppliers for original product design of Assembly Supplier 1

Assembly Supplier 1		**Production Cost ($)**	**Defect Loss Cost ($)**	**PS Switchover Cost ($)**	**Supplier Development Cost ($)**	**Total Cost ($)**	**Capacity of each supplier**
Trigger switch	Supplier 1	10	5	0	0	15	2000
	Supplier 2	11	6	0	0	17	1550
	Supplier 3	13	10	0	0	23	3000
	Supplier 4	14	13	0	0	27	7000
Electrical wires	Supplier 1	12	11	0	0	23	1275
	Supplier 2	13	5	0	0	18	3000
	Supplier 3	10	2	0	0	12	7000
Power Cord	Supplier 1	11	4	0	0	15	7000
	Supplier 2	12	8	0	0	20	3000
	Supplier 3	10	9	0	0	19	5400
Tapping Screws	Supplier 1	11	5	0	0	16	3000
	Supplier 2	10	7	0	0	17	4000
	Supplier 3	9	8	0	0	17	5000
	Supplier 4	8	8	0	0	16	4000

Table 13: Demand breakup of the various assembly suppliers

Assembly suppliers (AS)	**Total Capacity of the AS**	**Demand Breakups**				
AS1	1000.00	1000	-	-	-	-
AS2	3000.00	1000	2000	3000	-	-
AS3	5000.00	1000	2000.00	3000	4000	5000

Table 14: Comparison of the results of the two phases

Metrics	Original design		Modified design	
	Design Phase	**Production Phase**	**Design Phase**	**Production Phase**
Number of Suppliers	8	29	6	14
Total number of Inventory days	-	145	-	70
Total Manufacturing and Logistics lead time	-	235	-	77
Communication effectiveness	0.40	-	0.47	-

VITA

"Integrated product and its extended enterprise network design using lean principles" is a thesis authored by Mr. Abhijit K. Choudhury, beneficial to him in obtaining his Master of Science Degree from the University of Missouri –Rolla, USA in December 2007. Abhijit was born on July 1, 1981 in the city of Patna, India. Abhijit pursued his bachelors degree in Manufacturing Engineering from National Institute of Foundry and Forge Technology. Abhijit did several useful projects during undergraduate studies as well as in his intern in IISc Banglore and IIT Delhi. This interested him to pursue Master of Science in Engineering Management. During the pursuit of this degree, the author had the opportunity to publish three conference papers (American Society of Mechanical Engineers Conferences, International Conference on Agile Manufacturing 2006) and is attempting to submit the present work to a journal.

Apart from his academic life, Abhijit pursues interests in current affairs, driving, history, socializing with his friends, and war movies.