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## **Title:**

Multi-objective optimization of product variety in a mass customization process with considering three-dimensional concurrent engineering approach

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Defended the 7th July 2015

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# Acronyms

AHP	Analytic hierarchy process
ANP	Analytic network process
ATO	Assemble-to-order
CE	Concurrent engineering
CODP	Customer order decoupling point
DFMC	Design for mass customization
DFV	Design for Variety
ETO	Engineer-to-order
GA	Genetic algorithm
GP	Goal programming
MC	Mass customization
MCDM	Multiple Criteria Decision Making
MILP	Mixed Integer Linear Program
MLP	Multi-level programming
MOO	Multi-objective optimization
MP	Mass production
MTO	Make-to-order
MTS	Make to stock
NSGA	Non-dominated Sorting Genetic Algorithm
OPP	Order penetration point
PFA	Product family architecture
PI	Performance indicator
SCM	Supply chain management
SIM	Simple inversion mutation
3-DCE	Three-dimensional concurrent engineering
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
TQM	Total Quality Management
WIP inventory	Work-In-Process inventory

# **Chapter 1: Introduction**

## **1.1 Context**

In recent years, market environment is changing progressively due to increase individual needs of customers. Also, people are now more informed and willing to make their own decisions. Incremental growing of individual needs of customers has caused that manufacturing enterprises strive for customizing their products thus generating a high level of product variety, which increase the internal complexity in operations and manufacturing tasks. It seems that current manufacturing approaches cannot respond effectively (Pine, 1993) and need new concepts to shift the industry into a higher level of efficiency. This has caused companies to change their strategies from mass production (MP) to mass customization (MC) (Pine, 1993). Mass customization relates to the ability of providing customized products or services through flexible processes in high volumes and at reasonably low costs. In addition, mass customization appears as an alternative to differentiate companies in a highly competitive and segmented market.

This chapter, as an executive summary, highlights the major themes of the dissertation, defines the research problem, outlines the research approach and concludes by summarizing the key points of the chapters.

## **1.2 Problem definition**

The first question that arises when deciding on implementation of mass customization is whether the MC implantation is worthy. On the one hand, customization increases customer satisfaction thus increases sales rate and profit; but on the other hand, it increases internal variety and cost. It also implies to review all processes in the organization from redesign of products to delivery modes.

Determining the level of customization which really satisfies the customer is really hard. Providing a high product variety might not receive a favorable response from the customers, while, low product variety may provide customized products for a wide range of customers that cause low satisfaction for customers.

In MC, product variety can be produced by configuring different modular choices or varying extents of customizable features. Determining the set of components and/or feature choices which can provide both values for customer and enterprise with respect to different constraints is an important work in MC. Addressing this issue requires which a decision making process to be created in order to consider some main decision points in three domains product, process and supply chain. Although three criteria cost, quality and delay are usually more used in decision-making problems, but with using concept of value, other important criteria such as customer perception and environment respect are considered. Since major aim of a MC process is to provide customized products, the values perceived by all actors in value network that collaborate to deliver value to the end consumer have an important role in MC success or failure.

Effects of decisions such as selection of manufacturing methods and supplier selection on values perceived by customers and enterprises should be considered for true determination of product varieties. Also, one of main decision points in MC is position of customer order decoupling point. CODP positioning is recognized as a business level concept with strategic, tactical, as well as operational implications, that affects on whole supply chain system (Saghiri, 2007).

Therefore, the effect of product variety on customer satisfaction and thus customer value and other parties in value network with considering these main decision points should be considered.

This thesis investigates what product varieties are proper to offer customers through analyzing their effects on customer value and enterprise value. For this purpose, we consider some main decision points in product design, process, and supply chain design and investigate their effects on value perceived by customers and enterprises. We propose two multi-objective optimization models that integrate these decision points such as selection of the components/features (thus product varieties), the best CODP position in process and selection of the manufacturing method and suppliers. For this purpose, some qualitative and quantitative performance indicators are used. We apply fuzzy logic for evaluation of performance indicators with qualitative nature and use interval data for some parameters in our models to deal with uncertainty.

### **1.3 Research aim**

In view of challenges of implementation of mass customization, the research aim includes several issues concurrently as follows:

1. The first (main) aim: Deciding on components/features (or module) which should be chosen under resource limitation from a large amount of available alternatives.
2. The second aim: Decision making about some strategic and technical issues in supply chain management such as supplier selection, manufacturing method selection and position of customer order decoupling point.
3. The third aim: Concurrent evaluation of qualitative and quantitative performance indicators affecting on customer and enterprise value in a model with considering uncertainty both interval values and fuzzy numbers.
4. The fourth aim: To propose a new ranking method for interval-valued alternatives.

A contribution of this thesis is to integrate some decision points such as selection of set of components and/or feature options, position of customer order decoupling point and some strategic and technical issues in supply chain management through constructing a multi-objective optimization model.

Another contribution can be development of a novel method to integrate qualitative and quantitative performance indicators in a multi-objective optimization model as well as considering uncertainty in some parameters as interval numbers.

To propose a new ranking method which consider interval-valued reference vector as an ideal reference instead of crisp reference vector can be another contribution.

### **1.4 Methodology**

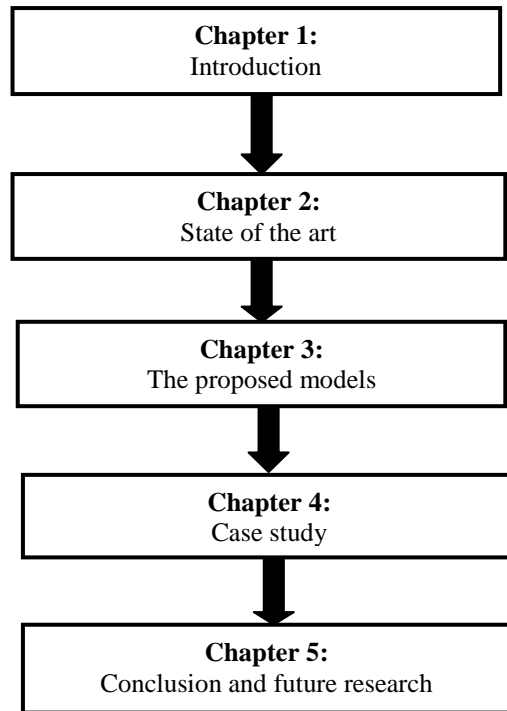
To meet the main aim of thesis, we, at first, consider some main decision points in product design, process, and supply chain design and investigate their effects on value perceived by customers and enterprises. Then, we determine some qualitative and quantitative performance indicators that are used to evaluate customer and enterprise values. Since some PIs in value have qualitative nature, we evaluate them with using fuzzy logic and linguistic terms and propose a novel method to integrate these qualitative and quantitative PIs in order to build a multi-objective



optimization model with considering interval data for some parameters. Finally, we apply a modified solution method based non-dominate sorting genetic algorithm (NSGAI) to get results.

## 1.5 Thesis organization

The thesis is comprised five chapters shown in Figure 1.



**Figure 1:** Different Chapters of thesis

Following the introductory chapter of the dissertation, Chapter 2 reviews the existing literature about key issues used in the thesis such as product design, product and supply chain optimization, customer order decoupling point (CODP), concept of value and multi objective optimization with interval value and ends with discussion about some deficiencies in literature and our contribution of thesis.

In chapter 3, we present two multi-objective optimization models based on analyzing key variables affecting on both value perceived by customers and value obtained by enterprise in order to get aims of research. For finding solution, a method based on non-dominated sorting genetic algorithm II (NSGAI) with considering uncertainty is proposed.

Chapter 4 is dedicated to test the validity and suitability of the proposed models with using a case study in the manufacturing domain.

Chapter 5 presents a synthesis of the research works carried out. It identifies comments on the limitations of the proposed models and proposes future research objectives and directions.



## **2 Chapter 2: State of the art**

## 2.1 Introduction

Change of paradigm from mass production to mass customization has caused the dramatic increase of the number of products offered in the marketplace (Huffman & Kahn, 1998). However, increase of variety does not necessarily translate into increased profit from increased sales. Initially, variety does improve sales and profits as the product offered become more attractive. As variety keeps growing, the profit may not keep due to reducing returns since the cost and complexity of manufacturing may be increasing (Wortmann et al., 1997).

In a mass customization process, configuration of different components or extent of features can build customized product. So, it is important to know which set of components and/or extent of feature choices can provide both values for customer and enterprise by considering different constraints. Indeed, decision making on level of customization build the basic step for implementation of MC. To deal with this issue need to consider some main decision points in three domains product, process and supply chain.

In this chapter, we review all issues linked to the thesis. At first, we review the evolution of manufacturing systems in literature and represent a brief literature of pre-requisites needed for implementation of MC process. Since determination of optimal components and/or features options is one of main aims of thesis, we investigate literature related to optimize design of products, shortly. Then, we argue the necessity of integrating decision points in other domains like process and supply chain when development of a new product and represent the works performed. After that, we deal with the concept of CODP position as one of main decision points in process domain and review the works done. Then, because of using value concept in thesis, we describe that with a number of related works. After, we represent the literature related to application of interval data in different problems because of his application for some parameters in the models. Finally, in the end of chapter, we argue a discussion about these literatures.

## 2.2 Evolution of manufacturing systems

The manufacturing industry has evolved through several paradigms. The first paradigm was Craft production which created products according to customers request but with high cost and without manufacturing system ( Hu, 2013).

When Henry Ford introduced the modern assembly line in production of automobiles in beginning of century 20, the world experienced a new era of industrialization. This method of production relied on standardization principles. In mass production workers perform standardized and repetitive tasks that lead to the manufacture of large amounts low-cost, standard goods and services.

Mass production provides a mass market with goods at a consistent quality and affordable prices. It builds upon main principals: Economies of scale, product standardization, division of labor, and hierarchical organization.

Although mass production made goods available and cheap for customers, there were still concerns about quality of products (Selladurai, 2004). Over time, mass production systems improved efficiency and reliability of their existing processes by implementing new quality initiatives, such as Total Quality Management (TQM), Design for Six Sigma and minimizing waste by applying Lean principles (Selladurai, 2004) .

Despite cheaper products and better quality, many customers are not satisfied with standard products because of the very low number of varieties offered by such production. In the late 1980s, global competition to satisfy customer demands for high product variety led to the development of Mass customization (MC) (Pine, 1993).

The vision of Mass customization (MC) was to offer customized products at essentially the price of mass produced products. It was the increasingly flexible and optimized production systems that led to this possibility. It was furthermore a way for companies to get a larger market share, obtain a competitive advantage and differentiate themselves in highly competitive and segmented markets (Da Silveira, Borenstein, & Fogliatto, 2001).

Before the advent of internet, the concept of mass customization rarely applied in real world business because of lack of adequate and necessary technology to cope with the processes of customer integration and co-creation (Piller, 2004). From then on, mass customization was more regularly implemented by companies in different sectors such as cars and footwear as an instrument to address the rapid changing market realities, while still preserving the efficiency of mass production. Table 1 shows the evolution of manufacturing systems extracted from different references (Pine, 1993; Sinopoli, 2003; Selladurai, 2004;Hu, 2013).

### 2.3 Definition of mass customization

Mass customization relates to the ability of providing customized products or services through flexible processes in high volumes and at reasonably low costs. In addition, mass customization appears as an alternative to differentiate companies in a highly competitive and segmented market. Da Silveira et al. (2001) defined mass customization as follows:

*“A system that uses information technology, flexible processes, and organizational structures to deliver a wide range of products and services that meet specific needs of individual customers, at a cost near that of mass-produced items”*

**Table 1.** Different manufacturing systems

Production system	Specification			Time period
	Product	Organization	Worker	
Craft production	- Unique - High quality	-	-	Before 1900
Mass production	-Low-cost - Standard - Quality: Lower than a craft-produced item	Bureaucratic Hierarchical Highly standardized	Operating under close supervision and with highly routine, standardized, and repetitive tasks	1900-1970
Improved mass production	low-cost, High quality Standard	Participative, team-based	Workers are given more participative and decision-making responsibilities	1980
Mass customization	Low cost, High quality, Customized	An efficient, well-integrated organizational system		Mid-1990s through the present time

According to a survey of Åhlström & Westbrook (1999) that is based on experience of several companies using mass customization, the most important benefit of MC implementation is ability of customers to design their own product. This action increases satisfaction and loyalty of customers. With implementation of MC, companies increase their market share compared to competitors which have not deployed mass customization. Also, efficiency increases due to lower inventory cost and more effective use of retail, factory and warehouse space (Berman, 2002). Åhlström & Westbrook (1999), also, mentioned other advantages for MC implementation such as increased customer knowledge, reduced order response time, reduced manufacturing cost, and increased profit.

Although firms have several incentives for implementing mass customization, there are however many other considerations that the firm has to address. Since customer is main driver of mass customization, the main question before implementing MC is whether customization will create a sufficient added value for customers (Blecker, Abdelkafi, Kaluza, & Friedrich, 2006). The main concern is to determine the specific organizational requirements and favorable market factors that will contribute to an increase in the probability of the success implementation of mass customization. Different researches dealt with a series of MC success factors and enablers that has been reviewed by Fogliatto, da Silveira, & Borenstein (2012).

## **2.4 Literature review of product design**

In order to provide a wide variety of products, researchers have paid attention to design of products in MC process. Research in product design is mainly characterized by two approaches. First approach deals with problem of product design from view of qualitative aspects, common terminology and addressing important business issues.

This approach in mass customization process includes approaches how to produce a wide variety of designs. For example, Product family development has been recognized as an effective means of achieving mass customization (Mitchell M Tseng & Jiao, 1998). Also, concepts modular product architecture, product platform and commonality are key concepts to provide flexibility for custom designs and form the basis for developing a set of derivative products with minimal redesign efforts (Ulrich, 1995; Sawhney, 1998). Approaches such as product family, product platform and product architecture have been used in order to increasing product variety while maintaining economies of scale (Daaboul et al., 2011). Mikkola & Skjøtt-Larsen (2004) expressed product customization can take place either based on a common platform with additional options or based on combining and mixing-and-matching modules to achieve different product characteristics. According to commonality and performance indices developed by Simpson (1998), Wang et al. (2009) applied robust design principles to address product family tradeoffs.

Some researchers dealt with terminology or concepts to better describe product architecture. For example, Qiao et al. (2003) recognized three types of products with different specifications that are developed in MC: “Standardized products”, “Configured products” and “Parameterized products”. Product variety can be achieved through combinations of components and modules. Ulrich & Tung (1991) classified various types of modularity in six categories, which can be used separately or in combination to provide a customized end product. Du et al. (2000) introduced the concepts of common bases (CB), differentiation enablers (DEs) and configuration mechanisms (CMs) to better understand product family architecture. Common bases (CB) relate to elements shared within a product family, differentiation enablers (DEs) identify as the basic elements for making products within a product family and configuration mechanisms (CMs) define the rules

and means in order to derive product variants. Du et al. (2001) introduced three basic mechanisms to generate product variety: attaching, swapping, and scaling. They discussed more complicated variety generation that can be composed by applying these basic methods to the hierarchical product structure.

Second approach applies mathematical models to optimize product design. Martin & Ishii (1996, 1997) developed quantitative tools to determine customer preference for variety and to estimate manufacturing costs of providing variety. Tseng et al. (1996) proposed a design approach for MC (DFMC) based on product family architecture (PFA) with Meta level design process integration. With formulation of PFA, optimization of reusability/commonality in both product design and process selection from the product family perspective becomes possible. Martin and Ishii (1997) proposed Design for Variety (DFV) as a methodology to develop products with minimum variety costs. Fujita et al. (1999) proposed a mathematical model for problem of product variety design under a fixed architecture and module communalization. Chen & Yuan (1999) proposed a probabilistic-based design model as a basis for providing the flexibility in a design process in order to develop a range of solutions that meet a ranged set of design requirements. Gonzales-Zugasti et al. (2000) presented a method that uses cost models as the driving force for designing the product platform while satisfying performance and budget constraints. Suh (2001) introduced a design metric based on the information axiom to evaluate design flexibility. Flexibility is implied by considering both design performance as achieved performance range (i.e. system range) to the customer expected level of performance as target range (i.e. design range). Gonzalez-Zugasti et al. (2001) formulated design of a platform-based product family as an optimization problem. Fellini et al. (2002) proposed a compromise decision support problem to optimize the design by developing a method to configure product platforms concepts. Fujita (2002) determined the contents of modules and their combinations under an optimization view and argued necessity of developing a quantitative and systematic approach to examine all possible combinations of the available alternative modules. Seepersad et al. (2002) presented a quantitative approach for designing multiple product platforms for an evolving family of products. The approach is based on the utility-based compromise Decision Support Problem (which is a multi-objective decision support model with an objective function derived from utility theory). Nayak et al. (2002) employed robust design concepts to formulate a variation-based platform design methodology consisting of two steps: identifying the platform by solving a compromise decision support problem and designing the family around this platform. D'Souza & Simpson (2003) introduced a genetic algorithm to find an acceptable balance between commonality in the product family and desired performance of the individual products in the family. Simpson (2003) provides a thorough review of 32 existing optimization-based product platform design approaches wherein their different characteristics are compared and contrasted. De Weck et al. (2003) presented a methodology to determine the optimum number of product platforms to maximize overall product family profit with simplifying assumptions. Nepal et al. (2005) presented a formal and integrated method for optimizing the performance attributes of prospective modules by minimizing the cost of modular architecture. Khajavirad & Michalek (2008) developed a method for both the optimal selection of components to be shared across product variants and the optimal values for design variables. Spahi (2008) studied the degree of customization from a product structural perspective and defined a model that would help determining an optimal or near to optimal degree of customization, based on strategic management goals and resource constraints. Indeed, he selected the optimum number of modules by developing a multi-objective model and proposed a method to determine MC level (or number of products offered to customer). Ben-Arieh et al. (2009) proposed multiple platforms for the production of a given product family while minimizing the overall production cost. The methodology considers the demand for each product variant, with the decision variables as the

optimal number of platforms, optimal configuration of each platform, and assignment of the products to the platforms. Khajavirad et al. (2009) proposed an efficient decomposed multi-objective genetic algorithm to jointly determine optimal (1) platform selection, (2) platform design, and (3) variant design in product family optimization. Wei et al. (2009) proposed a two-stage multi-objective optimization-based platform design methodology for solving the product family problem by using a multi-objective genetic algorithm. Wang et al. (2011) proposed a multi-objective optimization approach to balance product variety and manufacturing complexity when designing a product family and the mixed-model assembly system. Liu (2014) proposed a new method to deal with selection of module under resource limitation with using rough set theory and total quality development framework. Liu et al. (2014) proposed a design methodology for achieving optimal product architecture. They first used the analytic network process (ANP) to incorporate designers' knowledge in calculating relative importance of components regarding to customer needs. Then, the goal programming was applied to determine the platform and the variant components with incorporating the result of ANP and cost budget limitation.

Investigation of second approach – which are more related to our thesis due to determination of extent or number of product varieties- identifies which these papers just investigate the level of product varieties offered to customers by optimizing platforms, standard and customized components and design requirements and don't consider effects of other important decision point (such as CODP position or decisions in supply chain) on manufacturing cost and thus capability of company to offer product varieties.

Many researchers have emphasized necessity of integrating these decision points when developing a new product. In the next section, we discuss the need to integrate supply chain management in product development in order to correct evaluation of product architecture and product varieties.

## **2.5 Integrating decisions in new product development**

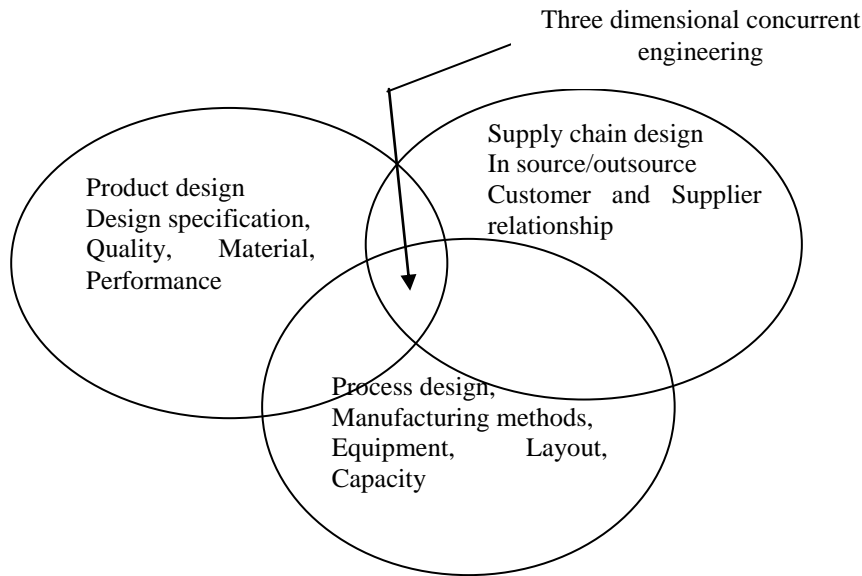
In a competitive environment, companies try to offer product varieties to meet customer's demands. This diversity affects on all processes involving in product development. In this condition, the question is what extent a product should be customized in order to offer a wide variety of products that meets customer's needs by considering different production and logistical constraints?

Works on product family design usually take into account production and logistical constraints with aim of reducing cost (Pine, 1993). Although product architecture is normally established during the early stages of the product development cycle, however, it influences decisions made downstream in domains of product, process and supply chain. It is estimated that product and process design influences 80% of manufacturing costs, 50% of quality, 50% of order lead time, and 50% of business complexity (Child, Diederichs, Sanders, & Wisniowski, 1991). More importantly, the decisions made during the conceptual design stage have direct effect on over 70% of the production costs, even though the actual cost of the design phase accounts for only 6% of the total development cost (Shehab & Abdalla, 2001). Individual product architecture characteristics such as the degree of commonality, the nature of interactions, and interfaces between components may constrain strategic decisions like postponement and late customization (Fixson, 2005). So, decisions related to new product development must be aligned with supply chain management to deliver the products at the targeted objectives. This will let the



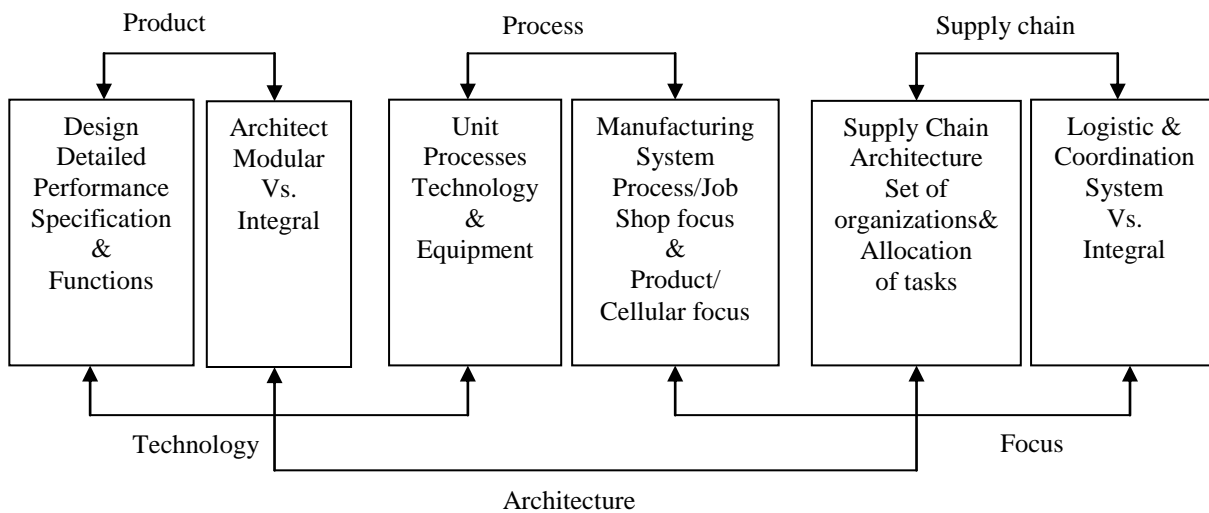
manufacturers to overcome manufacturing problems such as lack of product availability (Hasan et al. 2014).

Many researchers have emphasized necessity of integrating some main decision points in other domains such process or supply chain when developing a new product (Child, Diederichs, Sanders, & Wisniowski, 1991; Fisher, 1997; Fine, 1998; Garg, 1999; Jiao et al., 2009; Baud-Lavigne et al., 2012). Baud-Lavigne, Agard, & Penz (2014) argued that it is only in the last few years that the issues of product optimization and supply chain optimization have been addressed simultaneously. Fine (1998) argued which despite the many demonstrated benefits of concurrent engineering, it no longer provides a source of competitive advantage and introduced three dimensional concurrent engineering (3-DCE) concept. This concept that its roots are in concurrent engineering, are defined as the simultaneous development of products, processes and supply chains (Figure 2). Shortly, 3-DCE tries to consider, simultaneously, different aspects of design, process and supply chain in the early stages of product development.



**Figure 2:** 3-DCE linkages (Fine, 1998)

Figure 3 displays overlapping areas of product, process, and supply chain development.



**Figure 3:** The 3-DCE Concurrency Model (Fine, 1998)

Table 2 describes activities each of three developmental areas - product, process, and supply chain:

**Table 2.** Activities in three areas of product, process, and supply chain (Fine, 1998)

Area	Activity	Description	Example
Product development	Architecture	integrality vs. modularity decisions	
	detailed design	performance and functional specifications	
Process development	development of unit processes	the process technologies and equipment to be used	
	manufacturing systems development	decisions about plant and operations systems design and layout	process/job shop focus vs. product/cellular focus
Supply chain development	supply chain architecture	make or buy decision; sourcing decisions	
	logistics/coordination system decisions	Logistics and coordination decisions	inventory, delivery, and information systems

Design of a supply chain can include both strategic and tactical decisions. Decisions related to strategic level affect on the long term of the company. For example, the selection of production facilities, manufacturing capacities and technologies used may be viewed as strategic decision. Decisions related to the tactical level include decisions such as the choice of suppliers, the allocation of products to production facilities, and the flow of each product and sub-assembly in the network (Cordeau, Pasin, & Solomon, 2006). Riopel et al. (2005) presented a framework which highlights all the links between the product and supply chain design by a comprehensive study on the logistical decisions.

Feng et al. (2001) developed a stochastic programming model to determine the tolerances of product design and selection of suppliers, simultaneously, based on quality loss. Park (2001) presented a simulation model to integrate product platform and supply chain configuration. The proposed model included multiple platform strategies and a large number of supply chain decisions (e.g. raw material sourcing and transportation, manufacturing plant location, and etc). Kim et al. (2002) developed a mathematical model to configure supply chain for a mix of multiple products. The model was able to evaluate value of each raw material and/or component ordered to each supplier. Singhal & Singhal (2002) developed an expert based approach to identify desirable product ideas that considers operations and marketing capabilities in a compatibility matrix. The approach takes into account the design of the supply chain and product and the processes used to manufacture the product.

Thonemann & Bradley (2002) analyzed the effect of product variety on supply chain performance for a supply chain with a single manufacturer and multiple retailers with developing a mathematical. Salvador et al. (2004) investigated effect of MC level on supply chain configuration by applying an empirical research and explored how a firm's supply chain should be configured for different degrees of customization. Wang et al. (2004), at first, recognized relation between product characteristics and supply chain strategy. Then, they proposed a multi-criteria decision-making method by using analytic hierarchy process (AHP) and preemptive goal programming (PGP). They, in their model, take into account both qualitative and quantitative factors in supplier selection. Petersen et al. (2005) explained how to integrate suppliers into the new product development process and showed their effects on process design and supply chain decisions. Fine et al. (2005) studied relationships between product structure (modular and integral) and supply chain structures (modular and integral) and proposed a quantitative

formulation by using a weighted goal programming model to address 3-DCE problem with aim of assessment of trade-offs among potentially conflicting objectives. A set of configurations consisting of product version, product design, assembly sequence and a set of suppliers were evaluated by a weighted goal programming with objectives fidelity, costs, lead time, partnership, and dependency. Huang et al., (2005) developed an optimization model to deal with the effect of platform products, with and without commonality, on decisions related to supply chain configuration. They considered different decision point in supply chain configuration including supplier selection, selection of transportation delivery modes, determination of inventory quantities and stocking points, manufacturing processes to use, production time and etc. Blackhurst et al. (2005) proposed a modeling methodology based on network to formalize the Product Chain Decision Model (PCDM) in order to describe operations of a supply chain. They, in their models, considered decisions related to product design, manufacturing process design and the effect of such decisions on the supply chain. Fixson (2005) recognized the product architecture as the mechanism for coordinating decisions across the three domains of product, manufacturing process, and supply chain. They proposed an assessment framework to operationally define any given product architecture in terms of its functions, components, and interfaces. Table 3 shows the decisions of each domain and their relation with product architecture characteristics.

**Table 3.** Decisions related to each domain (Fixson, 2005)

Domain	Level	Decisions	Product architecture characteristics
Product (development)	Strategic	From capability development of design engineers to the selection of locations for development facilities to the formation of strategic development alliances	<ul style="list-style-type: none"> <li>-Product modularity</li> <li>-Component complexity</li> <li>- Product platforms</li> <li>- Component Commonality</li> </ul>
	Project	Product functionality, product line variety, material choices, and product styling (Paul, Beitz, & others, 1996).	
	Organizational	The number and size of project teams, whether these teams are cross-functional, methods to steer team group processes, and tools to plan product development milestones, sequences, and the degree of overlap (Brown & Eisenhardt, 1995).	
Process	Strategic	The size of production capacity, the type of manufacturing processes, or the locations of production facilities	<ul style="list-style-type: none"> <li>-Product modularity</li> <li>-Component complexity</li> <li>- Product platforms</li> <li>- Component Commonality</li> <li>-Loosely coupled interfaces</li> </ul>
	Tactical	Scheduling of production, the organization of teams, and the planning of maintenance	
Supply chain	Strategic	Number and location of logistics facilities, contractual relations with suppliers, long-term sourcing arrangements, and postponement and mass customization strategies	<ul style="list-style-type: none"> <li>-Product modularity</li> <li>-Number of components</li> <li>- Product platforms</li> <li>- Component Commonality</li> <li>-Loosely coupled interfaces</li> </ul>
	Operational	Service levels, delivery schedules (e.g., just-in-time), vehicle routing, and crew planning	

Saiz et al. (2006) proposed a decision support simulation in 3-DCE environment in order to design of a responsive and efficient supply network. They identified possible configurations based on customized demand scenarios and different network conditions (i.e. capacity constraints, suppliers lead times...). Famuyiwa & Monplaisr (2007) proposed an optimization model to integrate decisions about product architecture and supply chain during early design

stages of product development and examined effect of modularity decisions on supply chain policy.

Jiao et al. (2009) proposed a model based on factory loading allocation problem (FLAP) and from a constraint satisfaction perspective, for problem of coordination of product, process, and supply chain. Khalaf et al. (2010) proposed a model to choose simultaneously the modules and their suppliers in order to minimize the total production costs for the supply chain. They, also, compared two approaches which decisions related to the design of the products and the allocation of modules to suppliers are got simultaneously and separately. Baud-Lavigne et al. (2011) developed a Mixed Integer Linear Program (MILP) model which integrates product, sub-assembly and component substitution possibilities to a supply chain design model. Vandaele & Decouttere (2013) discussed about how to design a business by integrating product, process and supply chain design. Gan & Grunow (2013) introduced a novel conceptual framework called Concurrent Design Attribute Trade-Off Pyramid (CDA-TOP) for concurrent product and supply chain design. Deng et al. (2014) proposed a multi-objective optimization model to address an integrated product line design and supplier selection. Their model was constructed based on minimizing the cost of the product line and maximizing the profit, quality and performance. Hasan et al. (2014) argued the effects of the integration of supply chain management (SCM) with new product development and proposed a framework to link the product development within a SCM for an extended enterprise. Marsillac & Roh (2014) assessed product, process and supply chain links by using a multiple case study based on 3-DCE theory and developed a framework to show how supply chain capabilities are influenced from product, process and supply chains. Behncke et al. (2014) matched the supply chain network design with the product architecture by developing a multi-stage procedure. Morita et al. (2014) investigated the relationship between product characteristics and the supply chain and explored how their alignment should be constructed based on a survey-based experimental analysis.

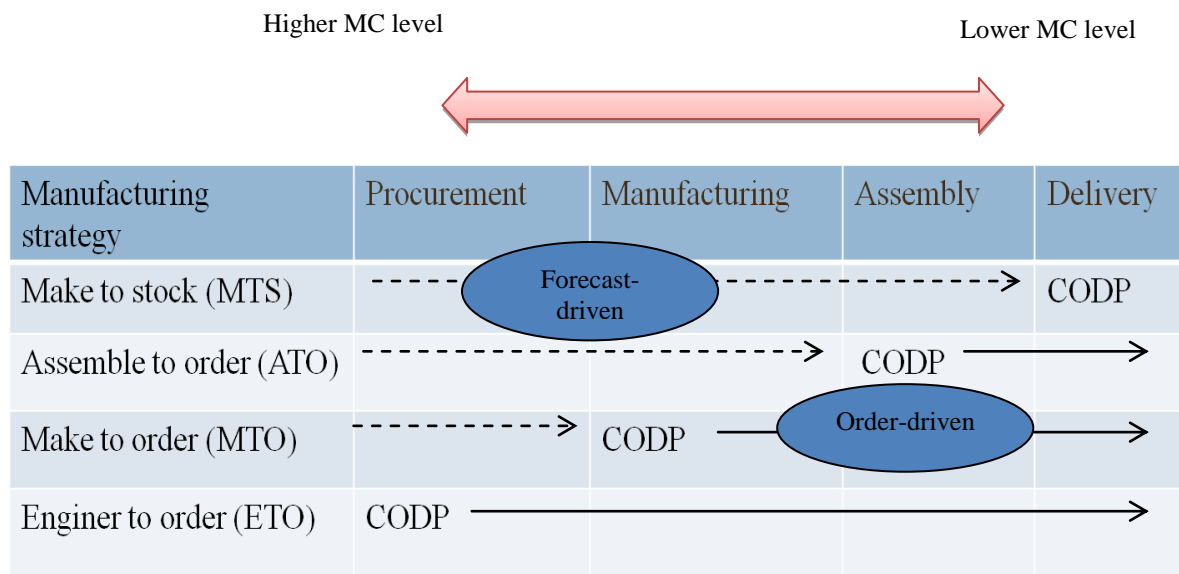
All the works reviewed, deal with integration of the product, process and supply chain design. They considered different decision points in these domains and proposed some models to manage the tradeoffs between them. One of main decision points in process of mass customization is position of customer order decoupling point that is usually neglected in these works. Since CODP affects on setup times and manufacturing cost and thus the optimum value of product varieties offered to customers, so it is important to consider its role in product customization.

In the next section, we represent the concept CODP and its effect on MC process and review literature about CODP position.

## **2.6 Customer Order Decoupling Point**

The Customer Order Decoupling Point that sometimes is called the order penetration point (OPP) is defined as the point in the value chain for a product, where the product is linked to a specific customer order (Olhager, 2003).

Position of the CODP affects on different manufacturing strategies such as make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO) and engineer- to-order (ETO)(Olhager, 2003). These different manufacturing strategies are related to the ability of manufacturing operations to accommodate product customization or a wide product range (See Fig. 5) (Olhager, 2003). Thereby, the customer order decoupling point is the point in the material flow that divides forecast-driven activities (upstream of the CODP) from the order-driven activities (downstream of the CODP).



**Figure 4:** Different customer order decoupling points (based on Sharman, 1984).

According to Brabazon & MacCarthy (2005), these four manufacturing strategies are described as follows:

- Make to stock (MTS): a production approach that is based on information of historical demand, along with sales forecast information. MTS is more sufficient for high volume products where the demand is either seasonal or easily predicted, or both.
- Assemble-to-order (ATO): Although this approach present some degree of customization, but the final products offered to customers are produced with (common) standardized parts.
- Make-to-order (MTO): Most or all the operations necessary to manufacture each specific product are started only when customer order is received. In some situations, even materials and component parts may procure on the receipt of a particular order. The MTO has more capability for product customization into ATO (Amaro, Hendry, & Kingsman, 1999).
- Engineer-to-order (ETO): Products are manufactured according to a specific customer's needs and therefore require unique engineering design or significant customization. Thus, each customer order has a unique set of part numbers, bill of material, and routing (Amaro et al., 1999).

Position of CODP and supply chain strategy has correlation with the organization and structure of material flow, information flow, and customer-supplier relationships and how to manage them in a supply chain (Saghiri, 2007).

Typically, activities before the CODP are usually determined based on forecast and the focus of production planning and control is on efficiency. The processes after the CODP are usually determined by customer demand and the focus of production planning is on fast delivery times.

Jan Olhager (2003) argued about two forces that balance the position of CODP: productivity force and flexibility force. When the cost is the major competitive priority, productivity force pushes the position of the CODP downstream. On the other hand, when flexibility and specific customer requirements are the subject, flexibility forces pushes the position of CODP upstream.

Sun et al. (2008) investigated the effect of the decoupling points in the supply chains. They, by considering supply network instead of supply chain, concluded hybrid strategy (MTO/ MTS) is better than a pure MTO or MTS strategy in a dynamic supply network.

Table 4 displays some attributes of supply chain upstream/downstream of CODP.

**Table 4.** Attributes of supply chain upstream/downstream of CODP (Talluri, Baker, & Sarkis, 1999)

Attribute	CODP upstream	CODP downstream
Product type	Standard, common	Special
Product range	Predetermined, narrow	Wide
Demand	High volume, predictable	Low volume, volatile
Market qualifier	Quality, on-time delivery	Price, quality
Process	Flow shop	Job shop
Facilities	Product focus	Process focus
Vertical integration	Supplier relationship	Customer relationship
Quality	Process focus	Product focus
Organization	Centralized	Decentralized
Performance measurement	Cost, productivity	Flexibility, delivery lead times
Production planning and control	Order promising based on stock availability, rate-based material planning	Order promising based on lead time agreement, time-phased material planning

Some authors have studied the main factors affecting the positioning of the CODP (Pagh & Cooper, 1998; Lehtonen, 1999; Olhager, 2003, 2005). According to Olhager (2003), these factors can be divided into three categories:

- Market-related factors, including delivery lead-time requirements, product demand volatility, product volume, product range and customer order size and frequency.
- Product-related factors, including modularity characteristics, customization opportunities and product structure.
- Production-related factors, including production lead time and process flexibility.

There exist two main different approaches in determining the position of the customer order decoupling point in literature: strategic approaches and analytic approaches (Jeong, 2011).

The strategic approaches usually offer guidelines for systems using knowledge or conceptual models to select CODP (Olhager, 2003).

The analytic approaches use mathematical models or simulation models to find an optimal position of the customer order decoupling point. Aviv & Federgruen (2001) developed a model with taking account uncertain demand and different costs, without considering lead time. Gupta & Benjaafar (2004) proposed a model to minimize sum of inventory holding cost and the product/process redesign cost subject to a service-level constraint. Wang & Ji (2006), firstly, recognized the factors affecting on position of CODP and then applied analytical hierarchy process (AHP) to analysis the importance of the factors to find position of the CODP. Ji et al. (2007) proposed a mathematical model for the problem of CODP position with minimizing the total cost subject to the delivery lead time and capacity. Wu et al. (2008) proposed a model for the CODP position based on profit and by using tandem queues. Sun et al. (2008) addressed the problem of positioning multiple decoupling points based on the bill of material of a product in a supply network. For this purpose, they developed a mathematical model with objective of

minimization of supply chain cost including different cost parameters (e.g. setup, inventory etc) subject to the delivery time constraint. Ahmadi & Teimouri, (2008) investigated the characteristics and concepts relating to the Order Penetration Point (OPP) and proposed a dynamic programming model to find OPP (or CODP) in auto export supply chain. Jewkes & Alfa (2009) incorporated CODP position optimization in a customization process that uses Make-To-Order (MTO) strategy. Rafiei & Rabbani (2009) proposed a mathematical programming model to find order penetration point in a hybrid MTS/MTO context with considering a degree of uncertainty. Li & Wang (2010) proposed a cost optimization model based on the queuing theory to find position of CODP. Daaboul et al. (2010) proposed a value network modeling and simulation to determine the position of the CODP based on its influence on the overall generated value of the MC system. Hajfathaliha et al. (2010) proposed a method to find the optimal fraction of processing time fulfilled by suppliers and optimal semi-finished products buffer storage capacity in OPP in a two-echelon production supply chain. Teimoury et al. (2012) proposed a method for decision making about order penetration point (OPP) similar with work Hajfathaliha et al. (2010), but in a multi-product multi-echelon production supply chain. Teimoury & Fathi (2013) proposed a mathematical model to find the optimum OPP, the optimum size of semi-finished goods buffer and the price of the products. Wei & Xiong (2013) developed a queuing theory model to optimize the total cost to support manufacturers to find position of CODP correctly. In order to optimize the CODP position and inventory level, Zhou et al. (2013) developed a two-stage tandem queuing network. Shidpour et al. (2014) developed a two-objective model based on company's profit and customer values perceived and analyzed effects of single-CODP and multiple-CODP.

The main reason to postpone some of the operations is the absence of customer order information. CODP is the point that the missing information which causes postponement of operations is held. So, the relationship between CODP and postponement is tight (Can, 2008). One of the important studies about the relationship of postponement and CODP was applied by Can (2008). They stated that companies may apply postponement to posit CODP. Huang & Li (2008) proposed a cost model for evaluation of value of postponement for a firm that produce two products in N stages. They considered demand uncertainty and CODP position to compare two different postponement approaches (standardization and modularization) in terms of cost. Wong et al. (2009) analyzed the use of form postponement based on the positioning of the differentiation point and stocking policy. Dan et al. (2009) proposed a cost optimization model with applying postponed production for the two-stage supply chain including retailer and manufacture and Zhang & Huang (2010) compared the operating cost before and after the CODP.

Li & Wang (2010) used the similar model with Dan et al. (2009) but without considering the cost change before and after the CODP. Qin and Geng (2013) developed a model based costs of production in a postponement system by considering different CODP.

As it argued, the mathematical models for CODP position try to minimize the manufacturing costs subject to satisfy the certain level of customer response time. They usually don't consider in their proposed models, some decision points in domains product such as selection of product variety and supply chain design such as supplier selection. With considering this issue that CODP position is a major decision point in MC, necessity of developing an integrated manner to deal with tradeoffs between CODP position and product and supply chain design is felt.

## 2.7 Value

Although three criteria cost, quality and delay are usually more used in decision-making problems, but with using concept of value, other important criteria such as customer perception and environment respect are considered. Value is customers' degree of satisfaction with the organization's products. It is the extent to which products provide benefits that customers believe are important (Da Silveira et al., 2001) . It increases when the satisfaction of the user increases or when the needed spending for the product decreases (Elhamdi, 2006). Daaboul, Da Cunha, Laroche, et al. (2011) represented different definitions of concept of value available in literature.

In mass customization, Value can include a large extent from process of ordering a customized product to receive services of after-sale and considerations in the end of product life cycle.

Different researchers paid attention to concept of value in mass customization. Daaboul, Da Cunha, Bernard, et al., (2011) described mass customization and provided a framework to understand the relationships among time-based manufacturing practices, mass customization, and value to the customer. Feller et al. (2006) discussed the concepts of value chain and supply chain from several perspectives. Merle et al. (2010) categorized the perceived value of mass customization into two parts: 1) mass-customized product value and 2) mass customization experience. They, also, proposed a framework that integrates parts of value and willingness to pay for mass-customized products. Khoddami et al. (2011) investigated about how and to what extent dimensions of the product value affect on the overall perceived value in MC. They stated that value of customized products is recognized in three dimensions: utilitarian value, interpersonal-differentiation value and self-expressiveness value.

Value network is a network in which a group of actors collaborates to deliver value to the end consumer and where each actor takes some responsibility for the success or failure of the network (Elhamdi, 2006). Daaboul et al. (2010) suggested the use of extended value network modeling and simulation for evaluating an MC strategy. Also, Daaboul et al. (2011,b) analyzed and proposed a model for customer's perceived value and tried to validate it empirically. Daaboul & Da Cunha (2014) evaluated effect of both differentiation points and customer-order decoupling point on enterprise and customer value through the creation of a generic causal diagram.

In this thesis, we use standard definition of concept value by AFNOR FNX50-151 that is based on the judgment carried by the user on the basis of his/her expectations and motivation. This definition determines the relation between satisfaction and value concept. Indeed, the value is a measure that increases when the satisfaction of the user increases or when the needed spending for the product decreases.

## 2.8 Qualitative and quantitative evaluations

To achieve mass customization objectives, organizations should control the MC process for increasing the efficiency and effectiveness. Managers use performance measurement to control the planned tasks for obtaining predetermined goals. In general, all the performance measures can be divided into two major groups: qualitative and quantitative. Many methodologies reviewed, have been developed in terms of quantitative measures. Some papers tried to deal with only qualitative aspects in MC process (Hermans, 2012; Kleer & Steiner, 2013; Pourabdollahian, 2014). For example, Kleer & Steiner (2013) provided a qualitative assessment of a mass customization production process for women's shoes in terms of its environmental effect.



In literature related to joint product and supply chain optimization, qualitative evaluation of products is very low (e.g. Shidpour et. al, 2013) compared to quantitative approaches. In many cases, nature of functions affecting on value perceived by customers is qualitative (e.g. Aesthetic). So, it is important to investigate the effect of qualitative criteria on customer value together with quantitative PIs to get closer to real situations.

Functional quality of product varieties is one of the qualitative measures which has big effects on both value perceived by customers and enterprises. Measuring this measurement is difficult because they usually are not represented numerically. Hence, in this thesis, we propose a method to measure the functional quality using fuzzy logic and evaluate them together with quantitative PIs by an integrated manner based on an interval-based approach.

In our thesis, with considering interval values and fuzzy linguistic terms to evaluate quantitative and qualitative PIs, respectively, we propose a new method to integrate these two types of PIs. In our method, the fuzzy numbers equivalence with linguistic terms used to evaluate qualitative PIs are converted to interval numbers.

## **2.9 Interval numbers and its application in multi-objective optimization**

In the real world, the existence of impreciseness is inevitable due to insufficient information. The main challenge for the researchers is how to handle this impreciseness when modeling the complicated uncertain situations as well as creating the appropriate solution methodologies.

Some popular approaches to deal with these problems are stochastic (Birge & Louveaux, 2011), fuzzy (Lodwick & Kacprzyk, 2010), or grey optimization techniques (Rosenberg, 2009) which have some advantages and disadvantages.

Alternatively, intervals can be used to deal with the vagueness of the available data or the impreciseness of any parameter. An interval can be expressed with its upper and lower limits.

Sengupta & Pal (2009) have explained the advantages of using intervals to represent uncertain or imprecise parameters over fuzzy set theory or probabilistic approaches for solving real world decision-making problems.

Some researchers modeled many real world applications by using intervals to represent impreciseness ( Neumaier, 2002; Neumaier & Pownuk, 2007; Bhunia, Biswas, & Sen, 2014).

Some researchers paid attention to ranking of interval numbers. First time, Moore (1979) developed the concept of interval numbers and their analytical characteristics and proposed a ranking definition. After that, some researchers tried to develop interval ordering definitions ( Sengupta & Pal, 2000; Hu & Wang, 2006; Mahato & Bhunia, 2006).

Some researchers proposed some solution methods to solve interval-oriented optimization problems. Pal & Gupta (2008) proposed a solution method based on genetic algorithm and goal programming formulation to solve interval valued multi-objective fractional programming problems. Moore et al. (2009) developed various approaches to solve interval-oriented optimization problems. Sahoo et al. (2012) developed different techniques based on interval metrics to solve the multi-objective optimization problems in the area of reliability optimization. They also proposed new definitions of interval ranking by modifying the earlier definitions.

Biswas et al. (2013) presented a goal programming (GP) procedure for solving Interval-valued multi-level programming (MLP) problems by using genetic algorithm (GA) in a hierarchical decision making and planning situation of an organization.

Bhunia & Samanta (2014) proposed the new definitions of interval order relations by modifying the existing definitions of interval mathematics. With these modifications, they dealt with the optimality of interval multi-objective optimization problems with the help of different interval metric. Karmakar & Bhunia (2014) proposed an optimization technique for optimization problems with interval-valued objectives through reduction of interval objective functions to those of crisp. Bhunia et al. (2014) proposed a modified non-dominated sorting and crowding distance based on interval mathematics and interval order relations to solve a multi-objective integer linear programming problem with interval objectives.

In this thesis, we use a modified method proposed in Bhunia et al. (2014) to solve a interval-valued multi-objective problem.

## 2.10 Discussion

As said in the beginning of chapter, each MC process should decide on number of product varieties offering to customers (or Level of customization). It issue requires an evaluation of values perceived by customers and enterprise for each product variety with taking account some main decision points in different domains (e.g. process and supply chain) such as CODP position.

Different papers about these issues reviewed. Some of literature about product design discusses about methods to design product family and another part of literature argues about optimization of specification of products such as number of modules and platform. Analyzing these papers identify some points:

- These papers just investigate the level of product varieties offered by optimizing platforms, standard and customized components and neglect effects of other important decision point (CODP position) on manufacturing cost and thus capability of company to offer product varieties.
- For evaluation of capability of product architecture to offer product varieties, usually, focus on reducing cost and satisfying functional requirements that it, lonely, is not enough to obtain true evaluation of product varieties. So, many researches discussed about necessity of integration supply chain management with product design and some, proposed methods to joint product, process and supply chain in MC process to better assessment of product varieties offered.
- The main measurement is cost no value that includes large extent of customers' satisfaction area (such as delivery time).

As said, the right evaluation of product architecture to satisfy individual needs of customers in mass customization is impossible without considering some decision points in supply chain. Some papers discussed importance of integrating product, process and supply chain design decisions when development of a new product and some papers proposed some models to deal with this problem. Analyzing these papers shows:

- Role and effect of CODP position either is not considered in supply chain.
- Mostly, focus on reducing cost with considering design requirements and mostly don't consider other criteria affecting on satisfaction of customers such as delivery time.

One of the main decision points that has big effect on values obtained by customers and thus level of customization is CODP position. Many papers have discussed about CODP definition, its role in MC and its factors affecting on position of CODP. Some papers in literature related to

CODP position-that our thesis focuses on it- are categorized two approaches: strategic approaches and analytic approaches. Most of the mathematical model-based approaches - that are most relevant to our discussion- try to minimize the manufacturing costs subject to satisfy the certain level of customer response time. Reviewing mathematical models of problems CODP position show that:

- Most of these approaches try to minimize the manufacturing costs subject to satisfy the certain level of customer response time. Indeed, the proposed models are single objective and based on manufacturing and inventory cost.
- Most of the previous mathematical models assume that the decoupling point is the unique decision variable. However, the production planning, inventory policy, and operational decisions such as scheduling, and sequencing also affect on performance of supply chain(Jeong, 2011).
- In all these papers, the product varieties are pre-determined and the problem is to find the best CODP position by considering cost as objective and time or service level as constraint. Indeed, the proposed models are not able to select automatically product varieties.

Optimal selection of product variants offered to the customers while attempting to satisfy certain objectives is one of the tasks in product family design (Wang et al., 2011) that it is obtained by considering different decision points from different domains. Many researches discussed importance of integrating decisions in product, process and supply chain design.

As said, most works in MC process focused on cost and few considered customer satisfaction as a main factor for deciding on product varieties. Since the customer is the main driver of each MC process, so, any decision should be made based on its influence on the generated value.

Value concept includes a large extent of measurement from financial value to environmental value. Due to value is a subjective concept (except financial value) and it is difficult to evaluate, so it has attracted less attentions. But with changing paradigm to mass customization, using this concept becomes more important.

Customer value is highly subjective and is affected by main several factors, such as the customization offer, the quality of the product, price, and the delivery lead time.

Determining level of customization what really satisfies the customer is hard. Providing a high product variety might not receive a favorable response from the customers, while, low product variety may not be able to provide customized products for a wide range of customers and thus decrease of customer satisfaction. Therefore the effect of product variety on customer satisfaction and thus customer value should be considered. More the customer receive more value, he/she is more satisfied that it lead to more will to buy and thus more sales. This, in turn, leads to increase financial value for the enterprise. For this purpose, the challenge of deciding on component/feature which should be chosen under resource limitation from a large amount of available alternatives has been well recognized in academia and industry correspondingly in producing customized products.

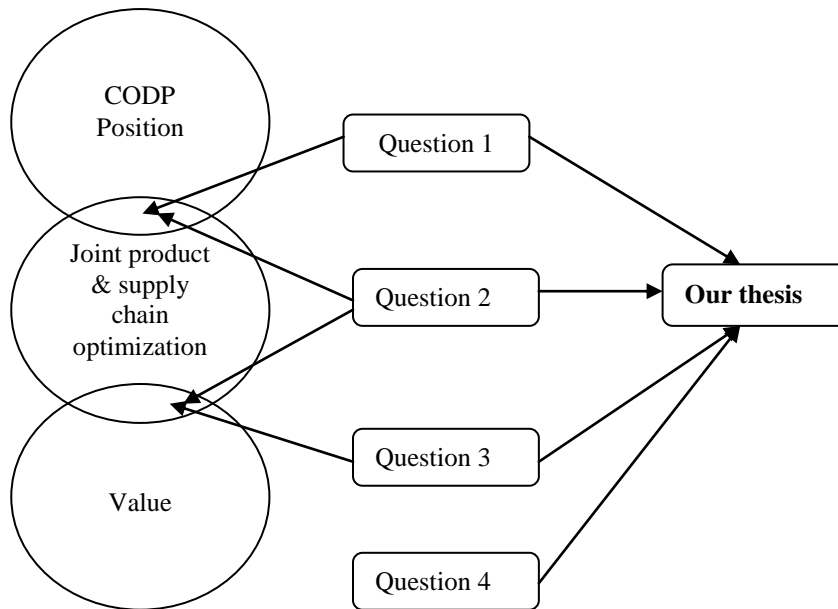
This paper investigates what components/features are proper to offer customers through analyzing their effects on values perceived by customers and enterprise. To better evaluation of values perceived by customers and enterprise, the paper uses three-dimensional concurrent engineering (3-DCE) approach which considers different decision points from domains of process and supply chain when development a new product. We propose two multi-objective optimization models which integrate these decision points such as the component/feature selection (thus product varieties), CODP position in process, the manufacturing method and selection of suppliers to participate in value network. For this purpose, some qualitative and

quantitative performance indicators are used with considering uncertainty. We apply uncertainty both fuzzy logic and linguistic terms to evaluate some performance indicators with qualitative nature and interval data for some quantitative parameters in our models.

In this thesis, we want to answer these questions:

- 1) What set of components/features (and thus product varieties) has to be offered to customers?
- 2) How to consider and integrate some technical and strategic decisions such selection of suppliers, manufacturing methods and CODP position problem?
- 3) How to concurrent evaluate qualitative and quantitative performance indicators affecting on customer and enterprise value in a model?
- 4) How to rank alternatives with interval values?

Question 1, as main question, determines the extent of features and/or components of a product to offer customers. Questions 2 and 3, in real, are related to question 1 and help to find solutions for that. Question 4 helps decision makers to rank alternatives with interval values. Figure 5 displays relation between questions, literature and thesis.



**Figure 5:** Relation between questions, literature and thesis

## **3 Chapter 3: The proposed models**

### 3.1 Introduction

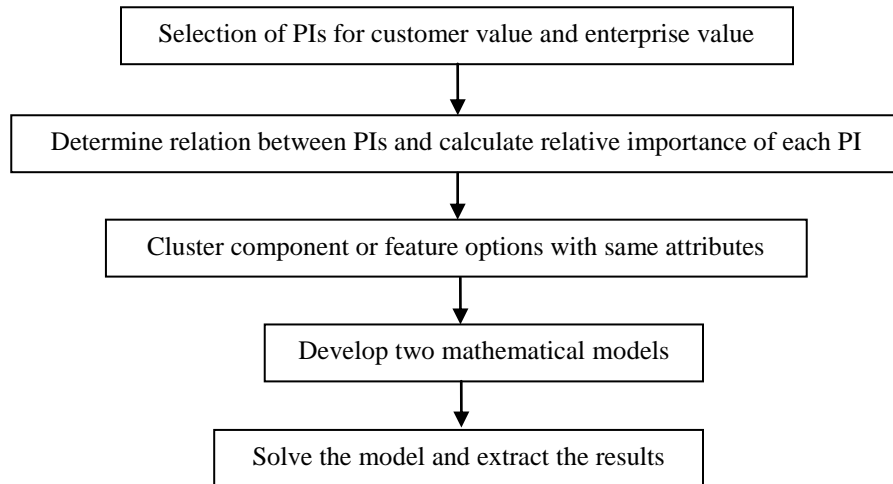
As described, the aim of the thesis is to propose a model to determine some decision points in product, process and supply chain, simultaneously, in MC process with evaluation of customer and enterprise values. In this thesis, we propose a novel method to simultaneous selection of component/features (or product variation offered to customers), CODP position, and some strategic decision in supply chain and manufacturing such as supplier selection and machine (technology) selection.

In this chapter, we propose our methodology with details to our problem.

### 3.2 Methodology

In this section, we propose our methodology to problem of simultaneous finding CODP position, product varieties offering to customers and suppliers participating in value network.

Following Flowchart (Figure 6) shows the steps of our model.



**Figure 6:** Steps of the models proposed

In following, we describe these steps with details.

#### 3.2.1 Selection of PIs for customer value and enterprise value

Customers are the main driver of the each business, so, their satisfaction degree affect on success or failure of MC process. Few researches considered customer satisfaction as a main driver to decide on product variety (Daaboul, Da Cunha, Bernard, et al., 2011). Providing value for customers must be the major aim of each value network. Thus, any decision in MC process should be made based on its effects on value.

Different partners have to cooperate to provide value for customers. A value network is consisted of different members, with specific responsibilities who work together to create value

(Elhamdi, 2006). Members of value network are customers, manufacturer, suppliers and dealers and other partners, such as distributors and shareholders, can be added to network partners. Table 5 shows the primary role of main partners of a value network in the mass customization.

**Table 5.** Main partners and their role in MC (Daaboul, 2011)

Partner	Role in value network
Customer	Customizing its product and define what exactly he wants to buy.
Manufacturer	Producing customized products with high quality and at a similar cost to the MP.
Supplier	Providing high quality products and services effectively
Dealer	Assist customers in product customization and in some cases perform customization of the product.

A performance indicator is defined as a quantified data that measures the effectiveness of all or part of a process or a system compared to a standard, a plan or a specific objective within a business strategy "(AFNOR FD X-50-158).

We extract different performance indicators from literature for customer and enterprise value (Olhager, 2003; Zha et al., 2004; Blecker et al., 2006; Spahi, 2008; Daaboul et al., 2011; Agbor, 2011; Verdecho et al., 2012; Wyse, 2012) that are shown in Tables 6 and 7, respectively.

**Table 6.** PIs for evaluation of customer value

	PI	Description
1	Sense of originality	Ability to design or compose a product that is unique to him/her, and that is unlikely to be duplicated
2	Control over the degree of functionality	Capability to establish control over the degree of functionality of a product
3	Perceived quality	Consumer's judgment about a product's overall excellence or superiority.
4	Premium price	
5	Abortion rate	Number of aborted interaction processes / number of log-ins
6	Average configuration (interaction) length of time	Time that customers need on average to completely configure a product variant.
7	Used variety indicator	Number of products offered/potential products
8	Time of Customization process	Total Time for customization process / max time considered for customization process.
9	Order reception reliability	Number of orders delivered on time $\cap$ Number of orders with zero defected products / total number of orders
10	Order delay time	Time elapsed between order placement time and order received time.
11	Service Quality	Reflect the customer's perception of reliability, assurance, responsiveness, empathy and tangibility.
12	Percent of demand satisfied	

**Table 7.** PIs for evaluation of enterprise value

	PI	Description
1	Increase of validity of brand	
2	Increase new customers	
3	Market efficiency	This metric represents a tradeoff between the marketing and the engineering design, which offers the least amount of variety to satisfy the greatest amount of customers i.e., targets the largest number of market niches with the fewest products (the number of the targetable market niches / the total market numbers)
4	Investment efficiency	This metric represents a tradeoff between the manufacturing and the

		engineering design, which invests a minimal amount of capital into machining and tooling equipment while still being able to produce as large a variety of products as possible. (the manufacturing equipment costs / the number of the product varieties)
5	Reduce cycle time	
6	Increase the degree of anticipation to industry changes (legislation, technological, etc.)	
7	Increase turnover	
8	Increase profitability	
9	Increase the power installed by customer	
10	Increase of sales rate	
11	Customer loyalty	Customer loyalty is the act of customers buying current brands repeatedly as opposed to choosing those of competitors.

Among these PIs, we select some PIs to evaluate customer and enterprise value shown in Table 8.

**Table 8.** The PIs selected for our thesis

PI	Customer value	Enterprise value
1	Quality perceived (PI11)	Benefit(PI21)
2	Average delivery time(PI12)	
3	Variety offered(PI13)	
4	Percent of demand satisfied (PI14)	
5	Control over the degree of functionality	

### 3.2.2 Determine relation between PIs and calculate relative importance of each PI

Evaluation of effects of PIs on each other and naturally on outputs of a problem always has been a challenging issue that rarely has been dealt with in literature. In our thesis, we calculate relative importance or weight of PIs with and without interdependency between them, and evaluate their effects on results of models.

To calculate weight with and without dependency, we use two methods Fuzzy Analytic Network Process (ANP) and Fuzzy Analytic Hierarchy Process (AHP) described in Appendix A.

### 3.2.3 Cluster component or feature options with same attributes

Clustering is used to face with huge data in many problems such as pattern recognition, machine learning and statistics. The clustering problem is defined as grouping data with similar objects together. Objects in each cluster are similar to each other and are dissimilar to objects belonging to other clusters. The goal of clustering is to identify groups objects based on a similarity metric. However, a similarity metric is mainly defined by the user according his needs (Al-Shboul & Myaeng, 2009).

In this thesis, to avoid the difficulty associated with huge data, the set of products, components or feature is reduced to a new set including a few representatives of the whole set.



## Developing mathematical models

In the mass customization process, we have two types manufacturing processes:

- 1) Manufacturing processes before CODP
- 2) Manufacturing processes after CODP.

In the process before CODP, semi-manufactured products are produced and stored in CODP position and process after CODP is performed based on orders. Due to differences between some elements of manufacturing processes before and after CODP such as setup time, our models are constructed based on consideration of these differences. In our models, the potential semi-manufactured products and products are determined for processes before and after CODP, respectively.

In this section, we develop two mathematical models with and without time period with aim of concurrent determination of CODP position, component/feature and some decision points in supply chain. For this purpose, we use the PIs selected (Table 4) in order to figure two-objective models; one objective to estimate customer value based on 5 PIs and second objective to obtain financial value of enterprise or benefit. One of main specification of our approach is to use qualitative evaluations based on linguistic terms (or fuzzy numbers) in our model (PI quality perceived). Accordingly, here, we describe these two models as follows:

### 3.2.4 Developing a mathematical model: model I

In this section, we evaluate PIs without considering time period and inventory/backorder values and develop a multi objective model. With considering interval value for both demand of products and purchasing time from suppliers, the upper and lower value of PIs are calculated. The following assumptions are considered for this model:

- Demand is known but uncertain and is expressed by interval data.
- Potential positions of CODP, the candidate suppliers for material and components and machines are pre-determined.
- The component/features and number of alternatives for each of them are recognized.
- Each product variety is composed of mixing different component/features.
- The sequence and type of operations are identified.
- Two types of operations are assumed: manufacturing and non-manufacturing.
- Several methods for manufacturing operations can exist.
- For each manufacturing method, the operation and setup cost and time, and quality rate are identified.
- The operation and setup time for each operation are known.
- The operation cost in each unit time is known.
- The data related to candidates of suppliers is known.
- For each supplier, the purchasing cost and time are known.
- The candidate suppliers are able to produce all required customized parts.
- All product varieties can be produced with a manufacturing method.
- Operation based on CODP position divided to two parts: before CODP, and after CODP.
- Customized components consumed in operations after CODP, have no stock and must be purchased from suppliers after getting order.

The notation of this model is represented as follows:

### Notation

$P$	Index of product
$f$	Index of function
$v$	Index of sub-function
$j$	Index of part (or material)
$s$	Index of suppliers
$m$	Index of manufacturing methods
$w$	Index of semi-manufactured product
$i$	Index of CODP position
$o$	Index of operations
$a (1, \dots, A)$	Index of component/features
$b=1, \dots, n_a$	Index of number of alternatives for each component/features

### Sets

$E$	Each element of this matrix $e_{pab}(p,b)=1$ if alternative $b$ of component/feature $a$ participate in product $p$
$S_w$	Set of products composed of semi-manufactured product $w$ .
$F^{Op}$	Functions influenced from non-manufacturing operations
$F^{sup}$	Functions influenced from suppliers
$F^{man}$	Functions influenced from manufacturing operations
$S_i^{Bef}$	Set of operations before CODP $i$
$S_i^{Aft}$	Set of operations after CODP $i$
$S^{man}$	Set of manufacturing operations
$S^{n-man}$	Set of non-manufacturing operations
$S_i^{sp}$	Set of semi-manufactured products for CODP $i$
SC	Set of features that affects on control on functionality control
Sup <sub>j</sub>	Set of suppliers of component $j$

### Input parameters

$d_p = [d_p^L \ d_p^U]$	Anticipated demand of product $p$
$N^{total}$	Total number of potential products
$q_{pfv}^{man}$	Quality of product $p$ processed with operation $o$ and with manufacturing method $m$ for sub-function $v$ from function $f$
$q_{pfvjs}^{sup}$	Quality of component $j$ product $p$ purchased from supplier $s$ for sub-function $v$ from function $f$
$q_{pfv}^{op}$	Quality of product $p$ for sub-function $v$ from function $f$
$C_o^{Op}$	Operation cost $o$ for each time unit
$N^c$	Number of features in set SC
$C_{js}^{sup}$	Purchasing cost of component $j$ supplied from supplier $s$ for product $j$

$T_{js}^{sup} = [T_{js}^{Lsup} T_{js}^{Usup}]$	Purchasing time of component $j$ supplied from supplier $s$ for product $j$
$def_m$	Quality rate of manufacturing method $m$
$W_f^{Fun}$	Importance of function $f$
$V_{fv}$	Importance of sub-function $v$ in function $f$
$T_{wom}^{man1}$	Operation time $o$ for semi-manufactured product $w$ processed with manufacturing method $m$
$T_{pom}^{man2}$	Operation time $o$ for product $p$ processed with manufacturing method $m$
$C_{om}^{man}$	Operation cost $o$ for manufacturing method $m$ for each time unit
$T_{wo}^{set1}$	Setup time of non-manufacturing operation $o$ for semi-manufactured product $w$
$T_{po}^{set2}$	Setup time of non-manufacturing operation $o$ for product $p$
$T_{wo}^{op1}$	Non-manufacturing operation time $o$ for semi-manufactured product $w$
$T_{po}^{Op2}$	Non-manufacturing operation time $o$ for product $p$
$T_{wom}^{mset1}$	Setup time of manufacturing operation $o$ for semi-manufactured product $w$ processed with manufacturing method $m$
$T_{pom}^{mset2}$	Setup time of manufacturing operation $o$ for product $p$ processed with manufacturing method $m$
$r_{wj}^{c1}$	Amount of component $j$ used in semi-manufactured product $w$
$r_{pj}^{c2}$	Amount of component $j$ used in product $p$
$pr_p$	Price of product $p$
<b>Budget</b>	The budget allocated to operation in time $t$
$N_a$	Number of alternatives for component/feature $a$
$w_{11}$	Weight of PI $z_{11}$
$w_{12}$	Weight of PI $z_{12}$
$w_{13}$	Weight of PI $z_{13}$
$w_{14}$	Weight of PI $z_{14}$
$w_{15}$	Weight of PI $z_{15}$
$w_{21}$	Weight of PI $z_{21}$
$g_{11}$	Goal of $z_{11}$
$g_{12}$	Goal of $z_{12}$
$g_{13}$	Goal of $z_{13}$
$g_{14}$	Goal of $z_{14}$
$g_{15}$	Goal of $z_{15}$
$g_{21}$	Goal of $z_{21}$

### Decision variables

$z_p$	1 if product $p$ is selected to offer customers, 0 otherwise
$r_w$	1 if semi-manufactured product $w$ is selected, 0 otherwise
$U_{om}$	1 if manufacturing method $m$ is selected in operation $o$ , 0 otherwise
$k_{ab}$	1 if alternative $b$ of component/feature $a$ is selected, 0 otherwise
$X_s$	1 if supplier $s$ is selected, 0 otherwise
$y_i$	1 if position $i$ for CODP is selected, 0 otherwise

$Z^{Tot}$	Total product varieties selected
$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$	Demand of semi-manufactured product $w$ in CODP $i$
$D = [D^L \ D^U]$	Total demand of all products
$Cost = [Cost^L \ Cost^U]$	Total operation cost
$Z_{11} = [z_{11}^L \ z_{11}^U]$	Upper and lower amount of PI quality perceived/price
$Z_{12} = [z_{12}^L \ z_{12}^U]$	Upper and lower amount of PI average delivery time
$Z_{13} = [z_{13}^L \ z_{13}^U]$	Upper and lower amount of PI percent of demand satisfied
$Z_{14} = [z_{14}^L \ z_{14}^U]$	Upper and lower amount of PI variety used
$Z_{15} = [z_{15}^L \ z_{15}^U]$	Upper and lower amount of PI control over the degree of functionality

The objectives and constraints of the proposed model are described as follows:

Objectives (1) and (2) maximize the weighted average of performance indicators involving in customer value and enterprise value, respectively. Because some parameters have interval values, PIs and objectives get values of interval.

$$Max \ Z_1 = W_{11}^o \frac{Z_{11}}{g_{11}} - W_{12}^o \frac{Z_{12}}{g_{12}} + W_{13}^o \frac{Z_{13}}{g_{13}} + W_{14}^o \frac{Z_{14}}{g_{14}} + W_{15}^o \frac{Z_{15}}{g_{15}} \quad (1)$$

$$Max \ Z_2 = W_{21}^o \frac{Z_{21}}{g_{21}} \quad (2)$$

Equation (3) shows the average of quality perceived by customers into price (PI12).

$$Z_{12} = \frac{1}{Z^{Tot}} \sum_{p=1} \frac{z_p}{Pr_p} \left( \underbrace{\sum_{f \in F^{op}} W_f^{Fun} \sum_{v \in S_j} V_{fv} q_{pfv}^{op}}_1 + \underbrace{\sum_{f \in F^{sup}} W_f^{Fun} \sum_{v \in S_j} V_{fv} \sum_j \sum_s X_s q_{pfvjs}^{sup}}_2 + \underbrace{\sum_{f \in F^{mm}} W_f^{Fun} \sum_{v \in S_j} V_{fv} \sum_o \sum_m q_{pfvom}^{mac} U_{om}}_3 \right) \quad (3)$$

where:

$$Z^{Tot} = \sum_p z_p \quad (4)$$

The quality perceived is evaluated based on customer satisfaction from functions. It means more quality perceived, more customer satisfaction. Although the quality perceived affects on customer satisfaction but it should be with a reasonable price. So, tradeoff between quality and price can show this challenge.

This objective assumes each operation in value network plays a role in obtaining quality of product and overall satisfaction is obtained from performance all functions. Another assumption, it is that performance of some functions may be relevant to quality of material and/or components purchased from suppliers. Each function is composed of several sub-functions. Each function has

a relative importance in customer satisfaction and each sub-function has a weight in function. Table 9 displays functions, sub-functions and their weights to provide quality.

**Table 9.** Functions and sub-functions

Function( $W_i$ )	Sub-function( $V_{fv}$ )										
	1	2	...	$v_1$	1	...	$v_2$	...	1	...	$v_f$
1	$v_{11}$	$v_{12}$	...	$v_{1v_1}$							
2					$v_{21}$	...	$v_{2v_2}$				
$\vdots$								...			
f									$v_{f1}$	...	$v_{fv_1}$

Since some functions (or sub-function) have qualitative nature, so, their evaluation with numeric methods is difficult. So, we use linguistic terms to assess functions.

Accordingly, term (1) in Eq. (10) identifies quality obtained from doing non-manufacturing operation on product. Since quality of component/material purchased suppliers affect on quality of product and thus quality perceived by customers, so, term (2) is applied to calculate quality of component/material purchased. Term (3) shows quality products resulted from manufacturing operation.

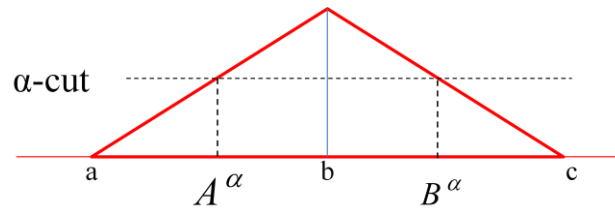
Parameters  $q_{pfv}^{op}$ ,  $q_{pfvjs}^{sup}$  and  $q_{pfvom}^{man}$ , show quality provided by company, suppliers and weaving machines, respectively. As described, these parameters are evaluated with linguistic terms shown in Table 10.

**Table 10.** Linguistic terms and equivalent fuzzy numbers

Linguistic terms	Fuzzy number
Poor (P)	(0, 0.2, 0.4)
Medium(M)	(0.3,0.45,0.6)
Good(G)	(0.45,0.65,0.85)
Very Good(VG)	(0.65,0.85,1)

Evaluation of these functions with linguistic terms cannot be applied in mathematical model. For using these fuzzy numbers, they can be converted to interval number with  $\alpha$  – cut method.

Let  $A = (a, b, c)$  be a triangular fuzzy number, in Figure 7, then:



**Figure 7:** Interval number obtained from  $\alpha$  – cut method

The fuzzy number is converted to interval number with following equation:

$$[A^\alpha, B^\alpha] = [(b-a)\alpha + a, -(c-b)\alpha + c] \quad \forall \alpha \in [0,1] \quad (5)$$

Where,  $\alpha$  usually is defined as confidence level of decision maker,  $A^\alpha$  and  $B^\alpha$  are lower and upper bound of interval number.

Equation (6) shows the average delivery time of products (PI12).

$$Z_{12} = \sum_{i=1}^I y_i \sum_{p=1}^P d_p z_p \left( \underbrace{\sum_{\substack{O \in \\ (S_i^{A^R} \cap S_i^{n-man})}} T_{po}^{op} + T_{po}^{set}}_1 + \underbrace{\sum_{\substack{O \in \\ (S_i^{A^R} \cap S_i^{man})}} \sum_m (T_{pom}^{man2} + T_{pom}^{mset2}) U_{om}}_2 / def_o \right) + \underbrace{\sum_j \sum_{s \in Sup_j} X_s T_{js}^{sup}}_3 / \sum_{p=1}^P d_p z_p \quad (6)$$

Term (1) in Eq. (6) identifies operation and setup time of non-manufacturing operations for each product. Term (2) shows setup and operation time to perform manufacturing operations. Since material or some components are provided from outside, delivery time of suppliers has an important role in total delivery time. Term (3) shows delivery time of components/materials purchased from suppliers.

Equation (7) identifies the percent of demand satisfied (PI13) and Eq. (8) shows percent of product variety offered to customers (PI14) where  $N^{total}$  is number of potential products.

$$Z_{13} = \frac{1}{D} \sum_p d_p z_p \quad (7)$$

$$Z_{14} = \frac{1}{N^{total}} \sum_p z_p \quad (8)$$

Equation (9) shows the PI control over the degree of functionality of a product (PI15).

$$z_{15} = \frac{1}{N^c} \sum_{a \in SC} \sum_b \frac{k_{ab}}{N_a} \quad (9)$$

This PI is related to component/feature that customers directly control over the degree of functionality of a product and thus it has a significant value-added contribution to customer satisfaction. For example, if a customer is able to decide the size of a carpet, he/she will select what best fits his/her application, without spending more on something not really needed.

The more  $z_{15}$ , causes to increase control degree over functions that customers can directly affect on them.

Term (10) identifies the total benefit obtained from selling product varieties and term (11) obtain amount of "Income".

$$Z_{21} = \text{Income} - \text{Cost} \quad (10)$$

$$\text{Income} = \sum_{p=1} pr_p d_p z_p \quad (11)$$

Total cost is identified with Eq. (12) as follows:

$$\begin{aligned} \text{Cost} = & \sum_{i=1}^I y_i \left( \sum_{w=1} r_w \left( \sum_{\substack{O \in \\ (S_i^{br} \cap S^{n-man})}} \left( \sum_{m=1} ((d_{iw}^{wip} T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_{om} \right) \right) \right) + \left( \sum_{\substack{O \in \\ (S_i^{br} \cap S^{n-man})}} d_{iw}^{wip} T_{wo}^{op1} + T_{wo}^{set1} \right) C_o^{Op} \quad (12) \\ & \underbrace{\hspace{15em}}_1 \quad \underbrace{\hspace{15em}}_2 \\ & \underbrace{\sum_j \sum_{s \in Sup_j} d_{iw}^{wip} r_{wj}^{c1} X_s C_{js}^{sup}}_3 + \sum_{p=1} d_p z_p \left( \sum_{\substack{O \in \\ (S_i^{br} \cap S^{n-man})}} \left( \sum_{m=1} ((T_{pom}^{man2} + T_{pom}^{mset2}) C_{om}^{man} / def_o) U_{om} \right) \right) \\ & \underbrace{\hspace{15em}}_4 \\ & + \left( \sum_{\substack{O \in \\ (S_i^{br} \cap S^{n-man})}} T_{po}^{op2} + T_{po}^{set2} \right) C_o^{Op} + \sum_j \sum_{s \in Sup_j} r_{pj}^{c2} X_s C_{js}^{sup} \\ & \underbrace{\hspace{15em}}_5 \quad \underbrace{\hspace{15em}}_6 \end{aligned}$$

Terms (1), (2) and (3) from Cost (Eq. 12), identify details of operation costs before CODP position and Terms (4), (5) and (6) recognize details of operation costs after CODP position.

Term (1) calculates cost of manufacturing, term (2) recognizes cost of non-manufacturing operations for semi-manufactured products and term (3) shows purchasing cost of material/component from suppliers. All these operations are performed before CODP position.

Term (4) calculates cost of manufacturing, term (5) recognizes cost of non-manufacturing operations for products and term (6) shows purchasing cost of material/component from suppliers. All these operations are performed before CODP position.

Constraint (13) shows cost restriction that should not violate from budget.

$$\text{Cost} \leq \text{Budget} \quad (13)$$

Equality (14) shows value of total demand of all products.

$$D = \sum_p d_p \quad (14)$$

Constraint (15) identifies demand of semi-manufactured products that is based on demand of products selected.

$$d_{iw}^{wip} = \sum_{p \in S_w} d_p z_p \quad \forall i, w \quad (15)$$

Constraint (16) identifies components/features participated in products.

$$z_p = \prod_a \sum_{b=1}^{n_a} k_{ab} e_{pab} \quad \forall p \quad (16)$$

This equation shows that each product is composed of unique features/components.  $e_{pab}$  is element of matrix E which displays features/components making product varieties. An instance of this matrix is displayed as follows:

		Component/Feature											
		1			2			...			a		
Product		1	2	...	$N_1$	1	...	$N_2$	...	1	...	$N_a$	
E =	1	1	0	...	0	1	...	0	...	1	...	0	
	2	1	0	...	0	1	...	0	...	0	...	0	
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
	P	0	0	0	1	0	0	1	...	0	0	1	

This equation says a product variety is selected when that all its constitutive features/components are chosen.

Constraint (17) expresses that at least one alternative of each component/feature should be selected.

$$\sum_{b=1}^{n_a} k_{ab} \geq 1 \quad \forall a \quad (17)$$

Constraints (18) and (19) express a semi-manufactured product is selected when at least a product belonging to set of products made from that semi-manufactured product, is selected.

$$r_w \leq \sum_{p \in S_w} z_p \quad \forall w \quad (18)$$

$$r_w \geq z_p \quad \forall w, p \in S_w \quad (19)$$

Constraint (20) selects a manufacturing method among the candidate methods.

$$\sum_{m=1}^{M_o} U_{om} = 1 \quad \forall o \in S^{man} \quad (20)$$



Constraint (21) identifies the supplier selected for components/material to involve in supply chain.

$$\sum_s X_s = 1 \quad (21)$$

Constraint (22) selects one position for CODP.

$$\sum_i y_i = 1 \quad (22)$$

These binary variables ( $y_i, X_s, U_{om}, z_p, k_{ab}, r_w \in \{0,1\}$ ) are used in our model.

Due to some interval parameters, PIs and objectives have interval values. Equations 23 to 28 show lower and upper bounds of interval PIs and objectives.

$$Max [Z_1^L Z_1^U] = W_{11}^o \frac{[Z_{11}^L Z_{11}^U]}{g_{11}} - W_{12}^o \frac{[Z_{11}^L Z_{11}^U]}{g_{12}} + W_{13}^o \frac{[Z_{11}^L Z_{11}^U]}{g_{13}} + W_{14}^o \frac{[Z_{11}^L Z_{11}^U]}{g_{14}} + W_{15}^o \frac{[Z_{11}^L Z_{11}^U]}{g_{15}} \quad (23)$$

$$Max [Z_2^L Z_2^U] = W_{21}^o \frac{[Z_{21}^L Z_{21}^U]}{g_{21}} \quad (24)$$

$$Z_1^L = \frac{W_{11}^o Z_{11}^L}{g_{11}} - \frac{W_{12}^o Z_{11}^U}{g_{12}} + \frac{W_{13}^o Z_{11}^L}{g_{13}} + \frac{W_{14}^o Z_{11}^L}{g_{14}} + \frac{W_{15}^o Z_{11}^L}{g_{15}} \quad (25)$$

$$Z_1^U = \frac{W_{11}^o Z_{11}^U}{g_{11}} - \frac{W_{12}^o Z_{11}^L}{g_{12}} + \frac{W_{13}^o Z_{11}^U}{g_{13}} + \frac{W_{14}^o Z_{11}^U}{g_{14}} + \frac{W_{15}^o Z_{11}^U}{g_{15}} \quad (26)$$

$$Z_2^L = \frac{W_{21}^o Z_{21}^L}{g_{21}} \quad (27)$$

$$Z_2^U = \frac{W_{21}^o Z_{21}^U}{g_{21}} \quad (28)$$

PI average delivery time ( $Z_{12}$ ), due to interval demand ( $d_p = [d_p^L d_p^U]$ ) and purchasing time of supplier ( $[T_{js}^{L\sup} T_{js}^{U\sup}]$ ), is converted to interval value with equations (29) and (30):

$$Z_{12}^L = \sum_{t=1}^T \sum_{p=1}^P d_p^L z_p \left( \sum_{\substack{O \in \\ (S_i^{A^p} \cap S^{t-man})}} T_{po}^{op2} + T_{po}^{set2} + \sum_{\substack{O \in \\ (S_i^{A^p} \cap S^{man})}} \sum_m (T_{pom}^{man2} + T_{pom}^{mset2}) U_{om} / def_o \right) \quad (29)$$

$$+ \sum_j \sum_{s \in Sup_j} X_s T_{js}^{L\sup} / \sum_{p=1}^P d_p^U z_p$$

$$Z_{12}^U = \sum_{t=1}^T \sum_{p=1}^P d_p^U z_p \left( \sum_{\substack{O \in \\ (S_i^{A^p} \cap S^{t-man})}} T_{po}^{op2} + T_{po}^{set2} + \sum_{\substack{O \in \\ (S_i^{A^p} \cap S^{man})}} \sum_m (T_{pom}^{man2} + T_{pom}^{mset2}) U_{om} / def_o \right) \quad (30)$$

$$+ \sum_j \sum_{s \in Sup_j} X_s T_{js}^{U\sup} / \sum_{p=1}^P d_p^L z_p$$

PI percent of demand satisfied ( $Z_{13}$ ), due to interval total demand, is converted to interval amounts with equation (31):

$$Z_{13} = \frac{1}{D} \sum_p d_p z_p = \begin{cases} Z_{13}^L = \frac{1}{D^U} \sum_p d_p^L z_p \\ Z_{13}^U = \frac{1}{D^L} \sum_p d_p^U z_p \end{cases} \quad (31)$$

Where upper and lower bounds of total demand ( $[D^L D^U]$ ) are calculated through equations (32) and (33):

$$D^L = \sum_p d_p^U z_p + \sum_p d_p^L (1 - z_p) \quad (32)$$

$$D^U = \sum_p d_p^L z_p + \sum_p d_p^U (1 - z_p) \quad (33)$$

Due to interval demand ( $d_p = [d_p^L d_p^U]$ ) of products and semi-manufactured products, cost has an interval amount which is deduced from equations (34) and (35):

$$Cost^L = \sum_{t=1}^I \left( \sum_{i=1} y_i \left( \sum_{w=1} r_w \left( \sum_{\substack{O \in \\ (S_i^{bef} \cap S^{man})}} \sum_{m=1} ((d_p^L T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_m \right) \right) \right) \quad (34)$$

$$+ \left( \sum_{\substack{O \in \\ (S_i^{bef} \cap S^{n-man})}} d_p^L T_{wo}^{op1} + T_{wo}^{set1} \right) C_o^{Op} + \sum_j \sum_{s \in Sup_j} d_p^L r_{wj}^{c1} X_s C_{js}^{sup} +$$

$$\sum_{p=1} d_p^L z_p \left( \sum_{\substack{O \in \\ (S_i^{Af} \cap S^{man})}} \sum_{m=1} ((T_{pom}^{man2} + T_{pom}^{mset2}) C_{om}^{man} / def_o) U_m \right) +$$

$$\left( \sum_{\substack{O \in \\ (S_i^{Af} \cap S^{n-man})}} T_{po}^{op2} + T_{po}^{set2} \right) C_o^{Op} + \sum_j \sum_{s \in Sup_j} r_{pj}^{c2} X_s C_{js}^{sup} \right)$$

$$Cost^U = \sum_{t=1}^I \left( \sum_{i=1} y_i \left( \sum_{w=1} r_w \left( \sum_{\substack{O \in \\ (S_i^{bef} \cap S^{man})}} \sum_{m=1} ((d_p^U T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_m \right) \right) \right) + \quad (35)$$

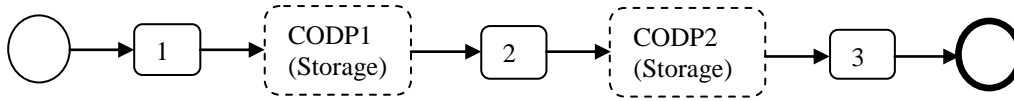
$$\left( \sum_{\substack{O \in \\ (S_i^{bef} \cap S^{n-man})}} d_p^U T_{wo}^{op1} + T_{wo}^{set1} \right) C_o^{Op} + \sum_j \sum_{s \in Sup_j} d_p^U r_{wj}^{c1} X_s C_{js}^{sup} +$$

$$\sum_{p=1} d_p^U z_p \left( \sum_{\substack{O \in \\ (S_i^{Af} \cap S^{man})}} \sum_{m=1} ((T_{pom}^{man2} + T_{pom}^{mset2}) C_{om}^{man} / def_o) U_m \right) +$$

$$\left( \sum_{\substack{O \in \\ (S_i^{Af} \cap S^{n-man})}} T_{po}^{op2} + T_{po}^{set2} \right) C_o^{Op} + \sum_j \sum_{s \in Sup_j} r_{pj}^{c2} X_s C_{js}^{sup} \right)$$

### 3.2.5 A little example to describe model I

Here, we represent a little example to clarify model I. At first, we assume manufacturing process consists of three operations with two potential positions for CODP (Figure 8) that in each operation some features/components are manufactured/assembled.



**Figure 8:** Operations and CODP positions

Operations 1 and 2 are manufacturing operation and non-manufacturing operation, respectively. Also, it assumed operation 3 is outsourced and performed by suppliers. Table 11 displays the features/components manufactured/assembled in each operation.

**Table 11.** Operations and feature/components

Operation	Feature/Component
1	f11,f12,f13
2	f21,f22,23
3	f31,f32
Potential product	18

We, here, describe the objectives and constraints with our example.

Matrix E defines components/ features participating in products (Table 12). Each element of this matrix  $e_{pab}(p,b)$  get value 1 if alternative  $b$  of component/ feature  $a$  participate in product  $p$ .

Based on constraint (16), the following equation for our example is concluded:

$$z_p=(k_{11}e_{p11}+k_{12}e_{p12}+k_{13}e_{p13})(k_{21}e_{p21}+k_{22}e_{p22}+k_{23}e_{p23})(k_{31}e_{p31}+k_{32}e_{p32});$$

**Table 12.** Matrix E

Product	Feature	F1			F2			F3	
		f11	f12	f13	f21	f22	f23	f31	f32
1		1	0	0	1	0	0	1	0
2		1	0	0	1	0	0	0	1
3		1	0	0	0	1	0	1	0
4		1	0	0	0	1	0	0	1
5		1	0	0	0	0	1	1	0
6		1	0	0	0	0	1	0	1
7		0	1	0	1	0	0	1	0
8		0	1	0	1	0	0	0	1
9		0	1	0	0	1	0	1	0
10		0	1	0	0	1	0	0	1
11		0	1	0	0	0	1	1	0
12		0	1	0	0	0	1	0	1
13		0	0	1	1	0	0	1	0
14		0	0	1	1	0	0	0	1
15		0	0	1	0	1	0	1	0
16		0	0	1	0	1	0	0	1
17		0	0	1	0	0	1	1	0
18		0	0	1	0	0	1	0	1

For example, relation between product 1( $z_1$ ) and components/features ( $k_{ab}$ ) shown in Table 12 are determined as:

$$z_1 = (k_{11} * 1 + k_{12} * 0 + k_{13} * 0) * (k_{21} * 1 + k_{22} * 0 + k_{23} * 0) * (k_{31} * 1 + k_{32} * 0) = k_{11} \cdot k_{21} \cdot K_{31}$$

Because our model is based on selection of features/components ( $k_{ab}$ ), we here, represent our example for one configuration of features/components that is randomly produced and is shown in Table 13. In final of this example, values of income and cost for PI benefit for this configuration of components/feature are obtained by considering values of other decision variables such as CODP position, manufacturing method or selection of suppliers.

**Table 13.** Configuration of features/components selected for our example

Feature/ component	F1			F2			F3	
Alternative	f11	f12	f13	f21	f22	f23	f31	f32
$k_{ab}$	1	0	1	1	1	0	1	1

Based on Table 13 and equation 23, some of products represented in Table 14 are selected. Also, this table shows the interval value of demand predicted for each product.

**Table 14.** Products selected for our example

Feature	F1			F2			F3		$z_p$	Demand
Product	f11	f12	f13	f21	f22	f23	f31	f32		
1	1	0	0	1	0	0	1	0	1	[2 6]
2	1	0	0	1	0	0	0	1	1	[3 7]
3	1	0	0	0	1	0	1	0	1	[1 5]
4	1	0	0	0	1	0	0	1	1	[2 5]
5	1	0	0	0	0	0	1	0	0	[3 6]
6	1	0	0	0	0	0	0	1	0	[2 7]
7	0	0	0	1	0	0	1	0	0	[4 8]
8	0	0	0	1	0	0	0	1	0	[3 6]
9	0	0	0	0	1	0	1	0	0	[1 5]
10	0	0	0	0	1	0	0	1	0	[2 5]
11	0	0	0	0	0	0	1	0	0	[3 6]
12	0	0	0	0	0	0	0	1	0	[3 7]
13	0	0	1	1	0	0	1	0	1	[1 5]
14	0	0	1	1	0	0	0	1	1	[2 5]
15	0	0	1	0	1	0	1	0	1	[3 6]
16	0	0	1	0	1	0	0	1	1	[1 5]
17	0	0	1	0	0	0	1	0	0	[3 7]
18	0	0	1	0	0	0	0	1	0	[3 7]

Table 15 shows the products selected and their related semi- manufactured products based on position of CODP.

**Table 15.** The potential semi-manufactured products and their relations with products

Operation	CODP	Semi-manufactured product	Product	$z_p$	$r_w$
1	1	1(f11)	1	1	1
			2	1	
			3	1	
			4	1	
			5	0	
			6	0	
		2(f12)	7	0	0
			8	0	
			9	0	
			10	0	
			11	0	
			12	0	
		3(f13)	13	1	1
			14	1	
			15	1	
			16	1	
			17	0	
			18	0	
1,2	2	4(f11,f21)	1	1	1
			2	1	
		5(f11,f22)	3	1	1
			4	1	
		6(f11,f23)	5	0	0
			6	0	
		7(f12,f21)	7	0	0
			8	0	
		8(f12,f22)	9	0	0
			10	0	
		9(f12,f23)	11	0	0
			12	0	
		10(f13,f31)	13	1	1
			14	1	
		11(f13,f32)	15	1	1
			16	1	
		12(f13,f33)	17	0	0
			18	0	

As this Table shows, for CODP 1, each semi-manufactured product participates in six products. Accordingly, semi-manufactured product 2 is not used to produce products. For CODP2, we have 9 potential semi-manufactured products that each of them participate in two products. Accordingly, semi-manufactured products 6, 7, 8, 9 and 12 are not produced.

We construct the mathematical model I with aim of evaluation of mass customization process with different PIs without considering amounts of inventory and backorder. In this model, the frequency of processes before and after CODP is equal with demand of semi-manufactured products and products, respectively. Demand of semi-manufactured products for process before CODP are consisted of products demand selected. So, demand of semi-manufactured products for model I is obtained with equation 15.

Table 16 shows the values of semi-manufactured products for CODP1 and CODP2.

**Table 16.** Values of semi-manufactured products for CODP1 and CODP2

CODP	Semi-manufactured product	Product	$z_p$	Demand	$r_w$	
1	1(f11)	1	1	[2 6]	1	
		2	1	[3 7]		
		3	1	[1 5]		
		4	1	[2 5]		
		5	0	[3 6]		
		6	0	[2 7]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				[8 23]	
	2(f12)	7	0	[4 8]	0	
		8	0	[3 6]		
		9	0	[1 5]		
		10	0	[2 5]		
		11	0	[3 6]		
		12	0	[3 7]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				0	
	3(f13)	13	1	[1 5]	1	
		14	1	[2 5]		
		15	1	[3 6]		
		16	1	[1 5]		
17		0	[3 7]			
18		0	[3 7]			
$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				[7 21]		
2	4(f11,f21)	1	1	[2 6]	1	
		2	1	[3 7]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				[5 13]	
	5(f11,f22)	3	1	[1 5]	1	
		4	1	[2 5]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				[3 10]	
	6(f11,f23)	5	0	[3 6]	0	
		6	0	[2 7]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				0	
	7(f12,f21)	7	0	[4 8]	0	
		8	0	[3 6]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				0	
	8(f12,f22)	9	0	[1 5]	0	
		10	0	[2 5]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				[3 7]	
	9(f12,f23)	11	0	[3 6]	0	
		12	0	[3 7]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				0	
	10(f13,f31)	13	1	[1 5]	1	
		14	1	[2 5]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				[3 10]	
	11(f13,f32)	15	1	[3 6]	1	
		16	1	[1 5]		
	$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$				[4 11]	
12(f13,f33)	17	0	[3 7]	0		
	18	0	[3 7]			

$d_{iw}^{wip} = [d_{iw}^{Lwip} \ d_{iw}^{Uwip}]$	0
--	---

Table 17 shows cost of operations 1 and 2.

**Table 17.** Cost of operations 1 and 2

Manufacturing operation 1 (Operation time, setup time)			Non-manufacturing operation 2	
Feature 1	Manufacturing Method (Operation time, setup time)		Feature 2	(Operation time, setup time)
	1	2		
1	(2,10)	(3,9)	1	(2,2)
2	(3,8)	(2,12)	2	(3,2)
3	(3,6)	(3,7)	3	(1,3)
$C_{om}^{man}$	10	22		

Here, we calculate the PIs and objectives for one configuration shown in Table 13.

### 3.2.5.1 PI11: Quality/price

We assume two functions with features/components (f11, f12, f13) and (f31, f32) affect on quality of carpet. It is assumed that the first function is resulted from quality of options provided by company and later is obtained based on quality of components purchased from different suppliers. Since nature of these functions is qualitative, we evaluate them with linguistic terms as follows (Table 18):

**Table 18.** Evaluation of features/components

Quality		F1			F3	
		f11	f12	f13	f31	f32
Components/features processed with manufacturing methods (operation 1)	Manufacturing method 1	G	P	VG	X	X
	Manufacturing method 2	M	G	G		
Components purchased from suppliers (Operation 3)	Supplier 1	X	X	X	P	G
	Supplier 2				G	M

Table 19 shows evaluation of components/features for products selected by considering manufacturing method 1 and supplier 1.

**Table 19.** Evaluation of components/features for products selected

Feature Product	F1			F3	
	f11	f12	f13	f31	f32
1	G	0	0	P	0
2	G	0	0	0	G
3	G	0	0	P	0
4	G	0	0	0	G
13	0	0	VG	P	0
14	0	0	VG	0	G
15	0	0	VG	P	0
16	0	0	VG	0	G

With considering confidence level  $\alpha = 0.5$  and the fuzzy numbers equivalence with linguistic terms shown in Table 10, interval-valued quality for products selected and total quality/price are calculated with formula (12) which are shown in Table 20.

**Table 20.** Interval-valued quality/price for products selected

Feature	F1			F3		Quality
Weight ( $V_{fv}$ )	0.6			0.4		
Product	f11	f12	f13	f31	f32	
1	[0.55 0.75]	0	0	[0.1 0.3]	0	[0.37 0.57]/ $pr_1$
2	[0.55 0.75]	0	0	0	[0.55 0.75]	[0.55 0.75]/ $pr_2$
3	[0.55 0.75]	0	0	[0.1 0.3]	0	[0.37 0.57]/ $pr_3$
4	[0.55 0.75]	0	0	0	[0.55 0.75]	[0.55 0.75]/ $pr_4$
13	0	0	[0.75 0.925]	[0.1 0.3]	0	[0.49 0.675]/ $pr_{13}$
14	0	0	[0.75 0.925]	0	[0.55 0.75]	[0.67 0.855]/ $pr_{14}$
15	0	0	[0.75 0.925]	[0.1 0.3]	0	[0.49 0.675]/ $pr_{15}$
16	0	0	[0.75 0.925]	0	[0.55 0.75]	[0.67 0.855]/ $pr_{16}$
Total quality/price ( $Z^{Tot} = 8$ )	Lower	$(1/8) * (0.37/ pr_1 + 0.55/ pr_2 + 0.37/ pr_3 + 0.55/ pr_4 + 0.49/ pr_{13} + 0.67/ pr_{14} + 0.49/ pr_{15} + 0.67/ pr_{16})$				
	Upper	$(1/8) * (0.57/ pr_1 + 0.75/ pr_2 + 0.57/ pr_3 + 0.75/ pr_4 + 0.675/ pr_{13} + 0.855/ pr_{14} + 0.675/ pr_{15} + 0.855/ pr_{16})$				

### 3.2.5.2 PI12: Average delivery time

Average delivery time is processing time of operations after CODP. According to supplier selected, values of upper and lower bound of delivery time is different. Tables 21 and 22 shows average delivery time for products selected with CODP1 and CODP2.

**Table 21.** Delivery time for products selected with CODP1

Product	$z_p$	$d_p$	$d_p z_p ((T_{po}^{op} + T_{po}^{set}) + X_s T_{js}^{sup})$
1	1	[2 6]	$[2 * z_1 ((2+2) + (X_1 T_{11}^{sup} + X_2 T_{12}^{sup})) , 6 * z_1 ((2+2) + (X_1 T_{11}^{sup} + X_2 T_{12}^{sup}))]$
2	1	[3 7]	$[3 * z_2 ((2+2) + (X_1 T_{21}^{sup} + X_2 T_{22}^{sup})) , 7 * z_2 ((2+2) + (X_1 T_{21}^{sup} + X_2 T_{22}^{sup}))]$
3	1	[1 5]	$[z_3 ((3+2) + (X_1 T_{11}^{sup} + X_2 T_{12}^{sup})) , 5 * z_3 ((3+2) + (X_1 T_{11}^{sup} + X_2 T_{12}^{sup}))]$
4	1	[2 5]	$[2 * z_4 ((3+2) + (X_1 T_{21}^{sup} + X_2 T_{22}^{sup})) , 5 * z_4 ((3+2) + (X_1 T_{21}^{sup} + X_2 T_{22}^{sup}))]$
5	0	[3 6]	0
6	0	[2 7]	0
7	0	[4 8]	0
8	0	[3 6]	0
9	0	[1 5]	0
10	0	[2 5]	0
11	0	[3 6]	0



12	0	[3 7]	0
13	1	[1 5]	$[z_{13} ((2+2) + (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}})) ,$ $6 * z_{13} ((2+2) + (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}))]$
14	1	[2 5]	$[2 * z_{14} ((2+2) + (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}})) ,$ $5 * z_{14} ((2+2) + (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}))]$
15	1	[3 6]	$[3 * z_{15} ((3+2) + (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}})) ,$ $6 * z_{15} ((3+2) + (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}))]$
16	1	[1 5]	$[z_{16} ((3+2) + (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}})) ,$ $5 * z_{16} ((3+2) + (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}))]$
17	0	[3 7]	0
18	0	[3 7]	0
$\sum_p d_p z_p ((T_{po}^{\text{op}} + T_{po}^{\text{set}}) + X_s T_{js}^{\text{sup}})$ $/ \sum_p d_p z_p$			$[(X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) (2 z_1 + z_3 + z_{13} + 3 z_{15}) +$ $(X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) (3 z_2 + 2 z_4 + 2 z_{14} + z_{16}) + 8 z_1 + 12 z_3 + 4 z_{13}$ $+ 15 z_{15} + 12 z_2 + 10 z_4 + 8 z_{14} + 5 z_{16}) / 44,$ $((X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) (6 z_1 + 5 z_3 + 5 z_{13} + 6 z_{16}) +$ $(X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) (7 z_2 + 5 z_4 + 5 z_{14} + 5 z_{16}) + 24 z_1 + 25 z_3 + 24$ $z_{13} + 30 z_{15} + 28 z_2 + 25 z_4 + 20 z_{14} + 25 z_{16}) / 15]$

**Table 22.** Delivery time for products selected with CODP2

Product	$z_p$	$d_p$	$d_p z_p X_s T_{js}^{\text{sup}}$
1	1	[2 6]	$[2 * z_1 (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) , 6 * z_1 (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}})]$
2	1	[3 7]	$[3 * z_2 (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) , 7 * z_2 (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}})]$
3	1	[1 5]	$[z_3 (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) , 5 * z_3 (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}})]$
4	1	[2 5]	$[2 * z_4 (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) , 5 * z_4 (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}})]$
5	0	[3 6]	0
6	0	[2 7]	0
7	0	[4 8]	0
8	0	[3 6]	0
9	0	[1 5]	0
10	0	[2 5]	0
11	0	[3 6]	0
12	0	[3 7]	0
13	1	[1 5]	$[z_{13} (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) , 6 * z_{13} (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}})]$
14	1	[2 5]	$[2 * z_{14} (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) , 5 * z_{14} (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}})]$
15	1	[3 6]	$[3 * z_{15} (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) , 6 * z_{15} (X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}})]$
16	1	[1 5]	$[z_{16} (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) , 5 * z_{16} (X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}})]$
17	0	[3 7]	0
18	0	[3 7]	0
$\sum_p d_p z_p ((T_{po}^{\text{op}} + T_{po}^{\text{set}}) + X_s T_{js}^{\text{sup}})$ $/ \sum_p d_p z_p$			$[(X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) (2 z_1 + z_3 + z_{13} + 3 z_{15}) +$ $(X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) (3 z_2 + 2 z_4 + 2 z_{14} + z_{16}) / 44,$ $((X_1 T_{11}^{\text{sup}} + X_2 T_{12}^{\text{sup}}) (6 z_1 + 5 z_3 + 5 z_{13} + 6 z_{16}) +$ $(X_1 T_{21}^{\text{sup}} + X_2 T_{22}^{\text{sup}}) (7 z_2 + 5 z_4 + 5 z_{14} + 5 z_{16})) / 15]$

### 3.2.5.3 PI13 and PI14

Next Table identifies values PI13 and PI14.

**Table 23.** Values of PI13 and PI14

Product	$z_p$	$d_p$
1	1	[2 6]
2	1	[3 7]
3	1	[1 5]
4	1	[2 5]
5	0	[3 6]
6	0	[2 7]
7	0	[4 8]
8	0	[3 6]
9	0	[1 5]
10	0	[2 5]
11	0	[3 6]
12	0	[3 7]
13	1	[1 5]
14	1	[2 5]
15	1	[3 6]
16	1	[1 5]
17	0	[3 7]
18	0	[3 7]
$D^L = \sum_p d_p^U z_p + \sum_p d_p^L (1 - z_p)$		71
$D^U = \sum_p d_p^L z_p + \sum_p d_p^U (1 - z_p)$		79
$\sum_p d_p z_p$		[15 44]
$Z_{13} = \frac{1}{D} \sum_p d_p z_p$		[0.19 0.62]
$Z_{14} = \frac{1}{N^{total}} \sum_p z_p$		8/16=0.5

### 3.2.5.4 PI15: control over the degree of functionality

This PI is related to component/feature that customers directly control over the degree of functionality of a product. If we assume that customers can control over the degree of functionality feature/component 1 with three alternatives, so, the value of PI15 is calculated as follows (Table 24):

**Table 24.** Value of PI15

Feature/ component	F1		
	f11	f12	f13
$k_{ab}$	1	0	1
$N^c$	3		
$N_a$	3		
$z_{15} = \frac{1}{N^c} \sum_{a \in SC} \sum_b \frac{k_{ab}}{N_a}$	(1/3)*(2/3)		

Where,  $N^c$  is number of components/features and  $N_a$  is number of alternatives of component/feature  $a$ .

**3.2.5.5 PI21: Benefit**

Here, we calculate the values of upper and lower bounds for cost and income according to operations in Figure 8. Table 25 displays the lower and upper bounds of manufacturing cost for semi-manufactured products processed in operation 1 for each two manufacturing method with CODP1.

**Table 25.** Calculation of manufacturing cost for semi-manufactured products (CODP=1)

Semi-manufactured product	$d_{iw}^{wip}$		$(d_{iw}^{wip} T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m U_{om}$		Interval cost
			Manufacturing method 1	Manufacturing method 2	
1	[8 23]	Lower	$y_1 r_1 ((8*2 + 10)*10/1) U_{11}$	$y_1 r_1 ((8*3 + 9)*12/1) U_{12}$	$y_1 r_1 (260U_{11} + 396U_{12})$
		Upper	$y_1 r_1 ((23*2 + 10)*10/1) U_{11}$	$y_1 r_1 ((23*3 + 9)*12/1) U_{12}$	$y_1 r_1 (560U_{11} + 936U_{12})$
2	0	0	0	0	0
3	[7 21]	Lower	$y_1 r_3 ((7*3 + 6)*10/1) U_{11}$	$y_1 r_3 ((7*3 + 7)*12/1) U_{12}$	$y_1 r_3 (270U_{11} + 336U_{12})$
		Upper	$y_1 r_3 ((21*3 + 6)*10/1) U_{11}$	$y_1 r_3 ((21*3 + 7)*12/1) U_{12}$	$y_1 r_3 (690U_{11} + 840U_{12})$
Total interval cost		Lower	$y_1 r_1 (260U_{11} + 396U_{12}) + y_1 r_3 (270U_{11} + 336U_{12})$		
		Upper	$y_1 r_1 (560U_{11} + 936U_{12}) + y_1 r_3 (690U_{11} + 840U_{12})$		

For this CODP (CODP1), cost of operations 2 and 3 are computed for each product selected. Table 26 represents the cost of operation 2 for products selected with CODP1.

**Table 26.** Cost of operation 2 for products selected with CODP1

Product	$z_p$	$d_p$	$d_p (T_{po}^{op2} + T_{po}^{set2}) z_p C_o^{Op}$
1	1	[2 6]	$[2*(2+2) z_1 C_2^{Op}, 6*(2+2) z_1 C_2^{Op}]$
2	1	[3 7]	$[3*(2+2) z_2 C_2^{Op}, 7*(2+2) z_2 C_2^{Op}]$
3	1	[1 5]	$[1*(3+2) z_3 C_2^{Op}, 5*(3+2) z_3 C_2^{Op}]$
4	1	[2 5]	$[2*(3+2) z_4 C_2^{Op}, 5*(3+2) z_4 C_2^{Op}]$
5	0	[3 6]	0
6	0	[2 7]	0
7	0	[4 8]	0
8	0	[3 6]	0
9	0	[1 5]	0
10	0	[2 5]	0

11	0	[3 6]	0
12	0	[3 7]	0
13	1	[1 5]	$[1^* (2+2) z_{13} C_2^{Op}, 5^* (2+2) z_{13} C_2^{Op}]$
14	1	[2 5]	$[3^* (2+2) z_{14} C_2^{Op}, 5^* (2+2) z_{14} C_2^{Op}]$
15	1	[3 6]	$[3^* (3+2) z_{15} C_2^{Op}, 6^* (3+2) z_{15} C_2^{Op}]$
16	1	[1 5]	$[1^* (3+2) z_{16} C_2^{Op}, 5^* (3+2) z_{16} C_2^{Op}]$
17	0	[3 7]	0
18	0	[3 7]	0
$\sum_{p=1} d_p z_p \sum_{\substack{O \in \\ (S_i^{AP} \cap S^{a-num})}} (T_{po}^{op2} + T_{po}^{set2}) C_o^{Op}$			$[C_2^{Op} (8 z_1 + 12 z_2 + 5 z_3 + 10 z_4 + 4 z_{13} + 12 z_{14} + 15 z_{15} + 5 z_{16}), C_2^{Op} (24 z_1 + 28 z_2 + 25 z_3 + 25 z_4 + 20 z_{13} + 20 z_{14} + 30 z_{15} + 25 z_{16})]$

Operation 3 is assumed that is done by two suppliers. Since operation 3 is last operation in our example that is performed on products after CODP2, so, cost of this operation is same for each two CODPs. Table 27 shows cost of operation 3 for products selected and for each two CODPs.

**Table 27.** Purchasing cost of operation 3 for products selected for CODP1 and CODP2

Product	$z_p$	$d_p$	$d_p r_{pj}^{c2} X_s C_{js}^{sup} z_p$
1	1	[2 6]	$[2^* z_1 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}), 6^* z_1 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})]$
2	1	[3 7]	$[3^* z_2 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}), 7^* z_2 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})]$
3	1	[1 5]	$[1^* z_3 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}), 5^* z_3 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})]$
4	1	[2 5]	$[2^* z_4 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}), 5^* z_4 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})]$
5	0	[3 6]	0
6	0	[2 7]	0
7	0	[4 8]	0
8	0	[3 6]	0
9	0	[1 5]	0
10	0	[2 5]	0
11	0	[3 6]	0
12	0	[3 7]	0
13	1	[1 5]	$[1^* z_{13} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}), 5^* z_{13} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})]$
14	1	[2 5]	$[2^* z_{14} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}), 5^* z_{14} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})]$
15	1	[3 6]	$[3^* z_{15} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}), 6^* z_{15} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})]$
16	1	[1 5]	$[1^* z_{16} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}), 5^* z_{16} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})]$
17	0	[3 7]	0
18	0	[3 7]	0
$\sum_{p=1} z_p \sum_j \sum_s d_p r_{pj}^{c2} X_s C_{js}^{sup}$			$[(X_1 C_{11}^{sup} + X_2 C_{12}^{sup}) (2 z_1 + z_3 + z_{13} + 3 z_{15}) + (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}) (3 z_2 + 2 z_4 + 2 z_{14} + z_{16}), (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}) (6 z_1 + 5 z_3 + 5 z_{13} + 6 z_{16}) + (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}) (7 z_2 + 5 z_4 + 5 z_{14} + 5 z_{16})]$

Next tables calculate cost of operations for CODP2. According the position CODP2 in the Figure 6, nine potential semi-manufactured products can be produced with considering feature/components selected. Operations 1 and 2 are performed on only 4 semi-manufactured products. Table 28 calculates manufacturing cost for 4 semi-manufactured products in operation 1 with CODP2.

**Table 28.** Manufacturing cost for semi-manufactured products (CODP=2)

Semi-manufactured product	$d_{iw}^{wip}$		$(d_{iw}^{wip}T_{wom}^{man1} + T_{wom}^{mset1})C_{om}^{man} / (def_m)U_{om}$		Interval cost
			Manufacturing method 1	Manufacturing method 2	
4	[5 13]	Lower	$y_2r_4((5*2+10)*10/1)U_{11}$	$y_2r_4((5*3+9)*12/1)U_{12}$	$y_2r_4(200U_{11} + 288U_{12})$
		Upper	$y_2r_4((13*2+10)*10/1)U_{11}$	$y_2r_4((13*3+9)*12/1)U_{12}$	$y_2r_4(360U_{11} + 576U_{12})$
5	[3 10]	Lower	$y_2r_5((3*3+6)*10/1)U_{11}$	$y_2r_5((3*3+7)*12/1)U_{12}$	$y_2r_5(150U_{11} + 192U_{12})$
		Upper	$y_2r_5((10*3+6)*10/1)U_{11}$	$y_2r_5((10*3+7)*12/1)U_{12}$	$y_2r_5(360U_{11} + 444U_{12})$
10	[3 10]	Lower	$y_2r_{10}((3*2+10)*10/1)U_{11}$	$y_2r_{10}((3*3+9)*12/1)U_{12}$	$y_2r_{10}(160U_{11} + 216U_{12})$
		Upper	$y_2r_{10}((10*2+10)*10/1)U_{11}$	$y_2r_{10}((10*3+9)*12/1)U_{12}$	$y_2r_{10}(300U_{11} + 468U_{12})$
11	[4 13]	Lower	$y_2r_{11}((4*3+6)*10/1)U_{11}$	$y_2r_{11}((4*3+7)*12/1)U_{12}$	$y_2r_{11}(180U_{11} + 228U_{12})$
		Upper	$y_2r_{11}((13*3+6)*10/1)U_{11}$	$y_2r_{11}((13*3+7)*12/1)U_{12}$	$y_2r_{11}(450U_{11} + 552U_{12})$
Total interval cost		Lower	$y_2r_4(200U_{11} + 288U_{12}) + y_2r_5(150U_{11} + 192U_{12}) + y_2r_{10}(160U_{11} + 216U_{12}) + y_2r_{11}(180U_{11} + 228U_{12})$		
		Upper	$y_2r_4(360U_{11} + 576U_{12}) + y_2r_5(360U_{11} + 444U_{12}) + y_2r_{10}(300U_{11} + 468U_{12}) + y_2r_{11}(450U_{11} + 552U_{12})$		

Table 29 identifies cost of operation 2 for semi-manufactured products selected with CODP2.

**Table 29.** Cost of operation 2 for semi-manufactured products with CODP2

Product	$r_w$	$d_{iw}^{wip}$	$(d_{iw}^{wip}T_{wo}^{op1} + T_{wo}^{set1})C_o^{Op} r_w$
4	1	[5 13]	$[(5*2+2) C_2^{Op} r_4, [(13*2+2) C_2^{Op} r_4]$
5	1	[3 10]	$[(3*3+2) C_2^{Op} r_5, [(10*3+2) C_2^{Op} r_5]$
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	1	[3 10]	$[(3*2+2) C_2^{Op} r_{10}, [(10*2+2) C_2^{Op} r_{10}]$
11	1	[4 13]	$[(4*3+2) C_2^{Op} r_{11}, [(13*3+2) C_2^{Op} r_{11}]$
12	0	0	0
$\sum_{\substack{O \in \\ (S_i^{def} \cap S^{a-man})}}$			$[C_2^{Op} (12r_4 + 11r_5 + 8r_{10} + 14r_{11}), C_2^{Op} (28r_4 + 32r_5 + 22r_{10} + 41r_{11})]$

Cost of operation 3 for CODP2 was performed before in Table 16.

Table 30 identifies interval income for products selected.

**Table 30.** Income

Product	$z_p$	$d_p$	Income= $pr_p Q_{tp}^{Pr} z_p$
1	1	[2 6]	$[2 z_1 pr_1, 6 z_1 pr_1]$
2	1	[3 7]	$[3 z_2 pr_2, 7 z_2 pr_2]$
3	1	[1 5]	$[z_3 pr_3, 5 z_3 pr_3]$
4	1	[2 5]	$[2 z_4 pr_4, 5 z_4 pr_4]$
5	0	[3 6]	0
6	0	[2 7]	0
7	0	[4 8]	0
8	0	[3 6]	0
9	0	[1 5]	0
10	0	[2 5]	0
11	0	[3 6]	0
12	0	[3 7]	0
13	1	[1 5]	$[z_{13} pr_{13}, 5 z_{13} pr_{13}]$
14	1	[2 5]	$[2 z_{14} pr_{14}, 5 z_{14} pr_{14}]$
15	1	[3 6]	$[3 z_{15} pr_{15}, 6 z_{15} pr_{15}]$
16	1	[1 5]	$[z_{16} pr_{16}, 5 z_{16} pr_{16}]$
17	0	[3 7]	0
18	0	[3 7]	0
$Income_t = \sum_{p=1} pr_p d_p z_p$		Lower	$2 z_1 pr_1 + 3 z_2 pr_2 + z_3 pr_3 + 2 z_4 pr_4 + z_{13} pr_{13} + 2 z_{14} pr_{14} + 3 z_{15} pr_{15} + z_{16} pr_{16}$
		Upper	$6 z_1 pr_1 + 7 z_2 pr_2 + 5 z_3 pr_3 + 5 z_4 pr_4 + 5 z_{13} pr_{13} + 5 z_{14} pr_{14} + 6 z_{15} pr_{15} + 5 z_{16} pr_{16}$

Table 31 shows interval income and total cost for our example for each CODP.

**Table 31.** Total cost

CODP	Interval	Income	Total cost
1	Lower	$2 z_1 pr_1 + 3 z_2 pr_2 + z_3 pr_3 + 2 z_4 pr_4 + z_{13} pr_{13} + 2 z_{14} pr_{14} + 3 z_{15} pr_{15} + z_{16} pr_{16}$	$y_1 r_1 (260U_{11} + 396U_{12}) + y_1 r_3 (270U_{11} + 336U_{12}) + C_2^{Op} (8 z_1 + 12 z_2 + 5 z_3 + 10 z_4 + 4 z_{13} + 12 z_{14} + 15 z_{15} + 5 z_{16}) + (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}) (2 z_1 + z_3 + z_{13} + 3 z_{15}) + (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}) (3 z_2 + 2 z_4 + 2 z_{14} + z_{16})$
	Upper	$6 z_1 pr_1 + 7 z_2 pr_2 + 5 z_3 pr_3 + 5 z_4 pr_4 + 5 z_{13} pr_{13} + 5 z_{14} pr_{14} + 6 z_{15} pr_{15} + 5 z_{16} pr_{16}$	$y_1 r_1 (560U_{11} + 936U_{12}) + y_1 r_3 (690U_{11} + 840U_{12}) + C_2^{Op} (24 z_1 + 28 z_2 + 25 z_3 + 25 z_4 + 20 z_{13} + 20 z_{14} + 30 z_{15} + 25 z_{16}) + (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}) (6 z_1 + 5 z_3 + 5 z_{13} + 6 z_{16}) + (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}) (7 z_2 + 5 z_4 + 5 z_{14} + 5 z_{16})$
2	Lower	$2 z_1 pr_1 + 3 z_2 pr_2 + z_3 pr_3 + 2 z_4 pr_4 + z_{13} pr_{13} + 2 z_{14} pr_{14} + 3 z_{15} pr_{15} + z_{16} pr_{16}$	$y_2 r_4 (200U_{11} + 288U_{12}) + y_2 r_5 (150U_{11} + 192U_{12}) + y_2 r_{10} (160U_{11} + 216U_{12}) + y_2 r_{11} (180U_{11} + 228U_{12}) + C_2^{Op} (12 r_4 + 11 r_5 + 8 r_{10} + 14 r_{11}) + (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}) (2 z_1 + z_3 + z_{13} + 3 z_{15}) + (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}) (3 z_2 + 2 z_4 + 2 z_{14} + z_{16})$
	Upper	$6 z_1 pr_1 + 7 z_2 pr_2 + 5 z_3 pr_3 + 5 z_4 pr_4 + 5 z_{13} pr_{13} + 5 z_{14} pr_{14} + 6 z_{15} pr_{15} + 5 z_{16} pr_{16}$	$y_2 r_4 (360U_{11} + 576U_{12}) + y_2 r_5 (360U_{11} + 444U_{12}) + y_2 r_{10} (300U_{11} + 468U_{12}) + y_2 r_{11} (450U_{11} + 552U_{12}) + C_2^{Op} (28 r_4 + 32 r_5 + 22 r_{10} + 41 r_{11}) + (X_1 C_{11}^{sup} + X_2 C_{12}^{sup}) (6 z_1 + 5 z_3 + 5 z_{13} + 6 z_{16}) + (X_1 C_{21}^{sup} + X_2 C_{22}^{sup}) (7 z_2 + 5 z_4 + 5 z_{14} + 5 z_{16})$

As expressed before, this example was constructed for one configuration of components/features shown in Table 13. According to this configuration, products 1, 2, 3, 4, 13, 14, 15 and 16 ( $z_p = 1 \forall p = 1, 2, 3, 4, 13, 14, 15, 16$ ) can be produced. So, final result for PI benefit (Income and cost) is obtained based on selection of CODP position ( $y_i$ ), manufacturing method ( $U_{om}$ ) or supplier ( $X_s$ ) shown in Tables 32 and 33.

**Table 32.** Cost and income for PI benefit with different values of decision variables

	Variable	Value			
CODP position	$y_1$	1	1	1	1
	$y_2$	0	0	0	0
manufacturing method	$U_{11}$	1	1	0	0
	$U_{12}$	0	0	1	1
Supplier	$X_1$	1	0	1	0
	$X_2$	0	1	0	1
Income	Lower	$2 pr_1 + 3 pr_2 + z_3 pr_3 + 2 pr_4 + pr_{13} + 2 pr_{14} + 3 pr_{15} + pr_{16}$			
	Upper	$6 pr_1 + 7 pr_2 + 5 pr_3 + 5 pr_4 + 5 pr_{13} + 5 pr_{14} + 6 pr_{15} + 5 pr_{16}$			
Cost	Lower	$530 + 71 C_2^{Op} + 7 C_{11}^{sup} + 8 C_{21}^{sup}$	$530 + 71 C_2^{Op} + 7 C_{12}^{sup} + 8 C_{22}^{sup}$	$732 + 71 C_2^{Op} + 7 C_{11}^{sup} + 8 C_{21}^{sup}$	$732 + 71 C_2^{Op} + 7 C_{12}^{sup} + 8 C_{22}^{sup}$
	Upper	$1250 + 197 C_2^{Op} + 22 C_{11}^{sup} + 22 C_{21}^{sup}$	$1250 + 197 C_2^{Op} + 22 C_{12}^{sup} + 22 C_{22}^{sup}$	$1776 + 197 C_2^{Op} + 22 C_{11}^{sup} + 22 C_{21}^{sup}$	$1776 + 197 C_2^{Op} + 22 C_{12}^{sup} + 22 C_{22}^{sup}$

**Table 33.** Cost and income for PI benefit with different values of decision variables

	Variable	Value			
CODP position	$y_1$	0	0	0	0
	$y_2$	1	1	1	1
manufacturing method	$U_{11}$	1	1	0	0
	$U_{12}$	0	0	1	1
Supplier	$X_1$	1	0	1	0
	$X_2$	0	1	0	1
Income	Lower	$2 pr_1 + 3 pr_2 + pr_3 + 2 pr_4 + pr_{13} + 2 pr_{14} + 3 pr_{15} + pr_{16}$			
	Upper	$6 pr_1 + 7 pr_2 + 5 pr_3 + 5 pr_4 + 5 pr_{13} + 5 pr_{14} + 6 pr_{15} + 5 pr_{16}$			
Cost	Lower	$690 + 45 C_2^{Op} + 7 C_{11}^{sup} + 8 C_{21}^{sup}$	$690 + 71 C_2^{Op} + 7 C_{12}^{sup} + 8 C_{22}^{sup}$	$924 + 45 C_2^{Op} + 7 C_{11}^{sup} + 8 C_{21}^{sup}$	$924 + 71 C_2^{Op} + 7 C_{12}^{sup} + 8 C_{22}^{sup}$
	Upper	$1065 + 45 C_2^{Op} + 7 C_{11}^{sup} + 8 C_{21}^{sup}$	$1065 + 71 C_2^{Op} + 7 C_{12}^{sup} + 8 C_{22}^{sup}$	$2040 + 45 C_2^{Op} + 7 C_{11}^{sup} + 8 C_{21}^{sup}$	$2040 + 71 C_2^{Op} + 7 C_{12}^{sup} + 8 C_{22}^{sup}$

In our model, this procedure is repeated for all configurations component/feature ( $k_{ab}$ ), CODP position ( $y_i$ ), manufacturing method ( $U_{om}$ ) or supplier ( $X_s$ ) to obtain amounts of PIs, objectives and a set of Pareto solutions.

### 3.2.6 Develop a mathematical model: model II

In this model, we develop a model considering time period. Because of uncertainty in demand of products, the model II investigates effect of lack or extra inventory of semi-manufactured products in CODP on backorder cost and inventory cost. In addition to assumptions of model I, some hypotheses are considered for model II as follows:

- Demand of each product for each time period is known and is estimated by interval numbers.
- Production level, after and before CODP position is different and is dependent to value of inventory, demand and back order value.
- Amounts backorder of this period have to be produced in the next period.

The notation of this model is represented as follows:

#### Notation

Index

$P$	Index of product
$f$	Index of function
$v$	Index of sub-function
$j$	Index of part (or material)
$s$	Index of suppliers
$m$	Index of manufacturing methods
$w$	Index of semi-manufactured products
$i$	Index of CODP position
$o$	Index of operations
$a (a=1, \dots, A)$	Index of component/features
$b=1, \dots, n_a$	Index of number of alternatives for each component/features
$t=1, \dots, T$	Index of time

#### Sets

$E$	Each element of this matrix $e_{pab}(p,b)=1$ if alternative $b$ of component/feature $a$ participate in product $p$
$S_w$	Set of products composed of semi-manufactured product $w$ .
$F^{Op}$	Functions influenced from non-manufacturing operations
$F^{sup}$	Functions influenced from suppliers
$F^{man}$	Functions influenced from manufacturing operations
$S_i^{Bef}$	Set of operations before CODP $i$
$S_i^{Aft}$	Set of operations after CODP $i$
$S^{man}$	Set of manufacturing operations
$S^{n-man}$	Set of non-manufacturing operations
$S_i^{sp}$	Set of semi-manufactured products for CODP $i$
SC	Set of features affecting on control on functionality degree
Sup <sub>j</sub>	Set of suppliers of component $j$



## Parameters

$d_{ip} = [d_{ip}^L \ d_{ip}^U]$	Anticipated demand of product $p$ in time $t$
$D = [D^L \ D^U]$	Total anticipated demand of all products
$N^{total}$	Total number of potential products
$q_{pfvom}^{man}$	Quality of product $p$ processed with operation $o$ and with manufacturing method $m$ for sub-function $v$ from function $f$
$q_{pfvjs}^{sup}$	Quality of component $j$ product $p$ purchased from supplier $s$ for sub-function $v$ from function $f$
$q_{pfv}^{op}$	Quality of product $p$ for sub-function $v$ from function $f$
$C_o^{Op}$	Operation cost $o$ for each time unit
$N^c$	Number of features in set SC
$C_{js}^{sup}$	Purchasing cost of component $j$ supplied from supplier $s$ for product $j$
$T_{js}^{sup} = [T_{js}^{Lsup} \ T_{js}^{Usup}]$	Purchasing time of component $j$ supplied from supplier $s$ for product $j$
$def_m$	Quality rate of manufacturing method $m$
$W_f^{Fun}$	Importance of function $f$
$V_{fv}$	Importance of sub-function $v$ in function $f$
$T_{wom}^{man1}$	Operation time $o$ for semi-manufactured product $w$ processed with manufacturing method $m$
$T_{pom}^{man2}$	Operation time $o$ for product $p$ processed with manufacturing method $m$
$C_{om}^{mac}$	Operation cost $o$ for manufacturing method $m$ for each time unit
$T_{wo}^{set1}$	Setup time of operation $o$ for semi-manufactured product $w$
$T_{po}^{set2}$	Setup time of operation $o$ for product $p$
$T_{wo}^{op1}$	Operation time $o$ for semi-manufactured product $w$
$T_{po}^{Op2}$	Operation time $o$ for product $p$
$T_{wom}^{mset1}$	Setup time of operation $o$ for semi-manufactured product $w$ processed with manufacturing method $m$
$T_{pom}^{mset2}$	Setup time of operation $o$ for product $p$ processed with manufacturing method $m$
$r_{wj}^{c1}$	Amount of component $j$ used in semi-manufactured product $w$
$r_{pj}^{c2}$	Amount of component $j$ used in product $p$
$pr_p$	Price of product $P$
$C_{iw}^{Inv}$	Inventory cost of semi-manufactured product $w$ for CODP $i$
$C_{iw}^B$	Backorder cost of semi-manufactured product $w$ for CODP $i$
$Cap_t$	Storage capacity for each period
<b>Budget</b>	The budget allocated to operation in time $t$
$N^A$	Number of alternatives for component/feature $a$
$w_{11}$	Weight of PI $z_{11}$
$w_{12}$	Weight of PI $z_{12}$
$w_{13}$	Weight of PI $z_{13}$
$w_{14}$	Weight of PI $z_{14}$
$w_{15}$	Weight of PI $z_{15}$

$w_{21}$	Weight of PI $z_{21}$
$g_{11}$	Goal of $z_{11}$
$g_{12}$	Goal of $z_{12}$
$g_{13}$	Goal of $z_{13}$
$g_{14}$	Goal of $z_{14}$
$g_{15}$	Goal of $z_{15}$
$g_{21}$	Goal of $z_{21}$

### Decision variables

$z_p$	1 if product $p$ is selected to offer customers, 0 otherwise
$r_w$	1 if semi-manufactured product $w$ is selected, 0 otherwise
$U_{om}$	1 if manufacturing method $m$ in operation $o$ is selected, 0 otherwise
$k_{ab}$	1 if alternative $b$ of component/feature $a$ is selected, 0 otherwise
$X_s$	1 if supplier $s$ is selected, 0 otherwise
$y_i$	1 if position $i$ for CODP is selected, 0 otherwise
$Q_{tp}^{Pr}$	Amount of production level of product $p$ in time $t$
$Q_{tiw}^S$	Amount of production level of semi-manufactured product $w$ in time $t$ in CODP $i$
$I_{tp} = [I_{tp}^L \ I_{tp}^U]$	Inventory product $p$ in time $t$
$B_{tp} = [B_{tp}^L \ B_{tp}^U]$	Backorder of product $p$ in period $t$
$I_{tiw}^S = [I_{tiw}^{Ls} \ I_{tiw}^{Us}]$	Inventory of semi-manufactured product $w$ in time $t$ in CODP $i$
$B_{tiw}^S = [B_{tiw}^{Ls} \ B_{tiw}^{Us}]$	Backorder of semi-manufactured product $w$ in period $t$ in CODP $i$
$\beta_t$	Production coefficient in time $t$
$Z^{Tot}$	Total product varieties selected
$D_{tp}^T = [D_{tp}^{Lt} \ D_{tp}^{Ut}]$	Total demand of product $p$ in time $t$
$Cost = [Cost^L \ Cost^U]$	Total operation cost
$Cost_{tiw}^{IB} = [Cost_{tiw}^{Lib} \ Cost_{tiw}^{Uib}]$	Inventory/backorder cost semi-manufactured product $w$ in period $t$ with CODP $i$
$Z_{11} = [z_{11}^L \ z_{11}^U]$	Upper and lower amount of PI quality perceived/price
$Z_{12} = [z_{12}^L \ z_{12}^U]$	Upper and lower amount of PI average delivery time
$Z_{13} = [z_{13}^L \ z_{13}^U]$	Upper and lower amount of PI percent of demand satisfied
$Z_{14} = [z_{14}^L \ z_{14}^U]$	Upper and lower amount of PI variety used
$Z_{15} = [z_{15}^L \ z_{15}^U]$	Upper and lower amount of PI control over the degree of functionality

The objectives and constraints of the proposed model are described as follows:

$$Max \ Z_1^o = W_{11}^o \frac{Z_{11}}{g_{11}} - W_{12}^o \frac{Z_{12}}{g_{12}} + W_{13}^o \frac{Z_{13}}{g_{13}} + W_{14}^o \frac{Z_{14}}{g_{14}} + W_{15}^o \frac{Z_{15}}{g_{15}} \quad (36)$$

$$Max \ Z_2^o = W_{21}^o \frac{Z_{21}}{g_{21}} \quad (37)$$

$$Z_{11} = \left( \sum_{t=1}^T \frac{1}{Z^{Tot}} \sum_{p=1}^P \frac{z_p}{Pr_p} \left( \sum_{f \in F^{op}} W_f^{Fun} \sum_{v \in S_j} V_{fv} q_{pfv}^{op} + \sum_{f \in F^{sup}} W_f^{Fun} \sum_{v \in S_j} V_{fv} \sum_j \sum_s X_s q_{pfvjs}^{sup} \right. \right. \quad (38)$$

$$\left. + \sum_{f \in F^{man}} W_f^{Fun} \sum_{v \in S_j} V_{fv} \sum_o \sum_m q_{pfvom}^{mac} U_{om} \right)$$

$$Z_{12} = \sum_{t=1}^T \sum_{p=1}^P Q_{tp}^{Pr} z_p \left( \sum_{\substack{O \in \\ S_i^{Af} \cap S^{a-man}}} T_{po}^{op2} + T_{po}^{set2} + \sum_{\substack{O \in \\ S_i^{Af} \cap S^{man}}} \sum_m (T_{pom}^{man2} + T_{pom}^{mset2}) U_{om} / def_o \right. \quad (39)$$

$$\left. + \sum_j \sum_s X_s T_{js}^{sup} \right) / \sum_{p=1}^P d_p z_p$$

$$Z_{13} = \frac{1}{D} \sum_{t=1}^T \sum_p Q_{tp}^{Pr} z_p \quad (40)$$

$$Z_{14} = \frac{1}{N^{total}} \sum_p z_p \quad (41)$$

$$z_{15} = \frac{1}{N^c} \sum_{a \in SC} \sum_b \frac{k_{ab}}{N_a} \quad (42)$$

$$Z_{21} = Income - Cost \quad (43)$$

$$Income = \sum_{t=1}^T \sum_{p=1}^P pr_p Q_{tp}^{Pr} z_p \quad (44)$$

$$Cost = \sum_{t=1}^T \sum_{i=1}^I y_i \left( \sum_{w=1}^W r_w \left( \sum_{\substack{O \in \\ (S_i^{Bf} \cap S^{man})}} \sum_{m=1}^M ((Q_{tiw}^S T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_{om} + \right. \right. \quad (45)$$

$$\left. \sum_{\substack{O \in \\ (S_i^{Bf} \cap S^{a-man})}} (Q_{tiw}^S T_{wo}^{op1} + T_{wo}^{set1}) C_o^{Op} + \sum_j \sum_{s \in Sup_j} Q_{tiw}^S r_{wj}^{c1} X_s C_{js}^{sup} + Cost_{tiw}^{IB} \right) +$$

$$\sum_{p=1}^P Q_{tp}^{Pr} z_p \left( \sum_{\substack{O \in \\ (S_i^{Af} \cap S^{man})}} \sum_{m=1}^M ((T_{pom}^{man2} + T_{pom}^{mset2}) C_{om}^{man} / def_o) U_{om} + \sum_{\substack{O \in \\ (S_i^{Af} \cap S^{a-man})}} (T_{po}^{op1} + T_{po}^{set2}) C_o^{Op} + \right.$$

$$\left. + \sum_j \sum_{s \in Sup_j} r_{pj}^{c2} X_s C_{js}^{sup} \right)$$

$$D_{tp}^T = d_{tp} z_p - I_{(t-1)p} + B_{(t-1)p} = \begin{cases} D_{tp}^{Lt} = z_p d_{tp}^L - I_{(t-1)p}^U + B_{(t-1)p}^L \\ D_{tp}^{Ut} = d_{tp}^U z_p - I_{(t-1)p}^L + B_{(t-1)p}^U \end{cases} \quad (46)$$

$$Q_{tp}^{Pr} = (\beta_t D_{tp}^{Ut} + (1 - \beta_t) \times \max(0, D_{tp}^{Lt})) \quad (47)$$

$$0 \leq \beta_t \leq 1 \quad (48)$$

$$I_{tp}^U = (-\min(0, D_{tp}^{Lt}) + Q_{tp}^{Pr} - \max(0, D_{tp}^{Lt})) \quad \forall t, p \quad (49)$$

$$B_{tp}^U = (D_{tp}^{Ut} - Q_{tp}^{Pr}) \quad \forall t, p \quad (50)$$

$$Q_{iiv}^S = \sum_{p \in s_w} Q_{tp}^{Pr} y_i \quad \forall t, i, w \in s_i^{sp} \quad (51)$$

$$I_{iiv}^{Us} = \sum_{p \in s_w} I_{tp}^U y_i \quad \forall t, i, w \in s_i^{sp} \quad (52)$$

$$B_{iiv}^{Us} = \sum_{p \in s_w} B_{tp}^U y_i \quad \forall t, i, w \in s_i^{sp} \quad (53)$$

$$\sum_w (I_{iiv}^L + I_{iiv}^U) / 2 \leq Cap_t \quad \forall i, t \quad (54)$$

$$Cost \leq Budget \quad (55)$$

$$D = \sum_t \sum_p d_{tp} \quad (56)$$

$$Z^{Tot} = \sum_p z_p \quad (57)$$

$$z_p = \prod_a \sum_{b=1}^{n_a} k_{ab} e_{pab} \quad \forall p \quad (58)$$

$$\sum_{b=1}^{n_a} k_{ab} \geq 1 \quad \forall a \quad (59)$$

$$r_w \leq \sum_{p \in s_w} z_p \quad \forall w \quad (60)$$

$$r_w \geq z_p \quad \forall w, p \in s_w \quad (61)$$

$$\sum_{m=1}^{M_o} U_{om} = 1 \quad \forall o \in s^{man} \quad (62)$$

$$\sum_s X_s = 1 \quad (63)$$

$$\sum_i y_i = 1 \quad (64)$$

$$y_i, X_s, U_{om}, z_p, k_{ab}, r_w \in \{0, 1\}$$

Objectives (36) and (37) maximize the weighted average of performance indicators involving in customer value and enterprise value, respectively.

Term (38) shows the PI “average of quality perceived by customers/price”. The quality perceived is evaluated based on customer satisfaction from functions. The more description for this PI has been represented in the previous model. Term (39) shows the PI as the average delivery time of products. Terms (40) and (41) are PIs that identify the percent of demand satisfied and percent of product variety offered to customers, respectively. Term (42) shows the PI control over the degree of functionality of a product. Term (43) identifies the total benefit obtained from selling product varieties. Terms (44) and (45) calculate the income and total cost.

Constraint (46) identifies total interval demand of a product variety in a period ( $D_{ip}^T = [D_{ip}^{Lt} \ D_{ip}^{Ut}]$ ) which is dependence to demand of products selected for this period and amounts of inventory and backorder of products remained from previous period. Constraints (47) and (48) show production level of products manufactured in each period. We assume that production level of product p in period t is determined as a linear combination of upper and lower bounds of total interval demand. So, a factor is defined as production coefficient ( $\beta_t$ ) in order to get production level. For simplicity, we assume that this factor is equal for all product varieties in a period. Constraints (49) and (50) show upper bound of inventory and back order of products obtained in each period for each product. Subtraction of production level and lower bound of  $D_{ip}^T$  identifies maximum inventory obtained ( $Q_{ip}^{Pr} - \max(0, D_{ip}^{Lt})$ ). Amounts of inventory for each product include (constraint (49)) the inventory remained from previous ( $-\min(0, D_{ip}^{Lt})$ ) and maximum inventory obtained ( $Q_{ip}^{Pr} - \max(0, D_{ip}^{Lt})$ ). Subtraction of production level and upper bound of  $D_{ip}^T$  identifies maximum backorder obtained ( $Q_{ip}^{Pr} - \max(0, D_{ip}^{Lt})$ ) shown in constraint (50). Constraint (51) calculates production level of semi-manufactured products in each period. We assume production level of a semi-manufactured product is obtained from summation of production levels of products using this semi-manufactured product. Constraints (52) and (53) identify upper bound of inventory and backorder of each semi-manufactured product in each period that is dependence to upper bounds of inventory and backorder of product varieties using same semi-manufactured product. Constraint (54) shows that average inventory of semi-manufactured products should not violate from capacity of storage in CODP position. Constraint (55) says that values of cost in each period have to be lower than budget in each period. Constraint (56) displays the total demand of products in each period. Constraint (57) shows the total number of products selected. Constraint (58) identifies components/features participated in products (see more description in constraint (16) of previous model). Constraint (59) expresses that at least one alternative of each component/feature should be selected. Constraints (60) and (61) express that a semi-manufactured product is selected when at least a product that belongs to set of products made from a given semi-manufactured product is selected. Constraints (62), (63) and (64) are same with constraints (20), (21) and (22) of previous model.

In this model, similar to the previous model, PIs and objectives get values of interval because of the parameters with interval values which are shown in equations (65) to (70).

$$Max [Z_1^L \ Z_1^U] = \frac{W_{11}^o [Z_{11}^L \ Z_{11}^U]}{g_{11}} - \frac{W_{12}^o [Z_{11}^L \ Z_{11}^U]}{g_{12}} + \frac{W_{13}^o [Z_{11}^L \ Z_{11}^U]}{g_{13}} + \frac{W_{14}^o [Z_{11}^L \ Z_{11}^U]}{g_{14}} + \frac{W_{15}^o [Z_{11}^L \ Z_{11}^U]}{g_{15}} \quad (65)$$

$$Max Z_2 = \frac{W_{21}^o [Z_{21}^L \ Z_{21}^U]}{g_{21}} \quad (66)$$

$$Z_1^L = \frac{W_{11}^o Z_{11}^L}{g_{11}} - \frac{W_{12}^o Z_{11}^U}{g_{12}} + \frac{W_{13}^o Z_{11}^L}{g_{13}} + \frac{W_{14}^o Z_{11}^L}{g_{14}} + \frac{W_{15}^o Z_{11}^L}{g_{15}} \quad (67)$$

$$Z_1^U = \frac{W_{11}^o Z_{11}^U}{g_{11}} - \frac{W_{12}^o Z_{11}^L}{g_{12}} + \frac{W_{13}^o Z_{11}^U}{g_{13}} + \frac{W_{14}^o Z_{11}^U}{g_{14}} + \frac{W_{15}^o Z_{11}^U}{g_{15}} \quad (68)$$

$$Z_2^L = \frac{W_{21}^o Z_{21}^L}{g_{21}} \quad (69)$$

$$Z_2^U = \frac{W_{21}^o Z_{21}^U}{g_{21}} \quad (70)$$

PI average delivery time ( $Z_{12}$ ), due to interval purchasing time of supplier ( $[T_{js}^{L\sup} T_{js}^{U\sup}]$ ), is converted to interval value with equations (71) and (72):

$$Z_{12}^L = \sum_{t=1} \sum_{p=1} Q_{tp}^{\text{Pr}} z_p \left( \sum_{O \in (S_i^{Ab} \cap S^{n-man})} T_{po}^{op2} + T_{po}^{set2} + \sum_{O \in (S_i^{Ab} \cap S^{man})} \sum_{m=1} (T_{pom}^{man2} + T_{pom}^{mset2}) U_{om} / def_o + \right. \quad (71)$$

$$\left. + \sum_j \sum_{s \in Sup_j} X_s T_{js}^{L\sup} \right) / \sum_{t=1} \sum_{p=1} d_p^U z_p$$

$$Z_{12}^U = \sum_{t=1} \sum_{p=1} Q_{tp}^{\text{Pr}} z_p \left( \sum_{O \in (S_i^{Ab} \cap S^{n-man})} T_{po}^{op1} + T_{po}^{set2} + \sum_{O \in (S_i^{Ab} \cap S^{man})} \sum_{m=1} (T_{pom}^{man2} + T_{pom}^{mset2}) U_{om} / def_o + \right. \quad (72)$$

$$\left. + \sum_j \sum_{s \in Sup_j} X_s T_{js}^{U\sup} \right) / \sum_{t=1} \sum_{p=1} d_p^L z_p$$

PI percent of demand satisfied ( $Z_{13}$ ), due to interval total demand, is converted to interval amounts with equation (73):

$$Z_{13} = \frac{1}{D} \sum_{t=1}^T \sum_p Q_{tp}^{\text{Pr}} z_p = \begin{cases} Z_{13}^L = \frac{1}{D^U} \sum_{t=1}^T \sum_p Q_{tp}^{\text{Pr}} z_p \\ Z_{13}^U = \frac{1}{D^L} \sum_{t=1}^T \sum_p Q_{tp}^{\text{Pr}} z_p \end{cases} \quad (73)$$

where upper and lower bounds of total demand ( $[D^L D^U]$ ) are calculated with equations (74) and (75):

$$D^L = \sum_t \sum_p d_{tp}^L \quad (74)$$

$$D^U = \sum_t \sum_p d_{tp}^U \quad (75)$$

Cost of inventory or backorder is used to calculate total cost. Since production level of each semi-manufactured product is a linear combination of total interval demand ( $D_{ip}^T = [D_{ip}^{Lt} \ D_{ip}^{Ut}]$ ), so, we calculate lower and upper inventory and/or backorder costs for each semi-manufactured product used in total cost as follows:

$$Cost_{tiw}^{Lib} = \min(I_{tiw}^{Ls} C_{iw}^{Inv}, B_{tiw}^{Ls} C_{iw}^B) \quad \forall t, i, w \in S_i^{sp} \quad (76)$$

$$Cost_{tiw}^{Uib} = \max(I_{tiw}^{Ls} C_{iw}^{Inv}, B_{tiw}^{Ls} C_{iw}^B) \quad \forall t, i, w \in S_i^{sp} \quad (77)$$

In our model, values  $I_{tiw}^{Ls}$  and  $B_{tiw}^{Ls}$  are zero and values  $I_{tiw}^{Us}$  and  $B_{tiw}^{Us}$  are obtained with terms (60) and (61).

Interval amounts of inventory and backorder of semi-manufactured products cause an interval amount for total cost deduced from equations (78) and (79):

$$Cost^L = \sum_{t=1}^I \sum_{i=1}^I y_i \left( \sum_{w=1}^I r_w \left( \sum_{O \in (S_i^{bf} \cap S^{mn})} \sum_{m=1}^I ((Q_{tiw}^S T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_{om} + \right. \right. \quad (78)$$

$$\left. \sum_{O \in (S_i^{bf} \cap S^{mn})} (Q_{tiw}^S T_{wo}^{op1} + T_{wo}^{set1}) C_o^{Op} + \sum_j \sum_{s \in Sup_j} Q_{tiw}^S r_{wj}^{c1} X_s C_{js}^{sup} + Cost_{tiw}^{Lib} \right) +$$

$$\sum_{p=1}^I Q_{ip}^{Pr} z_p \left( \sum_{O \in (S_i^{bf} \cap S^{mn})} \sum_{m=1}^I ((T_{pom}^{man2} + T_{pom}^{mset2}) C_{om}^{man} / def_o) U_{om} + \sum_{O \in (S_i^{bf} \cap S^{n-man})} (T_{po}^{op1} + T_{po}^{set2}) C_o^{Op} + \right. \\ \left. + \sum_j \sum_{s \in Sup_j} r_{pj}^{c2} X_s C_{js}^{sup} \right)$$

$$Cost^U = \sum_{t=1}^I \sum_{i=1}^I y_i \left( \sum_{w=1}^I r_w \left( \sum_{O \in (S_i^{bf} \cap S^{mn})} \sum_{m=1}^I ((Q_{tiw}^S T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_{om} + \right. \right. \quad (79)$$

$$\left. \sum_{O \in (S_i^{bf} \cap S^{mn})} (Q_{tiw}^S T_{wo}^{op1} + T_{wo}^{set1}) C_o^{Op} + \sum_j \sum_{s \in Sup_j} Q_{tiw}^S r_{wj}^{c1} X_s C_{js}^{sup} + Cost_{tiw}^{Uib} \right) +$$

$$\sum_{p=1}^I Q_{ip}^{Pr} z_p \left( \sum_{O \in (S_i^{bf} \cap S^{mn})} \sum_{m=1}^I ((T_{pom}^{man2} + T_{pom}^{mset2}) C_{om}^{man} / def_o) U_{om} + \sum_{O \in (S_i^{bf} \cap S^{n-man})} (T_{po}^{op1} + T_{po}^{set2}) C_o^{Op} + \right. \\ \left. + \sum_j \sum_{s \in Sup_j} r_{pj}^{c2} X_s C_{js}^{sup} \right)$$

Because of interval values for cost, PI benefit ( $Z_{21}$ ), has an interval amount that is calculated as follows:

$$Z_{21}^L = \sum_{t=1}^I \sum_{p=1}^I pr_p Q_{ip}^{Pr} z_p - cost^U \quad (80)$$

$$Z_{21}^U = \sum_{t=1} \sum_{p=1} pr_p Q_{tp}^{Pr} z_p - \text{cost}^L$$

In model II, the main part is to determine production level of products and semi-manufactured products and amounts of inventory and back order of semi-manufactured products. We consider role of backorder and inventory values to calculate different PIs and thus to select products offered.

### 3.2.7 A little example to describe model II

We, here, describe the model II with details by using previous example. Since in model II, we have some new parameters into model I such as production level, so, we show the method of calculating these new parameters and PI benefit. Evaluation of other PIs is similar to model I.

We assume two time periods and two positions for CODP according to Figure 13. We consider a configuration of products selected (see Table 13), the products selected (see Table 14) and the potential semi-manufactured products (see Table 15) to perform the example.

Table 34 displays values of demand of each product, inventory and back order of products for previous and current period, total demand and production level of products for period 1 which are calculated by equations 54 to 58.

**Table 34.** Amounts of production level, inventory and back order of products for period 1

Product	$z_p$	Demand	$I_{(t-1)p}^U$	$B_{(t-1)p}^L$	$D_{tp}^{Lt}$	$D_{tp}^{Ut}$	$D_{tp}^T$	$Q_{tp}^{Pr}$ ( $\beta_t = 0.8$ )	$I_{tp}^U$	$B_{tp}^U$
1	1	[2 6]	0	0	2	6	[2 6]	5	3	1
2	1	[3 7]	0	0	3	7	[3 7]	6	3	1
3	1	[1 5]	0	0	1	5	[1 5]	4	3	1
4	1	[2 5]	0	0	2	5	[2 5]	4	2	1
5	0	[3 6]	0	0	0	0	0	0	0	0
6	0	[2 7]	0	0	0	0	0	0	0	0
7	0	[4 8]	0	0	0	0	0	0	0	0
8	0	[3 6]	0	0	0	0	0	0	0	0
9	0	[1 5]	0	0	0	0	0	0	0	0
10	0	[2 5]	0	0	0	0	0	0	0	0
11	0	[3 6]	0	0	0	0	0	0	0	0
12	0	[3 7]	0	0	0	0	0	0	0	0
13	1	[1 5]	0	0	1	5	[1 5]	4	3	1
14	1	[2 5]	0	0	2	5	[2 5]	4	2	1
15	1	[3 6]	0	0	3	6	[3 6]	5	2	1
16	1	[3 8]	0	0	3	8	[3 8]	7	4	1
17	0	[3 7]	0	0	0	0	0	0	0	0
18	0	[3 7]	0	0	0	0	0	0	0	0

For example, total interval-value demand of product variety 1 in period T=1 ( $D_{1p}^T = [D_{1p}^{Lt} \ D_{1p}^{Ut}]$ ) calculated with equation (54) is equal with anticipated demand of product in time T ([2 6]), because of zero values of backorder and inventory in beginning of period. With considering  $\beta_t = 0.8$  (coefficient of manufacturing in time t), the production level that is linear combination upper and lower total demand is obtained with equation (55).



Table 35 shows values of demand, inventory and back order of products for previous and current period, total demand and production level of products for period 2 which are calculated by equations 54 to 58.

**Table 35.** Amounts of production level, inventory and back order of products for period 2

Product	$z_p$	Demand	$I_{(t-1)p}^U$	$B_{(t-1)p}^U$	$D_{tp}^{Lt}$	$D_{tp}^{Ut}$	$D_{tp}^T$	$Q_{tp}^{Pr}$ ( $\beta_t = 0.6$ )	$I_{tp}^U$	$B_{tp}^U$
1	1	[4 9]	3	1	1	10	[1 10]	6	5	4
2	1	[5 8]	3	1	2	9	[2 9]	6	4	3
3	1	[2 5]	3	1	-1	6	[-1 6]	4	5	2
4	1	[2 5]	2	1	0	6	[0 6]	4	4	2
5	0	[4 7]	0	0	0	0	0	0	0	0
6	0	[4 7]	0	0	0	0	0	0	0	0
7	0	[4 8]	0	0	0	0	0	0	0	0
8	0	[3 8]	0	0	0	0	0	0	0	0
9	0	[2 5]	0	0	0	0	0	0	0	0
10	0	[2 5]	0	0	0	0	0	0	0	0
11	0	[4 7]	0	0	0	0	0	0	0	0
12	0	[5 8]	0	0	0	0	0	0	0	0
13	1	[3 6]	3	1	0	7	[0 7]	4	4	3
14	1	[2 5]	2	1	0	6	[0 6]	4	4	2
15	1	[4 8]	2	1	2	9	[2 9]	6	4	3
16	1	[2 5]	4	1	-2	6	[-2 6]	4	6	2
17	0	[4 7]	0	0	0	0	0	0	0	0
18	0	[5 8]	0	0	0	0	0	0	0	0

For better comprehension, we calculate values  $D_{tp}^T$ , production level, backorder and inventory for product 3 as follows:

$$D_{tp}^{Lt} = z_p d_{tp}^L - I_{(t-1)p}^U + B_{(t-1)p}^L = 2 - 3 + 0 = -1$$

$$D_{tp}^{Ut} = z_p d_{tp}^U - I_{(t-1)p}^L + B_{(t-1)p}^U = 5 - 0 + 1 = 6$$

$$Q_{tp}^{Pr} = \beta_t D_{tp}^{Ut} + (1 - \beta_t) \times \max(0, D_{tp}^{Lt}) = 0.6 * 6 + 0.4 * \max(0, -1) = 3.6 \cong 4$$

$$I_{tp}^U = -\min(0, D_{tp}^{Lt}) + Q_{tp}^{Pr} - \max(0, D_{tp}^{Lt}) = -1 * -1 + 4 - 0 = 5$$

$$B_{tp}^U = D_{tp}^{Ut} - Q_{tp}^{Pr} = 6 - 4 = 2$$

Negative value  $D_{tp}^{Lt}$  demonstrates that amount inventory is more than summation of demand and backorder. So, one unit inventory is remained.

Table 36 displays products selected and their semi-manufactured products, inventory, back order and production level of semi-manufactured products for period 1 and CODP1 calculated by equations 59 to 61.

**Table 36.** Production level, inventory and back order of semi-manufactured products (CODP1, T=1)

Semi-product	Product	$z_p$	$r_w$	$Q_{tp}^{Pr}$	$I_{tp}^L$	$I_{tp}^U$	$B_{tp}^L$	$B_{tp}^U$
1(f11)	1	1	1	5	0	3	0	1
	2	1		6	0	3	0	1
	3	1		4	0	3	0	1
	4	1		4	0	2	0	1
	5	0		0	0	0	0	0
	6	0		0	0	0	0	0
$Q_{tiw}^S$				19				
$I_{tiw}^{Us}$						11		
$B_{tiw}^{Us}$								4
2(f12)	7	0	0	0	0	0	0	0
	8	0		0	0	0	0	0
	9	0		0	0	0	0	0
	10	0		0	0	0	0	0
	11	0		0	0	0	0	0
	12	0		0	0	0	0	0
$Q_{tiw}^S$				0				
$I_{tiw}^{Us}$						0		
$B_{tiw}^{Us}$								0
3(f13)	13	1	1	4	0	3	0	1
	14	1		4	0	2	0	1
	15	1		5	0	2	0	1
	16	1		7	0	4	0	1
	17	0		0	0	0	0	0
	18	0		0	0	0	0	0
$Q_{tiw}^S$				20				
$I_{tiw}^{Us}$						11		
$B_{tiw}^{Us}$								4

For better comprehension, we calculate production level, inventory and back order of semi-manufactured product 1 for period 1 and CODP1 as follows:

$$Q_{tiw}^S = \sum_{p \in S_w} Q_{tp}^{Pr} y_i = (5+6+4+4) * y_1 = 19$$

$$I_{tiw}^{Us} = \sum_{p \in S_w} I_{tp}^U y_i = (3+3+3+2) * y_1 = 11$$

$$B_{tiw}^{Us} = \sum_{p \in S_w} B_{tp}^U y_i = (1+1+1+1) * y_1 = 4$$

Values  $Q_{tp}^{Pr}$ ,  $I_{tp}^U$  and  $B_{tp}^U$  extracted from columns 10, 11 and 12 of Table 34, are shown in Table 36.

With using these equation (59 to 61), amounts inventory, back order and production level of semi-manufactured products for period 2 and CODP1 are calculated which are shown in Table 37.

**Table 37.** Production level, inventory and back order of semi-manufactured products (CODP1, T=2)

Semi-product	Product	$z_p$	$r_w$	$Q_{tp}^{Pr}$	$I_{tp}^L$	$I_{tp}^U$	$B_{tp}^L$	$B_{tp}^U$
1(f11)	1	1	1	6	0	5	0	4
	2	1		6	0	4	0	3
	3	1		4	0	5	0	2
	4	1		4	0	4	0	2
	5	0		0	0	0	0	0
	6	0		0	0	0	0	0
$Q_{tiw}^S$				20				
$I_{tiw}^{Us}$						18		
$B_{tiw}^{Us}$								11
2(f12)	7	0	0	0	0	0	0	0
	8	0		0	0	0	0	0
	9	0		0	0	0	0	0
	10	0		0	0	0	0	0
	11	0		0	0	0	0	0
	12	0		0	0	0	0	0
$Q_{tiw}^S$				0				
$I_{tiw}^{Us}$						0		
$B_{tiw}^{Us}$								0
3(f13)	13	1	1	4	0	4	0	3
	14	1		4	0	4	0	2
	15	1		6	0	4	0	3
	16	1		4	0	6	0	2
	17	0		0	0	0	0	0
	18	0		0	0	0	0	0
$Q_{tiw}^S$				18				
$I_{tiw}^{Us}$						18		
$B_{tiw}^{Us}$								10

Tables 38 and 39 display products selected with CODP2, inventory, back order and production level of semi-manufactured products for periods 1 and 2, respectively, calculated by equations 59 to 61.

**Table 38.** Production level, inventory and back order of semi-manufactured products (CODP2, T=1)

Semi-product	Product	$z_p$	$r_w$	$Q_{tp}^{Pr}$	$I_{tp}^L$	$I_{tp}^U$	$B_{tp}^L$	$B_{tp}^U$
4(f11,f21)	1	1	1	5	0	3	0	1
	2	1		6	0	3	0	1
$Q_{tiw}^S$				11				
$I_{tiw}^{Us}$						6		
$B_{tiw}^{Us}$								2
5(f11,f22)	3	1	1	4	0	3	0	1
	4	1		4	0	2	0	1
$Q_{tiw}^S$				8				
$I_{tiw}^{Us}$						5		
$B_{tiw}^{Us}$								2
6(f11,f23)	5	0	0	0	0	0	0	0

	6	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
7(f12,f21)	7	0	0	0	0	0	0	0	
	8	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
8(f12,f22)	9	0	0	0	0	0	0	0	
	10	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
9(f12,f23)	11	0	0	0	0	0	0	0	
	12	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
10(f13,f31)	13	1	1	4		3		1	
	14	1		4		2		1	
	$Q_{tiw}^S$			8					
				$I_{tiw}^{Us}$			5		
				$B_{tiw}^{Us}$					2
11(f13,f32)	15	1	1	5		2		1	
	16	1		7		4		1	
	$Q_{tiw}^S$			12					
				$I_{tiw}^{Us}$			6		
				$B_{tiw}^{Us}$					2
12(f13,f33)	17	0	0	0	0	0	0	0	
	18	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0

**Table 39.** Production level, inventory and back order of semi-manufactured products (CODP2, T=2)

Semi-product	Product	$z_p$	$r_w$	$Q_{ip}^{Pr}$	$I_{ip}^L$	$I_{ip}^U$	$B_{ip}^L$	$B_{ip}^U$	
4(f11,f21)	1	1	1	6	0	5	0	4	
	2	1		6	0	4	0	3	
	$Q_{tiw}^S$			12					
				$I_{tiw}^{Us}$			9		
				$B_{tiw}^{Us}$					7
5(f11,f22)	3	1	1	4	0	5	0	2	

	4	1		4	0	4	0	1	
	$Q_{tiw}^S$			8					
				$I_{tiw}^{Us}$			9		
				$B_{tiw}^{Us}$					3
6(f11,f23)	5	0	0	0	0	0	0	0	
	6	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
7(f12,f21)	7	0	0	0	0	0	0	0	
	8	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
8i(f12,f22)	9	0	0	0	0	0	0	0	
	10	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
9(f12,f23)	11	0	0	0	0	0	0	0	
	12	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0
10(f13,f31)	13	1	1	4		4		3	
	14	1		4		4		2	
	$Q_{tiw}^S$			8					
				$I_{tiw}^{Us}$			8		
				$B_{tiw}^{Us}$					5
11(f13,f32)	15	1	1	6		4		3	
	16	1		4		6		2	
	$Q_{tiw}^S$			10					
				$I_{tiw}^{Us}$			10		
				$B_{tiw}^{Us}$					5
12(f13,f33)	17	0	0	0	0	0	0	0	
	18	0		0	0	0	0	0	
	$Q_{tiw}^S$			0					
				$I_{tiw}^{Us}$			0		
				$B_{tiw}^{Us}$					0

Amounts of production level of products and semi-manufactured products are used as frequency of process after and before CODP, respectively. Also, amounts inventory and back order of semi-manufactured products are used to calculate cost inventory/backorder to compute PI benefit.

Since the PI Benefit is more complicated among other PIs, in continuous, we represent the method to calculate cost for our example. We calculate income and cost for each CODP and two periods based on position of CODP and the processes before and after CODP. For CODP1, operation 1 before CODP and operations 2 and 3 after CODP happen. For CODP2, operations 1 and 2 before CODP and operation 3 after CODP happen.

According the position CODP1 in the Figure 8, three semi-manufactured products are manufactured in operation 1 with two potential manufacturing methods. So, Tables 40 and 41 calculate manufacturing cost for these semi-manufactured products in operation 1 for periods 1 and 2 with CODP1.

**Table 40.** Manufacturing cost of three semi-manufactured products (T=1,CODP=1)

	Formula used: $((Q_{i1w}^S T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_m$		
Semi-manufactured product	1	2	3
$Q_{i1w}^S$	19	0	20
$I_{i1w}^{Us}$	11	0	11
$B_{i1w}^{Us}$	4	0	4
Manufacturing method 1	$y_1 r_w ((19*2+10)*10/1)U_{11}$	0	$y_1 r_w ((20*3+6)*10/1)U_{11}$
Manufacturing method 2	$y_1 r_w ((19*3+9)*12/1)U_{12}$	0	$y_1 r_w ((20*3+7)*12/1)U_{12}$
$\max(I_{twi}^{SU} C_{iw}^{Inv}, B_{twi}^{SU} C_{iw}^B)$	$\max(11*C_{iw}^{Inv}, 4*C_{iw}^B) r_w$	0	$\max(11*C_{iw}^{Inv}, 4*C_{iw}^B) r_w$
$\min(I_{twi}^{Ls} C_{iw}^{Inv}, B_{twi}^{Ls} C_{iw}^B)$	0	0	0
Total cost	$y_1 r_w (480U_{11} + 792U_{12}) + \max(11*C_{iw}^{Inv}, 4*C_{iw}^B) r_w$	0	$y_1 r_w (660U_{11} + 804U_{12}) + \max(11*C_{iw}^{Inv}, 4*C_{iw}^B) r_w$

**Table 41.** Manufacturing cost of three semi-manufactured products (T=2,CODP=1)

	Formula used: $((Q_{i2w}^S T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_m$		
Semi-manufactured product	1	2	3
$Q_{i2w}^S$	20	0	18
$I_{i2w}^{Us}$	18	0	18
$B_{i2w}^{Us}$	11	0	10
Manufacturing method 1	$y_1 r_1 ((20*2+10)*10/1)U_{11}$	0	$y_1 r_3 ((18*3+6)*10/1)U_{11}$
Manufacturing method 2	$y_1 r_1 ((20*3+9)*12/1)U_{12}$	0	$y_1 r_3 ((18*3+7)*12/1)U_{12}$
$\max(I_{twi}^{SU} C_{iw}^{Inv}, B_{twi}^{SU} C_{iw}^B)$	$\max(18*C_{iw}^{Inv}, 11*C_{iw}^B) r_w$	0	$\max(18*C_{iw}^{Inv}, 10*C_{iw}^B) r_3$
$\min(I_{twi}^{Ls} C_{iw}^{Inv}, B_{twi}^{Ls} C_{iw}^B)$	0	0	0
Total cost	$y_1 r_1 (500U_{11} + 828U_{12}) r_w + \max(18*C_{iw}^{Inv}, 11*C_{iw}^B) r_1$		$y_1 r_3 (540U_{11} + 732U_{12}) + \max(18*C_{iw}^{Inv}, 10*C_{iw}^B) r_3$

In continuous, cost of operations 2 and 3 are computed for each product selected and CODP1. Table 42 represents the cost of operation 2 for products selected with CODP1 for periods 1 and 2.

**Table 42.** Cost of operation 2 for products selected for two periods with CODP1

Time		1		2	
Product	$z_p$	$Q_{tp}^{Pr}$	$Q_{tp}^{Pr} (T_{po}^{op2} + T_{po}^{set2}) z_p C_o^{Op}$	$Q_{tp}^{Pr}$	$Q_{tp}^{Pr} (T_{po}^{op2} + T_{po}^{set2}) z_p C_o^{Op}$
1	1	5	$5^* (2+2) z_1 C_2^{Op}$	6	$6^* (2+2) z_1 C_2^{Op}$
2	1	6	$6^* (2+2) z_2 C_2^{Op}$	6	$6^* (2+2) z_2 C_2^{Op}$
3	1	4	$4^* (3+2) z_3 C_2^{Op}$	4	$4^* (3+2) z_3 C_2^{Op}$
4	1	4	$4^* (3+2)^* z_4 C_2^{Op}$	4	$4^* (3+2)^* z_4 C_2^{Op}$
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	1	4	$4^* (2+2) z_{13} C_2^{Op}$	4	$4^* (2+2) z_{13} C_2^{Op}$
14	1	4	$4^* (2+2) z_{14} C_2^{Op}$	4	$4^* (2+2) z_{14} C_2^{Op}$
15	1	5	$5^* (3+2) z_{15} C_2^{Op}$	6	$6^* (3+2) z_{15} C_2^{Op}$
16	1	7	$7^* (3+2) z_{16} C_2^{Op}$	4	$4^* (3+2) z_{16} C_2^{Op}$
17	0	0	0	0	0
18	0	0	0	0	0
$\sum_{p=1} Q_{tp}^{Pr} z_p \sum_{O \in (S_i^{Pr} \cap S^{*max})} (T_{po}^{op2} + T_{po}^{set2}) C_o^{Op}$		$C_2^{Op} (20 z_1 + 24 z_2 + 20 z_3 + 20 z_4 + 16 z_{13} + 16 z_{14} + 25 z_{15} + 35 z_{16})$		$C_2^{Op} (24 z_1 + 24 z_2 + 20 z_3 + 20 z_4 + 16 z_{13} + 16 z_{14} + 30 z_{15} + 20 z_{16})$	

Operation 3 is assumed to be performed by suppliers. Since operation 3 is last operation in our example performed on products after CODP2, so, cost of this operation is same for each two CODPs. Table 43 shows cost of operation 3 for products selected in each period and CODP.

**Table 43.** Purchasing cost of operation 3 for products selected for CODP1 and CODP2

Time		1		2	
Product	$z_p$	$Q_{tp}^{Pr}$	$Q_{tp}^{Pr} r_{pj}^{c2} X_s C_{js}^{sup} z_p$	$Q_{tp}^{Pr}$	$Q_{tp}^{Pr} r_{pj}^{c2} X_s C_{js}^{sup} z_p$
1	1	5	$5^* z_1 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$	6	$6^* z_1 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$
2	1	6	$6^* z_2 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$	6	$6^* z_2 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$
3	1	4	$4^* z_3 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$	4	$4^* z_3 (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$
4	1	4	$4^* z_4 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$	4	$4^* z_4 (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	1	4	$4^* z_{13} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$	4	$4^* z_{13} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$

14	1	4	$4 * z_{14} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$	4	$4 * z_{14} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$
15	1	5	$5 * z_{15} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$	6	$6 * z_{15} (X_1 C_{11}^{sup} + X_2 C_{12}^{sup})$
16	1	7	$7 * z_{16} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$	4	$4 * z_{16} (X_1 C_{21}^{sup} + X_2 C_{22}^{sup})$
17	0	0	0	0	0
18	0	0	0	0	0
$\sum_{p=1} z_p \sum_j \sum_s Q_{tp}^{Pr} r_{pj}^{c2} X_s C_{js}^{sup}$			$X_1((5z_1 + 4z_3 + 4z_{13} + 5z_{15})C_{11}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 7z_{16})C_{21}^{sup}) + X_2((5z_1 + 4z_3 + 4z_{13} + 5z_{15})C_{12}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 7z_{16})C_{22}^{sup})$	$X_1((6z_1 + 4z_3 + 4z_{13} + 6z_{15})C_{11}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 4z_{16})C_{21}^{sup}) + X_2((6z_1 + 4z_3 + 4z_{13} + 6z_{15})C_{12}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 4z_{16})C_{22}^{sup})$	

Next tables calculate cost of operations for CODP2. According the position CODP2 in the Figure 2, nine potential semi-manufactured products can be produced with considering feature/components selected. Operations 1 and 2 are performed on only 4 semi-manufactured products. Tables 44 and 45 show calculations related to manufacturing cost for 4 semi-manufactured products in operation 1 for periods 1 and 2 with CODP2.

**Table 44.** Manufacturing cost in operation 1(T=1,CODP=2)

Operation 1	CODP2			
	Formula used: $((Q_{tiw}^S T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_m$			
Semi-manufactured product	4	5	10	11
$Q_{tiw}^S$	11	8	8	12
$I_{tiw}^{Us}$	6	5	5	6
$B_{tiw}^{Us}$	2	2	2	2
Manufacturing method 1	$y_2 r_4 ((11 * 2 + 10) * 10 / 1) U_{11}$	$y_2 r_5 ((8 * 3 + 6) * 10 / 1) U_{11}$	$y_2 r_{10} ((8 * 2 + 10) * 10 / 1) U_{11}$	$y_2 r_{11} ((12 * 3 + 6) * 10 / 1) U_{11}$
Manufacturing method 2	$y_2 r_4 ((11 * 3 + 9) * 12 / 1) U_{12}$	$y_2 r_5 ((8 * 3 + 7) * 12 / 1) U_{12}$	$y_2 r_{10} ((8 * 3 + 9) * 12 / 1) U_{12}$	$y_2 r_{11} ((12 * 3 + 7) * 12 / 1) U_{12}$
max $(I_{twi}^{SU} C_{iw}^{Inv}, B_{twi}^{SU} C_{iw}^B)$	$\max(6 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_4$	$\max(5 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_5$	$\max(5 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_{10}$	$\max(6 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_{11}$
min $(I_{twi}^{LS} C_{iw}^{Inv}, B_{twi}^{LS} C_{iw}^B)$	0	0	0	0
Total cost	$y_2(320U_{11} + 504U_{12})r_4$ + $\max(6 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_4$	$y_2(300U_{11} + 372U_{12})r_5$ + $\max(5 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_5$	$y_2(260U_{11} + 396U_{12})r_{10}$ + $\max(5 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_{10}$	$y_2(420U_{11} + 516U_{12})r_{11}$ + $\max(6 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_{11}$

**Table 45.** Manufacturing cost in operation 1(T=2,CODP=2)

Operation 1	CODP2			
	Formula used: $((Q_{tiw}^S T_{wom}^{man1} + T_{wom}^{mset1}) C_{om}^{man} / def_m) U_m$			
Semi-manufactured product	4	5	10	11
$Q_{tiw}^S$	12	8	8	10



$I_{i1w}^{Us}$	9	9	8	10
$B_{i1w}^{Us}$	7	3	5	5
Manufacturing method 1	$y_2 r_4 ((12*2+10)*10/1)U_{11}$	$y_2 r_5 ((8*3+6)*10/1)U_{11}$	$y_2 r_{10} ((8*2+10)*10/1)U_{11}$	$y_2 r_{11} ((10*3+6)*10/1)U_{11}$
Manufacturing method 2	$y_2 r_4 ((12*3+9)*12/1)U_{12}$	$y_2 r_5 ((8*3+7)*12/1)U_{12}$	$y_2 r_{10} ((8*3+9)*12/1)U_{12}$	$y_2 r_{11} ((10*3+7)*12/1)U_{12}$
max ( $I_{i1w}^{SU} C_{i1w}^{Inv}, B_{i1w}^{SU} C_{i1w}^B$ )	$\max(9*C_{i1w}^{Inv}, 7*C_{i1w}^B)r_4$	$\max(9*C_{i1w}^{Inv}, 3*C_{i1w}^B)r_5$	$\max(8*C_{i1w}^{Inv}, 5*C_{i1w}^B)r_{10}$	$\max(10*C_{i1w}^{Inv}, 5*C_{i1w}^B)r_{11}$
min ( $I_{i1w}^{LS} C_{i1w}^{Inv}, B_{i1w}^{LS} C_{i1w}^B$ )	0	0	0	0
Total cost	$y_2(340U_{11} + 540U_{12})r_4$ + $\max(9*C_{i1w}^{Inv}, 7*C_{i1w}^B)r_4$	$y_2(300U_{11} + 372U_{12})r_5$ + $\max(9*C_{i1w}^{Inv}, 3*C_{i1w}^B)r_5$	$y_2(260U_{11} + 396U_{12})r_{10}$ + $\max(8*C_{i1w}^{Inv}, 5*C_{i1w}^B)r_{10}$	$y_2(360U_{11} + 444U_{12})r_{11}$ + $\max(10*C_{i1w}^{Inv}, 5*C_{i1w}^B)r_{11}$

Table 46 identifies cost of operation 2 for semi-manufactured products selected for two periods with CODP2.

**Table 46.** Cost of operation 2 for semi-manufactured products for two periods with CODP2

Time		1		2	
Product	$r_w$	$Q_{i1w}^S$	$(Q_{i1w}^S T_{wo}^{op1} + T_{wo}^{set1})C_o^{Op} r_w$	$Q_{i1w}^S$	$(Q_{i1w}^S T_{wo}^{op1} + T_{wo}^{set1})C_o^{Op} r_w$
4	1	11	$(11*2+6) C_2^{Op} r_4$	12	$(12*2+6) C_2^{Op} r_4$
5	1	8	$(8*2+6) C_2^{Op} r_5$	8	$(8*2+6) C_2^{Op} r_5$
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	1	8	$(8*1+3) C_2^{Op} r_{10}$	8	$(8*1+3) C_2^{Op} r_{10}$
11	1	12	$(12*1+3) C_2^{Op} r_{11}$	10	$(10*1+3) C_2^{Op} r_{11}$
12	0	0	0	0	0
$\sum_{\substack{O \in \\ (S_i^{set} \cap S^{a-man})}}$			$C_2^{Op} (28r_4 + 22r_5 + 11r_{10} + 15r_{11})$		$C_2^{Op} (30r_4 + 22r_5 + 11r_{10} + 13r_{11})$

Cost of operation 3 for CODP2 was performed before in Table 43.

Table 47 identifies income for products selected for period 1 and 2.

**Table 47.** Income for two periods

Time		1		2	
Product	$z_p$	${}^2Q_{ip}^{Pr}$	Income = $pr_p Q_{ip}^{Pr} z_p$	${}^2Q_{ip}^{Pr}$	Income
1	1	5	$5 z_1 pr_1$	6	$6 z_1 pr_1$
2	1	6	$6 z_2 pr_2$	6	$6 z_2 pr_2$
3	1	4	$4 z_3 pr_3$	4	$4 z_3 pr_3$
4	1	4	$4 z_4 pr_4$	4	$4 z_4 pr_4$
5	0	0	0	0	0
6	0	0	0	0	0

7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	1	4	$4 z_{13} pr_{13}$	4	$4 z_{13} pr_{13}$
14	1	4	$4 z_{14} pr_{14}$	4	$4 z_{14} pr_{14}$
15	1	5	$5 z_{15} pr_{15}$	6	$6 z_{15} pr_{15}$
16	1	7	$7 z_{16} pr_{16}$	4	$4 z_{16} pr_{16}$
17	0	0	0	0	0
18	0	0	0	0	0
$Income_t = \sum_{p=1} pr_p Q_{ip}^{Pr} z_p$			$5 z_1 pr_1 + 6 z_2 pr_2 + 4 z_3 pr_3 + 4 z_4 pr_4 + 4 z_{13} pr_{13} + 4 z_{14} pr_{14} + 5 z_{15} pr_{15} + 7 z_{16} pr_{16}$	$6 z_1 pr_1 + 6 z_2 pr_2 + 4 z_3 pr_3 + 4 z_4 pr_4 + 4 z_{13} pr_{13} + 4 z_{14} pr_{14} + 6 z_{15} pr_{15} + 4 z_{16} pr_{16}$	

Table 48 shows income and total cost for our example.

**Table 48.** Total cost

CODP	Time	Income	Total cost
1	1	$5 z_1 pr_1 + 6 z_2 pr_2 + 4 z_3 pr_3 + 4 z_4 pr_4 + 4 z_{13} pr_{13} + 4 z_{14} pr_{14} + 5 z_{15} pr_{15} + 7 z_{16} pr_{16}$	$y_1 r_w (480U_{11} + 792U_{12}) + \max(11 * C_{iw}^{Inv}, 4 * C_{iw}^B) r_w + y_1 r_w (660U_{11} + 804U_{12}) + \max(11 * C_{iw}^{Inv}, 4 * C_{iw}^B) r_w + C_2^{Op} (20 z_1 + 24 z_2 + 20 z_3 + 20 z_4 + 16 z_{13} + 16 z_{14} + 25 z_{15} + 35 z_{16}) + X_1 ((5z_1 + 4z_3 + 4z_{13} + 5z_{15}) C_{11}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 7z_{16}) C_{21}^{sup}) + X_2 ((5z_1 + 4z_3 + 4z_{13} + 5z_{15}) C_{12}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 7z_{16}) C_{22}^{sup})$
	2	$6 z_1 pr_1 + 6 z_2 pr_2 + 4 z_3 pr_3 + 4 z_4 pr_4 + 4 z_{13} pr_{13} + 4 z_{14} pr_{14} + 6 z_{15} pr_{15} + 4 z_{16} pr_{16}$	$y_1 r_w (500U_{11} + 828U_{12}) + \max(18 * C_{iw}^{Inv}, 11 * C_{iw}^B) r_w + y_1 r_w (540U_{11} + 732U_{12}) + \max(18 * C_{iw}^{Inv}, 10 * C_{iw}^B) r_w + C_2^{Op} (24 z_1 + 24 z_2 + 20 z_3 + 20 z_4 + 16 z_{13} + 16 z_{14} + 30 z_{15} + 20 z_{16}) + X_1 ((6z_1 + 4z_3 + 4z_{13} + 6z_{15}) C_{11}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 4z_{16}) C_{21}^{sup}) + X_2 ((6z_1 + 4z_3 + 4z_{13} + 6z_{15}) C_{12}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 4z_{16}) C_{22}^{sup})$
Total		$11 z_1 pr_1 + 12 z_2 pr_2 + 8 z_3 pr_3 + 8 z_4 pr_4 + 8 z_{13} pr_{13} + 8 z_{14} pr_{14} + 11 z_{15} pr_{15} + 11 z_{16} pr_{16}$	$y_1 r_w (2180U_{11} + 3156U_{12}) + \max(11 * C_{iw}^{Inv}, 4 * C_{iw}^B) r_w + \max(11 * C_{iw}^{Inv}, 4 * C_{iw}^B) r_w + \max(18 * C_{iw}^{Inv}, 11 * C_{iw}^B) r_w + \max(18 * C_{iw}^{Inv}, 10 * C_{iw}^B) r_w + C_2^{Op} (88 z_1 + 96 z_2 + 64 z_3 + 64 z_4 + 32 z_{13} + 32 z_{14} + 44 z_{15} + 44 z_{16}) + X_1 ((11z_1 + 8z_3 + 8z_{13} + 10z_{15}) C_{11}^{sup} + (12z_2 + 8z_4 + 8z_{14} + 11z_{16}) C_{21}^{sup}) + X_2 ((11z_1 + 8z_3 + 8z_{13} + 11z_{15}) C_{12}^{sup} + (12z_2 + 8z_4 + 8z_{14} + 11z_{16}) C_{22}^{sup})$
2	1	$5 z_1 pr_1 + 6 z_2 pr_2 + 4 z_3 pr_3 + 4 z_4 pr_4 + 4 z_{13} pr_{13} + 4 z_{14} pr_{14} + 5 z_{15} pr_{15} + 7 z_{16} pr_{16}$	$y_2 r_w (320U_{11} + 504U_{12}) + \max(6 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_w + y_2 r_w (300U_{11} + 372U_{12}) + \max(5 * C_{iw}^{Inv}, 2 * C_{iw}^B) r_w + y_2 r_w (260U_{11} + 396U_{12}) + \max(8 * C_{iw}^{Inv}, 5 * C_{iw}^B) r_w + y_2 r_w (360U_{11} + 444U_{12}) + \max(10 * C_{iw}^{Inv}, 5 * C_{iw}^B) r_w + C_2^{Op} (28 r_4 + 22 r_5 + 11 r_{10} + 15 r_{11}) + X_1 ((5z_1 + 4z_3 + 4z_{13} + 5z_{15}) C_{11}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 7z_{16}) C_{21}^{sup}) + X_2 ((5z_1 + 4z_3 + 4z_{13} + 5z_{15}) C_{12}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 7z_{16}) C_{22}^{sup})$

	2	$6z_1 pr_1 + 6z_2 pr_2 + 4z_3 pr_3 + 4z_4 pr_4 + 4z_{13} pr_{13} + 4z_{14} pr_{14} + 4z_{15} pr_{15} + 4z_{16} pr_{16}$	$y_2(340U_{11} + 540U_{12})r_w + \max(9*C_{iw}^{Inv}, 7*C_{iw}^B)r_w + y_2(300U_{11} + 372U_{12})r_w + \max(9*C_{iw}^{Inv}, 3*C_{iw}^B)r_w + y_2(260U_{11} + 396U_{12})r_w + \max(8*C_{iw}^{Inv}, 5*C_{iw}^B)r_w + y_2(360U_{11} + 444U_{12})r_w + \max(10*C_{iw}^{Inv}, 5*C_{iw}^B)r_w + C_2^{Op}(30r_4 + 22r_5 + 11r_{10} + 13r_{11}) + X_1((6z_1 + 4z_3 + 4z_{13} + 6z_{15})C_{11}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 4z_{16})C_{21}^{sup}) + X_2((6z_1 + 4z_3 + 4z_{13} + 6z_{15})C_{12}^{sup} + (6z_2 + 4z_4 + 4z_{14} + 4z_{16})C_{22}^{sup})$
Total		$11z_1 pr_1 + 12z_2 pr_2 + 8z_3 pr_3 + 8z_4 pr_4 + 8z_{13} pr_{13} + 8z_{14} pr_{14} + 11z_{15} pr_{15} + 11z_{16} pr_{16}$	$y_2(2500U_{11} + 3468U_{12})r_w + \max(9*C_{iw}^{Inv}, 7*C_{iw}^B)r_w + \max(9*C_{iw}^{Inv}, 3*C_{iw}^B)r_w + \max(8*C_{iw}^{Inv}, 5*C_{iw}^B)r_w + \max(10*C_{iw}^{Inv}, 5*C_{iw}^B)r_w + \max(6*C_{iw}^{Inv}, 2*C_{iw}^B)r_w + \max(5*C_{iw}^{Inv}, 2*C_{iw}^B)r_w + \max(8*C_{iw}^{Inv}, 5*C_{iw}^B)r_w + \max(10*C_{iw}^{Inv}, 5*C_{iw}^B)r_w + C_2^{Op}(58r_4 + 44r_5 + 22r_{10} + 38r_{11}) + X_1((11z_1 + 8z_3 + 8z_{13} + 10z_{15})C_{11}^{sup} + (12z_2 + 8z_4 + 8z_{14} + 11z_{16})C_{21}^{sup}) + X_2((11z_1 + 8z_3 + 8z_{13} + 11z_{15})C_{12}^{sup} + (12z_2 + 8z_4 + 8z_{14} + 11z_{16})C_{22}^{sup})$

By using equations 87 and 88, total benefit is obtained.

As expressed before, this example was constructed for one configuration of components/features shown in Table 13. Final result of PI benefit (Income and cost) is obtained based on other decision variables such as selection of CODP position ( $y_i$ ), manufacturing method ( $U_{om}$ ) or supplier selection ( $X_s$ ).

### 3.2.8 The expected outcome of the models

The results provided by the Multi-objective non-linear programming for each two models give a set of Pareto solution which includes the proper CODP position, the alternatives selected for component/features, the suppliers selected for material and some components, the manufacturing method selected, production levels (for model II) and values of material needed in beginning of work.

Since some data (such as demand) are identified with interval number, so, the models estimate lower and upper bounds for the value of objectives and PIs. Knowing lower and upper limits of decisions, helps decision-makers to get better decisions. In addition, in Model II, lower and upper values of WIP inventory and back order for each time period are evaluated.

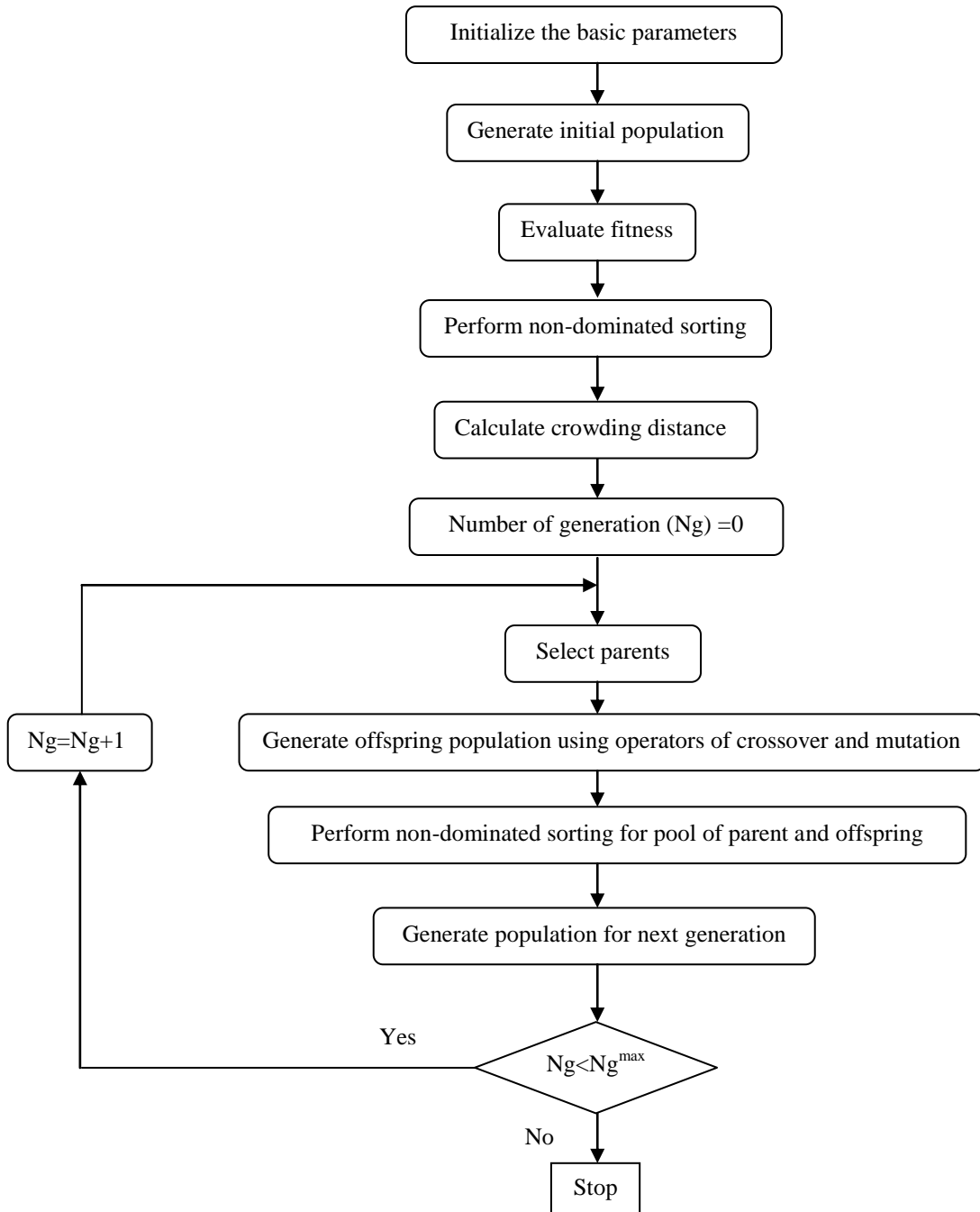
### 3.2.9 A solution procedure

Multi-objective optimization models are used to deal with many real-life problems. In the multi-objective model, concept of optimality is not same as single objective and optimizing a particular solution with respect to a single objective can result in unacceptable results with respect to the other objectives.

There are generally two approaches to solve multi-objective optimization problems. In the approach one, at first, the problem is converted to a single-objective optimization using one of multi-criteria decision making (MCDM) methods. Then, by using a single-objective evolutionary algorithm (SOEA) such as GA, simulated annealing (SA), particle swarm optimization and etc, the single-objective problem is solved.

In the second approach, the multi-objective problem is directly solved with one of multi-objective evolutionary algorithm (MOEA) such as non-dominated sorting genetic algorithm

(NSGA-II), multi-objective particle swarm optimization (MOPSO) and etc, to find a set of optimal solutions called Pareto optimal front (Al Jadaan, Rao, & Rajamani, 2006). MOEAs are usually applied to solve the complex multi-objective optimization problem to fast find Pareto fronts in a single run. Konak, Coit, & Smith (2006) reviewed the Multi-objective optimization models as well.

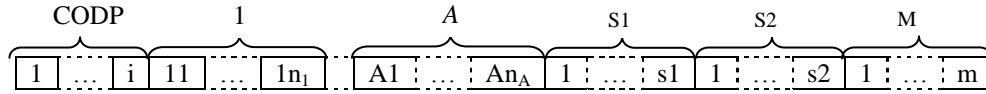


**Figure 9:** Flowchart of NSGA II

In our thesis, we apply a multi-objective genetic algorithm method based on the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) proposed by Deb et al. (2000) to obtain Pareto-optimal solutions. Required steps for implementation of NSGA II are shown in Figure 9.

Here, we explain the chromosomes proposed for two models, and cross over and mutation. The chromosomes are randomly generated to size of population to develop initial population.

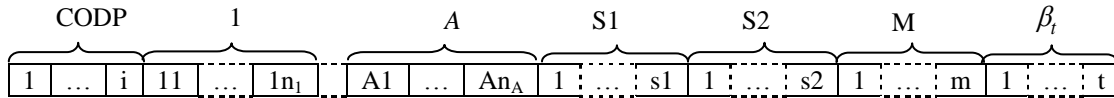
For evaluation of all product varieties, we propose two chromosomes for two models (Figures 10 and 11) that are consisted of several parts with following structure:



**Figure 10:** Representation of chromosome for model I

In chromosome of Model I (Figure 10), part CODP shows the CODP selected. Parts  $I, \dots, A$  show components/features that get binary or permutation coding (dependence to each case) to show alternatives in each components/features.

Parts S1, S2 and M are related to material suppliers, component suppliers and manufacturing method, respectively. Due to only one supplier (for material and component) and manufacturing method are selected in our problem, only one gene get value 1 that identify suppliers and type of manufacturing method (or technology) used in operations.



**Figure 11:** Representation of chromosome for model II

Chromosome II for model II is same as chromosome I with an additional part that shows production coefficient in time  $t$  ( $\beta_t$ ) which is randomly determined between 0 and 1.

New generations are produced by using crossover and mutation. Since the chromosome is consisted of several parts, we use crossover operations for each part to explore more solution space. For this purpose, we use several types of crossover operation such as single-point crossover and order crossover (OX1) (Davis, 1985; Picek & Golub, 2010). The mutation operator preserves diversification in the search in solution space. This operator is applied to each offspring in the population with a predetermined probability. For this purpose, we use random mutation and simple inversion mutation (SIM) (Grefenstette, 2013) in our models.

### 3.2.10 Non-dominated sorting genetic algorithm II with uncertainty

In most of multi-objective optimization problems existing in literature, parameters of the problem are fixed (precise). However, in the real world, in most of the cases, the parameters of the problems have imprecise nature. Different approaches have been used to confront uncertainty and impreciseness of parameters, such as stochastic, fuzzy and fuzzy–stochastic approaches. In these approaches, problems are converted into deterministic problems. In stochastic approach, the parameters are considered to be random variables with known probability distribution. In fuzzy approach, constraints and goals are assumed as fuzzy sets with known membership functions. In

fuzzy–stochastic approach, some parameters are considered as random variables and others as fuzzy numbers (A. K. Bhunia & Samanta, 2014). However, the main challenge of these approaches is how to select the appropriate membership function or type of fuzzy numbers or probability distribution.

Interval number can be used to represent the imprecise number for overcoming challenges existing in these approaches as the most significant representation among others (A. K. Bhunia & Samanta, 2014).

In the next sections, we, at first, express some rules and definitions for interval numbers and then describe the NSGAI modified with interval data.

### 3.2.10.1 Finite interval mathematics

An interval number  $X$  is a closed connected subset of  $R$  denoted by  $X = [a_L, a_U]$  and defined as follows:

$$A = [a_L, a_U] = \{p : a_L \leq p \leq a_U, p \in R\} \quad (82)$$

where,  $a_L$  and  $a_U$  are the left and right limits, respectively. An interval number can also be stated in terms of its centre and radius  $A = [a_L, a_U]$ :

$$a_c = \frac{a_L + a_U}{2} \quad (83)$$

$$a_w = \frac{a_U - a_L}{2} \quad (84)$$

Where,  $a_c$  and  $a_w$  are the centre and the radius of the interval  $A$  respectively.

Actually, every real number  $p \in R$  can be expressed as an interval number  $[p, p]$  with centre  $p$  and radius zero.

### 3.2.10.2 Interval Arithmetic

According to Moore (2009), the definitions of addition, subtraction, multiplication, and division of interval numbers are as follows:

If  $A = [a_L, a_U]$  and  $B = [b_L, b_U]$

$$A + B = [a_L, a_U] + [b_L, b_U] = [a_L + b_L, a_U + b_U] \quad (85)$$

$$A - B = [a_L, a_U] - [b_L, b_U] = [a_L - b_U, a_U - b_L] \quad (86)$$

$$\lambda A = \lambda [a_L, a_U] = \begin{cases} [\lambda a_L, \lambda a_U] & \text{if } \lambda \geq 0 \\ [\lambda a_U, \lambda a_L] & \text{if } \lambda < 0 \end{cases} \quad (87)$$

$$A \times B = [\min\{a_L b_L, a_L b_U, a_U b_L, a_U b_U\}, \max\{a_L b_L, a_L b_U, a_U b_L, a_U b_U\}] \quad (88)$$

$$\frac{A}{B} = A \times \frac{1}{B} = [a_L, a_U] \times \left[ \frac{1}{b_U}, \frac{1}{b_L} \right], 0 \notin [b_L, b_U] \quad (89)$$

**Definition 3.1.** Let  $X$  be any non empty set. A function  $d: X \times X \rightarrow R$  is said to be a metric on  $X$  if it satisfies the following properties:

$$d(x, y) \geq 0 \text{ for all } \quad (\text{non-negative})$$

**Definition 3.2:** Let  $IR$  be the set of all real intervals. Moore (1979) defined a distance, DM:  $R^2 \rightarrow R$  between  $x = [x_L, x_U]$  and  $y = [y_L, y_U] \in R$  is given by:

$$d_m(X, Y) = \max\{|x_L - y_L|, |x_U - y_U|\} \quad (90)$$

**Definition 3.3**(R E Moore, 1979):. Let  $X \in R$  be an interval. The norm of the interval  $X$  is defined as the non-negative real number,  $|X|_M = D_M(X, 0)$  which shows the distance from  $X$  to zero. In other words:  $|X|_M = D_M(X, 0) = \max\{|X_L|, |X_U|\}$

Since, Moore Distance is a real metric space, Bhunia & Samanta (2014) redefined an interval metric proposed by (Trindade, Bedregal, Neto, & Acioly, 2010) to overcome the drawbacks arisen as follows:

**Definition 3.4**(A. K. Bhunia & Samanta, 2014): Let  $X = \langle x_c, x_w \rangle$  and  $Y = \langle y_c, y_w \rangle \in R$ . An interval distance between  $X$  and  $Y$ , denoted by  $D_I(X, Y)$  is defined by:

$$d_I(X, Y) = \tilde{|X - Y|} = \tilde{|\langle x_c, x_w \rangle - \langle y_c, y_w \rangle|} = \tilde{|\langle x_c - y_c, x_w + y_w \rangle|} \quad (91)$$

$$= \langle |x_c - y_c|, x_w + y_w \rangle.$$

**Definition 3.5** (A. K. Bhunia & Samanta, 2014): Let  $X = (X_1, X_2, \dots, X_K)$  and  $Y = (Y_1, Y_2, \dots, Y_K) \in R^k$ . An interval distance between  $X$  and  $Y$  is defined:

$$d_I(X, Y) = \sum_{i=1}^k \tilde{|X_i - Y_i|} \quad (92)$$

Order relation between interval numbers has important role in solving the decision making problems with interval objectives. Sahoo et al. (2012) proposed an order relation for different types of intervals and by considering different conditions. Bhunia & Samanta (2014) suggested a simpler way to represent order relations  $\geq^{\max}$  and  $\leq^{\min}$  for maximization and minimization problems, respectively as follows:

**Definition 3.6:** The order relation  $\geq^{\max}$  between two intervals  $A = [a_L, a_U] = \langle a_c, a_w \rangle$  and  $B = [b_L, b_U] = \langle b_c, b_w \rangle$  for maximization problems is:

$$A \geq^{\max} B \begin{cases} a_c > b_c & \text{if } a_c \neq b_c \\ a_w \leq b_w & \text{if } a_c = b_c \end{cases} \quad (93)$$

and  $A >^{\max} B \Leftrightarrow A \geq^{\max} B$  and  $A \neq B$ .

**Definition 3.7:** The order relation  $\leq^{\min}$  between two intervals  $A = [a_L, a_U] = \langle a_c, a_w \rangle$  and  $B = [b_L, b_U] = \langle b_c, b_w \rangle$  for maximization problems is:

$$A \leq^{\min} B \begin{cases} a_c < b_c & \text{if } a_c \neq b_c \\ a_w \leq b_w & \text{if } a_c = b_c \end{cases} \quad (94)$$

and  $A <^{\min} B \Leftrightarrow A \leq^{\min} B$  and  $A \neq B$ .

### 3.2.11 Non-dominated sorting genetic algorithm with interval data

The steps of NSGA II for interval objectives is same general NSGA II except in steps related to non-dominated sorting and calculation of crowding distance that are redefined for the interval values.

Ranking of solutions in population are done based on number of being dominated by other solutions. Since objectives are based interval values, so we have to use interval order relation to rank solution.

Domination concept for interval multi-objective is mathematically represented. If A and B be two solutions, then for max problem:

$$A \geq B (A \text{ dom } B) \Leftrightarrow \forall i : f_i(A) \geq^{\max} f_i(B) \wedge \exists j : f_j(A) >^{\max} f_j(B) \quad i, j = 1, \dots, n \quad (95)$$

And for min problem:

$$A \leq B (A \text{ dom } B) \Leftrightarrow \forall i : f_i(A) \leq^{\min} f_i(B) \wedge \exists j : f_j(A) <^{\min} f_j(B) \quad i, j = 1, \dots, n \quad (96)$$

Where,  $f_i(A)$  and  $f_i(B)$  are interval objective  $i$  for solutions A and B, respectively. Definitions 3.6 and 3.7 (the order relation  $\geq^{\max}$  and  $\leq^{\min}$ ) are applied for domination concept for interval data. A smaller rank is assigned to a better non-dominated front.

The crowding distance for each solution for interval multi-objective problem is calculated as follows:

$$d_j = \sum_{i=1}^n \frac{d(f_i^{j+1}, f_i^{j-1})}{d(f_i^{\max}, f_i^{\min})} \quad (97)$$

Where,  $d_j$  is crowding distance of  $j$  th solution;  $n$  is number of objectives;  $d(f_i^{j+1}, f_i^{j-1})$  is distance of interval objective  $i$  for  $(j+1)$  and  $(j-1)$ th solutions after sorting the population



according to interval values of  $i^{\text{th}}$  objective;  $d(f_i^{\max}, f_i^{\min})$  is distance of maximum and minimum interval value of  $i^{\text{th}}$  objective among solutions of the current population. We use Moore distance (definition 3.2) to calculate crowding distance.

### 3.2.12 Developing a computer program

For doing NSGA II for these two models, we develop a computer program based on Visual Studio 2008. We develop two user interfaces (for our two models) which get variable data related to some parameters from user in each run and display the results (Figure 12). Main part of input data transfer from a data base developed based on Microsoft Office's Access 2007 to the main program. After running the program, the results are displayed on user interface and also printed automatically in Microsoft Office's Excel 2007 in order to help for comparison of different solutions (Figure 12). The results include the values of objectives and PIs, the options selected to offer customers, the selected suppliers, manufacturing method and CODP position and amounts of inventory, backorder and production levels for model II.

After extracting the components/features which can be offered to customers, for demonstration of applicability of this method, we develop a user interface based on the options selected to help customers to customize products. We show these two interfaces in the next chapter based on our case.

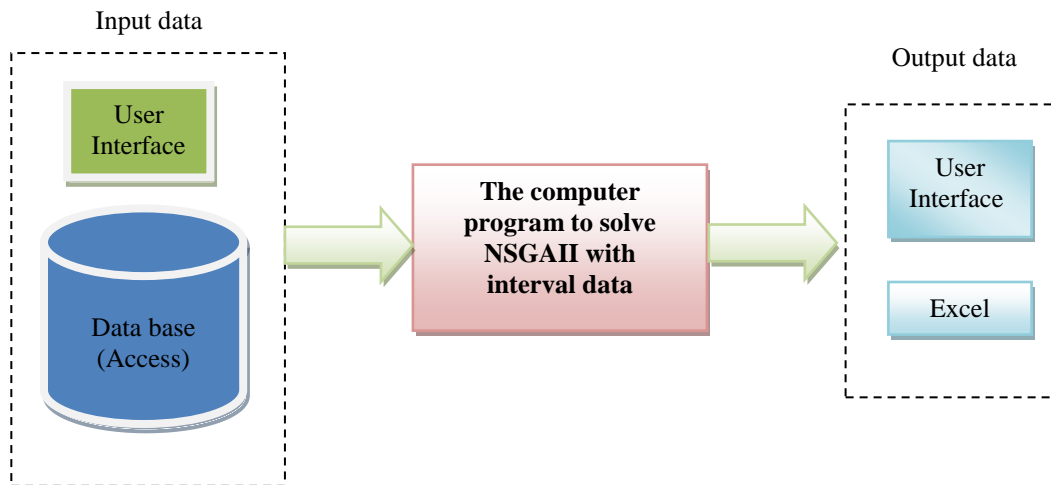


Figure 12: Framework of the computer program developed

### 3.2.13 Developing a new method for ranking of interval data

We, here, propose a new method to rank interval-valued alternatives.

Some papers consider quantitative and qualitative performance measures to deal with ranking of alternatives in different problems (Tseng, 1998; Ulutas et al., 2012; Shidpour et al., 2013). In these papers, usually qualitative PIs are expressed with fuzzy logic and quantitative PIs are identified with crisp numbers. Two approaches usually exist to deal with concurrent evaluation of quantitative and qualitative PIs. In the first approach, such as paper Shidpour et al. (2013), all

values of qualitative PIs are converted to crisp numbers with using some methods and then the alternatives are ranked. Converting fuzzy numbers to crisp numbers destroys some information about qualitative PIs. In another approach, such as paper Tseng (1998), all values of quantitative PIs are converted to fuzzy numbers with using some methods and then the alternatives are ranked based on fuzzy number ranking. This approach has some difficulties such as finding a true member function to convert crisp to fuzzy numbers.

We propose a method based on interval-valued distance between vectors of alternatives and interval-valued reference vector. In this method, each two types of PIs (quantitative and qualitative) are used to evaluate alternatives and fuzzy numbers applied to evaluate qualitative PIs, are converted to interval values.

The following steps are proposed to evaluate the alternatives:

- 1- Construct the decision matrix.

In this matrix, quantitative PIs are expressed as interval numbers with known upper and lower limits and qualitative PIs are evaluated with linguistic terms and fuzzy numbers shown in Table 49.

**Table 49.** Linguistic variables for evaluation qualitative PIs

Linguistic values	Triangular fuzzy numbers
Very Poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium Poor(MP)	(1,3,5)
Medium (M)	(3,5,7)
Medium Good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very Good (VG)	(9,10,11)

Qualitative PIs evaluated with linguistic terms cannot be applied directly in our method and should be converted to interval numbers. Therefore, they are converted to interval number with  $\alpha$  – cut method shown in formula (5).

The interval values of PIs construct the decision matrix R.

$$R = \begin{array}{c} \begin{array}{|c|c|c|c|c|} \hline \text{Solution} & \text{PI1} & \text{PI2} & \dots & \text{PI}_n \\ \hline 1 & [L_{11}, U_{11}] & [L_{12}, U_{12}] & \dots & [L_{1n}, U_{1n}] \\ \hline 2 & [L_{21}, U_{21}] & [L_{22}, U_{22}] & \dots & [L_{2n}, U_{2n}] \\ \hline \vdots & \vdots & \vdots & \vdots & \vdots \\ \hline m & [L_{m1}, U_{m1}] & [L_{m2}, U_{m2}] & \dots & [L_{mn}, U_{mn}] \\ \hline \end{array} \end{array}$$

Where  $[L_{mn}, U_{mn}]$  denotes the upper and lower limits of interval values for  $m^{\text{th}}$  solution and  $n^{\text{th}}$  PI.

- 2- Determine the interval-valued reference vector.

Accordingly, we, at first, calculate the mean and radius of interval values with formulas (83) and (84). Then, ideal reference vector is constructed by determining the ideal value for each PI with using formula (98)

$$R^* = \{R_1^*, R_2^*, \dots, R_j^*\} = \{(\max_i R_{ij} \mid j \in J_1), (\min_i R_{ij} \mid j \in J_2)\} \quad (98)$$

Where,  $R_j^* = [r_{ij}^-, r_{ij}^+]$  for  $j \in J_1$  is related to the PIs of “larger-the-better” and is identified based on formula in the definition (93). Also,  $R_j^* = [r_{ij}^-, r_{ij}^+]$  for  $j \in J_2$  is related to the PIs of “smaller-the-better” and is calculated by using formula in definition (94).

3- Compute the distance between elements of each solution vector with corresponding element of reference vector with formula (91) and construct the matrix distance:

$$D = \begin{bmatrix} [d_{11}^-, d_{11}^+] & \dots & [d_{1n}^-, d_{1n}^+] \\ \vdots & \vdots & \vdots \\ [d_{m1}^-, d_{m1}^+] & \dots & [d_{mn}^-, d_{mn}^+] \end{bmatrix}$$

4- Normalize the distance matrix as follows:

$$d_{ij}^{\prime-} = \frac{d_{ij}^-}{\max_{i=1}^n \{\max[|d_{ij}^-|, |d_{ij}^+|]\}} \quad (99)$$

$$d_{ij}^{\prime+} = \frac{d_{ij}^+}{\max_{i=1}^n \{\max[|d_{ij}^-|, |d_{ij}^+|]\}} \quad (100)$$

and construct the normalized distance matrix:

$$N = \begin{bmatrix} [d_{11}^{\prime-}, d_{11}^{\prime+}] & \dots & [d_{1n}^{\prime-}, d_{1n}^{\prime+}] \\ \vdots & \vdots & \vdots \\ [d_{m1}^{\prime-}, d_{m1}^{\prime+}] & \dots & [d_{mn}^{\prime-}, d_{mn}^{\prime+}] \end{bmatrix}$$

5- Calculate the weighted normalized decision matrix  $K (= [k_{ij}])$  obtained by multiplying the normalized decision matrix by its related weights. The weighted normalized value  $K_{ij}$  is calculated as:

$$k_{ij} = w_j \times d_{ij}^{\prime} \quad \forall i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n \quad (101)$$

where,  $w_j$  represents the weight of  $j^{\text{th}}$  PI and  $d_{ij}^{\prime} = [d_{ij}^{\prime-}, d_{ij}^{\prime+}]$ . Final weighted matrix is developed as follows:

$$D = \begin{bmatrix} [k_{11}^-, k_{11}^+] & \dots & [k_{1n}^-, k_{1n}^+] \\ \vdots & \vdots & \vdots \\ [k_{m1}^-, k_{m1}^+] & \dots & [k_{mn}^-, k_{mn}^+] \end{bmatrix}$$

6- Final evaluation of solutions is performed by using this formula:

$$E_i = \sum_{j=1}^n k_{ij} \quad \forall i \quad (102)$$

Since  $E_i$  shows interval distance of solution  $i$  with reference vector, so, whatever this value is lower, this solution is better. Finally, we have an interval value for each alternative that are ranked by using the formula proposed in definition 3.7.

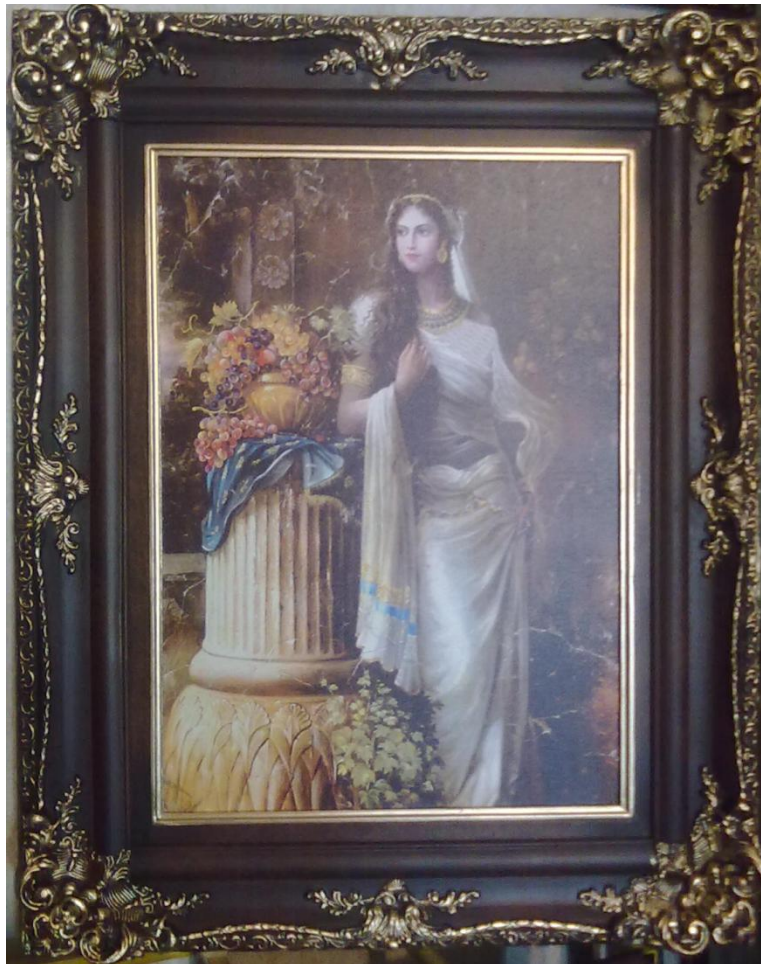
### 3.3 Conclusion

In this section, we proposed the models to achieve the aims of our problem. The problem is optimum determination of component/features with respect to different restrictions that exist in real situations. For this purpose, we proposed two mathematical models to evaluate customer and enterprise value perceived from different product variety by considering decision points of product, process and supply chain. These decision points include number of component/features selected for product domain, the position of CODP and selection of the production method for process domain and selection of suppliers for supply chain domain. Accordingly, we integrated problem of CODP position in determination of component/features and applied some PIs to evaluate customer and enterprise value.

Since, in the some cases in real situation, we encounter with uncertain data such as interval data, we used this type of data for some parameters and proposed a solution method based NSGA II for this type of data. Also, to help for decision makers to get the best decision, we proposed a new method to rank solutions with interval values.

Two proposed models are able to determine a set of pareto solution that concurrently give upper and lower values of PIs (for interval data), the component/features selected and thus product varieties which can offer, the CODP position selected, suppliers chosen for material and some component and the machine selected for production line. Also, in model II, production level and the maximum and minimum values of WIP inventory and back orders are determined.

## **4 Chapter 4: Implementation of the proposed models on case study: Carpet Tableau**



## 4.1 Overview of the Case Study

In this chapter we study a case of carpet tableau to analyze and validate the proposed models. To solve the models, we used the method NSGAI with considering uncertainty as interval values and developed a computer program with Visual Studio 2008. Data applied in our program collect as two ways: constant data that are collected from company and other sources and are stored in a developed data bank. Some of other data required enter with hand through an interface user. Also, output results are displayed both user interface and in Excel file. The following sections are represented in this chapter:

Section 2 introduces the case considered (carpet tableau) and describes shortly about history of carpet and carpet tableau. Also, a list of potentially customizable components and features in carpet tableau are represented in this section. In section 3, we implement our models and adopts with our case. According to the procedure proposed, we, step by step, describe the process of gathering information from the manufacturer for each variable. In section 4, the set of solutions for different states of some main parameters (such as budget value) are represented. Ranking method based on the method suggested in the previous chapter is presented in section 5. In the final section, we represent our finding from running the models.

## 4.2 Introduction of the case

We selected the carpet tableau as a case to test the models. Talking about carpet tableau without considering carpet is not possible because of the carpet tableau has been obtained from heart of industry of weaving carpets.

Although beginning of weaving carpet is not well understood yet and is also not clear that the weaving carpet was begun from which region, but, it is certain that the Iranians are among the first nations who started carpet weaving. Although historians estimate lifetime of weaving of carpet back to 2,500 years ago, but carpet tableau, in the present form, has not age more than 60 years.

Main product in most of companies in carpet-weaving industry is carpet. Today, by increasing demand for other products such as carpet tableau, progress in weaving technology and customizability of Carpet tableau, a new opportunity has been created in weaving industry.

Kashan Zarrin industrial group began with manufacturing and installing weaving machines, more than three decades ago. About 1996, this company decided to produce carpet. After near two decades, Kashan Zarrin industrial group is one of 5 top collections of Kashan (the city known with his carpets) and one of 10 top collections in Iran that produce different types of carpets and carpet tableaus.

### 4.2.1 Customizable components and features in carpet tableau

Different customizable components and features can be defined for carpet Tableau (Anayati Bidgoli, 2013) that is described as follows:

1. Material type: type of yarn used in carpet tableau affects on price as well as beauty of a carpet tableau (Anayati Bidgoli, 2013). For example, using heat set acrylic yarn makes different into acrylic or polyester or silk. In the thesis, we consider three types of yarn including acrylic, heat set acrylic and silk (Table 50).

2. Design (plan) model: One of the main factors when selection of carpet tableau is design or plan model. A good plan can cover possible disadvantages. In our thesis, we apply 100 popular design options used in carpet tableaux (Table 50).
3. Density: The carpets (or carpet tableaux) include two types of density; Course-wise (horizontal row) density and Wale-wise (length-wise) density. These two types of density show the number of roots (color nodes) in each meter of width and length of carpet, respectively. With increasing density, the carpet is more similar to handmade carpets.
4. Size: customers' needs include a wide extent of size of carpet tableaux.
5. Panel: type of panel applied in carpet tableau affects on the price as well as aesthetic.
6. Packing: packaging is one of the most important factors in the marketing of a product that affects on satisfaction of customers. With attention to daily intense competition in market, importance of packing for carpet tableau increases.
7. Delivery type: Type of delivery of customized products affect on customer satisfaction.

Table 50 shows these customizable components and features along with alternatives for each of them. Each product variety is obtained from mixing the alternatives in each customizable component and feature.

**Table 50.** Customizable components and features

No	Customizable components/features	Alternatives	Number
1	Material type	Acrylic, Heat set Acrylic; Silk	3
2	Design model	50 types including images from nature, art, history, portray and religious pictures	50
3	Density type (width, length)	(500,1200); (500,1500); (500,2550); (700,1200); (700,1500); (700,2550); (1000,2250); (1000,2550); (1000,2700); (1000,3000)	10
4	Size (Length*Width)cm	size $\leq$ 200	-
5	Panel type	Steel, PVC, Royal (Wooden)	3
6	Packing	Standard, Customize	2

### 4.3 Implementation of the models for case

In our thesis, we analyze our models with a case from carpet and carpet tableau industry. Main product of this company is carpet, but agrees the orders for carpet tableau.

The management of this company collaborated to provide information about the processes and products. In our model, we need to large amounts of data, but in reality, it is impossible getting all of data. So, we designed several questionnaires to get data for the model formulation. In continues, we perform the methodology for the case selected step by step.

#### 4.3.1 Selection of PIs for customer value and enterprise value

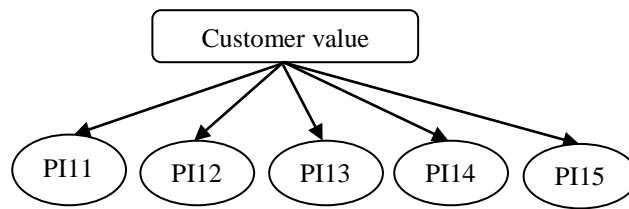
The proposed models are composed of two objectives called customer value and enterprise value which are evaluated by performance indicators determined in Table 8.

### 4.3.2 Determine relation between PIs and calculate relative importance of each PI

One of main works that has to perform when developing a mathematical model is to determine weight or importance of PIs making objectives. For this purpose, one should consider influences of PIs on each other. Here, we obtain weight of PIs of customer value with and without considering interdependency between them. Weight of PIs for objective of customer value without considering interdependency between PIs are obtained with fuzzy analytical hierarchy process (AHP) and with taking account interdependency between PIs are obtained with fuzzy analytical network process (ANP).

We calculate the weights of PIs for objective of customer value with fuzzy AHP and fuzzy ANP as follows:

Step 1: Assume that there is no dependence among the PIs of customer value (Figure 13) and determine the importance degrees with respect to control criterion (customer value) and construct Sub-Matrix  $W_1$ .



**Figure 13:** PIs of customer value without dependence

For this purpose, the following steps are performed:

1. Construct pairwise comparison matrix shown in Table 51 by using fuzzy numbers  $\tilde{1}$ ,  $\tilde{3}$ ,  $\tilde{5}$ ,  $\tilde{7}$  and  $\tilde{9}$  shown in Figure 53.

**Table 51.** Fuzzy pairwise comparison

Customer value	Average delivery time	Quality perceived/Price	Variety offered	Percent of demand satisfied	Control over the degree of functionality
Average delivery time	1	$\tilde{1}$	$\tilde{1}$	$\tilde{5}$	$\tilde{5}$
Quality perceived/Price	$\tilde{1}^{-1}$	1	$\tilde{3}$	$\tilde{5}$	$\tilde{5}$
Variety offered	$\tilde{1}^{-1}$	$\tilde{3}^{-1}$	1	$\tilde{3}$	$\tilde{3}$
Percent of demand satisfied	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	1	$\tilde{3}$
Control over the degree of functionality	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	1

2. Making  $\alpha$ -cut fuzzy comparison matrix. So, at first  $\alpha$ -cut fuzzy numbers are defined according to Eq. 1 as follows:

$$\begin{aligned} \tilde{1}_\alpha &= [1, 3 - 2\alpha], & \tilde{1}_\alpha^{-1} &= \left[ \frac{1}{3 - 2\alpha}, 1 \right] \\ \tilde{3}_\alpha &= [1 + 2\alpha, 5 - 2\alpha], & \tilde{3}_\alpha^{-1} &= \left[ \frac{1}{5 - 2\alpha}, \frac{1}{1 + 2\alpha} \right] \end{aligned} \quad (120)$$



$$\begin{aligned} \tilde{5}_\alpha &= [3+2\alpha, 7-2\alpha], & \tilde{5}_\alpha^{-1} &= \left[ \frac{1}{7-2\alpha}, \frac{1}{3+2\alpha} \right] \\ \tilde{7}_\alpha &= [5+2\alpha, 9-2\alpha], & \tilde{7}_\alpha^{-1} &= \left[ \frac{1}{9-2\alpha}, \frac{1}{5+2\alpha} \right] \\ \tilde{9}_\alpha &= [7+2\alpha, 11-2\alpha], & \tilde{9}_\alpha^{-1} &= \left[ \frac{1}{11-2\alpha}, \frac{1}{7+2\alpha} \right] \end{aligned}$$

Then, interval-valued comparison matrix is obtained by replacing  $\alpha = 0.5$   $\alpha$ -cut fuzzy numbers that is defined in the formulas (120) shown in Table 52.

**Table 52.** Interval-valued comparison matrix

Customer value	Average delivery time	Quality perceived/Price	Variety offered	Percent of demand satisfied	Control over the degree of functionality
Average delivery time	1	[1,2]	[1,2]	[4,6]	[4,6]
Quality perceived/Price	[1/2,1]	1	[2,4]	[4,6]	[4,6]
Variety offered	[1/2,1]	[1/4,1/2]	1	[2,4]	[2,4]
Percent of demand satisfied	[1/6,1/4]	[1/6,1/4]	[1/4,1/2]	1	[2,4]
Control over the degree of functionality	[1/6,1/4]	[1/6,1/4]	[1/4,1/2]	[1/4,1/2]	1

Interval values in the matrix are converted to crisp numbers by replacing  $\mu = 0.5$  in equation 2 that are displayed in Table 53.

- To compute eigenvector of  $\alpha$ -cut fuzzy comparison matrix. All Eigen-values ( $\lambda$ ) of  $\alpha$ -cut fuzzy comparison matrix are resulted from solving  $\det(F - \lambda I) = 0$ .

By finding the largest Eigen-value of comparison matrix F,  $\lambda_{\max}$ , weight vector ( $\bar{w}$ ) is calculated by using equation 4 shown in Table 53.

- To compute consistency ratio (CR) for each judgment matrix by applying equation 6 shown in Table 53.

**Table 53.** Crisp comparison matrix and weight of PIs

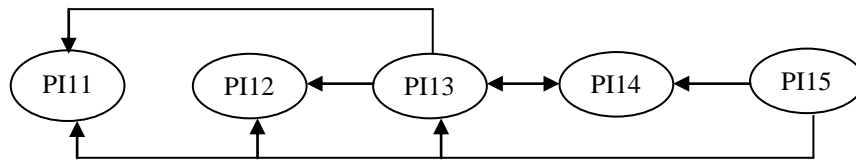
Customer value	Average delivery time	Quality perceived/Price	Variety offered	Percent of demand satisfied	Control over the degree of functionality	weight
Average delivery time	1	1.5	1.5	5	5	0.336
Quality perceived/Price	0.75	1	3	5	5	0.337
Variety offered	0.75	0.375	1	3	3	0.18
Percent of demand satisfied	0.208	0.208	0.375	1	3	0.09
Control over the degree of functionality	0.208	0.208	0.375	0.375	1	0.057
$\lambda_{\max}$				5.4		
RI				1.12		
CI				0.1		
CR				0.0893		

DMs' judgment is acceptable because of  $CR < RI_n$ . So,  $W_1$ , a matrix that represents the weights without dependency of the sub-factors, is obtained:

$$W_1 = \begin{bmatrix} 0.336 \\ 0.337 \\ 0.180 \\ 0.090 \\ 0.057 \end{bmatrix}$$

Step 2: Determine the inner dependence matrix of among PIs of the customer value with respect to control criterion and construct Sub-Matrix  $W_2$ .

Relation among PIs of the customer value is represented in Figure 14.



**Figure 14:** Interrelation among PIs of the customer value

With respect to the inner dependencies presented in Figure 14, the pairwise comparison matrices are constructed.

The solutions of question, “What is the relative importance of PI1, PI2 and PI4 when compared together on control factor PI3?” build fuzzy comparison matrix in Table 54.

With respect to Figure 14, steps of previous stage for pairwise comparison (steps 1 to 4) are repeated. With considering PI3 as control criterion, the interval-value and crisp pairwise matrices are constructed in Tables 55 and 56. The resulting eigenvectors are presented in the last column of Tables 56.

**Table 54.** Fuzzy pairwise comparison

Variety offered	Average delivery time	Quality perceived/Price	Percent of demand satisfied
Average delivery time	1	$\tilde{1}$	$\tilde{7}$
Quality perceived/Price	$\tilde{1}^{-1}$	1	$\tilde{7}$
Percent of demand satisfied	$\tilde{7}^{-1}$	$\tilde{7}^{-1}$	1

**Table 55.** Interval-valued comparison matrix

Variety offered	Average delivery time	Quality perceived/Price	Percent of demand satisfied
Average delivery time	1	[1,2]	[6,8]
Quality perceived/Price	[1/2,1]	1	[6,8]
Percent of demand satisfied	[1/8,1/6]	[6,8]	1

**Table 56.** Crisp comparison matrix and weight of PIs

Variety offered	Average delivery time	Quality perceived/Price	Percent of demand satisfied	weight
Average delivery time	1	1.5	7	0.520
Quality perceived/Price	0.75	1	7	0.413
Percent of demand satisfied	0.146	0.146	1	0.067
		$\lambda_{\max}$	3.069	
		RI	0.58	
		CI	0.0344	
		CR	0.059	

The solutions of question, “What is the relative importance of PI1, PI2, PI3 and PI4 when compared together on control factor PI5?” build fuzzy comparison matrix in Table 57.

With considering PI5 as control criterion, the interval-value and crisp pairwise matrices are constructed in Tables 58 and 59. The resulting eigenvectors are presented in the last column of Tables 59.

**Table 57.** Fuzzy pairwise comparison

Control over the degree of functionality	Average delivery time	Quality perceived/Price	Variety offered	Percent of demand satisfied
Average delivery time	1	$\tilde{1}$	$\tilde{1}$	$\tilde{7}$
Quality perceived/Price	$\tilde{1}^{-1}$	1	$\tilde{3}$	$\tilde{5}$
Variety offered	$\tilde{1}^{-1}$	$\tilde{3}^{-1}$	1	$\tilde{3}$
Percent of demand satisfied	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	1

**Table 58.** Interval-valued comparison matrix

Control over the degree of functionality	Average delivery time	Quality perceived/Price	Variety offered	Percent of demand satisfied
Average delivery time	1	[1,2]	[1,2]	[6,8]
Quality perceived/Price	[1/2,1]	1	[2,4]	[4,6]
Variety offered	[1/2,1]	[1/4,1/2]	1	[2,4]
Percent of demand satisfied	[1/8,1/6]	[1/6,1/4]	[1/4,1/2]	1

**Table 59.** Crisp comparison matrix and weight of PIs

Control over the degree of functionality	Average delivery time	Quality perceived/Price	Variety offered	Percent of demand satisfied	weight
Average delivery time	1	1.5	1.5	7	0.389
Quality perceived/Price	0.75	1	3	5	0.358
Variety offered	0.75	0.375	1	3	0.191
Percent of demand satisfied	0.146	0.208	0.375	1	0.062
		$\lambda_{\max}$	4.247		
		RI	0.9		
		CI	0.0824		
		CR	0.0916		

So,  $W_2$ , a matrix representing the inner dependence of the sub-factors is obtained:

$$W_2 = \begin{bmatrix} 1 & 0 & 0.520 & 0 & 0.389 \\ 0 & 1 & 0.413 & 0 & 0.358 \\ 0 & 0 & 1 & 1 & 0.191 \\ 0 & 0 & 0.067 & 1 & 0.062 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

As PI3 is affected only by PI4, no pairwise comparison matrix is formed for PI3.

Step 5. Determine the global weight PIs of customer value with multiplying  $W_1$  and  $W_2$ .

$$W_g = w_2 \times w_1 = \begin{bmatrix} 1 & 0 & 0.520 & 0 & 0.389 \\ 0 & 1 & 0.413 & 0 & 0.358 \\ 0 & 0 & 1 & 1 & 0.191 \\ 0 & 0 & 0.067 & 1 & 0.062 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 0.336 \\ 0.337 \\ 0.180 \\ 0.090 \\ 0.057 \end{bmatrix} = \begin{bmatrix} 0.452 \\ 0.432 \\ 0.281 \\ 0.106 \\ 0.057 \end{bmatrix}$$

The values of  $W_g$  should be normalized to get the weight of PIs. Weight of PIs of customer value after normalizing is:

$$W_{Vs-f} = \begin{bmatrix} 0.340 \\ 0.325 \\ 0.211 \\ 0.08 \\ 0.044 \end{bmatrix}$$

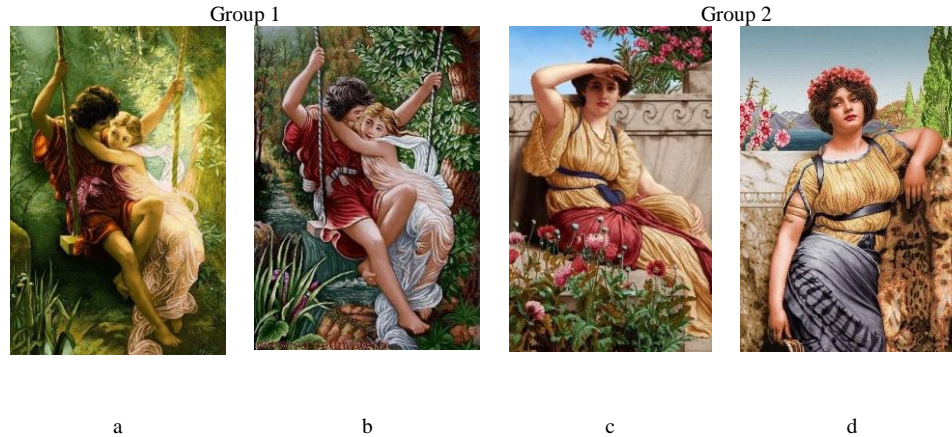
Table 60 shows the weight of PIs for customer and enterprise value based on two methods fuzzy AHP and fuzzy ANP.

**Table 60.** Weight of PIs based on fuzzy AHP and fuzzy ANP

Value factors	Value sub-factors	Overall Priority of PIs for fuzzy ANP	Overall Priority of PIs for fuzzy AHP
Customer value	Average delivery time	0.340	0.336
	Quality perceived/Price	0.325	0.337
	Variety offered	0.211	0.18
	Percent of demand satisfied	0.08	0.09
	Control over the degree of functionality	0.044	0.057
Enterprise value	Benefit	1	1

### 4.3.3 Cluster component or feature options with same attributes

In this case, we have many design options with different categories such as nature, animal, regional, portray and etc that can be used to produce a lot of carpet tableaus. For decreasing size of data that has to be analyzed, we cluster the design options. One can use different clustering methods, but we group these according two attributes design and color similarity. For example, two following pictures *a* and *b* in Figure 15 are same from design perspective, but with different color configuration. Also, pictures *c* and *d* are very similar from design perspective and have only some difference in details. So, these can be grouped in a group.



**Figure 15:** Grouping the design options

### 4.3.4 Develop mathematical models

In this section, we develop two mathematical models to determine set of customizable components/features and product variety offered to customers together decision making about CODP position and selection of suppliers and carpet weaving machine.

Since our models have been constructed based on operations in production process, before dealing with details of models, it is important to describe operations used to produce carpets and tableau carpets. The process of production is composed of following operations:

**Weaving:** After providing the colored yarns weaving operation is done by weaving machines. These machines can work based on different technologies. Figures 16 and 17 displays the yarn colored and weaving machine of this company.

Here, we assume that we have two candidate weaving machines as two manufacturing methods that one of them should be selected. This is the most important operation of producing carpets and carpet tableaus because in this operation, three of most important features of a carpet tableau that have the highest effect on satisfaction of customers such as design, density and size are configured.

**Finishing:** After weaving, some finishing operations are needed to complete production process. Carpets woven by weaving machines need to perform additional operations that it mainly is obtained by sizing and shearing machines to realize the required properties such as strength, dimensional stability, resistance against to static and dynamic pressures, connection of roots and uniform surface without the ups and downs.

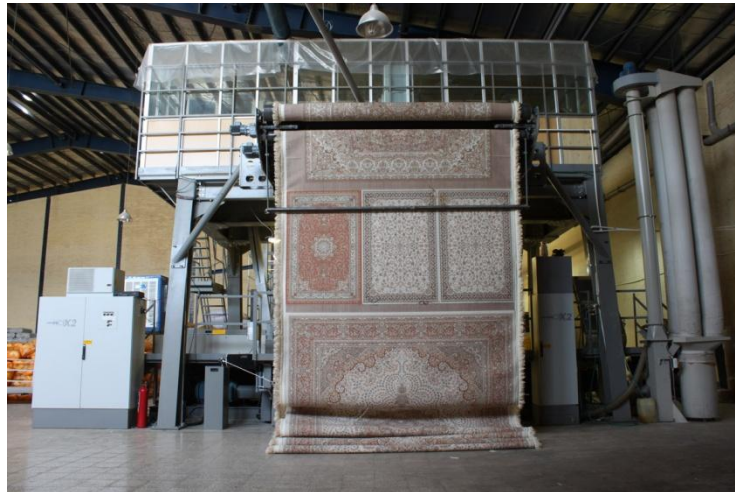


a



b

**Figure 16:** a: Colored yarn provided; b: Weaving machine

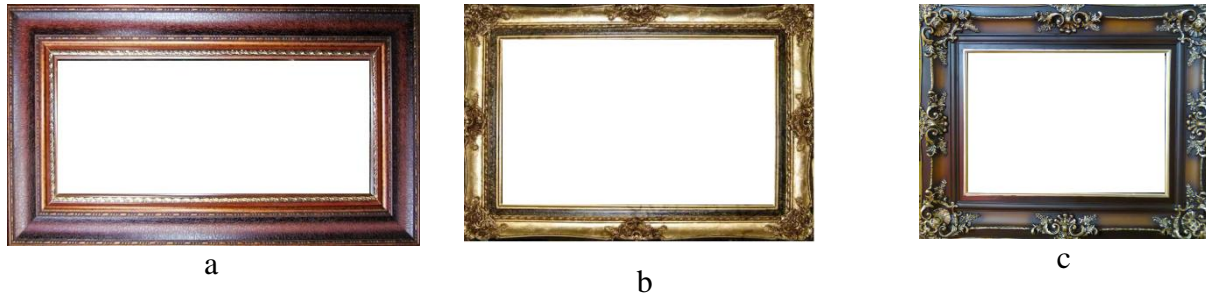


**Figure 17:** Weaving machine

Sizing operation is used to stabilize underlying layers of carpet tableaus through using glue. In the meantime, shearing operations is one of required stages in producing of carpet and carpet tableaus as well as one of the most difficult stages of production. The aim of this operation is to develop a stylish and sleek appearance with a uniform and beautiful view for carpet tableaus.

**Inspection and repairing:** After doing finishing operation on carpets, inspection and repairing operations are started to find and repair potential errors.

**Assembling:** in this company, the woven carpet tableaus are sent to an external producer of panels to manufacture and assemble panels with the size and type determined by customers. Today, three types of panels are used which are called Steel, Royal and PVC. Figure 18 displays these different types of panels.



**Figure 18:** Different type of panel: a) PVC; b) Royal; c) Steel

**Packing:** After returning carpet tableaus from external manufactures of panels, this operation is done based on two types of pack called “standard” and “customize”. While type of standard is performed based on a determined pattern, type of “customize” is done based on opinion of customer and as usual is used to give gifts.

**Delivery:** This operation which is based on need of customers is divided to “Delivery by agent” and “Express delivery” through post.

In continuous, we describe the models and method of gathering data for parameters.

#### 4.3.4.1 PI11: functional quality

The first performance indicator to obtain customer value in our model is functional quality that is based on ratio quality perceived into price.

Different functions listed in Table 61 (Anayati Bidgoli, 2013) affect on quality of carpet tableau. As this Table shows, different quality providers play role in total quality of products.

**Table 61.** Function and sub-function including in the model

Function	Sub- Function	Quality provider	Evaluation type
1-Aesthetic	1-Conformance between designs and colors (F11)	Company	Linguistic terms
	2-Density (the length and width) (F12)	Company	Linguistic terms
	3-Panel(F13)	Supplier	Linguistic terms
	4-Yarn(Smooth and rough) (F14)	Supplier	Linguistic terms
2-Durability	1-Yarn strength(F21)	Supplier	Linguistic terms
	2-Weaving quality (tissue resistance) (F22)	Weaving machine	Linguistic terms

Since all these sub-functions have qualitative nature, therefore, they are evaluated with linguistic terms shown in Table 10.

Evaluation of these sub-functions is performed with linguistic terms by experts as follows:

1-Sub-function “*Conformance between design model and colors*” is an important part affecting on aesthetic of a carpet tableau. The first thing that attracts attentions in the first look is design and colors used in a carpet tableau. The design and color are interdependent because design is well figured when producer uses colors near to fact and mind of designer. Therefore, one can find different prices for same designs between manufactures.

This sub-function is evaluated for all design models based on expertise of a carpet expert. Results of evaluation of this sub-function are shown in Appendix B.

2- Sub-function “*Density*” usually is related to capability of company to provide different densities in horizontal row (Course-wise density) and length-wise (Wale-wise density). Table 62 represents acceptability of each density for customers.

**Table 62.** Evaluation of different density

Density (Length, Width)	Evaluation
500,1200	M
500,1500	G
500,2550	G
700,1200	G
700,1500	G
700,2550	G
1000,2250	VG
1000,2550	VG
1000,2700	VG

3-Sub-function “*Panel*” affects on aesthetic of carpet tableau. Since, the panels are usually out-sourced, so, quality of panels manufactured by suppliers becomes important. Table 63 represents the evaluation of three panels produced by three suppliers.

**Table 63.** Evaluation of suppliers of panels

Panel	Supplier p1	Supplier p2	Supplier p3
Royal	Good	Very good	Medium
PVC	Medium	Good	Good
Steel	Good	Good	Good

4-Sub-functions “*Yarn (Smooth and rough)*” of aesthetic function is related to quality of yarn purchased from suppliers for smoothness and roughness. Table 64 shows evaluations of three different yarns for weaving of carpets purchased from suppliers.

**Table 64.** Evaluation smoothness and roughness of yarn

Yarn (smoothness, roughness)	Supplier y1	Supplier y2	Supplier y3
Acrylic	Medium	Good	Good
Heat set Acrylic	Good	Good	Very Good
Silk	Medium	Good	Very Good

5- Sub-function “*Yarn strength*” of durability function is related to quality of yarn purchased from suppliers for strength. Table 65 identifies evaluations of three different yarns purchased from suppliers.

**Table 65.** Evaluation of yarn strength

Yarn (strength)	Supplier y1	Supplier y2	Supplier y3
Acrylic	Good	Good	Very Good
Heat set Acrylic	Good	Good	Good
Silk	Medium	Good	Very Good

6-Dependence to type of technology used, quality of carpets weaved is different. Sub-function “*Weaving quality (tissue resistance)*” evaluates weaving machines from perspective of resistance of texture used in carpets. Table 66 shows the Weaving quality for two machines.



**Table 66.** Evaluation of machines

Weaving quality (tissue resistance)	Machine 1 Good	Machine 2 Very Good
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For applying these linguistic terms in the PI11, they are converted to interval values by using formula (5).

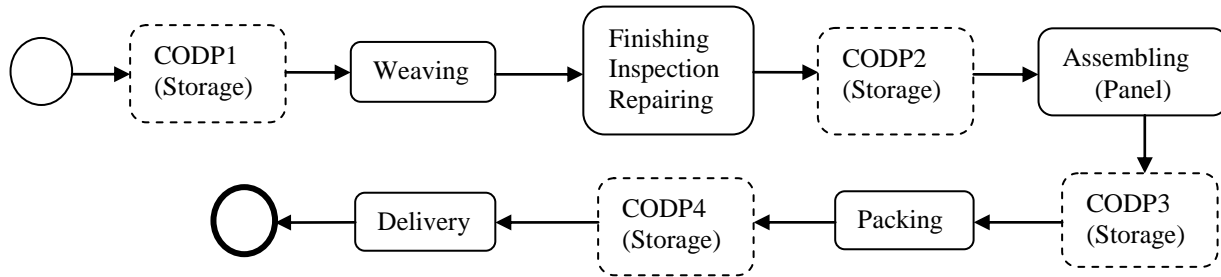
Values of  $w_f$  and  $V_{fv}$  in PI11 representing importance of functions and sub-functions are shown in Table 67:

**Table 67.** Weight of functions and sub-functions

Function (weight)	Aesthetic (0.6)				Durability(0.4)	
Sub-function	F11	F12	F13	F14	F21	F22
Weight	0.4	0.25	0.25	0.1	0.4	0.6

#### 4.3.4.2 PI12: Average delivery lead time

This PI is obtained from summation of operations times after CODP for each product. So, it is dependence to position of CODP. In manufacturing process of carpet tableau, potential CODP positions are defined and represented in Figure 19.



**Figure 19:** The shortened manufacturing process of carpet tableau and CODP positions

In position of CODP 1 which is before the operation weaving, material is stored and production operation is started when that all details of orders including design, density, size, panel, pack and type of delivery are determined.

Position of CODP 2 is before the operation assembling of panels which in this storage, semi-products obtained from operations before CODP stored. Customization of orders is started when details of orders including type of panel, pack and type of delivery are determined.

Position of CODP 3 is after the assembling of panels and before operation packing. In this storage, the semi-products obtained from operations before CODP are stored and are waited to get the details of customers orders to perform customization.

In Position of CODP 4, after determining type of delivery, the orders are sent to customers.

For better comprehension, we divide the operations to operations before and after CODP by helping Figure 19.

Values of setup time for preparing weaving machines ( $T_{pom}^{mset 2}$ ) are dependence to size of carpet tableau. Company can produce the carpet tableaus with dimensions less or equal 200” cm<sup>2</sup>. For

simplicity, we divided this distance to ranges based on standard sizes used in market. Values of setup time for sizes between standard sizes are very low, so, setup time for these sizes is considered similar to setup time of standard sizes. Table 68 shows setup time for each weaving machine and each standard size.

**Table 68.** Setup time (Min)

Machine	Size (m <sup>2</sup> )						
	0.35	0.54	0.7	0.8	1.2	1.8	3
1	10	12	15	16	18	19	22
2	13	14	16	18	19	21	23

Weaving time for both machine ( $T_{pom}^{man^2}$ ) is same and is 1.43 (hr) for each meter square (m<sup>2</sup>). Another time in our formula is unloading time ( $T_{pom}^{ul}$ ) that is time of unloading carpet tableau from production line that is estimated about 4 (hr).

Two main factors affecting on cost and price as well as some PIs (naturally, value for customers and enterprise) are material and panels used in carpet tableau. So, determination of suppliers providing more value for material and panels is important.

For assembling panels, this company sends the woven carpet tableaus to one of panel manufactures. Delivery time of assembled products ( $T_{js}^{sup}$ ) is shown in Table 69.

**Table 69.** Delivery time of suppliers for panels

Supplier	Panel (day)		
	Steel	PVC	Royal
1	7	2	3
2	6	3	3
3	7	2.5	3.5

Time of performing other operations such as “Finishing”, “Inspection” and “Repairing” is dependence to size of carpet tableau and are evaluated 2.8 (hr) for each m<sup>2</sup>.

Time of packing operation is related to type of packing. For standard packing, it is about 1 hr and for customized packing is about 4 hrs.

Time of delivery with “Express post” is about 2 days and delivery by agent is 6 days.

#### 4.3.4.3 PI13 and PI14: Percent of demand satisfied and variety used

PI13 and PI14 are based on number of products selected ( $z_p$ ) that it, itself, is related to customizable components and features selected. For PI13, demand of products selected ( $d_p$ ) and total demand are estimated based on m<sup>2</sup>.

#### 4.3.4.4 PI15: Control over degree of functionality

PI15 is defined based on customizable features which customers can control over degree of functionality. Among customizable components and/or features proposed in this case, “size” is only feature that customers can directly control it according to their needs. Since feature size is continuous, method of calculating PI for this feature is difference and is shown in Table 70.

**Table 70.** Method of obtaining PI control over degree of functionality for feature Size

Feature	Potential range for feature ( $N_a$ )	Method
Size	200cm	Interval selected/200

#### 4.3.4.5 PI21: Benefit

With considering order of operations, we adopt the main formula with our case as follows:

Before beginning of operation, materials must be purchased from suppliers. Weaving each  $1m^2$  carpet tableau consumes about 4 kg ( $r_{wj}^1, r_{pj}^2$ ) material. Purchasing cost of suppliers ( $C_{js}^m$ ) for material is displayed in Table 71.

**Table 71.** Purchasing cost of suppliers for material (\$/kg)

$C_{js}^m$	Material		
Supplier	Acrylic	Acrylic heat set	Silk
1	3.85	5	53.5
2	4	5.2	52
3	3.6	5	55

In our models, the demands are used based on both number of orders and unit  $m^2$ . Since demands are predicted based on number of orders, for application in our formula for cost, they should be converted to demands based on unit  $m^2$ .

We, here, show application of these two types of demand in our formulas for calculating weaving cost which is represented in Table 72:

**Table 72.** Using two types of demand in our formulas

The main formula	The adopted formula
$\sum_{p=1} d_p z_p \left( \sum_{O=1} \left( \sum_{m=1} ((T_{pom}^{man2} + T_{pom}^{mset2} + T_{pom}^{ul2}) C_{om}^{man} / def_o) U_{om} \right) \right)$	$\sum_{p=1} z_p ((1.43(Size(x) \times Size(y)) d_p) + (d_p T_{pom}^{mset2} / (60)) + T_{pom}^{ul2} d_p) C_{om}^{man} / def_o) U_{om} )$

In the adopted formula, setup time ( $T_{pom}^{mset2}$ ) and unloading time ( $T_{pom}^{ul2}$ ) are calculated for each order and weaving time for each order ( $T_{pom}^{man2}$ ) is computed according weaving time for each unit  $m^2$  that is 1.43 hr/  $m^2$ .  $Size(x)$  and  $Size(y)$  are length and width size, respectively, that are used to convert orders to unit  $m^2$ .

Some of other data for this PI are represented as follows:

- In the case, only operation 1 is a manufacturing operation. In operation 1, weaving cost ( $C_{om}^{man}$ ) for machine 1 and 2 are 2 \$/hr and 1.8 \$/hr for each  $m^2$ .
- Since some time data are according different units such as day and hour, in the adapted formula they are converted to same units.
- Values of demand for each product are estimated according a method represented in Appendix C.
- For simplicity, we integrate operations Finishing, Inspection and Repairing in one operation with cost ( $C_o^{Op}$ ) 2 \$/hr for each  $m^2$  and time 1.4 hr/ $m^2$ .

- Packing operation is done with cost ( $C_o^{Op}$ ) 5\$/hr. Packing time ( $T_{po}^{op2}$ ) is dependence to type of packing. For Standard Packing, time is 1hr and for Customize packing is average 4 hr.

Since our models are based on operations before and after CODP, Table 73 shows operations before and after CODP according to Figure 31.

**Table 73.** Operations before and after CODPs

CODP position	Operation before CODP	Operation After CODP
1	-	1-2-3-4-5
2	1-2	3-4-5
3	1-2-3	4-5
4	1-2-3-4	5

#### 4.3.5 Solve the models and extract the results

In our thesis, we apply a multi-objective genetic algorithm method based on the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) proposed by Deb et al. (2000) to obtain Pareto-optimal solutions. We, here, describe main information for implementation of NSGA II for our case as follows:

In our case, we determine population size 50, cross probability 0.6, mutation probability 0.05 and number of generation 200.

Different parts of chromosome for the models are represented in Table 74:

**Table 74.** Parts of chromosome

No	Part	Length	Type	Model I	Model II
1	CODP	4	Binary	√	√
2	Material type	3	Permutation	√	√
3	Design	50	Permutation	√	√
4	Density	10	Binary	√	√
5	Size	7	Binary	√	√
6	Panel	3	Binary	√	√
7	Pack	2	Binary	√	√
8	Supplier material	3	Binary	√	√
9	Supplier panel	3	Binary	√	√
10	Machine	2	Binary	√	√
11	Time period	4	Continuous	*	√

Parts of CODP, supplier of material, supplier of panel and machine, gets only one gene with values 0-1 that identify CODP position, suppliers and type of machine (or technology) used in process.

Feature of “size” is continues and customers can determine the size based on their needs. For simplicity, we divided this distance to ranges based on standard sizes used in market. We propose a structure with genes equal with these standard ranges and randomly select one gene which shows upper limit of feature size. This point shows maximum size that can be offered to customers.

Since the chromosome is consisted of several parts, we use crossover and mutation for each part. Table 75 shows type of cross over and mutation used in the thesis.

**Table 75.** Type of cross over and mutation used

No	Part	Cross over type	Mutation Type
1	CODP	Single-point	Random
2	Material type	Single-point (For permutation code)	Random
3	Design	Order1	Inverse
4	Density	Single-point	Random
5	Size	Random	Random
6	Panel	Single-point	Random
7	Pack	Single-point	Random
8	Supplier material	-	Random
9	Supplier panel	-	Random
10	Machine	-	Random
11	Time period	-	Random

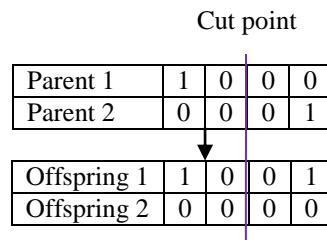
After coding of customizable components and features, number of potential products that can be produced is determined. But, all products cannot be manufactured likely due to different constraints such as budget and inventory capacity. Since calculation of fitness is dependence on number of products, fitness of product varieties is evaluated until restrictions are not violated.

For two models, we use non-dominated sorting genetic algorithm with interval data, which has a special method for ranking solutions and calculation of crowding distance based on definitions 3.2, 3.6 and 3.7.

Cross over operator is performed based on following stages:

1- Do Single-point crossover for CODP and Size and check feasibility.

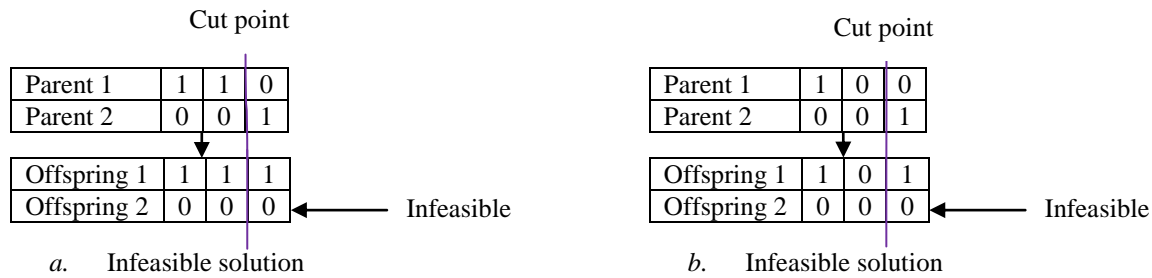
When we use single-point crossover for parts of chromosome such as CODP that only one gene gets 1, it is possible which infeasible chromosomes are produced (Figure 20).



**Figure 20:** Two infeasible solutions

For this state, we act such as random mutation and select a random gene among genes 0 for each parent. The gene with amount 1 gets 0 and gene selected get 1.

2- Do single-point crossover for parts “Density”, “Panel” and “Pack”, which all genes can get values 0 and 1. Infeasibility for this type of parts is shown in Figure 21 as follows:



**Figure 21:** Infeasible solutions

For state *a*, we randomly select one gene between 1 and size of this part of offspring 2 and put values 1 for gene selected. For state *b*, we apply the method used for infeasible solutions in parts such as CODP which only have a gene with value 1.

For part of Material type, we use single-point crossover for permutation code. When a crossover point was selected, the numbers in gens till this point are copied from the first parent, then the second parent is scanned and if the number is not yet in the offspring, it is added.

For part Design, Order1 cross over for permutation code is performed.

When cross over is done on part “pack”, the changes is exerted for all parts after “Pack”.

For mutation, we, at first, select randomly a part and perform the Mutation. For all parts except “Design” that is used from inverse mutation, we use random mutation.

For selection of next generation, parent and offspring populations are combined and are ranked by using procedure the non-dominated sorting for interval data. The parent population is replaced by the best members of the combined population which is based on rank and crowding distance for interval data. This process is repeated until maximum number of generation.

We develop a program in Visual Studio 2008 for solving the problem based on NSGA II with interval data. The results include the values of objectives and PIs, the options selected to offer customers, suppliers selected for panels and materials, manufacturing method, CODP position and amounts of inventory, backorder and production levels for model II. Appendix D shows the code of program to solve the model II.

#### 4.4 Results obtained from solving model I with interval data

Since some data in the model are uncertain, we assume some parameters such as demand of products and delivery time of panels bought from suppliers are expressed as interval numbers.

We, here, show the details of steps needed to get results for one situation (weights obtained from fuzzy ANP; Budget 100000 and confidence level  $\alpha=0.5$ ).

With each time run of the program, the results are displayed in user interface shown in Figure 22.

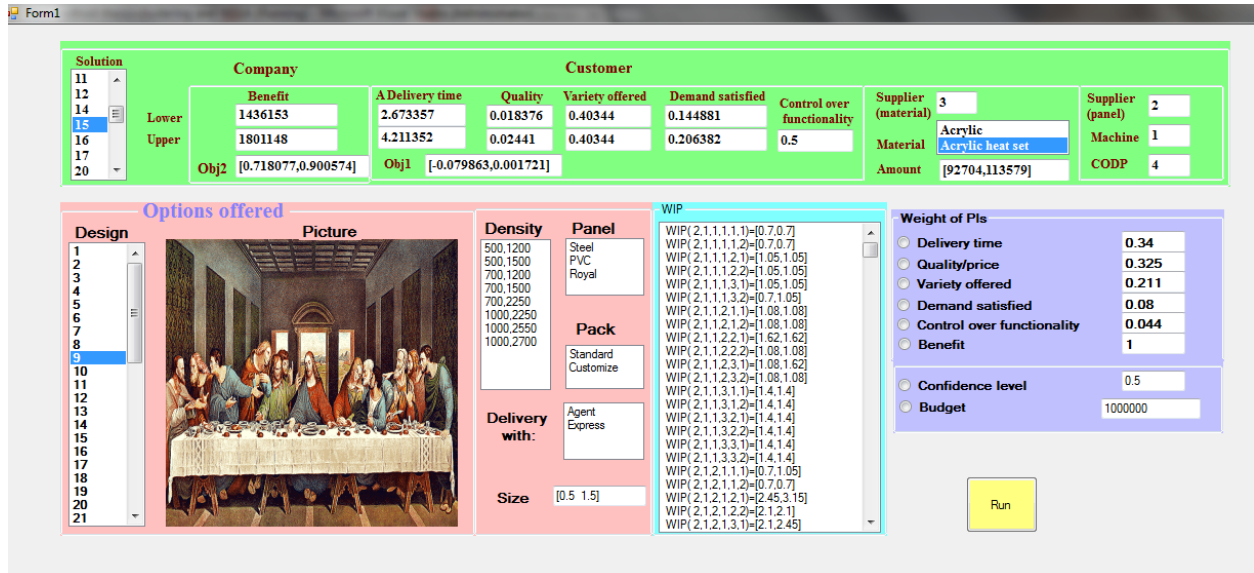


Figure 22: Displaying the solutions with all details in the program (model I-Interval data)

As this figure shows, the program is able to display lower and upper values of objectives and PIs, suppliers selected for panels and materials, machine and CODP position with different constraints. In this figure, the section of “options offered” displays the designs selected, the density, size, panels and type of pack for carpet tableaus. Section “WIP” identifies primary lower and upper values of each semi-manufactured product stored in CODP position in beginning of work.

After solving the mathematical model for this state, values of Pareto front are shown in Figure 23. It is noted according to dominance rule for interval numbers defined in definition 3.6, Pareto front is investigated based on the mean and radius of interval values.

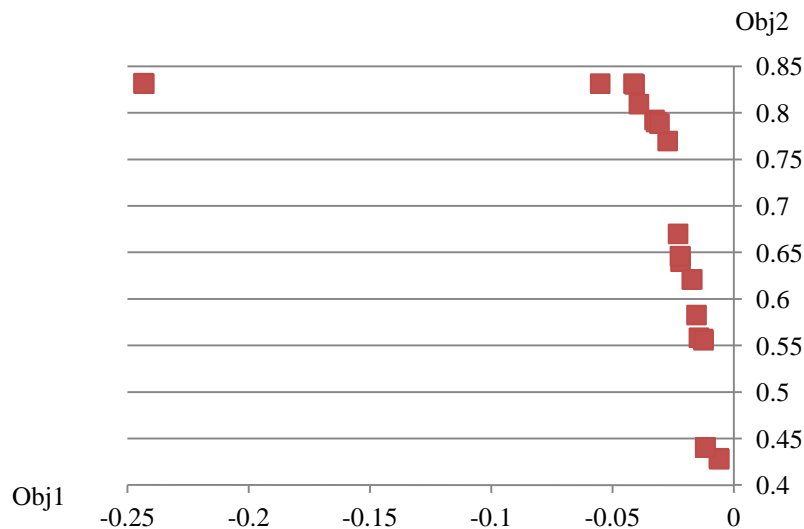
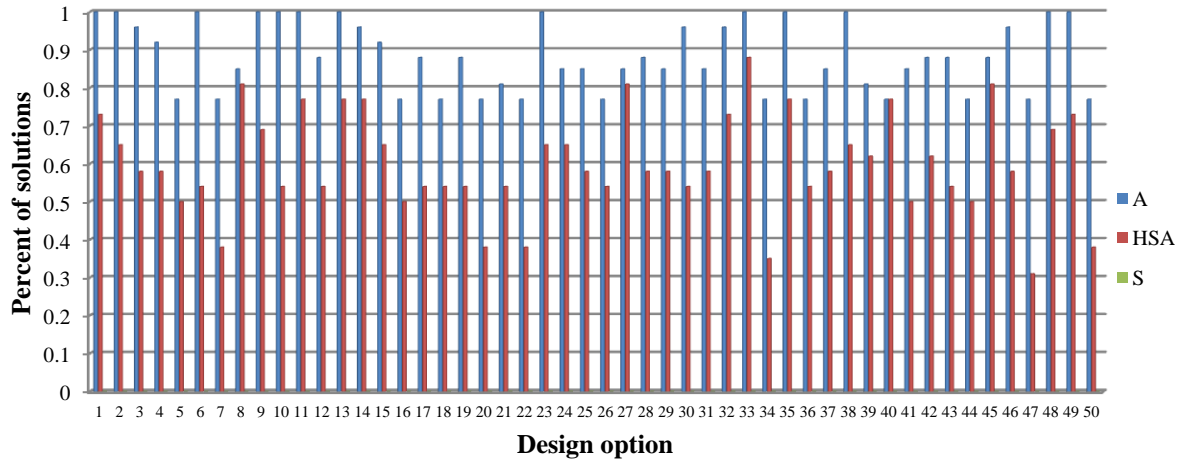


Figure 23: The Pareto front (model I-Interval data)

Amounts of objective 1 (customer value) are negative because PI average delivery time gets both more weight and less value in comparison to other PIs.

Here, we analyze details of these solutions and represent them with charts as follows:

The first chart (Figure 24) shows percent of solutions offering the design options with different material.



A: Acrylic; HSA: Heat Set Acrylic; S: Silk

Figure 24: Percent of design options including in solutions (model I-Interval data)

As chart shows, some design options are proposed by all solutions while other design options are offered by some solutions. For example, design option 1 with material “Acrylic” is proposed by 100% solutions while same design option with material “Heat set acrylic” is only offered by 73% solutions.

Next chart (Figure 25) shows percent of solutions offering the density options.

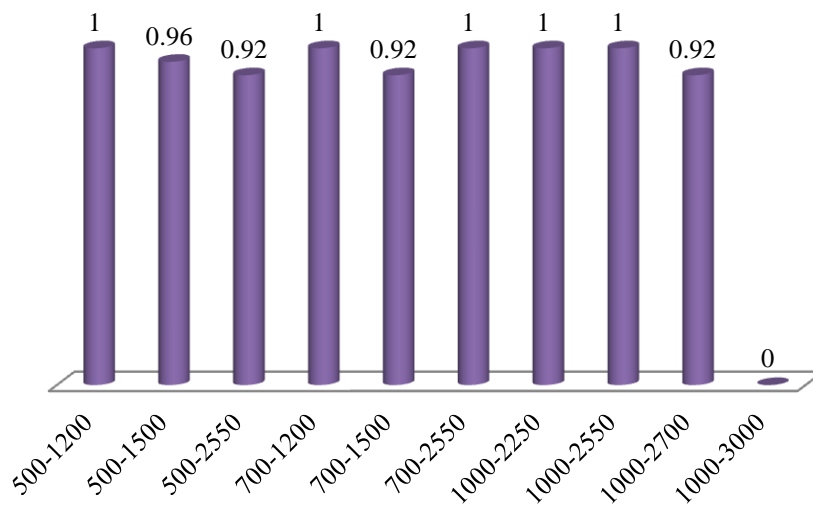
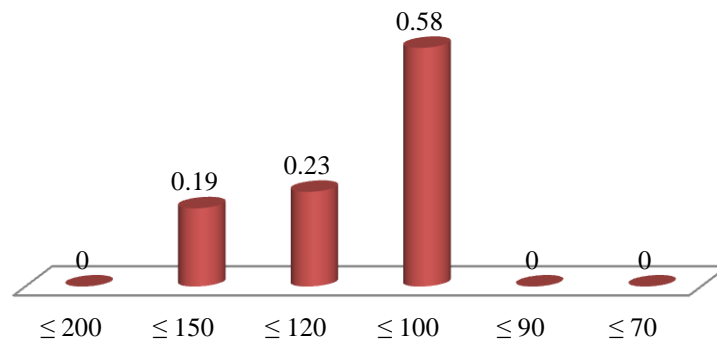


Figure 25: Percent of density options in solutions (model I-Interval data)



As this chart shows, 5 from 10 density options are proposed by all solutions. For instance, 96% solutions in the set of Pareto solutions offer density “500-1500”, while 100% solutions propose density “500-1200”.

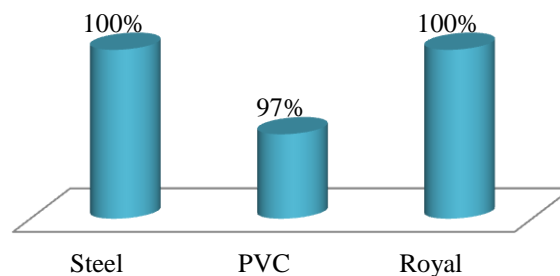
The next chart (Figure 26) displays percent of solutions proposing carpet tableau with different extent of size.



**Figure 26:** Percent of size extent in solutions (model I-Interval data)

As chart identifies, 19% solutions propose the size less or equal than 150 cm, while 58% offer the size less than 100. Analyzing solutions shows solutions that propose less size, have more benefit and less customer value and solutions that offer more extent of size, have less benefit and more customer value. It can be because PI5 (control on degree of functionality) in objective 1 (customer value) that tries to increase extent of size offered to customers. Another reason it can be that with lower size, more types of material and design options that have more benefit, are selected.

The next chart (Figure 27) displays percent of solutions proposing different panels.

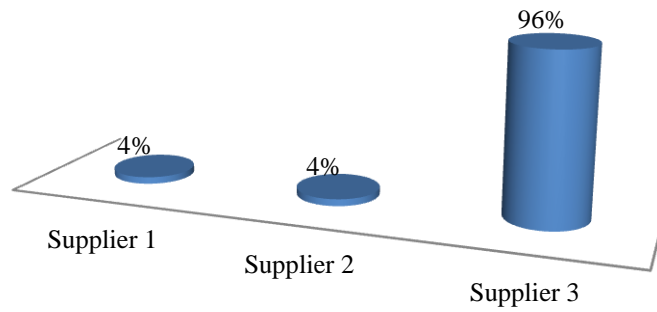


**Figure 27:** Percent of panel options in solutions (model I-Interval data)

This chart shows that all solutions propose panel Steel and Royal, while 97% solutions offer panels PVC.

About packing options (Standard and customize), set of solutions identifies that all solution propose two types of packing.

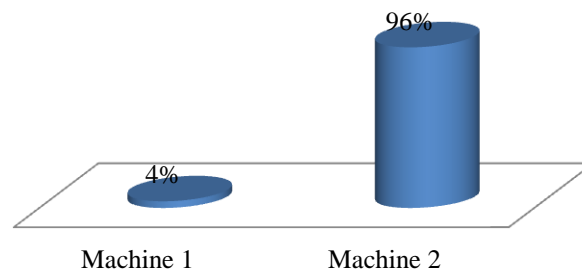
The next chart (Figure 28) displays percent of solutions selecting different suppliers of panels. As this chart shows, 96% solutions prefer supplier 3.



**Figure 28:** Percent of solution which select suppliers' panel (model I-Interval data)

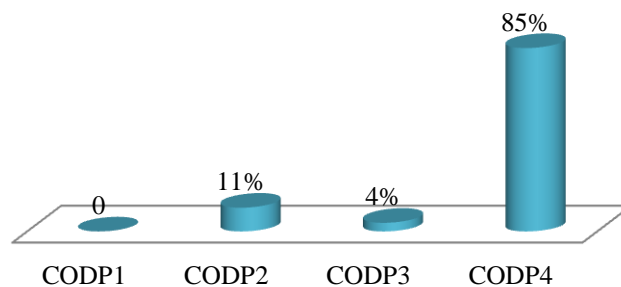
About suppliers of materials, all solutions select supplier 3 for providing materials.

Another chart (Figure 29) shows percent of solutions selecting weaving machine. According this chart, most solutions (96%) select machine 2 to weave carpet tableaus.



**Figure 29:** Percent of solution which select weaving machine (model I-Interval data)

Another chart (Figure 30) shows percent of selection CODPs in all solutions. For example, 85% solutions select position 4 as CODP.



**Figure 30:** Percent of CODPs selected by suppliers (model I-Interval data)

After solving the model I with Visual Studio 2008, a set of Pareto solutions are obtained. Here, we represent the details of two solutions in Table 76.

**Table 76.** Details of two solutions for Model I with interval data

Solution		1			2		
Material		A	AHS	S	A	AHS	S
		Amount	[27623,36967]	[101069,123679]	-	[128523,157769]	[23689,28083]
Objective	1	[-0.38416,-0.10249]			[-0.05368,0.03028]		
	2	[0.741,0.923]			[0.39,0.491]		
PI11 (Quality/price)	1	[4.76,10.43]			[2.83,4.41]		
PI12(Average delivery time)	2	[0.0192,0.0248]			[0.02,0.0258]		
PI13 (Variety used)	3	0.391			0.509		
PI14 (Percent of demand satisfied)	4	[0.14432,0.20384]			[0.171,0.236]		
PI15(Control over functionality degree)	5	0.5			0.75		
PI21(Benefit)	1	[1481400,1846208]			[779996,981832]		
Design option	1	√	√	-	√	√	-
	2	√	√	-	√	*	-
	3	√	√	-	√	*	-
	4	√	√	-	√	*	-
	5	√	√	-	√	*	-
	6	√	√	-	√	*	-
	7	*	√	-	√	*	-
	8	*	√	-	√	√	-
	9	√	√	-	√	*	-
	10	√	√	-	√	*	-
	11	√	√	-	√	*	-
	12	*	√	-	√	*	-
	13	√	√	-	√	*	-
	14	√	√	-	√	*	-
	15	√	√	-	√	*	-
	16	*	√	-	√	*	-
	17	√	√	-	√	*	-
	18	*	√	-	√	*	-
	19	*	√	-	√	*	-
	20	*	√	-	√	*	-
	21	*	√	-	√	*	-
	22	*	√	-	√	*	-
	23	√	√	-	√	*	-
	24	√	√	-	√	*	-
	25	*	√	-	√	*	-
	26	*	√	-	√	*	-
	27	*	√	-	√	√	-
	28	√	√	-	√	*	-
	29	*	√	-	√	*	-
	30	√	√	-	√	*	-
	31	*	√	-	√	*	-
	32	√	√	-	√	*	-
	33	√	√	-	√	√	-
	34	*	√	-	√	*	-
	35	√	√	-	√	*	-
	36	*	√	-	√	*	-
	37	*	√	-	√	*	-
	38	√	√	-	√	*	-
	39	*	√	-	√	*	-

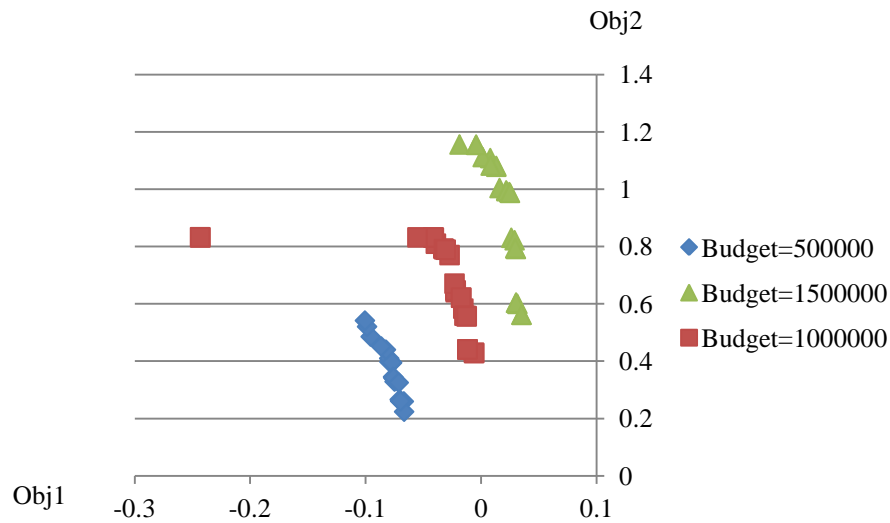
	40	*	√	-	√	√	-
	41	√	√	-	√	*	-
	42	√	√	-	√	*	-
	43	√	√	-	√	*	-
	44	*	√	-	√	*	-
	45	√	√	-	√	√	-
	46	√	√	-	√	*	-
	47	*	√	-	√	*	-
	48	√	√	-	√	*	-
	49	√	√	-	√	*	-
	50	*	√	-	√	*	-
Density	500,1200		√			*	
	500,1500		√			√	
	500,2550		√			√	
	700,1200		√			√	
	700,1500		√			√	
	700,2550		√			√	
	1000,2250		√			√	
	1000,2550		*			√	
	1000,2700		√			√	
	1000,3000		*			√	
size	X=[70,200]		[0,100]			[0,150]	
panel	Steel		√			√	
	PVC		√			√	
	Royal		√			√	
pack	Standard		√			√	
	Customize		√			√	
Supplier material	1,2,3		3			3	
Supplier panel	1,2,3		2			2	
Machine	1,2		2			2	
CODP	1,2,3,4		2			4	

As this table identifies, solution 2 has more interval value for objective 1 and less interval value for objective 2 in comparison with solution 1. Solution 1 offers more design options with material “Acrylic Heat set” that produce more benefit in comparison with material “Acrylic”. Also this solution selects CODP 2 which it has significant effect on decrease of average delivery time and thus customer value (objective 1).

Analysis shows solutions which have more benefit and lower value for objective 1; offer mainly design options with material “Acrylic Heat set” and less design options with material “Acrylic” with less size. Also, solutions with lower benefit and more value of objective 1, propose more design options with material “Acrylic Heat set” and less design options with material “Acrylic” and more size.

Indeed, this issue demonstrates that if company offers material “Acrylic” with the determined design as well as more extent of size, it can provide more value for customers. Versus, if company gives more importance to enterprise value (here, benefit), it has to offer design options with material “Acrylic Heat set” as well as less extent of size.

We solve the model for different budgets to investigate their effects on the solutions. Figure 31 compares the Pareto front for different budget limitations.



**Figure 31:** The comparison between Pareto fronts with different budget (model I-Interval data)

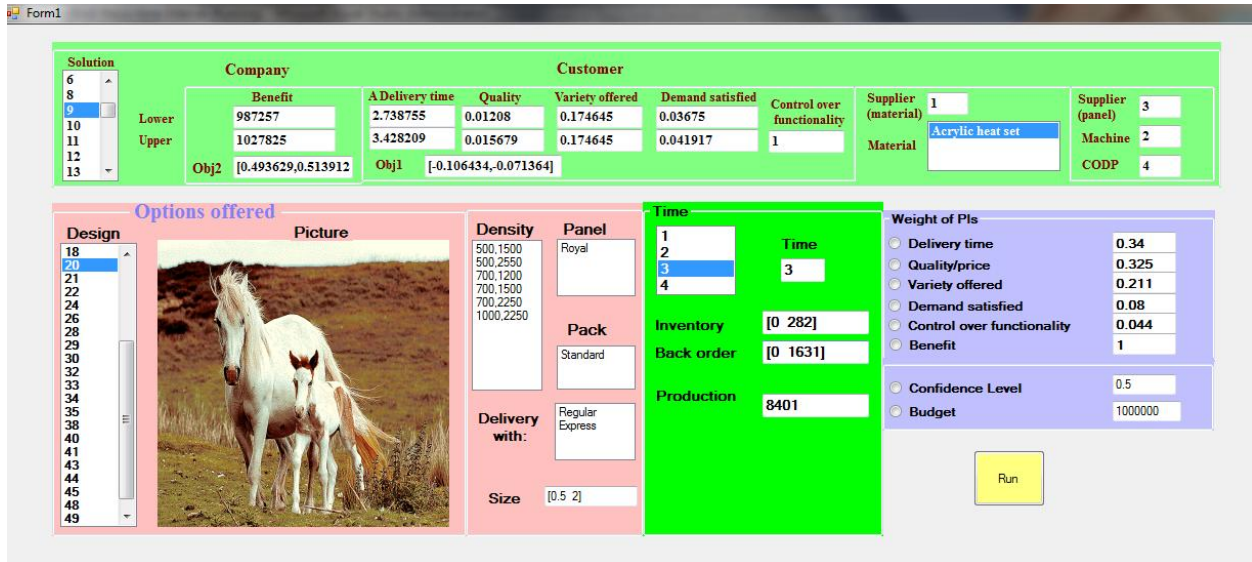
As this chart shows, when the budget is low, the values of objectives 1 and 2 are low because less product varieties are selected to offer customers.

#### 4.5 Results obtained from solving model II with interval data

Since some data in the model are uncertain, we assume that some parameters such as demand of products bought from suppliers are expressed as interval numbers.

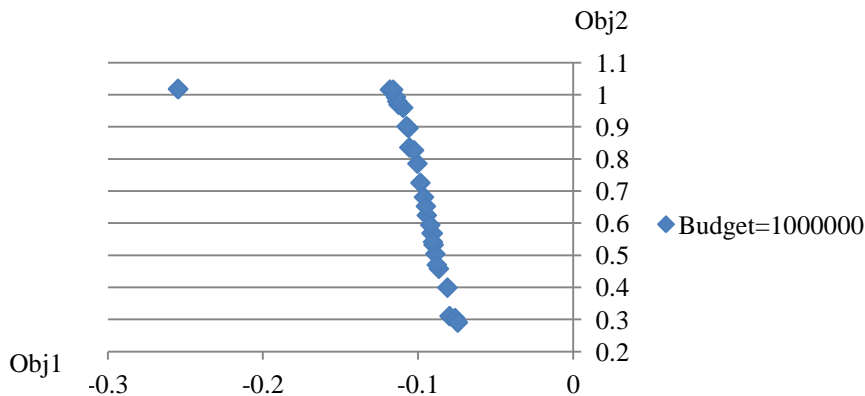
We, here, show the details of the steps needed to get results for a state (weight of PIs obtained from fuzzy ANP; Budget 100000; Confidence level  $\alpha=0.5$ ) with considering the interval data for some parameters.

With implementation of the program, the results are displayed in user interface shown in Figure 32. This interface is similar to interface developed for model I except it has an additive part called section “Time” that identifies lower and upper bounds of inventory/backorder and production level for all semi-manufactured products.



**Figure 32:** Displaying the solutions with all details in the program (model II-Interval data)

After solving the mathematical model for this state, values of Pareto front obtained are shown in Figure 33. It is noted according to dominance rule for interval numbers defined in definition 3.6; dominance is investigated based on the mean and radius of interval values.

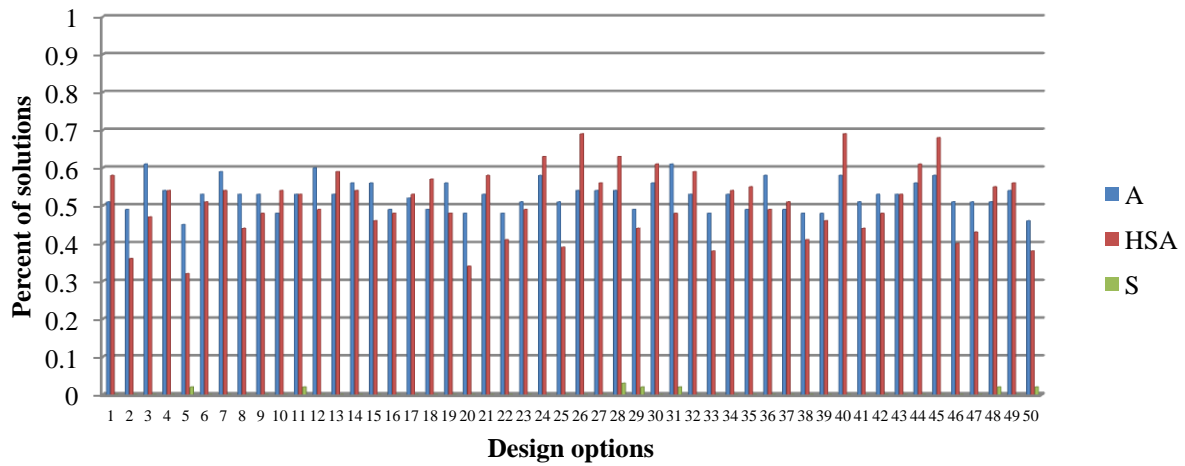


**Figure 33:** The Pareto front (model II-Interval data)

Since PI “Average delivery time” has both more weight and fewer amounts compared to other PIs in objective one, so, it has a decisive role in objective one. So, its negative effect causes that objective one gets negative interval values.

In continuous, we analyze details of these solutions and represent them with charts as follows:

In our model, each design option with three different materials is evaluated in order to propose to customers. The first chart (Figure 34) shows percent of solutions that offer the design options with different material.

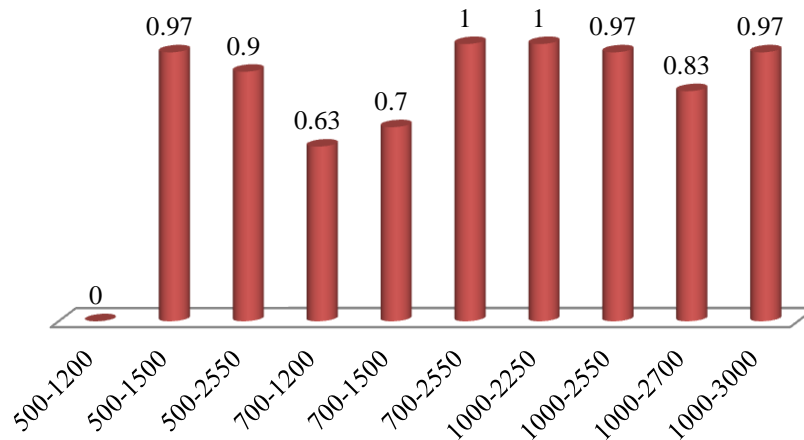


A: Acrylic; HSA: Heat Set Acrylic; S: Silk

**Figure 34:** Percent of designs including in solutions (model II-Interval data)

For example, 51% solutions choice design option 1 with material “Acrylic” in order to offer to customers while 58% solutions propose design option 1 with material “Heat Set Acrylic”.

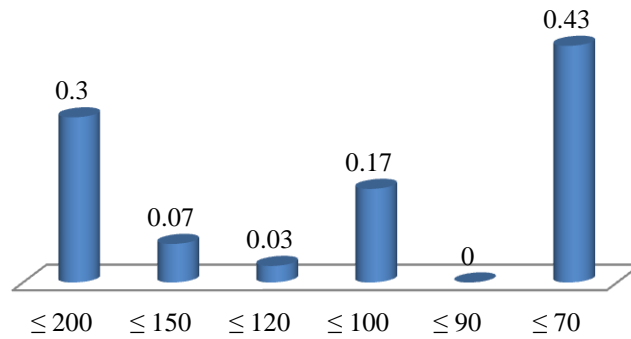
Next chart (Figure 36) shows percent of solutions offering the density options.



**Figure 35:** Percent of density options in solutions (model II-Interval data)

As this chart shows, 2 from 10 density options are proposed by all solutions. For instance, 70% solutions in the set of Pareto solutions offer density “700-1500”, while 100% solutions propose density “700-2550”.

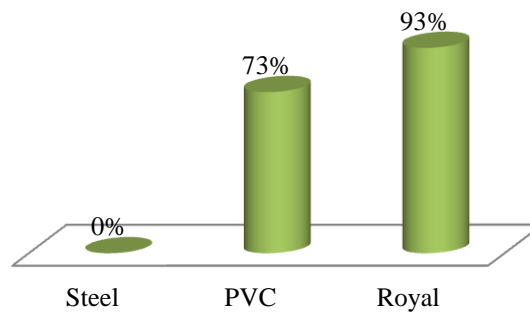
The next chart (Figure 36) displays percent of solutions proposing carpet tableau with different extent of size.



**Figure 36:** Percent of solutions that select an extent of Size (model II-Interval data)

Analysis shows solutions that propose less size, have more benefit and less customer value and while, solutions that offer more extent of size, have less benefit and more customer value. It can be due to existence of PI5 (control on degree of functionality) in objective 1 (customer value) that in this case try to increase extent of size offered to customers. Another reason it can be that with lower size, more types of material and design options that have more benefit, are selected.

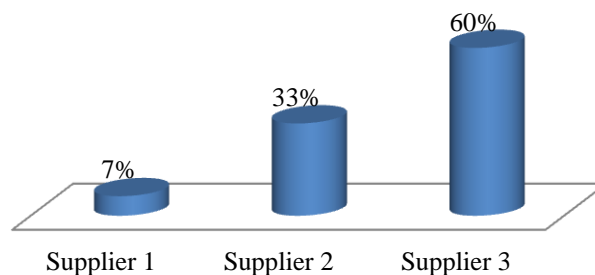
The next chart (Figure 37) displays percent of solutions proposing different panels.



**Figure 37:** Percent of panel options in solutions (model II-Interval data)

This chart shows that no solutions don't propose panel Steel.

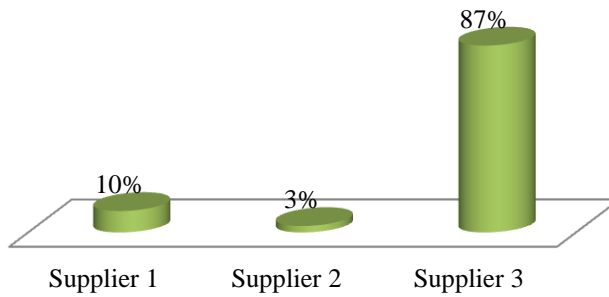
The next chart (Figure 38) displays percent of solutions selecting different suppliers of panels.



**Figure 38:** Percent of solution which select suppliers' panel (model II-Interval data)

The next chart (Figure 39) identifies percent of solutions that select different suppliers of materials.

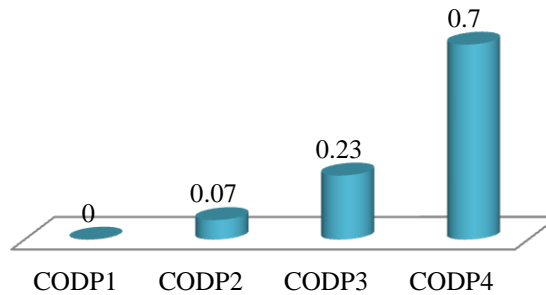




**Figure 39:** Percent of solution which select suppliers of material (model II-Interval data)

Output analysis of model shows that all solutions select weaving machine 2 and “Standard” packing to offer customers.

The last chart (Figure 40) displays percent of solutions selecting different CODPs.



**Figure 40:** Percent of solutions that select different CODP (model II-Interval data)

As this chart shows, majority of solutions select CODP4 as the selected CODP. Since position of CODP has significant effect on “Average delivery time” and this PI has most effect on objective one (because of both more weight and lower amount in comparison with other PIs), it is logical the majority of solutions select CODP4 in order to decrease negative effects of this PI on objective one.

In continuous, we represent the details of two solutions in Table 77.

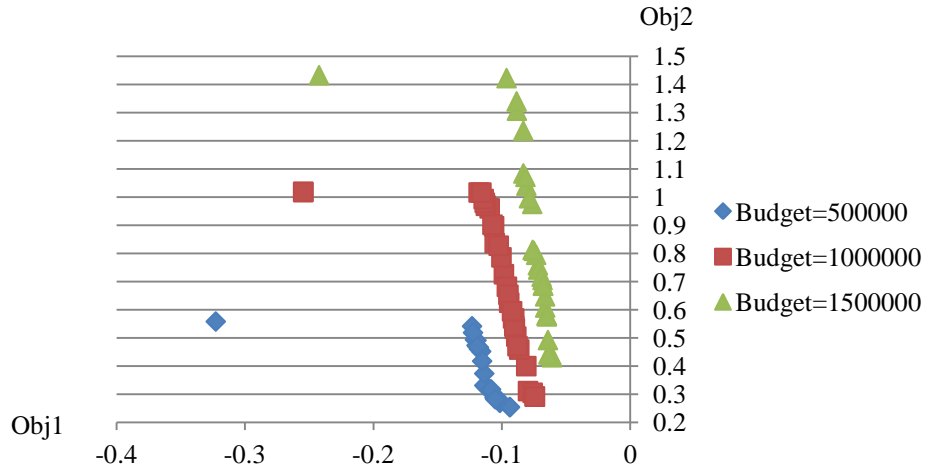
**Table 77.** Details of solutions for Model II with interval data

Solution		1			2		
Objective	1	[-0.1349,-0.09365]			[-0.10643,-.07136]		
	2	[0.9831,1.0012]			[0.49363,0.51391]		
PI11 (Quality/price)	1	[0.01904,0.02453]			[0.0121,0.01568]		
PI12(Average delivery time)	2	[2.819,3.623]			[2.7387,3.428]		
PI13 (Variety used)	3	0.2291			0.1746		
PI14 (Percent of demand satisfied)	4	[0.03762,0.04291]			[0.036675,0.04192]		
PI15(Control over functionality degree)	5	0.45			1		
PI21(Benefit)	1	[1966235,2002414]			[987257,1027825]		
Material		A	AHS	S	A	AHS	S
Design options	1	*	√	*	*	√	*

	2	*	√	*	*	*	*
	3	√	√	*	*	*	*
	4	√	√	*	*	√	*
	5	*	√	*	*	√	*
	6	*	√	*	*	√	*
	7	√	√	*	*	*	*
	8	*	√	*	*	√	*
	9	*	√	*	*	*	*
	10	*	√	*	*	√	*
	11	*	√	*	*	√	*
	12	√	√	*	*	*	*
	13	√	√	*	*	*	*
	14	√	√	*	*	√	*
	15	√	√	*	*	*	*
	16	*	√	*	*	√	*
	17	√	√	*	*	√	*
	18	*	√	*	*	√	*
	19	√	√	*	*	*	*
	20	*	√	*	*	√	*
	21	*	√	*	*	√	*
	22	*	√	*	*	√	*
	23	*	√	*	*	*	*
	24	√	√	*	*	√	*
	25	*	√	*	*	*	*
	26	√	√	*	*	√	*
	27	√	√	*	*	*	*
	28	√	√	*	*	√	*
	29	*	√	*	*	√	*
	30	√	√	*	*	√	*
	31	√	√	*	*	*	*
	32	√	√	*	*	√	*
	33	*	√	*	*	√	*
	34	*	√	*	*	√	*
	35	*	√	*	*	√	*
	36	√	√	*	*	*	*
	37	*	√	*	*	√	*
	38	*	√	*	*	√	*
	39	*	√	*	*	√	*
	40	√	√	*	*	√	*
	41	√	√	*	*	√	*
	42	*	√	*	*	*	*
	43	√	√	*	*	√	*
	44	√	√	*	*	√	*
	45	√	√	*	*	√	*
	46	*	√	*	*	*	*
	47	*	√	*	*	*	*
	48	*	√	*	*	√	*
	49	√	√	*	*	√	*
	50	*	√	*	*	√	*
Density	500,1200		*			*	
	500,1500		√			√	
	500,2550		√			√	
	700,1200		*			√	
	700,1500		*			√	
	700,2550		√			√	
	1000,2250		√			√	
	1000,2550		√			*	

		1000,2700	√	*
		1000,3000	√	*
Size		X=[50,200]	≤90	≤200
Panel		Steel	*	*
		PVC	√	*
		Royal	√	√
Pack		Standard	√	√
		Customize	*	*
Supplier material		1,2,3	3	1
Supplier panel		1,2,3	3	3
Machine		1,2	2	2
CODP		1,2,3,4	3	4
Inventory	Time	1	[0 582]	[0 216]
		2	[0 672]	[0 281]
		3	[0 684]	[0 282]
		4	[0 614]	[0 224]
Back order	Time	1	[0 1772]	[0 1754]
		2	[0 1491]	[0 1631]
		3	[0 1491]	[0 1631]
		4	[0 1720]	[0 1743]
Production level of Semi-manufactured products	Time	1	8692	8400
		2	8516	8400
		3	8503	8400
		4	8686	8398

We solve the model II for different budget for investigating effect of this constraint on the solutions. Figure 41 compares the values of objectives for different budgets.



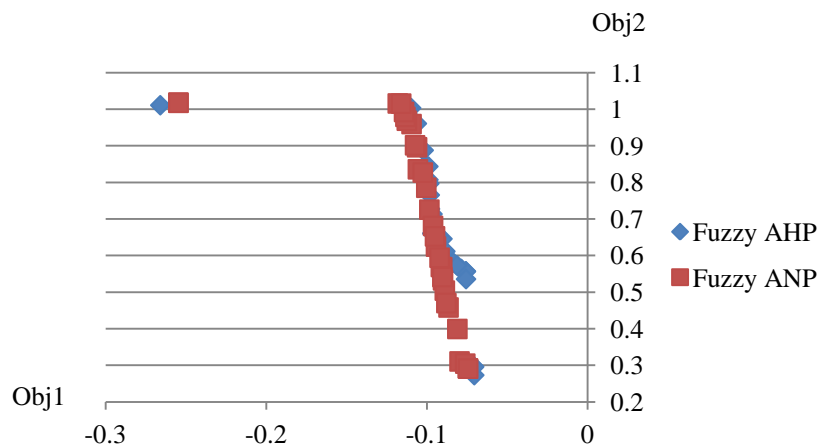
**Figure 41:** Comparing objectives for different budgets (model II-Interval data)

As Figure 41 shows, with increase of budget and naturally increase of objectives values, Pareto front move up that it can be due to increase of capability of company to offer components or feature and thus product varieties. Augmentation of product varieties can increase the value perceived by customers and company.

## 4.6 Model II with interval data with weights of PIs obtained from fuzzy AHP

So far, we considered effect of dependency between PIs in calculation of their weights and thus outputs of models. Here, we want to investigate effect of independence between PIs on outputs that is obtained through applying fuzzy AHP method (see Table 12 to compare the weights obtained from fuzzy ANP and fuzzy AHP).

At first, we compare amounts of two objectives with weights of PIs obtained through fuzzy ANP and fuzzy AHP (Figure 42).

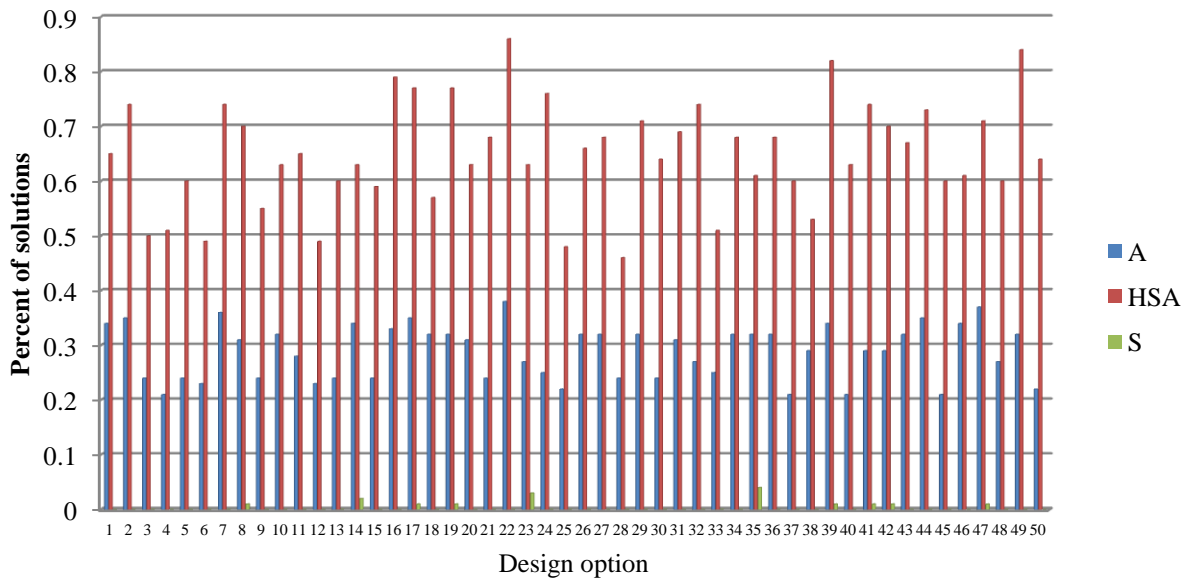


**Figure 42:** Comparison of objectives with weights obtained from fuzzy ANP and fuzzy AHP

Comparison of objectives recognizes a very slight difference in Pareto front of two states that it can be due to small changes in weights of PIs of objective 1 that practically has not significant effect on amounts of objective 1.

In continuous, we analyze details of solutions in Pareto set and represent them with charts as follows:

The first chart (Figure 43) shows percent of solutions offering the design with different material.

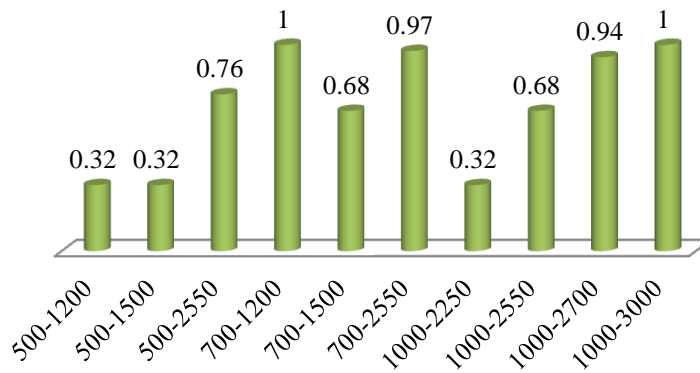


A: Acrylic; HSA: Heat Set Acrylic; S: Silk

**Figure 43:** Percent of designs including in solutions (model II- fuzzy AHP weight)

As chart shows, design options with material “Heat set Acrylic” dominate on other material. For example, 64% solutions choice design option 50 with material “Heat Set Acrylic” while only 22% solutions propose design option 50 with material “Acrylic” in order to offer to customers. Also, only a very small percentage of solutions propose design options with material Silk. For instance, only 4% solutions propose design option 35 with material “Silk”.

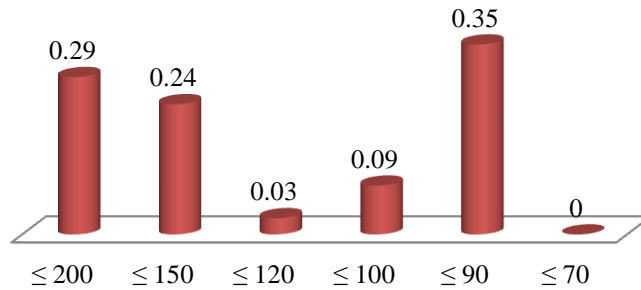
Next chart (Figure 44) shows percent of solutions offering the density options.



**Figure 44:** Percent of density options in solutions (model II- fuzzy AHP weight)

As this chart shows, two density options are proposed by 100% solutions.

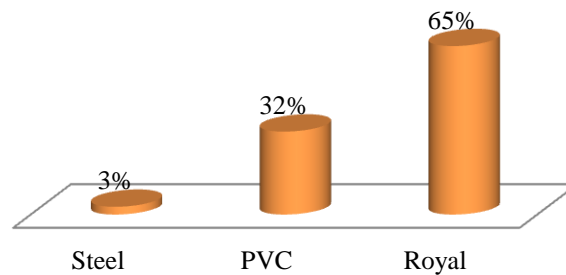
Next chart (Figure 45) displays percent of solutions proposing different extent of feature “size”.



**Figure 45:** Percent of solutions which select extent of Size (model II- fuzzy AHP weight)

35% solutions propose extent “≤ 90” as least size extent while 29% offer extent “≤ 200 “. Analysis of these two types of solutions demonstrates solutions that propose extent “≤ 200” have less interval benefit and more interval objective one (customer value) while solutions with extent “≤ 90” have more interval benefit and less interval objective one. The reason of this issue, it can be that solutions proposing extent “≤ 200”, only propose design options with material “Acrylic” that produce less benefit in comparison with material “Heat set Acrylic”. While, solutions that propose extent “≤ 90”, mainly offer design options with material “Heat set Acrylic” which produce more benefit.

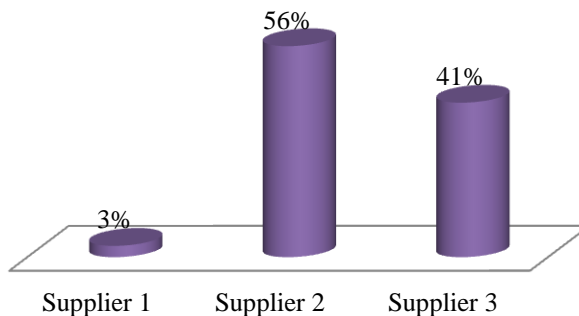
The next chart (Figure 46) displays percent of solutions that propose different panels.



**Figure 46:** Percent of panel options in solutions (model II- fuzzy AHP weight)

This chart shows that most solutions propose panel Royal while least solutions offer panel Steel.

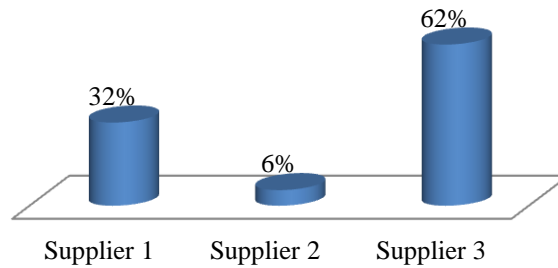
The next chart (Figure 47) displays percent of solutions selecting different suppliers of panels.



**Figure 47:** Percent of solution which select suppliers' panel (model II- fuzzy AHP weight)

As this chart shows, most solutions prefer supplier 2.

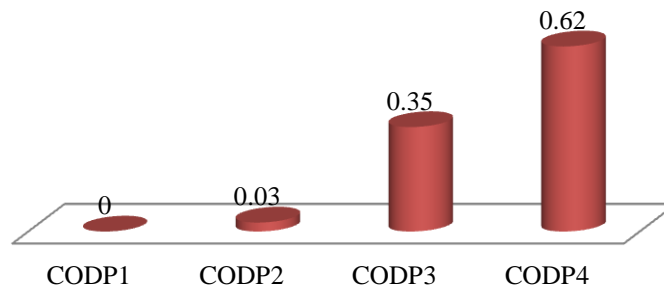
Next graph (Figure 48) identifies percent of solutions choosing suppliers of material. For material, supplier 3 is recognized with more percent in comparison with other suppliers.



**Figure 48:** Percent of solution which select suppliers' material (model II- fuzzy AHP weight)

Analysis of solutions shows that all solutions select weaving machine 2 to weave carpet tableaux. Also, all solutions select “Standard” packing to offer customers.

Finally, last chart (Figure 49) shows percent of CODPs selected by solutions.



**Figure 49:** Percent of solutions that select different CODP (model II- fuzzy AHP weight)

Comparing details of solutions through graphs of fuzzy ANP and fuzzy AHP recognize some differences.

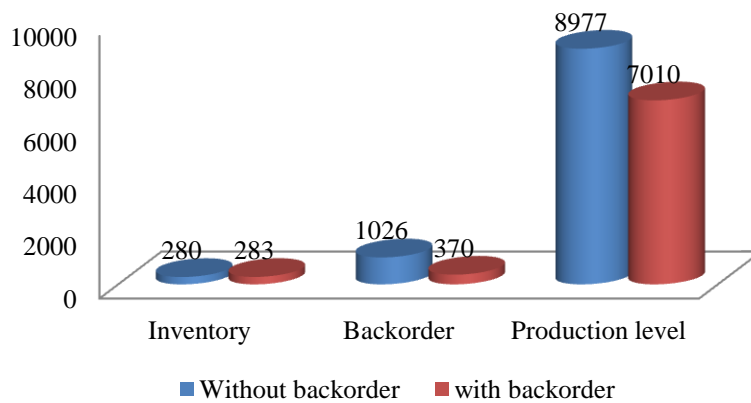
Graphs of design options, size, density options and suppliers of panels have significant changes. For example, percent of solutions which select design options with material “Acrylic” and “Heat set Acrylic” in Fuzzy ANP are near to each other, while in fuzzy AHP, percent of solutions which select design options with material “Heat set Acrylic” dominate on other material. But some graphs such as panels, suppliers' material and CODP position hold their trend. For instance, graph CODP in fuzzy ANP displays an increasing trend from CODP1 to CODP4 which this trend is kept for fuzzy AHP.

## 4.7 Model II with interval data with considering backorder constraint

In model II, we considered limitation on capacity of inventory. Investigation of solutions in the main model shows high levels of backorders. Since production level is assumed as a linear combination of upper and lower total demand, so, the model, naturally, determines production level which produces less inventory and more back order in order to satisfy inventory limitation. Here, we consider effect of backorder capacity on our model II.

Because of specifications of our case, inventory costs of semi-manufactured products for different CODP are near to each other. So, position of CODP has not significant effect on cost or benefit.

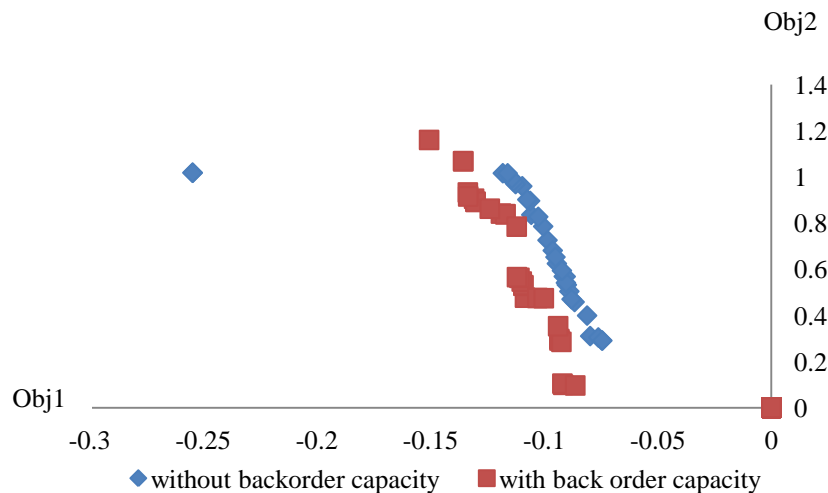
Graph 50 compares average inventory and backorder for two states with and without backorder capacity.



**Figure 50:** Comparison of average inventory, backorder and production level

As this graph shows, backorder amounts have significant reduction.

Graph 51 displays Pareto fronts for two states with and without backorder capacity.



**Figure 51:** Pareto fronts for two states with and without backorder capacity

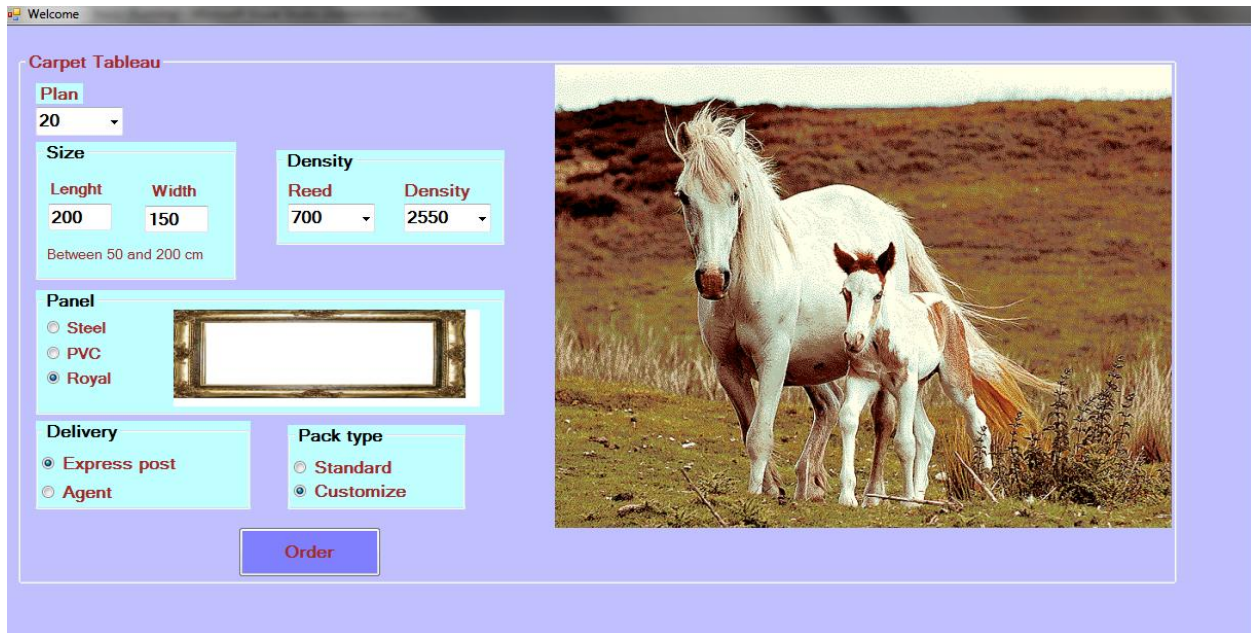


Comparison of two Pareto fronts shows higher front for more points without considering backorder capacity that it can be due to more production level for this state. Details of solutions in Pareto set are represented in Appendix E.

After selection of a solution among Pareto set solutions by decision makers, features and components selected can be used to offer customers. For this purpose, we built a primary version of a user interface in order to display the features offered to customers. This interface is capable to display design options with favorite size of customers (between offered ranges), panel types, density options (width and length), and extent of size, pack and delivery mode. With this user interface shown in Figure 52, customers can configure their orders.

To validate our model, we have to gather evidences that demonstrate usefulness of the proposed models. The main challenge for validating our models is to wait for long term implementation of MC process in company. But, one can find some evidences in the manufacturer’s current situation for verifying the model output (or least a part of model output).

Analysis of solutions obtained from solving models show solutions that propose design options with material “Heat set acrylic” and less size, have more benefit that it is conformance with real situations. Also, the panels Royal and PVC and Standard pack are more ordered by customers that are matched with our finding.



**Figure 52:** The primary customer interface developed

## 4.8 Our ranking method for Interval-valued alternatives

In final, we apply our method for ranking alternatives with applying a numeric example used in Shidpour et al. (2013).

A mobile manufacturer decides to introduce a new product for survival in a competitive market. So, the development & design department proposes 3 design alternatives with different specifications. The experts evaluate the alternatives based on three quantitative criteria cost,

Functional quality and time to market and three qualitative criteria Ergonomic, Serviceability and Aesthetic. The results of these evaluations are shown in Table 78.

**Table 78.** Evaluation of criteria

PI Alternative	Quantitative			Qualitative		
	Cost (\$/1000)	Time to market (day)	Functional quality	Safety	Serviceability	Aesthetic
1	[630 742]	[253 287]	[0.89 0.93]	VG	M	MP
2	[709 861]	[290 332]	[0.87 0.91]	MG	M	VG
3	[728 814]	[278 314]	[0.85 0.94]	M	MP	G

According to the proposed method, the following steps are established for quantitative and qualitative evaluation of design alternatives:

1. Construct the decision matrix. For this purpose, linguistic terms in Table 78 are converted to interval value with formula (5) and the interval value-based decision matrix is constructed which is shown in Table 79.

**Table 79.** Interval-valued decision matrix

Alternative	Cost	Time to market (day)	Functional quality	Safety	Serviceability	Aesthetic
1	[630 742]	[253 287]	[0.89 0.93]	[9.5 10.5]	[4 6]	[2 4]
2	[709 861]	[290 332]	[0.87 0.91]	[6 8]	[4 6]	[9.5 10.5]
3	[728 814]	[278 314]	[0.85 0.94]	[4 6]	[2 4]	[8 9.5]

2. Determine the reference vector based on ideal value for criteria.

Accordingly, we, at first, calculate the mean and radius of interval values with formulas (83) and (84). Then, ideal reference vector is constructed by determining the ideal value for each criterion according to formula (98). The values of elements of ideal reference vectors are calculated by considering its type “larger-the-better” and “smaller-the-better” and by using formulas (93) and (94), respectively. Criteria “Cost” and “Time to market” are from type of “smaller-the-better” and other criteria are from type of “larger-the-better”. Amounts of mean and radius of criteria for each solution and ideal reference vector are shown in Table 80.

**Table 80.** Amounts of mean and radius of criteria for each solution and ideal reference

Alternative	Cost		Time to market		Functional quality		Safety		Serviceability		Aesthetic	
	Mean	Radius	Mean	Radius	Mean	Radius	Mean	Radius	Mean	Radius	Mean	Radius
1	686	56	270	17	0.91	0.02	10	0.5	5	1	3	1
2	785	76	311	21	0.89	0.02	7	1	5	1	10	0.5
3	771	43	296	18	0.895	0.045	5	1	3	1	8.75	0.75
<b>Ideal Reference</b>	686	56	270	17	0.91	0.02	10	0.5	5	1	10	0.5

3. Compute the distance between elements of each solution vector with corresponding element of reference vector with formula (91) and construct the distance matrix that is shown in Table 81.

**Table 81.** Distance matrix

Alternative	Cost		Time to market		Functional quality		Safety		Serviceability		Aesthetic	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
1	0	112	0	34	0	0.04	0	1	0	2	5.5	8.5
2	0	231	3	79	0	0.06	1.5	4.5	0	2	0	1
3	0	184	0	61	0	0.08	3.5	6.5	0	4	0	2.5

4. Normalize the distance matrix with formulas (99) and (100) and construct the normalized distance matrix displayed in Table 82.

**Table 82.** Normalized distance matrix

Alternative	Cost		Time to market		Functional quality		Safety		Serviceability		Aesthetic	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
1	0	0.4848	0	0.4304	0	0.5	0	0.1538	0	0.5	0.6471	1
2	0	1	0.038	1	0	0.75	0.2308	0.6923	0	0.5	0	0.1176
3	0	0.7965	0	0.7722	0	1	0.5385	1	0	1	0	0.2941

5. Calculate the weighted normalized decision matrix R obtained by multiplying the normalized decision matrix by its related weights (Formula (101)). The weight is assumed as:  $W_1=0.256$ ;  $W_2=0.179$ ;  $W_3=0.261$ ;  $W_4=0.076$ ;  $W_5=0.048$ ;  $W_6=0.18$ . The weighted normalized matrix is developed as follows (Table 83):

**Table 83.** The weighted normalized matrix

Alternative	Cost		Time to market		Functional quality		Safety		Serviceability		Aesthetic	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
1	0	0.1241	0	0.1123	0	0.0895	0	0.0277	0	0.038	0.0311	0.048
2	0	0.256	0.0099	0.261	0	0.1343	0.0415	0.1246	0	0.038	0	0.0056
3	0	0.2039	0	0.2015	0	0.179	0.0969	0.18	0	0.076	0	0.0141

6. Final evaluation of solutions is firstly performed by using formula (102). Table 84 identifies amounts of final evaluation for each alternative as limits of interval and mean and radius.

**Table 84.** Amounts of final evaluation

Alternative	Lower	Upper	Mean	Radius
1	0.0311	0.4396	0.2354	0.2043
2	0.0514	0.8195	0.4355	0.384
3	0.0969	0.8546	0.4757	0.3788

Since  $E_i$  shows interval distance of solution  $i$  with reference vector, so, whatever these values are lower, these solutions are better. According definition 3.7, alternatives are ranked as follows:  
 $1 \succ 2 \succ 3$

## 4.9 Conclusion

The aim of our models was to find features/components for offering to customers with considering different objectives and constraints. For this purpose, some decision points have to be considered in different domains such as design product, process, supply chain and position of customer order decoupling point. We, in our thesis, integrated these decision points by trading-off between different PIs defined for customer value and enterprise value. Since nature of one of PIs is qualitative, we evaluated that with linguistic terms and used in our mathematical models.

We solved the models proposed for different states of weights of PI, budget limitation and inventory and backorder capacity and represent the graphs to analyze solutions and to show the options selected for some solutions. Analysis of solutions in the Pareto set appears the interesting conclusions as follows:

1. Majority of solutions offer two types of material: “Acrylic” and “Heat set acrylic” that is perfectly consistent with real situations.

2. Solutions proposing more design options with material “Heat set acrylic” and with less size, get less amount of objective 1 (called customer value) and more amount of benefit or objective 2 (called enterprise value) and while, solutions proposing more design options with material “Acrylic” and more size, get more amount of objective 1 and less amount of benefit or objective 2 (the reason is described in continuous). So, it can be concluded that if company want to obtain more benefit, it is better to propose design options with material “Heat set acrylic” and less size and if want to consider more value for customers, it has to offer more design options with more size.

## **5 Chapter 5: Conclusions and perspectives**

## 5.1. Our work

Today, customers have individual needs that want to be satisfied in a reasonable manner. In a mass customization environment, personalized products can be produced with configuring different component choices or varying extents for customizable features. One of first steps to implement MC is to know set of components and/or feature choices (thus product varieties) which can be offered to customers. It issue affects on strategies, plans and operations of a company that want to produce customizable products. Indeed, the company develops his next activities in mass customization process based on product varieties determined to offer customers.

Main evaluations for determining set of components/features are performed mostly with performance measurement “cost”. The cost dimension refers to the global price of a system, product or process (in monetary units). In most cases, it remains the most prevailing or final decision-making criterion.

Because the cost (or benefits) measurements have been largely studied in the past and are now widely used in practice, they have not been developed in the dissertation lonely. We in this thesis take in account the concept value that includes financial, environmental, social and emotional aspects of a system, product or process.

In this thesis, with respect to effect of product variety and CODP position on values perceived by customers and other parties in supply network, we proposed two qualitative and quantitative models (with and without considering time period) that integrates main decision points in product design, process, and supply chain design in MC process. In each two models, we deal with some decision points such as selection of components/features (thus product varieties), selection of the best CODP position in process, selection of manufacturing machine and selection of suppliers of material and components. We evaluate these decisions by developing a new method based on their influences on the customer value and enterprise value. For this purpose, we use qualitative and quantitative performance indicators in our model to evaluate these decision points with considering some interval data.

The output of the proposed models is expected to aid management to better meet both the individual needs of customer and organizational restrictions. Indeed, a set of solutions is given to management for decision making. Also, we proposed a method to rank solution with interval values.

## 5.2. Advantages

The advantages of the model are listed as follows:

1. Considering concurrent qualitative and quantitative evaluations in MC process. We used from an integrated manner to evaluate quantitative and qualitative PIs. Evaluation of functional quality together with other quantitative PIs helps to obtain more real solutions.
2. Integrating main decision point in different domains in MC process such as decision making about set of components/features offered, CODP position, manufacturing method and supplier selection.
3. Considering uncertainty from type of interval for some parameters to get closer to real situations. This issue causes that our model provides the upper and lower bounds of performance indicators which it facilitates decision-making process for managements.

Indeed, management can see the worst and best values of PIs for each decision including set of components/features offered to customers, the CODP position, manufacturing method and the suppliers selected.

4. Developing a computer program to run the proposed models and analyzing different states (such as weight of PIs and constraints). The model is capable to extract and to display solutions with all details. With this program, the decision makers can see amounts of objectives and all options selected for each solution that it can help to make decisions.

### **5.3. Future directions**

Although the models have the major benefits but it can improve with some propositions that we mention in following:

1. The case that we applied for our model is considered as an average case from view of number of potential product variety that has to be considered. For some cases with huge potential products, both data collection is difficult and the process of getting solutions is long time. So, a suggestion can be to develop methods for data clustering. We, now, are working on a new method for clustering the components/feature alternatives based on interval data to decrease size of solution space.
2. One of main parameters affecting on delivery time and thus customer value is waiting time of order to get service. Researchers have considered it in their problem by using queue theory but without considering some main decision point in product and supply chain. Although, considering this parameter complicates developing a model, but it is closer to real situations. For example, we are working on a production system in which potential suppliers can produce semi-finished items on a make-to-stock basis for a manufacturer that decide to customize the items on a make-to-order basis with potential manufacturing methods. In this problem, we consider role of products which wait to get service and assume that the suppliers stop producing items until the number waiting falls below a certain limit. The aim can be to determine the optimal point of differentiation and its optimal semi-finished goods buffer size and selection of proper supplier and manufacturing method.
3. Although concept value includes different aspects, but we considered a limited number of PIs for evaluation customer value and specially enterprise value due to restriction both in data collection and optimization problem. Researchers can develop the problem with other PIs in customer and especially for enterprise value (reviewed in Table 7) with using sufficient cases.
4. In this thesis, we paid attention to only values perceived by customers and enterprises as two main actors in value network. Values perceived by other benefit parties such as suppliers, distributors and stockholders can affect on evaluation of our problem. The models can be reconstructed from view two or more benefit parties. For this purpose, first, sufficient PIs for them are developed. To avoid more complexity resulted from large number of PIs in our problem, at first, one can determine one or two of most important PIs for benefit parties selected and then he can propose the new optimization models to get solution.
5. As said in the models, suppliers play important role in values perceived by customers through their effects on functional quality, cost and delivery time. In our thesis, we evaluated suppliers in integrated manner with other decision points based on quality, cost and delivery time. Dependence to type of manufacturing strategy make-to-stock (MTS),

assemble-to-order (ATO), make-to-order (MTO) and engineer-to-order (ETO) that affect on customization level, both criteria for supplier selection and importance degree of each of them can be different. For example, with MTS, cost, delivery and quality will be most important among criteria. In the ATO, suppliers have to work in close association with the company to forecast demand of semi-manufactured products. So, suppliers expect to carry some inventory of parts and components. Hence supplier's capacity and strategic fit between suppliers and manufacturer can be added to other criteria cost, delivery and quality that can affect on weight of each criterion. For other strategies which consider high degree of customization, it is important to build a strategic and long term relation between manufacturers and suppliers. This issue needs to consider other criteria such as adoption between aims, cultures and etc. So, an interesting extension for our problem can be considering criteria and their weights in our model with attention to manufacturing strategies MTS, ATO, MTO and ETO.



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- 7) Shidpour, H., Da Cunha, C, & Bernard, A. A new method for evaluation of design concept with interval data.
- 8) Shidpour, H., Da Cunha, C, & Bernard, A. A new interval-valued ranking method for evaluation of design concepts
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<sup>1</sup> About carpet tableau

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# **APPENDICES**

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# A: Fuzzy AHP and fuzzy ANP

## Fuzzy AHP

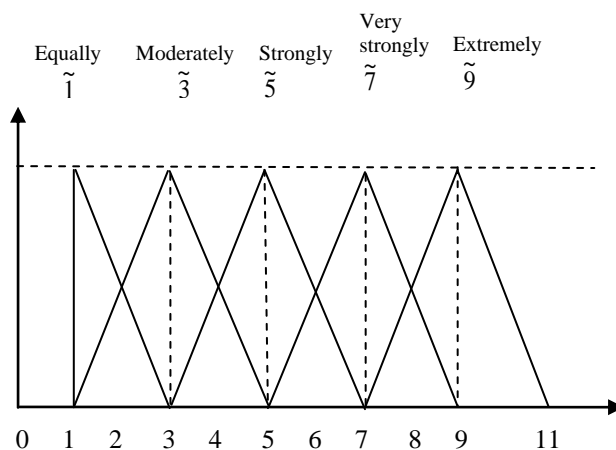
Analytic Hierarchy Process (AHP) proposed by Saaty in 1980 (Satty, 1980) is one of useful tools to solve a wide range of decision-making problems (Ayag<sup>ç</sup> & Özdemir, 2009; Ertay, Ruan, & Tuzkaya, 2006).

In AHP is assumed independence of the upper part from all its lower parts, and from the criteria or items in each level (Ayag<sup>ç</sup> & Özdemir, 2009). AHP is constructed based on pairwise comparisons of alternatives or criteria that are done by using verbal comparisons and equivalent numbers (see Table 85).

**Table 85.** Numbers Corresponding to Verbal Comparisons (Saaty, 1980)

1	Equal importance
3	Moderate importance of one over another
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values
	Use Reciprocals for Inverse Comparisons

The Fuzzy AHP (Van Laarhoven & Pedrycz, 1983) is identified as an advanced version of AHP which considers fuzziness and vagueness existing in many decision-making problems. In the Fuzzy AHP, triangular fuzzy numbers  $\tilde{1}$ ,  $\tilde{3}$ ,  $\tilde{5}$ ,  $\tilde{7}$  and  $\tilde{9}$  are used for pair wise comparisons (Figure 53) instead numbers of Table 85.



**Figure 53:** The membership functions of triangular fuzzy numbers

The Structure of this method is illustrated as follows:

- 1- To construct the pair wise comparison matrix by using triangular fuzzy numbers (TFN).

$$\tilde{F} = \begin{bmatrix} 1 & \tilde{f}_{12} & \dots & \tilde{f}_{1n} \\ \tilde{f}_{21} & 1 & \dots & \tilde{f}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{f}_{n1} & \tilde{f}_{n2} & \dots & 1 \end{bmatrix}, \quad \tilde{f}_{ij} = \frac{1}{\tilde{f}_{ji}} \quad \forall i, j$$

Where  $\tilde{f}_{ij}$  indicate the relative importance of each pair of elements in the same hierarchy.

2- Making  $\alpha$  – cut fuzzy comparison matrix.

For constructing  $\alpha$  – cut fuzzy comparison matrix, first the TFN (l, m, u) can be displayed by defining the interval of confidence level  $\alpha$  as:

$$\tilde{X}_\alpha = [l^\alpha, u^\alpha] = [(m-l)\alpha + l, -(u-m)\alpha + u] \quad \forall \alpha \in [0,1] \quad (1)$$

$$\tilde{F}^\alpha = \begin{bmatrix} 1 & \tilde{f}_{12}^\alpha & \dots & \tilde{f}_{1n}^\alpha \\ \tilde{f}_{21}^\alpha & 1 & \dots & \tilde{f}_{2n}^\alpha \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{f}_{n1}^\alpha & \tilde{f}_{n2}^\alpha & \dots & 1 \end{bmatrix}$$

Degree of satisfaction for comparison matrix is estimated by the index of optimism  $\mu$  determined by the decision maker (DM). The index of optimism is a linear convex combination (A. R. Lee & Adviser-Tonkay, 1995) as defined in the following equation:

$$f_{ij}^\alpha = \mu f_{iju}^\alpha + (1-\mu) f_{ijl}^\alpha \quad \forall \mu \in [0,1] \quad (2)$$

3- Computing eigenvector of  $\alpha$  – cut fuzzy comparison matrix.

For this purpose, all Eigen-values ( $\lambda$ ) of the comparison matrix F are found by solving the following equation:

$$\det(F - \lambda I) = 0 \quad (3)$$

By finding largest Eigen value of  $n \times n$  comparison matrix F,  $\lambda_{\max}$ , weight vector ( $\vec{w}$ ) is calculated by using following equation (Ayag˘ & Özdemir, 2009).

$$(\vec{F} - \lambda_{\max} I)\vec{w} = 0 \quad \text{or} \quad \vec{F} \cdot \vec{w} = \lambda_{\max} \vec{w} \quad (4)$$

4- Computing consistency ratio (CR) for each judgment matrix.

The consistency is an important concept for evaluating validation of output of the AHP and is defined as relation between the elements of pair wise comparison:

$$f_{ij} \times f_{jk} = f_{ik} \quad (5)$$

Consistency ratio (CR) is a measurement which can be evaluated if the pairwise assessments of parameters are sufficiently consistent. Before calculating CR, first consistency index (CI) is assessed:

$$\text{Consistency index: } CI = \frac{\lambda_{\max} - n}{n - 1} \quad (6)$$

Where n is matrix dimension. Consistency ratio (CR) of compromise matrix is defined as follows:

$$CR = \frac{CI}{RI} \quad (7)$$

where RI (random consistency index) is average index for randomly generated weights and obtained from table of RI (Saaty, 1980), by considering matrix dimension.

The DMs' judgment is acceptable when  $CR < 10\%$ , otherwise pair wise comparison process for rejected matrixes should be repeated.

### **Fuzzy ANP**

Many decision-making problems cannot be structured hierarchically because of existence a complex relation or inter-dependency between elements of a level (Saaty, 1996). Saaty proposed ANP to solve the problem of dependency among alternatives or criteria (Lee & Kim, 2000).

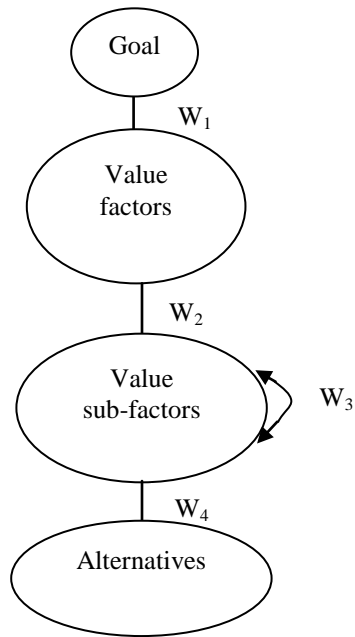
Fuzzy ANP is a Fuzzy multi-criteria decision-making (MCDM) tool that considers fuzziness and vagueness existing in many decision-making problems. A good review of the fuzzy ANP was presented by (Etati, Sadi-Nezhad, & Moghadam-Abyaneh, 2011).

The steps 1 and 2-“model construction and problem structuring” and “pairwise comparison matrices to get priority vectors” - for fuzzy ANP is same the fuzzy AHP. Other steps are expressed as follows:

Step3. To build pairwise comparison matrices to reflect the interdependencies in network.

In the case of interdependencies, elements affecting on other elements are selected as controlling elements. The pairwise comparisons are constructed with respect to control criteria and in their consistency are checked by calculating consistency ratios.

A network representation of the problem is represented in Figure 54 that illustrates hierarchies and inner dependence within clusters and Sub-factors. The goal is indicated in the first level; the value factors and value sub-factors are found in the second and third levels, respectively. The last level is composed of the alternatives.



**Figure 54:** Network representation of dependency between factors

The  $W_1$ ,  $W_2$ ,  $W_3$  and  $W_4$  in Figure 54 show the relationship between levels of a decision-making problem denoted by sub-matrices for evaluation of super-matrix of the relative importance weights. With respect to Figure 54, the super-matrix is constructed as follows:

$$W = \begin{matrix} \text{Goal} \\ \text{Value factors} \\ \text{Value sub-factors} \\ \text{Alternatives} \end{matrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ w_1 & 0 & 0 & 0 \\ 0 & w_2 & w_3 & 0 \\ 0 & 0 & w_4 & I \end{pmatrix}$$

In this matrix,  $W_1$ ,  $W_2$  and  $W_4$  are vectors that characterize the effect of the goal on value factors, value factors on value sub-factors and value sub-factors on alternatives, respectively.  $W_3$  shows a matrix that represents the inner dependence of the sub-factors, respectively.

In order to obtain the weight of the degree of influence among the criteria, we show the procedure by using the matrix manipulation based on Saaty and Takizawa's concept (Saaty & Takizawa, 1986) instead of Saaty's super matrix (Saaty, 1996).

Using the above notations, the priorities of the sub-factors ( $W_c$ ) are calculated by multiplying  $W_1$ ,  $W_2$  and  $W_3$ . The overall priorities of the alternatives are obtained by multiplying  $W_c$  and  $W_4$ .

**Step V.** Rank the alternatives.

The obtained values for alternatives rows in super-matrix show priority weight of them. In order to rank alternatives, these values must be normalized.

## B: Evaluation of sub-function 1 (aesthetic)

One of main elements affecting on Aesthetic function in carpet tableau is conformance between design options and colors used. This sub-function is evaluated by a carpet expert with linguistic terms shown in Table 86. For example, conformance between design option 1 and the colors used is evaluated “Medium”.

**Table 86.** Evaluation of conformance between design and colors

Design option No	Poor	Medium	Good	Very Good
1		√		
2				√
3			√	
4		√		
5				√
6				√
7		√		
8			√	
9		√		
10				√
11				√
12		√		
13			√	
14		√		
15				√
16	√			
17			√	
18				√
19		√		
20		√		
21			√	
22	√			
23				√
24		√		
25	√			
26				√
27		√		
28			√	
29				√
30		√		
31				√
32			√	
33		√		
34				√
35			√	
36	√			
37	√			
38		√		
39			√	
40		√		
41				√
42		√		
43				√

44	√			
45				√
46			√	
47		√		√
48			√	
49		√		
50				√



# C: Data collection for demand

In this appendix, we describe the method to get data. Since one of aims of our model is to determine the optimum (or near optimum) number of product varieties offering to customers, so, we need data for some parameters such as demand for all these product varieties. Due to large amount of data, it is not possible getting all data for all product varieties. So, we proposed a method to estimate data for demand.

For prediction of demand for all potential product varieties, we, at first, asked one of experts company to estimate demand for 50 type of design options with types of material used in the carpet tableau (Table 87) as a basic to evaluation other product varieties. It is noted that the demand values are predicted with an upper (U) and lower (L) limit (interval data).

**Table 87.** Total demand for each design option with different material

No	Acrylic		Heat Set Acrylic		Silk	
	L	U	L	U	L	U
1	600	1000	1200	1500	100	200
2	600	1000	1200	1500	100	200
3	600	1000	1200	1500	100	200
4	600	1000	1500	2000	100	200
5	600	1000	1500	2000	100	200
6	600	1000	1200	1500	150	250
7	600	1000	1200	1500	150	250
8	600	1000	1400	1700	150	250
9	600	1000	1400	1700	150	250
10	600	1000	1400	1700	150	250
11	600	1000	1500	2000	150	250
12	600	1000	1500	2000	150	250
13	800	1200	1500	2000	150	250
14	800	1200	1200	1500	100	200
15	800	1200	1200	1500	100	200
16	800	1200	1200	1500	100	200
17	600	1000	1500	2000	100	200
18	400	600	1500	2000	100	200
19	400	600	1500	2000	100	200
20	600	800	1500	2000	100	150
21	600	800	1500	2000	100	150
22	600	1000	1500	2000	100	150
23	600	1000	1200	1500	100	150
24	400	600	1200	1500	100	150
25	600	1000	1500	1800	100	150
26	600	1000	1500	1800	100	150
27	600	1000	1500	1800	100	150
28	600	1000	1500	1800	100	150

29	600	1000	1500	1800	150	200
30	600	1000	1200	1500	150	200
31	600	1000	1200	1500	150	200
32	400	600	1500	2000	150	200
33	400	600	1500	2000	150	200
34	600	1000	1500	2000	150	200
35	600	1000	1500	2000	150	200
36	600	1000	1600	2000	150	200
37	400	600	1600	2000	100	150
38	400	600	1600	2000	100	150
39	400	600	1600	2000	100	150
40	600	1000	1500	2000	100	150
41	600	1000	1500	2000	100	150
42	600	1000	1600	2000	100	150
43	600	1000	1600	2000	100	150
44	600	1000	1600	2000	100	150
45	400	600	1500	2000	100	150
46	400	600	1500	2000	120	150
47	400	600	1500	2000	120	150
48	400	600	1500	2000	120	150
49	400	600	1500	2000	120	150
50	400	600	1500	2000	120	150

Since combination of material and design options constructs different product varieties, from the smallest to largest size and density, different panel, packing and delivery type, so we proposed a method to get the estimated demands of other product varieties. For this purpose, we asked from company's expert to estimate percent of demand products with a specific customizable component or feature shown in Table 88. For example, percent of demand for a carpet tableau with density "500, 1200" is 0.02 which it means only 0.02 customers select this density.

**Table 88.** Ratios used to predict demand for product varieties

Feature	Option	Ratio
Density type (width, length) ( $W_d$ )	500,1200	0.02
	500,1500	0.06
	500,2550	0.07
	700,1200	0.1
	700,1500	0.15
	700,2550	0.2
	1000,2250	0.09
	1000,2550	0.11
	1000,2700	0.1
	1000,3000	0.1
Size ( $W_s$ )	50*70	0.3
	60*90	0.2
	70*100	0.15
	80*100	0.15
	100*120	0.08

	120*150	0.07
	150*2	0.05
Panel ( $W_{pan}$ )	Steel	0.1
	PVC	0.5
	Royal	0.4
Packing ( $W_{pac}$ )	Standard	0.6
	Customized	0.4

The demand for a product variety is obtained as follows:

$$W_{product} = D_b * W_d * W_s * W_{pan} * W_{pac} \quad (103)$$

Where,  $D_b$  is basic demand in Table 87. To better understanding, we show our method with an example. Assume  $D_b=600$  be lower bound of total demand of products including design option 1 and Acrylic yarn (Row 1 in Table 87). Demand for a product variety with design model 1, Acrylic yarn, Density option 10(1000, 3000), size 1(50\*70), panel 1(steel) and packing 1(Standard) is calculated based to Formula (103):

$$W_{product} = 600 * 0.1 * 0.3 * 0.1 * 0.6 \cong 1$$

In the same way, demands for all product varieties are predicted.

# D: The code of program

In this appendix, we express structure of coding in Visual studio.net 2008 for the proposed model II and represent the major functions used in the program.

```
//Imporitng data with user unterface and databank//
```

```
Imports System.Data
Imports System.Data.OleDb
Imports System.Drawing.Font
Public Class Form1
    Dim mc As Single = 0.6
    Dim pm As Single = 0.05
    Dim ns As Short = 50
    Dim m1 As Short = Math.Round(ns * mc / 2)
    Dim m2 As Short = Math.Round(ns * pm) + 1
    Dim schrom As Short
    Dim maxt = 4
    Dim slevel As Single = 0.5
    Dim ncodp As Short = 4
    Dim nsupplier1 As Short = 3
    Dim nsupplier2 As Short = 3
    Dim nmachine As Short = 2
    Dim nsource As Short = 7
    Dim Budget As Integer = InputBox("Enter Budget", "Budget constraint")
    Dim nvar() As Short = {3, 50, 10, 7, 3, 2, 2}
    Dim p1(ns + 2 * m1 + m2 - 1, 5, 1), qwip1(ns + 2 * m1 + m2 - 1, maxt, nvar(0) - 1, 1), qwip2(ns + 2 * m1 + m2 - 1, maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, 1), qwip3(ns + 2 * m1 + m2 - 1, maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, 1), qwip4(ns + 2 * m1 + m2 - 1, maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, nvar(5) - 1, 1), Dwipl3(0), Dwipu3(0), sumwip3(maxt, nvar(0) - 1, 1), sumwip71(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1), sumwip72(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1), sumwip81(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1), sumwip82(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, nvar(5) - 1), sumwip91(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, nvar(5) - 1), sumwip92(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, nvar(5) - 1) As Single
    Dim front1(ns + 2 * m1 + m2 - 1, 92), front2(ns + 2 * m1 + m2 - 1, 88), e1, t, CODPf(ns + 2 * m1 + m2 - 1), maxdesign(ns + 2 * m1 + m2 - 1, maxt, nvar(0) - 1) As Short
    Dim fg1(ns + 2 * m1 + m2 - 1, 1), fg2(ns + 2 * m1 + m2 - 1, 1), sumf1(100, maxt, 1), backf(100, maxt, 1), TD(1), pbft(100, maxt, 1), pafit(100, maxt, 1) As Single
    Dim Sumord(1) As Integer

    Private Sub Button1_Click_1(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles Button1.Click

        Dim CODP() As Short = {1, 2, 3, 4}
        TextBox21.Text = InputBox("Enter W11", "Weight of PIs")
        TextBox22.Text = InputBox("Enter W12", "Weight of PIs")
        TextBox23.Text = InputBox("Enter W13", "Weight of PIs")
        TextBox24.Text = InputBox("Enter W14", "Weight of PIs")
        TextBox25.Text = InputBox("Enter W15", "Weight of PIs")
        TextBox26.Text = InputBox("Enter W21", "Weight of PIs")
        TextBox28.Text = InputBox("Enter Confidence Level", "Confidence Level")
        TextBox27.Text = Budget
    End Sub
End Class
```

Values of this inputs are displayed in part 5 shown in Figure 2.

```
Dim we1(5) As Single
we1(0) = TextBox21.Text
```

```

we1(1) = TextBox22.Text
we1(2) = TextBox23.Text
we1(3) = TextBox24.Text
we1(4) = TextBox25.Text
we1(5) = TextBox26.Text

```

```

Dim schrom, npop As Short
Dim nproduct, i As Integer
Dim nvariety, j As Short
Dim vsource() As Short = {3, 1, 3500, 1, 1, 1, 3, 2, 2}
Dim maxF(5, 1), tmacmin(1) As Single
Dim wtarakom() As Single = {0.02, 0.06, 0.07, 0.1, 0.15, 0.2, 0.09, 0.11, 0.1, 0.1}
Dim wsize() As Single = {0.3, 0.2, 0.15, 0.15, 0.08, 0.07, 0.05}
Dim wpanel() As Single = {0.1, 0.5, 0.4}
Dim wpack() As Single = {0.6, 0.4}
Dim wdelivery() As Single = {0.3, 0.7}

```

```

tmacmin(0) = 1.43
tmacmin(1) = 1.5
maxF(1, 0) = 200
maxF(1, 1) = 300
maxF(5, 0) = 2 * (10 ^ 6)
maxF(5, 1) = 5 * (10 ^ 6)
maxF(0, 0) = 7
maxF(0, 1) = 7
maxF(2, 0) = 1
maxF(2, 1) = 1
maxF(3, 0) = 1
maxF(3, 1) = 1
maxF(4, 0) = 1
maxF(4, 1) = 1

```

```

nproduct = 1
For v = 0 To nope - 1
    nproduct = nproduct * vsource(v)
Next
For i = 0 To nsource - 1
    nvariety = nvariety + nvar(i)
Next
schrom = ncodp + nvariety + nsupplier1 + nsupplier2 + nmachine + maxt - 1
Dim r1, Fr(ns + 2 * m1 + m2 - 1) As Short
Dim n2(ns + 2 * m1 + m2 - 1), nr1 As Short
Dim product1(ncodp - 1, nsupplier1 - 1, nsupplier2 - 1, nmachine - 1, nproduct - 1, 4, 1) As Single
Dim Obj1(ns + 2 * m1 + m2 - 1, 1), Obj2(ns + 2 * m1 + m2 - 1, 1), Tsum(5, 1) As Single
Dim product(ns + 2 * m1 + m2 - 1, nproduct - 1) As Short
Dim mat(ns - 1, schrom) As Integer
Dim pool(ns + 2 * m1 + m2 - 1, schrom) As Short
Dim sort1(nproduct - 1), no As Short
Dim fitp(ns + 2 * m1 + m2 - 1), dis(ns + 2 * m1 + m2 - 1), finalg1(ns - 1, 1), finalg2(ns - 1, 1), Alfa As Single
Dim size(.) As Single = {{0.5, 0.7}, {0.6, 0.9}, {0.7, 1.0}, {0.8, 1.0}, {1.0, 1.2}, {1.2, 1.5}, {1.5, 2.0}}
Dim Tmac3(nmachine - 1, nvar(2) - 1, nvar(3) - 1) As Single
Dim norder1(1), norder2(1), tset3(nmachine - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1) As Single
Dim cpanel(nvar(0) - 1, nvar(3) - 1) As Single
Dim defrate(8), Dpnew(maxt, nproduct - 1), Dpnew2(maxt, nproduct - 1), norder(maxt, nproduct - 1),
norder12(maxt, nproduct - 1), CustomizationTime(1), price1(nproduct - 1) As Single
Dim F11(99, 1), F12(1, 9, 1), F13(6, 1), F14(2, 2, 1), F15(2, 2, 1), F21(2, 2, 1), F22(1, 1), F31(1, 9, 1), F41(1, 9,
1) As Single
Dim h11(nvar(1) - 1), h2(nmachine - 1, nvar(2) - 1), h4(nsupplier2 - 1, nvar(4) - 1), h5(nvar(0) - 1, nsupplier1 -
1), h6(nvar(0) - 1, nsupplier1 - 1), h7(nmachine - 1) As Object
Dim mean1(ns - 1), mean2(ns - 1), var1(ns - 1), var2(ns - 1) As Single

```

```
Dim mean3(ns + 2 * m1 + m2 - 1), mean4(ns + 2 * m1 + m2 - 1), var3(ns + 2 * m1 + m2 - 1), var4(ns + 2 * m1 + m2 - 1) As Single
```

```
// Getting data from data bank Access//
```

```
Dim strsql20, strsql21, strsql22, strsql23, strsql24, strsql25, strsql19, strsql26 As String
Dim strcon1 As String
strcon1 = "Provider=Microsoft.ACE.OLEDB.12.0;" & "Data Source=G:\PhD-nantes\alie-for a new
article\thesis model\DATA for thesis\thesis-carpet-new.accdb"
Dim con1 As New OleDbConnection(strcon1)
con1.Open()
strsql26 = "select*from [Cpanel]"
strsql25 = "select*from [F2]"
strsql24 = "select*from [NF11]"
strsql23 = "select*from [price]"
strsql22 = "select*from [NTmac]"
strsql21 = "select*from [Tope3]"
strsql20 = "select*from [NDp1]"
strsql19 = "select*from [NTset]"
Dim da26 As New OleDbDataAdapter(strsql26, con1)
Dim da25 As New OleDbDataAdapter(strsql25, con1)
Dim da24 As New OleDbDataAdapter(strsql24, con1)
Dim da23 As New OleDbDataAdapter(strsql23, con1)
Dim da22 As New OleDbDataAdapter(strsql22, con1)
Dim da21 As New OleDbDataAdapter(strsql21, con1)
Dim da20 As New OleDbDataAdapter(strsql20, con1)
Dim da19 As New OleDbDataAdapter(strsql19, con1)
Dim ds20, ds21, ds22, ds23, ds24, ds25, ds19, ds26 As New DataSet()
da26.Fill(ds26, "[Cpanel]")
da25.Fill(ds25, "[F2]")
da24.Fill(ds24, "[NF11]")
da23.Fill(ds23, "[price]")
da22.Fill(ds22, "[NTmac]")
da21.Fill(ds21, "[Tope3]")
da20.Fill(ds20, "[NDp1]")
da19.Fill(ds19, "[NTset]")
```

```
// Calculation of interval value of functions in PI12//
```

```
Alfa = TextBox28.Text
For i = 0 To nvar(1) - 1
    h11(i) = ds24.Tables("[NF11]").Rows(i)(1) 'Conformance between design and colors
    If h11(i) = "VG" Then
        F11(i, 0) = 0.2 * Alfa + 0.65
        F11(i, 1) = 1 - (0.15 * Alfa)
    ElseIf h11(i) = "G" Then
        F11(i, 0) = 0.2 * Alfa + 0.45
        F11(i, 1) = 0.85 - (0.2 * Alfa)
    ElseIf h11(i) = "M" Then
        F11(i, 0) = 0.15 * Alfa + 0.3
        F11(i, 1) = 0.6 - (0.15 * Alfa)
    ElseIf h11(i) = "P" Then
        F11(i, 0) = 0.2 * Alfa
        F11(i, 1) = 0.4 - (0.2 * Alfa)
    End If
Next

For j = 0 To nvar(2) - 1
    h2(0, j) = ds24.Tables("[NF11]").Rows(j)(5) 'Tissue density (the length and width)
```

```

If h2(0, j) = "VG" Then
  F12(0, j, 0) = 0.2 * Alfa + 0.65
  F12(0, j, 1) = 1 - (0.15 * Alfa)
ElseIf h2(0, j) = "G" Then
  F12(0, j, 0) = 0.2 * Alfa + 0.45
  F12(0, j, 1) = 0.85 - (0.2 * Alfa)
ElseIf h2(0, j) = "M" Then
  F12(0, j, 0) = 0.15 * Alfa + 0.3
  F12(0, j, 1) = 0.6 - (0.15 * Alfa)
ElseIf h2(0, j) = "P" Then
  F12(0, j, 0) = 0.2 * Alfa
  F12(0, j, 1) = 0.4 - (0.2 * Alfa)
End If
Next

For i = 0 To nvar(4) - 1
  For j = 0 To nsupplier2 - 1
    h4(i, j) = ds24.Tables("[NF11]").Rows(j)(i + 2) 'panel
    If h4(i, j) = "VG" Then
      F14(i, j, 0) = 0.2 * Alfa + 0.65
      F14(i, j, 1) = 1 - (0.15 * Alfa)
    ElseIf h4(i, j) = "G" Then
      F14(i, j, 0) = 0.2 * Alfa + 0.45
      F14(i, j, 1) = 0.85 - (0.2 * Alfa)
    ElseIf h4(i, j) = "M" Then
      F14(i, j, 0) = 0.15 * Alfa + 0.3
      F14(i, j, 1) = 0.6 - (0.15 * Alfa)
    ElseIf h4(i, j) = "P" Then
      F14(i, j, 0) = 0.2 * Alfa
      F14(i, j, 1) = 0.4 - (0.2 * Alfa)
    End If
  Next
Next

For i = 0 To nvar(0) - 1
  For j = 0 To nsupplier1 - 1
    h5(i, j) = ds24.Tables("[NF11]").Rows(j)(i + 7) 'yarn(Smooth and rough)

    If h5(i, j) = "VG" Then
      F15(i, j, 0) = 0.2 * Alfa + 0.65
      F15(i, j, 1) = 1 - (0.15 * Alfa)
    ElseIf h5(i, j) = "G" Then
      F15(i, j, 0) = 0.2 * Alfa + 0.45
      F15(i, j, 1) = 0.85 - (0.2 * Alfa)
    ElseIf h5(i, j) = "M" Then
      F15(i, j, 0) = 0.15 * Alfa + 0.3
      F15(i, j, 1) = 0.6 - (0.15 * Alfa)
    ElseIf h5(i, j) = "P" Then
      F15(i, j, 0) = 0.2 * Alfa
      F15(i, j, 1) = 0.4 - (0.2 * Alfa)
    End If
  Next
Next

For i = 0 To nvar(0) - 1
  For j = 0 To nsupplier1 - 1
    h6(i, j) = ds24.Tables("[NF11]").Rows(j + 3)(i + 7) 'Yarn strength
    If h6(i, j) = "VG" Then
      F21(i, j, 0) = 0.2 * Alfa + 0.65
      F21(i, j, 1) = 1 - (0.15 * Alfa)
    ElseIf h6(i, j) = "G" Then
      F21(i, j, 0) = 0.2 * Alfa + 0.45

```

```

        F21(i, j, 1) = 0.85 - (0.2 * Alfa)
    ElseIf h6(i, j) = "M" Then
        F21(i, j, 0) = 0.15 * Alfa + 0.3
        F21(i, j, 1) = 0.6 - (0.15 * Alfa)
    ElseIf h6(i, j) = "P" Then
        F21(i, j, 0) = 0.2 * Alfa
        F21(i, j, 1) = 0.4 - (0.2 * Alfa)
    End If
Next
Next
For i = 0 To nmachine - 1
    h7(i) = ds24.Tables(["NF11"]).Rows(0)(i + 10) 'Quality tissues (tissue resistance)
    If h7(i) = "VG" Then
        F22(i, 0) = 0.2 * Alfa + 0.65
        F22(i, 1) = 1 - (0.15 * Alfa)
    ElseIf h7(i) = "G" Then
        F22(i, 0) = 0.2 * Alfa + 0.45
        F22(i, 1) = 0.85 - (0.2 * Alfa)
    ElseIf h7(i) = "M" Then
        F22(i, 0) = 0.15 * Alfa + 0.3
        F22(i, 1) = 0.6 - (0.15 * Alfa)
    ElseIf h7(i) = "P" Then
        F22(i, 0) = 0.2 * Alfa
        F22(i, 1) = 0.4 - (0.2 * Alfa)
    End If
Next

```

\*\*\*\*\*

## // Calculation of demand//

```

Dim hp, p4 As Single
For t1 = 1 To maxt
    For i = 0 To nvar(0) - 1
        For j1 = 0 To nvar(1) - 1
            For j2 = 0 To nvar(2) - 1
                For j3 = 0 To nvar(3) - 1
                    For a1 = 0 To nvar(4) - 1
                        For a2 = 0 To nvar(5) - 1
                            For a3 = 0 To nvar(6) - 1
                                p4 = i * nvar(1) * nvar(2) * nvar(3) * nvar(4) * nvar(5) * nvar(6) + j1 * nvar(2) * nvar(3) * nvar(4) * nvar(5) *
                                nvar(6) + j2 * nvar(3) * nvar(4) * nvar(5) * nvar(6) + j3 * nvar(4) * nvar(5) * nvar(6) + a1 * nvar(5) * nvar(6) + a2 *
                                nvar(6) + a3

                                If t1 = maxt Then
                                    norder(t1, p4) = Math.Ceiling(ds20.Tables(["NDp1"]).Rows(j1)(2 * i + 1) * wtarakom(j2) * wsize(j3) * wpanel(a1)
                                    * wpack(a2) * wdelivery(a3))
                                    norder12(t1, p4) = Math.Ceiling(ds20.Tables(["NDp1"]).Rows(j1)(2 * i + 2) * wtarakom(j2) * wsize(j3) *
                                    wpanel(a1) * wpack(a2) * wdelivery(a3))
                                Else
                                    norder(t1, p4) = Math.Ceiling((ds20.Tables(["NDp1"]).Rows(j1)(2 * i + 1) * wtarakom(j2) * wsize(j3) * wpanel(a1)
                                    * wpack(a2) * wdelivery(a3)) + 0.1 * norder(t1 - 1, p4))
                                    norder12(t1, p4) = Math.Ceiling((ds20.Tables(["NDp1"]).Rows(j1)(2 * i + 2) * wtarakom(j2) * wsize(j3) *
                                    wpanel(a1) * wpack(a2) * wdelivery(a3)) + 0.1 * norder12(t1 - 1, p4))
                                End If
                                Dpnew(t1, p4) = (size(j3, 0) * size(j3, 1)) * norder(t1, p4)
                                Dpnew2(t1, p4) = (size(j3, 0) * size(j3, 1)) * norder12(t1, p4)
                                price1(p4) = ds23.Tables(["price"]).Rows((j1 * 10 + j2))(i * 7 + j3 + 1)
                            Next
                        Next
                    Next
                Next
            Next
        Next
    Next
Next

```



```

Next
Next
Next
Next
Next

```

\*\*\*\*\*

**// Calculation of total demand //**

```

For t1 = 1 To maxt
  For i = 0 To nproduct - 1
    TD(0) = TD(0) + Dpnew(t1, i)
    TD(1) = TD(1) + Dpnew2(t1, i)
  Next
Next
//

```

\*\*\*\*\*

**// Calculation of some PIs for each unit product//**

```

For nc = 0 To ncodp - 1
  For s1 = 0 To nsupplier1 - 1
    For s2 = 0 To nsupplier2 - 1
      For m = 0 To nmachine - 1
Fitnessp(product1, nc, s1, s2, m, nvar, ncodp, Dpnew, Dpnew2, norder, norder12, TD, price1, F11, F12, F13, F14,
F15, F21, F22, F31, F41, size, tmacmin, nproduct)
      Next
    Next
  Next
Next

```

\*\*\*\*\*

**//Main body of algorithm//**

```

Dim jj As Short
For j = 0 To ns - 1
  generation4(pool, schrom, j, t2)
  For k = 0 To 5
    Tsum(k, 0) = 0
    Tsum(k, 1) = 0
  Next
  Fitness2a(pool, nvar, j, product1, maxF, Obj1, Obj2, we1, CODP, size, nvariety, Tsum, norder, norder12,
tmacmin, price1, schrom, nproduct)
Next

For p = 0 To ns - 1
  mean1(p) = (Obj1(p, 0) + Obj1(p, 1)) / 2
  var1(p) = Obj1(p, 1) - mean1(p)
  mean2(p) = (Obj2(p, 0) + Obj2(p, 1)) / 2
  var2(p) = Obj2(p, 1) - mean2(p)
Next

Rankint(ns, Fr, r1, mean1, mean2, var1, var2)
Dim h9(r1) As Short
Crowdisint2(ns, r1, Fr, Obj1, Obj2, dis, h9, mean1, mean2, var1, var2)

```

```

r2 = 1
npop = 100
For ng = 0 To npop
  crossever4(pool, ns, m1, schrom, ncodp, nproduct, nsupplier1, nsupplier2, nmachine, nvariety, nvar,
nsource, Fr, dis, CODP)
  For i = 0 To 2 * m1 - 1
    For k = 0 To 5
      Tsum(k, 0) = 0
      Tsum(k, 1) = 0
    Next
    Fitness2a(pool, nvar, i + ns, product1, maxF, Obj1, Obj2, we1, CODP, size, nvariety, Tsum, norder,
norder12, tmacmin, price1, schrom, nproduct)
  Next
  mutation12(pool, m2, m1, ncodp, ns, schrom, nproduct, nsupplier1, nsupplier2, nmachine, nvariety, nsource,
nvar, Fr, dis, CODP)
  For f = 0 To m2 - 1
    For k = 0 To 5
      Tsum(k, 0) = 0
      Tsum(k, 1) = 0
    Next
    Fitness2a(pool, nvar, f + 2 * m1 + ns, product1, maxF, Obj1, Obj2, we1, CODP, size, nvariety, Tsum,
norder, norder12, tmacmin, price1, schrom, nproduct)
  Next
  For p = 0 To ns + 2 * m1 + m2 - 1
    mean1(p) = (Obj1(p, 0) + Obj1(p, 1)) / 2
    var1(p) = Obj1(p, 1) - mean1(p)
    mean2(p) = (Obj2(p, 0) + Obj2(p, 1)) / 2
    var2(p) = Obj2(p, 1) - mean2(p)
  Next
  Rankint(ns + 2 * m1 + m2, Fr, r2, mean1, mean2, var1, var2) /Rank based on interval values/
  Dim h1(r2) As Short
  Crowdisint2(ns + 2 * m1 + m2, r2, Fr, Obj1, Obj2, dis, h1, mean1, mean2, var1, var2) /Calculation crowding
distance for interval values/
  If ng <> npop Then
    selectint(ns, r2, h1, m1, m2, schrom, mat, pool, finalg1, finalg2, Obj1, Obj2, Fr, dis)
  Else
    nr1 = h1(0)
  End If
Next

```

\*\*\*\*\*

## // Getting outputs//

```

Dim hr(ns + 2 * m1 + m2 - 1), e2, n1(nr1 - 1), m9(maxt, nvar(0) - 1) As Short
Dim control(100) As Single
Dim objf1(nr1 - 1, 1), objf2(nr1 - 1, 1), totalback(maxt, 1), sum1(maxt, 1), pbef(maxt, 1), paf1(maxt, 1) As Single
Dim g5(100, maxt, nvar(0) - 1, 100) As Short
Dim k3() As Object = {"Steel", "PVC", "Royal"}
Dim k4() As Object = {"Standard", "Customize"}
Dim np As Integer

e1 = 0
For k = 0 To ns + 2 * m1 + m2 - 1
  If Fr(k) = 1 Then
    e1 = e1 + 1
    ReDim Preserve n1(e1 - 1)
    n1(e1 - 1) = k + 1
    fg1(e1 - 1, 0) = Obj1(k, 0)
  End If
Next

```

```

fg1(e1 - 1, 1) = Obj1(k, 1)
fg2(e1 - 1, 0) = Obj2(k, 0)
fg2(e1 - 1, 1) = Obj2(k, 1)

```

```

End If
Next
checkrepeat(e1, fg1, fg2, n1)
e2 = 0
For t1 = 0 To nr1 - 1
  If n1(t1) <> 0 Then
    For q = 0 To schrom
      front1(t1, q) = pool(n1(t1) - 1, q)
      If q < 4 Then
        If front1(t1, q) = 1 Then
          CODPf(t1) = CODP(q)
        End If
      End If
    Next
    ListBox1.Items.Add(t1 + 1)
    For k = 0 To 5
      Tsum(k, 0) = 0
      Tsum(k, 1) = 0
    Next

```

Fitnessfinala(front1, nvar, t1, product1, maxF, objf1, objf2, we1, CODPf, size, nvariety, Tsum, norder, norder12, sum1, Dpnew, Dpnew2, m9, np, tmacmin, price1, totalback, schrom, pbef, paft, nproduct)

```

fg1(t1, 0) = objf1(t1, 0)
fg1(t1, 1) = objf1(t1, 1)
fg2(t1, 0) = objf2(t1, 0)
fg2(t1, 1) = objf2(t1, 1)
For k1 = 0 To 5
  p1(t1, k1, 0) = Tsum(k1, 0)
  p1(t1, k1, 1) = Tsum(k1, 1)
Next
For t5 = 1 To maxt
  sumf1(t1, t5, 0) = Math.Round(sum1(t5, 0), 2)
  sumf1(t1, t5, 1) = Math.Round(sum1(t5, 1), 2)
  pbef1(t1, t5, 0) = pbef(t5, 0)
  pbef1(t1, t5, 1) = pbef(t5, 1)
  paft1(t1, t5, 0) = paft(t5, 0)
  paft1(t1, t5, 1) = paft(t5, 1)
  For z1 = 0 To nvar(0) - 1
    maxdesign(t1, t5, z1) = m9(t5, z1)
  Next
  backf(t1, t5, 0) = backf(t1, t5, 0) + Math.Round(totalback(t5, 0), 2)
  backf(t1, t5, 1) = backf(t1, t5, 1) + Math.Round(totalback(t5, 1), 2)
  For i = 0 To nvar(3) - 1
    If front1(t1, ncodp + nvar(0) + nvar(1) + nvar(2) + i) = 1 Then
      t2 = i
      Exit For
    End If
  Next
  For h1 = 0 To nvar(0) - 1
    If sumwip3(t5, h1, 0) > 0 Then
      qwip1(t1, t5, h1, 0) = sumwip3(t5, h1, 0)
      qwip1(t1, t5, h1, 1) = sumwip3(t5, h1, 1)
    End If
  Next
  For z1 = 0 To nvar(0) - 1
    m9(t5, z1) = 0

```

```

Next
Next
End If
Next

```

```

*****

```

### //Displaying outputs in Excell//

```

Dim oExcel As Object
Dim oBook As Object
Dim oSheet1, osheet2, osheet3 As Object
oExcel = CreateObject("Excel.Application")
oBook = oExcel.Workbooks.Add

Dim objectives(3 * nr1 - 1, 29), design1(3 * maxt * nr1 - 1, 52 + 4 + 4), density1(3 * nr1 - 1, 13), Size1(3 * e1 -
1, 8) As Object
oSheet1 = oBook.Worksheets(1)
osheet2 = oBook.Worksheets(2)
osheet3 = oBook.Worksheets(3)

For i = 0 To nr1 - 1
  If CODPf(i) <> 0 Then
    objectives(3 * i, 0) = Format(i + 1)
    objectives(3 * i, 1) = fg1(i, 0)
    objectives(3 * i, 2) = fg1(i, 1)
    objectives(3 * i, 3) = fg2(i, 0)
    objectives(3 * i, 4) = fg2(i, 1)
    objectives(3 * i, 5) = p1(i, 0, 0)
    objectives(3 * i, 6) = p1(i, 0, 1)
    objectives(3 * i, 7) = p1(i, 1, 0)
    objectives(3 * i, 8) = p1(i, 1, 1)
    objectives(3 * i, 9) = p1(i, 2, 0)
    objectives(3 * i, 10) = p1(i, 2, 1)
    objectives(3 * i, 11) = p1(i, 3, 0)
    objectives(3 * i, 12) = p1(i, 3, 1)
    objectives(3 * i, 13) = p1(i, 4, 0)
    objectives(3 * i, 14) = p1(i, 4, 1)
    objectives(3 * i, 15) = p1(i, 5, 0)
    objectives(3 * i, 16) = p1(i, 5, 1)
    For f = 1 To maxt
      For q3 = 0 To nvar(0) - 1
        If maxdesign(i, f, q3) > 0 Then
          For q1 = 0 To maxdesign(i, f, q3) - 1
            g5(i, f, q3, q1) = front1(i, ncodp + nvar(0) + q1)
          Next
        End If
      Next
      findmin12(g5, maxdesign, i, f)
    Next
  End If
Next
For i = 0 To nr1 - 1
  If CODPf(i) <> 0 Then
    design1(12 * i, 0) = Format(i + 1)
    density1(3 * i, 0) = Format(i + 1)
    For f = 1 To maxt
      design1(12 * i + f - 1, 53) = sumf1(i, f, 0)
      design1(12 * i + f - 1, 54) = sumf1(i, f, 1)
    Next
  End If
Next

```

```

design1(12 * i + f - 1, 55) = backf(i, f, 0)
design1(12 * i + f - 1, 56) = backf(i, f, 1)
design1(12 * i + f - 1, 57) = pbefit(i, f, 0)
design1(12 * i + f - 1, 58) = pbefit(i, f, 1)
design1(12 * i + f - 1, 59) = pafitt(i, f, 0)
design1(12 * i + f - 1, 60) = pafitt(i, f, 1)
For j = 0 To nvar(0) - 1
    design1(12 * i + 4 * j + f - 1, 2) = Format(f)
    design1(12 * i + 4 * j, 1) = Format(j + 1)
    density1(3 * i + j, 1) = Format(j + 1)
    If maxdesign(i, f, j) > 0 Then
        For k = 3 To maxdesign(i, f, j) + 2
            design1(12 * i + 4 * j + f - 1, k) = g5(i, f, j, k - 3)
        Next
    End If
    If qwip1(i, f, j, 0) > 0 Then
        objectives(3 * i + j, 28) = qwip1(i, f, j, 0)
        objectives(3 * i + j, 29) = qwip1(i, f, j, 1)
    End If
Next
Next
For q1 = ncodp + nvar(0) + nvar(1) To ncodp + nvar(0) + nvar(1) + nvar(2) - 1
    If front1(i, q1) = 1 Then
        density1(3 * i, 2 + q1 - ncodp - nvar(0) - nvar(1)) = "√"
    Else
        density1(3 * i, 2 + q1 - ncodp - nvar(0) - nvar(1)) = "*"
    End If
Next
For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) To ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3)
+ nvar(4) - 1
    If front1(i, q1) = 1 Then
density1(3 * i + q1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3)), 12) = k3(q1 - (ncodp + nvar(0) + nvar(1) +
nvar(2) + nvar(3)))
    End If
Next
For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) To ncodp + nvar(0) + nvar(1) + nvar(2)
+ nvar(3) + nvar(4) + nvar(5) - 1
    If front1(i, q1) = 1 Then
density1(3 * i + q1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4)), 13) = k4(q1 - (ncodp + nvar(0) +
nvar(1) + nvar(2) + nvar(3) + nvar(4)))
    End If
Next
For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) To ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) - 1
    If front1(i, q1) = 1 Then
        For z = 0 To q1 - (ncodp + nvar(0) + nvar(1) + nvar(2))
            objectives(3 * i, 20 + z) = "√"
        Next
    Exit For
    End If
Next
For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) To ncodp + nvar(0)
+ nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 - 1
    If front1(i, q1) = 1 Then
objectives(3 * i, 17) = Val(q1 + 1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6)))
    Exit For
    End If
Next
For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 To
ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 + nsupplier2 - 1
    If front1(i, q1) = 1 Then

```

```

        objectives(3 * i, 18) = Val(q1 + 1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) +
nvar(5) + nvar(6) + nsupplier1))
        Exit For
    End If
Next
For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 + nsupplier2 To
ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 + nsupplier2 + nmachine -
1
    If front1(i, q1) = 1 Then
objectives(3 * i, 19) = Val(q1 + 1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) +
nsupplier1 + nsupplier2))
        Exit For
    End If
Next
    objectives(3 * i, 27) = CODPf(i)
End If

```

Next

```

osheet2.Range("A1").Value = "Solution"
osheet2.Range("B1").Value = "Material"
osheet2.Range("C1").Value = "Time"
osheet2.Range("D1").Value = "Design"
osheet2.Range("BB1").Value = "LInv"
osheet2.Range("BC1").Value = "UInv"
osheet2.Range("BD1").Value = "LBack"
osheet2.Range("BE1").Value = "UBack"
osheet2.Range("BF1").Value = "LPbCODP"
osheet2.Range("BG1").Value = "UPbCODP"
osheet2.Range("BH1").Value = "LPaCODP"
osheet2.Range("BI1").Value = "UPaCODP"
osheet2.Range("A2").Resize(3 * maxt * nr1, 61).Value = design1

```

```

osheet3.Range("A1").Value = "Solution"
osheet3.Range("B1").Value = "Material"

```

```

osheet3.Range("C1").Value = " 500" & "," & "1200"
osheet3.Range("D1").Value = " 500" & "," & "1500"
osheet3.Range("E1").Value = " 500" & "," & "2550"
osheet3.Range("F1").Value = " 700" & "," & "1200"
osheet3.Range("G1").Value = " 700" & "," & "1500"
osheet3.Range("H1").Value = " 700" & "," & "2550"
osheet3.Range("I1").Value = " 1000" & "," & "2250"
osheet3.Range("J1").Value = "1000" & "," & "2550"
osheet3.Range("K1").Value = " 1000" & "," & "2700"
osheet3.Range("L1").Value = " 1000" & "," & "3000"
osheet3.Range("M1").Value = " Panel"
osheet3.Range("N1").Value = " Pack"
osheet3.Range("A2").Resize(3 * nr1, 14).Value = density1

```

```

oSheet1.Range("U1").Value = " 50" & "," & "70"
oSheet1.Range("V1").Value = " 60" & "," & "90"
oSheet1.Range("W1").Value = " 70" & "," & "100"
oSheet1.Range("X1").Value = " 80" & "," & "100"
oSheet1.Range("Y1").Value = " 100" & "," & "120"
oSheet1.Range("Z1").Value = " 120" & "," & "150"
oSheet1.Range("AA1").Value = " 150" & "," & "200"
oSheet1.Range("AB1").Value = "CODP"
oSheet1.Range("AC1").Value = "Value Mat"

```

```

oSheet1.Range("A1").Value = "Solution"
oSheet1.Range("B1").Value = "LObj1"
oSheet1.Range("C1").Value = "UObj1"
oSheet1.Range("D1").Value = "LObj2"
oSheet1.Range("E1").Value = "UObj2"
oSheet1.Range("F1").Value = "LTime"
oSheet1.Range("G1").Value = "UTime"
oSheet1.Range("H1").Value = "LQuality"
oSheet1.Range("I1").Value = "UQuality"
oSheet1.Range("J1").Value = "LVariety"
oSheet1.Range("K1").Value = "UVariety"
oSheet1.Range("L1").Value = "LDemand"
oSheet1.Range("M1").Value = "UDemand"
oSheet1.Range("N1").Value = "LControl"
oSheet1.Range("O1").Value = "UControl"
oSheet1.Range("P1").Value = "LBenefit"
oSheet1.Range("Q1").Value = "UBenefit"
oSheet1.Range("R1").Value = "Supplier mat"
oSheet1.Range("S1").Value = "Supplier Panel"
oSheet1.Range("T1").Value = "Machine"

```

```
oSheet1.Range("A2").Resize(3 * nr1, 30).Value = objectives
```

```
oBook.SaveAs("G:\PhD-nantes\alie-for a new article\thesis model\DATA for thesis\writing the thesis\results"
& "Results3.xls")
```

```

oSheet1 = Nothing
oBook = Nothing
oExcel.Quit()
oExcel = Nothing
GC.Collect()

```

End Sub

In Figure 55, we show an instance from output displayed in Excel.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Solution	Material	500 1200	500 1500	500 2550	700 1200	700 1500	700 2550	1000 2250	1000 2550	1000 2700	1000 3000	Panel	Pack
2		1	1 *	√	√	*	*	√	√	√	√	√		Standard
3			2										PVC	
4			3											
5		2	1 *	√	√	*	*	√	√	√	√	√		Standard
6			2										PVC	
7			3										Royal	
8		3	1 *	√	√	√	√	√	√	√	*	√		Standard
9			2											
10			3										Royal	
11		4	1 *	√	√	√	√	√	√	√	√	√		Standard
12			2											
13			3										Royal	
14		5	1 *	√	√	√	√	√	√	√	√	√		Standard
15			2										PVC	
16			3										Royal	
17		6	1 *	√	√	√	√	√	√	√	√	√		Standard
18			2										PVC	
19			3										Royal	
20														
21														
22														
23		8	1 *	√	√	*	*	√	√	√	√	√		Standard
24			2										PVC	
25			3											

Figure 55: An instance from output displayed in Excel

This Figure, for each solution, shows options selected for feature “density” shown with “√” in Excel, the type of panel and packing selected. Other outputs are displayed in Sheet1 and Sheet2.

\*\*\*\*\*

**//Displaying outputs in interface//**

By clicking on elements of ListBox1 (Figure 56) which shows solutions obtained, parts 1, 2, 3, 4 and 7 are filled with results achieved. The following lines show the codes used to extract results.

```
Private Sub ListBox1_SelectedIndexChanged(ByVal sender As System.Object, ByVal e As System.EventArgs)
Handles ListBox1.SelectedIndexChanged
```

```
Dim a As Short
```

```
Dim k1() As Object = {"50*70", "60*90", "70*100", "80*100", "100*120", "120*150", "150*200"}
```

```
Dim k2() As Object = {"700,2100", "700,2250", "700,2550", "700,2700", "700,3000", "1000,2100", "1000,2250",
"1000,2550", "1000,2700", "1000,3000"}
```

```
Dim k3() As Object = {"Style", "PVC", "Royal"}
```

```
Dim k4() As Object = {"Standard", "Customize"}
```

```
Dim k5() As Object = {"Regular", "Express"}
```

```
Dim k6() As Object = {"Acrylic", "Acrylic heat set", "Silk"}
```



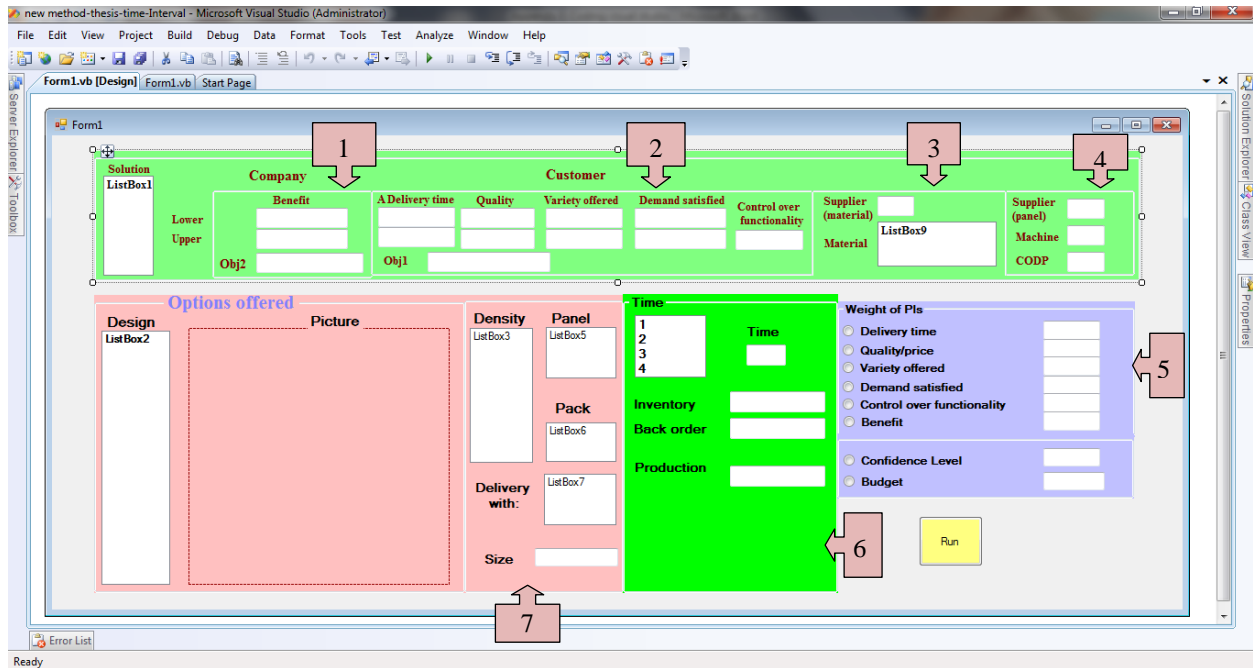


Figure 56: User interface developed

```
Dim size(.) As Single = {{0.5, 0.7}, {0.6, 0.9}, {0.7, 1.0}, {0.8, 1.0}, {1.0, 1.2}, {1.2, 1.5}, {1.5, 2.0}}
```

```
a = ListBox1.SelectedItem
```

```
TextBox1.Clear()
```

```
TextBox2.Clear()
```

```
TextBox3.Clear()
```

```
TextBox4.Clear()
```

```
TextBox5.Clear()
```

```
TextBox6.Clear()
```

```
TextBox7.Clear()
```

```
TextBox8.Clear()
```

```
TextBox9.Clear()
```

```
TextBox10.Clear()
```

```
TextBox11.Clear()
```

```
TextBox12.Clear()
```

```
TextBox13.Clear()
```

```
TextBox14.Clear()
```

```
TextBox17.Clear()
```

```
TextBox18.Clear()
```

```
ListBox2.Items.Clear()
```

```
ListBox3.Items.Clear()
```

```
ListBox5.Items.Clear()
```

```
ListBox6.Items.Clear()
```

```
ListBox7.Items.Clear()
```

```
ListBox9.Items.Clear()
```

```
TextBox1.Text = Math.Round(Val(p1(a - 1, 0, 0)), 6)
```

```
TextBox2.Text = Math.Round(Val(p1(a - 1, 0, 1)), 6)
```

```
TextBox3.Text = Math.Round(Val(p1(a - 1, 1, 0)), 6)
```

```
TextBox4.Text = Math.Round(Val(p1(a - 1, 1, 1)), 6)
```

```
TextBox5.Text = Math.Round(Val(p1(a - 1, 5, 0)))
```

```
TextBox6.Text = Math.Round(Val(p1(a - 1, 5, 1)))
```

```
TextBox7.Text = Math.Round(Val(p1(a - 1, 2, 0)), 6)
```

```
TextBox8.Text = Math.Round(Val(p1(a - 1, 2, 0)), 6)
```

```
TextBox9.Text = Math.Round(Val(p1(a - 1, 3, 0)), 6)
```

```
TextBox10.Text = Math.Round(Val(p1(a - 1, 3, 1)), 6)
```

```

    TextBox19.Text = Math.Round(Val(p1(a - 1, 4, 0)), 6)
    TextBox14.Text = CODPf(a - 1)
    TextBox18.Text = "[" & Math.Round(fg1(a - 1, 0), 6) & ";" & Math.Round(fg1(a - 1, 1), 6) & "]"
    TextBox17.Text = "[" & Math.Round(fg2(a - 1, 0), 6) & ";" & Math.Round(fg2(a - 1, 1), 6) & "]"
    For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) To ncodp + nvar(0) +
nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 - 1
        If front1(a - 1, q1) = 1 Then
    TextBox11.Text = Val(q1 + 1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6)))
            Exit For
        End If
    Next
    For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 To ncodp +
nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 + nsupplier2 - 1
        If front1(a - 1, q1) = 1 Then
    TextBox12.Text = Val(q1 + 1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) +
nsupplier1))
            Exit For
        End If
    Next
    For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 + nsupplier2
To ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) + nsupplier1 + nsupplier2 +
nmachine - 1
        If front1(a - 1, q1) = 1 Then
    TextBox13.Text = Val(q1 + 1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) +
nsupplier1 + nsupplier2))
            Exit For
        End If
    Next
    For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) To ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) +
nvar(4) - 1
        If front1(a - 1, q1) = 1 Then
            ListBox5.Items.Add(k3(q1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3))))
        End If
    Next
    For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) To ncodp + nvar(0) + nvar(1) + nvar(2) +
nvar(3) + nvar(4) + nvar(5) - 1
        If front1(a - 1, q1) = 1 Then
            ListBox6.Items.Add(k4(q1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4))))
        End If
    Next
    For q1 = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5) To ncodp + nvar(0) + nvar(1) +
nvar(2) + nvar(3) + nvar(4) + nvar(5) + nvar(6) - 1
        If front1(a - 1, q1) = 1 Then
            ListBox7.Items.Add(k5(q1 - (ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + nvar(5))))
        End If
    Next
    Dim t2 As Short
    For i = 0 To nvar(3) - 1
        If front1(a - 1, ncodp + nvar(0) + nvar(1) + nvar(2) + i) = 1 Then
            t2 = i
        End If
    Next
    TextBox16.Text = "[" & size(0, 0) & " " & size(t2, 1) & "]"
End Sub
*****

```

By clicking on elements of ListBox9, the material and design options selected for each material are shown in ListBox2. The following codes show how to get design options.

```

Private Sub ListBox9_SelectedIndexChanged(ByVal sender As System.Object, ByVal e As System.EventArgs)
Handles ListBox9.SelectedIndexChanged
    Dim a As String
    Dim b, c, d, sum1 As Short
    Dim k6() As Object = {"Acrylic", "Acrylic heat set", "Silk"}
    Dim k1() As Object = {"50*70", "60*90", "70*100", "80*100", "100*120", "120*150", "150*200"}
    Dim k2() As Object = {"500,1200", "500,1500", "500,2550", "700,1200", "700,1500", "700,2250",
"1000,2250", "1000,2550", "1000,2700", "1000,3000"}
    Dim size(,) As Single = {{0.5, 0.7}, {0.6, 0.9}, {0.7, 1.0}, {0.8, 1.0}, {1.0, 1.2}, {1.2, 1.5}, {1.5, 2.0}}
    a = ListBox9.SelectedItem.ToString
    Select Case a
        Case "Acrylic"
            c = 0
            d = 0
        Case "Acrylic heat set"
            c = 1
            d = 1
        Case "Silk"
            c = 2
            d = 2
    End Select
    b = ListBox1.SelectedItem
    t = TextBox20.Text
    ListBox2.Items.Clear()
    Dim g4(nvar(0) - 1, maxt, 100) As Short
    For q3 = 0 To nvar(0) - 1
        If maxdesign(b - 1, t, q3) > 0 Then
            For q1 = 0 To maxdesign(b - 1, t, q3) - 1
                g4(q3, t, q1) = front1(b - 1, ncodp + nvar(0) + q1)
            Next
        End If
    Next
    findmin1(g4, maxdesign, b, t, d)
    If maxdesign(b - 1, t, d) > 0 Then
        For q1 = 0 To maxdesign(b - 1, t, d) - 1
            ListBox2.Items.Add(g4(d, t, q1))
        Next
    End If
    ListBox3.Items.Clear()
    sum1 = 0
    For q1 = ncodp + nvar(0) + nvar(1) To ncodp + nvar(0) + nvar(1) + nvar(2) - 1
        If front1(b - 1, q1) = 1 Then

            ListBox3.Items.Add(k2(q1 - (ncodp + nvar(0) + nvar(1))))
        End If
    Next
    Dim t2 As Short
    For i = 0 To nvar(3) - 1
        If front1(b - 1, ncodp + nvar(0) + nvar(1) + nvar(2) + i) = 0 Then
            t2 = i
        End If
    Next
End Sub

```

\*\*\*\*\*

By clicking on each design option in ListBox2, the related image is exhibited in section “Picture” of interface.

```

Private Sub ListBox2_SelectedIndexChanged_2(ByVal sender As System.Object, ByVal e As System.EventArgs)
Handles ListBox2.SelectedIndexChanged

```

```
Dim a As String
```

```
a = ListBox2.SelectedItem.ToString()  
Dim folder As String = "G:\PhD-nantes\alie-for a new article\new new\axhaye tablofarsh-mohem\new"  
Dim filename As String = System.IO.Path.Combine(folder, a & ".jpg")  
PictureBox1.Image = Image.FromFile(filename)
```

```
End Sub
```

```
*****
```

By clicking on “time” in ListBox10 (part 6 in Figure 56), values of inventory, backorder and production level are exhibited.

```
Private Sub ListBox10_SelectedIndexChanged(ByVal sender As System.Object, ByVal e As System.EventArgs)  
Handles ListBox10.SelectedIndexChanged
```

```
Dim a, t As Short
```

```
Dim k6() As Object = {"Acrylic", "Acrylic heat set", "Silk"}
```

```
ListBox9.Items.Clear()
```

```
TextBox29.Clear()
```

```
TextBox30.Clear()
```

```
t = ListBox10.SelectedItem
```

```
a = ListBox1.SelectedItem
```

```
TextBox20.Text = t
```

```
TextBox29.Text = "[" & Math.Round(sumf1(a - 1, t, 0)) & " " & Math.Round(sumf1(a - 1, t, 1)) & "]"
```

```
TextBox30.Text = "[" & Math.Round(backf(a - 1, t, 0)) & " " & Math.Round(backf(a - 1, t, 1)) & "]"
```

```
TextBox31.Clear()
```

```
TextBox31.Text = Math.Round(pbeft(a - 1, t, 0))
```

```
For q1 = ncdp To ncdp + nvar(0) - 1
```

```
    If maxdesign(a - 1, t, q1 - ncdp) > 0 Then
```

```
        ListBox9.Items.Add(k6(q1 - ncdp))
```

```
    End If
```

```
Next
```

```
End Sub
```

```
*****
```

## Main Functions used in program:

This function calculates values of some PIs for each unit of product varieties in order to decrease run time.

```
Private Sub Fitnessp(ByRef product1, ByVal nc, ByVal s1, ByVal s2, ByVal m, ByVal nvar, ByVal ncdp, ByVal  
Dpnew, ByVal Dpnew2, ByVal norder, ByVal norder12, ByVal TD, ByVal price1, ByVal F11, ByVal F12, ByVal  
F13, ByVal F14, ByVal F15, ByVal F21, ByVal F22, ByVal F31, ByVal F41, ByVal size, ByVal tmacmin, ByVal  
nproduct)
```

```
Dim p As Integer
```

```
Dim WF1, WF2, VF11, VF12, VF14, VF15, VF21, VF22 As Single
```

```
Dim Cope8 As Short
```

```
Dim Cpur1(1) As Single
```

```
Dim Cop3(1), Cop4(1), Cop7(1), Cop8(1), Top3(1), Top4(1), Top7(1), Top8(1), Top9(1) As Single
```

```
Dim Tope7(.) As Short = {{45, 55, 75}, {55, 75, 95}, {65, 80, 105}, {75, 90, 120}, {85, 100, 135}, {105, 115,  
155}, {110, 125, 165}}
```

```
Dim tsup2(.,.) As Short = {{5, 10}, {1, 3}, {2, 4}}, {{4, 9}, {2, 4}, {2, 4}}, {{5, 9}, {1, 4}, {2, 5}}
```

```
Dim Cint3() As Short = {2, 3, 5}
```

```
Dim Cop456() As Short = {1.2, 0, 0}
```

```
Dim Tope8() As Single = {1, 4}
```

```
Dim Tope9() As Short = {6, 2}
```

```
Cope8 = 3
```

```
Dim Tope456() As Single = {4, 0, 0}
```

```

Dim Cope456() As Single = {4, 4.5, 4}
Dim Cbaft() As Single = {2, 1.8}
Dim Cpura(.) As Short = {{14, 12, 15}, {15, 13, 16}, {13, 12, 16}}
Dim Cpumat(.) As Single = {{3.85, 4, 3.6}, {5, 5.2, 5}, {53.5, 52, 55}}
Dim Tpumat(.) As Single = {{1, 1, 1.5}, {1.5, 1, 1}, {10, 12, 9}}
Dim ts3(.) As Short = {{10, 12, 15, 16, 18, 19, 22}, {13, 14, 16, 18, 19, 21, 23}}
Dim Sumord(1) As Integer
WF1 = 0.6
WF2 = 0.4
VF11 = 0.4
VF12 = 0.25
VF14 = 0.25
VF15 = 0.1
VF21 = 0.4
VF22 = 0.6
If nc = 0 Then
  For i1 = 0 To nvar(0) - 1
    For i2 = 0 To nvar(1) - 1
      For i3 = 0 To nvar(2) - 1
        For i4 = 0 To nvar(3) - 1
          For i5 = 0 To nvar(4) - 1
            For i6 = 0 To nvar(5) - 1
              For i7 = 0 To nvar(6) - 1
                p = i7 + i6 * nvar(6) + i5 * nvar(6) * nvar(5) + i4 * nvar(6) * nvar(5) * nvar(4) + i3 * nvar(6) * nvar(5) * nvar(4) *
                nvar(3) + i2 * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) + i1 * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) *
                nvar(1)
                Cop3(0) = ((ts3(m, i4) / (60)) + tmacmin(m) * size(i4, 0) * size(i4, 1)) * Cbaft(m)
                Cop4(0) = (Tope456(0) / 8 + 1) * Cope456(0) * size(i4, 0) * size(i4, 1)
                Cop8(0) = (Tope8(i6) / 8) * Cope8
                Cop3(1) = ((ts3(m, i4) / (60)) + tmacmin(m) * size(i4, 0) * size(i4, 1)) * Cbaft(m)
                Cop4(1) = ((Tope456(0) / 8) + 1) * Cope456(0) * size(i4, 0) * size(i4, 1)
                Cop8(1) = (Tope8(i6) / 8) * Cope8
                product1(nc, s1, s2, m, p, 4, 0) = Cop3(0) + Cop4(0) + Cop8(0) + Cop7(0)
                product1(nc, s1, s2, m, p, 4, 1) = Cop3(1) + Cop4(1) + Cop8(1) + Cop7(1)
                product1(nc, s1, s2, m, p, 1, 0) = (1 / price1(p)) * (WF1 * (F11(i2, 0) * VF11 + F12(0, i3, 0) * VF12 + F14(i5, s2, 0)
                * VF14 + F15(i1, s1, 0) * VF15) + WF2 * (F21(i1, s1, 0) * VF21 + VF22 * F22(m, 0)))
                product1(nc, s1, s2, m, p, 1, 1) = (1 / price1(p)) * (WF1 * (F11(i2, 1) * VF11 + F12(0, i3, 1) * VF12 + F14(i5, s2, 1)
                * VF14 + F15(i1, s1, 1) * VF15) + WF2 * (F21(i1, s1, 1) * VF21 + VF22 * F22(m, 1)))

                Top3(0) = (ts3(m, i4) / (8 * 60)) + tmacmin(m) * (size(i4, 0) * size(i4, 1) / 8) + 4 / 8
                Top3(1) = (ts3(m, i4) / (8 * 60)) + tmacmin(m) * (size(i4, 0) * size(i4, 1) / 8) + 4 / 8
                Top4(0) = Tope456(0) * (size(i4, 0) * size(i4, 1) / 8) + 1
                Top4(1) = Tope456(0) * (size(i4, 0) * size(i4, 1) / 8) + 1
                Top7(0) = (tsup2(s2, i5, 0))
                Top7(1) = (tsup2(s2, i5, 1))
                Top8(0) = (Tope8(i6) / 8)
                Top8(1) = (Tope8(i6) / 8)
                Top9(0) = Tope9(i7)
                Top9(1) = Tope9(i7)
                product1(nc, s1, s2, m, p, 0, 0) = (Top3(0) + Top4(0) + Top7(0) + Top8(0) + Top9(0))
                product1(nc, s1, s2, m, p, 0, 1) = (Top3(1) + Top4(1) + Top7(1) + Top8(1) + Top9(1))
                product1(nc, s1, s2, m, p, 2, 0) = 1 / (nproduct / 2)
                Limit1(product1, nc, s1, s2, m, p)
              Next
            Next
          Next
        Next
      Next
    Next
  Next
Next
Next
Next
Next
Next

```

Next

End If

If nc = 1 Or nc = 2 Or nc = 3 Then

For i1 = 0 To nvar(0) - 1

For i2 = 0 To nvar(1) - 1

For i3 = 0 To nvar(2) - 1

For i4 = 0 To nvar(3) - 1

For i5 = 0 To nvar(4) - 1

For i6 = 0 To nvar(5) - 1

For i7 = 0 To nvar(6) - 1

p = i7 + i6 \* nvar(6) + i5 \* nvar(6) \* nvar(5) + i4 \* nvar(6) \* nvar(5) \* nvar(4) + i3 \* nvar(6) \* nvar(5) \* nvar(4) \* nvar(3) + i2 \* nvar(6) \* nvar(5) \* nvar(4) \* nvar(3) \* nvar(2) + i1 \* nvar(6) \* nvar(5) \* nvar(4) \* nvar(3) \* nvar(2) \* nvar(1)

Cpur1(0) = (size(i4, 0) \* size(i4, 1)) \* 4 \* Cpmat(i1, s1)

Cpur1(1) = (size(i4, 0) \* size(i4, 1)) \* 4 \* Cpmat(i1, s1)

Cop4(0) = ((Tope456(0) / 8) + 1) \* Cope456(0) \* size(i4, 0) \* size(i4, 1)

Cop8(0) = (Tope8(i6) / 8) \* Cope8

Cop4(1) = ((Tope456(0) / 8) + 1) \* Cope456(0) \* size(i4, 0) \* size(i4, 1)

Cop8(1) = (Tope8(i6) / 8) \* Cope8

product1(nc, s1, s2, m, p, 1, 0) = (1 / price1(p)) \* (WF1 \* (F11(i2, 0) \* VF11 + F12(0, i3, 0) \* VF12 + F14(i5, s2, 0) \* VF14 + F15(i1, s1, 0) \* VF15) + WF2 \* (F21(i1, s1, 0) \* VF21 + VF22 \* F22(m, 0)))

product1(nc, s1, s2, m, p, 1, 1) = (1 / price1(p)) \* (WF1 \* (F11(i2, 1) \* VF11 + F12(0, i3, 1) \* VF12 + F14(i5, s2, 1) \* VF14 + F15(i1, s1, 1) \* VF15) + WF2 \* (F21(i1, s1, 1) \* VF21 + VF22 \* F22(m, 1)))

Top7(0) = (tsup2(s2, i5, 0))

Top7(1) = (tsup2(s2, i5, 1))

Top8(0) = (Tope8(i6) / 8)

Top8(1) = (Tope8(i6) / 8)

Top9(0) = Tope9(i7)

Top9(1) = Tope9(i7)

If nc = 1 Then

product1(nc, s1, s2, m, p, 0, 0) = Top7(0) + Top8(0) + Top9(0)

product1(nc, s1, s2, m, p, 0, 1) = Top7(1) + Top8(1) + Top9(1)

product1(nc, s1, s2, m, p, 4, 0) = Cpur1(0) + Cop4(0)

product1(nc, s1, s2, m, p, 4, 1) = Cpur1(1) + Cop4(1)

ElseIf nc = 2 Then

product1(nc, s1, s2, m, p, 0, 0) = Top8(0) + Top9(0)

product1(nc, s1, s2, m, p, 0, 1) = Top8(1) + Top9(1)

product1(nc, s1, s2, m, p, 4, 0) = Cpur1(0) + Cop4(0)

product1(nc, s1, s2, m, p, 4, 1) = Cpur1(1) + Cop4(1)

Else

product1(nc, s1, s2, m, p, 0, 0) = Top9(0)

product1(nc, s1, s2, m, p, 0, 1) = Top9(1)

product1(nc, s1, s2, m, p, 4, 0) = Cpur1(0) + Cop4(0) + Cop8(0)

product1(nc, s1, s2, m, p, 4, 1) = Cpur1(1) + Cop4(1) + Cop8(1)

End If

product1(nc, s1, s2, m, p, 2, 0) = 1 / (nproduct / 2)

Limit1(product1, nc, s1, s2, m, p)

Next

Next

Next

Next

Next

Next

Next

End If

End Sub

\*\*\*\*\*

Private Sub generation4(ByRef pool, ByVal schrom, ByVal j, ByRef t2)

```
Dim y1, v, s1, s2, s3, sum As Integer
Dim nvarw() As Short = {nvar(0), nvar(1), nvar(2), nvar(3), nvar(4), nvar(5), nvar(6), nsupplier1, nsupplier2,
nmachine}
Dim nsource1 As Short = 10
Dim k1(schrom), r, i As Short
Call Randomize()
s3 = Rnd() * (ncodp - 1)
k1(s3) = 1
pool(j, s3) = 1
s1 = ncodp
For v = 0 To nsource1 - 1
    If v = 0 Or v = 1 Then
        Dim mat(nvarw(v) - 1) As Short
        For i = 0 To nvarw(v) - 1
            mat(i) = i + 1
        Next
        r = 0
        While r < nvarw(v)
            Call Randomize()
            y1 = Rnd() * (i - 1)
            k1(s1 + r) = mat(y1)
            pool(j, r + s1) = k1(r + s1)
            correctionmat(mat, y1, nvarw, v, i)
            r = r + 1
        End While
    Else
        If v = 6 Then
            k1(s1) = 1
            k1(s1 + 1) = 1
            pool(j, s1) = 1
            pool(j, s1 + 1) = 1
        Else
            Call Randomize()
            y1 = (nvarw(v) - 1) * Rnd()
            k1(y1 + s1) = 1
            pool(j, y1 + s1) = k1(y1 + s1)
        End If
    End If
    s1 = s1 + nvarw(v)
Next
sum = 4
For s2 = 0 To nsource1 - 1
    If s2 = 2 Or s2 = 4 Or s2 = 5 Then
        For i = sum To sum + nvarw(s2) - 1
            If k1(i) <> 1 Then
                Call Randomize()
                k1(i) = Rnd()
                pool(j, i) = k1(i)
            End If
        Next
        Exit For
    End If
    sum = sum + nvarw(s2)
Next
For s3 = 0 To maxt - 1
    Call Randomize()
```

```

s2 = Rnd() * 9 + 1
k1(schrom + s3 + 1 - maxt) = s2
pool(j, schrom + s3 + 1 - maxt) = s2
Next
For i = 0 To nvar(3) - 1
    If pool(j, ncdop + nvar(0) + nvar(1) + nvar(2) + i) = 1 Then
        t2 = i
    End If
Next
End Sub
*****

Private Sub Fitness2a(ByVal pool, ByVal nvar, ByVal j, ByVal product1, ByVal maxF, ByRef Obj1, ByRef Obj2,
ByVal we1, ByVal CODP, ByVal Size, ByVal nvariety, ByVal Tsum, ByVal norder, ByVal norder12, ByVal
tmacmin, ByVal price1, ByVal schrom, ByVal nproduct)
Dim k, q, p, capacity, capacity1, backcap, backcap1 As Integer
Dim rr, CODP1 As Short
Dim WF1, WF2, VF11, VF12, VF14, VF15, VF21, VF22, prodvalue3(1), prodvalue7(1), prodvalue8(1),
prodvalue9(1) As Single
Dim s2, s1, back(maxt, nvar(0) - 1, 1), totalback(maxt, 1) As Single
Dim wip31(maxt, (nproduct / nvar(0)) - 1, 1), wip7(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, 11, 1),
wip8(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, 5, 1), wip9(maxt, nvar(0) - 1, nvar(1) - 1,
nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, nvar(5) - 1, 1, 1) As Single
Dim Bw31(maxt, (nproduct / nvar(0)) - 1, 1), Bw7(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, 11, 1),
Bw8(maxt, nvar(0) - 1, nvar(1) - 1, nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, 5, 1), Bw9(maxt, nvar(0) - 1, nvar(1) - 1,
nvar(2) - 1, nvar(3) - 1, nvar(4) - 1, nvar(5) - 1, 1, 1) As Single
Dim u, u1, u2, t2, Cope8 As Short
Dim Cinv3(maxt, 1), Cinv7(maxt, 1), Cinv8(maxt, 1), Cinv9(maxt, 1), Cpur1(1), sum(maxt, 1), sum3(maxt, 1),
summan(maxt, 1), income(1) As Single
Dim Cop3(maxt, 1), Cop4(maxt, 1), Cop5(maxt, 1), Cop6(maxt, 1), Cop7(maxt, 1), Cop8(maxt, 1), Cop9(maxt, 1)
As Single
Dim Tope7(,) As Short = {{45, 55, 75}, {55, 75, 95}, {65, 80, 105}, {75, 90, 120}, {85, 100, 135}, {105, 115, 155},
{110, 125, 165}}
Dim Cint3() As Single = {0.2, 0.5, 2}
Dim Cint7() As Single = {0.5, 1, 4}
Dim Cint8(,) As Single = {{0.5, 1, 4}, {0.5, 1, 4}, {4, 5, 7}}
Dim Cint9(,) As Single = {{{0.5, 1}, {1, 2}, {4, 6}}, {{0.5, 1}, {1, 2}, {4, 6}}, {{4, 6}, {5, 7}, {7, 9}}}
Dim tsup2(,) As Short = {{{5, 10}, {1, 3}, {2, 4}}, {{4, 9}, {2, 4}, {2, 4}}, {{5, 9}, {1, 4}, {2, 5}}}
Dim Cop456() As Single = {2.8, 0, 0}
Dim Tope8() As Single = {1, 4}
Dim Tope9() As Short = {6, 2}
Cope8 = 3
Dim Tope456() As Single = {4, 0, 0}
Dim Cope456() As Single = {2.8, 4.5, 4}
Dim Cbaft() As Single = {2, 1.8}
Dim Cpura(,) As Short = {{14, 12, 15}, {15, 13, 16}, {13, 12, 16}}
Dim Cpumat(,) As Single = {{{3.85, 4, 3.6}, {5, 5.2, 5}, {53.5, 52, 55}}
Dim Tpumat(,) As Single = {{1, 1, 1.5}, {1.5, 1, 1}, {10, 12, 9}}
Dim ts3(,) As Short = {{10, 12, 15, 16, 18, 19, 22}, {13, 14, 16, 18, 19, 21, 23}}
Dim Sumord(1), p9 As Integer
Dim backprice() As Short = {4, 6, 9}
Dim c1, c2, Totalcost(maxt, 1) As Single
WF1 = 0.6
WF2 = 0.4
VF11 = 0.4
VF12 = 0.25
VF14 = 0.25
VF15 = 0.1
VF21 = 0.4
VF22 = 0.6

```



```

u2 = 5
u = 5
u1 = 5
capacity = 1000
capacity1 = 4000
backcap = 500
backcap1 = 2000
Obj1(j, 0) = 0
Obj1(j, 1) = 0
Obj2(j, 0) = 0
Obj2(j, 1) = 0
t2=-1
For i1 = 0 To ncodp - 1
    If pool(j, i1) = 1 Then
        CODP1 = CODP(i1)
        k = 1
        Exit For
    End If
Next
For i = 0 To nvar(3) - 1
    If pool(j, ncodp + nvar(0) + nvar(1) + nvar(2) + i) = 1 Then
        t2 = i
        Exit For
    End If
Next
If t2 < 0 Then
    t2 = -1
End If
For s1 = 0 To nsupplier1 - 1
    If pool(j, ncodp + nvariety + s1) = 1 Then
        u2 = s1
        Exit For
    End If
Next
For m = 0 To 1
    If pool(j, ncodp + nvariety + nsupplier1 + nsupplier2 + m) = 1 Then
        u = m
        Exit For
    End If
Next
For s2 = 0 To nsupplier2 - 1
    If pool(j, ncodp + nvariety + nsupplier1 + s2) = 1 Then
        u1 = s2
        Exit For
    End If
Next
Dim semival As Short
Dim invbac(1, 1), sumbac(1), suminv(1), maxinvbac, mininvbac As Single
q = 0
Sumord(0) = 0
Sumord(1) = 0
rr = 0
If CODP1 = 1 Then
    For t1 = 1 To maxt
        Cpur1(0) = 0
        Cpur1(1) = 0
    
```

```

rr = 0
For i1 = 0 To nvar(0) - 1
  back(t1, (pool(j, ncodp + i1) - 1), 0) = 0
  back(t1, (pool(j, ncodp + i1) - 1), 1) = 0
  For i2 = 0 To nvar(1) - 1

    For i3 = 0 To nvar(2) - 1
      If pool(j, ncodp + nvar(0) + nvar(1) + i3) = 1 Then
        For i4 = 0 To t2
          For i5 = 0 To nvar(4) - 1
            If pool(j, ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + i5) = 1 Then
              For i6 = 0 To nvar(5) - 1
                If pool(j, ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + i6) = 1 Then
                  For i7 = 0 To nvar(6) - 1
                    p = i7 + i6 * nvar(6) + i5 * nvar(6) * nvar(5) + i4 * nvar(6) * nvar(5) * nvar(4) + i3 * nvar(6) * nvar(5) * nvar(4) *
                    nvar(3) + (pool(j, ncodp + nvar(0) + i2) - 1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) + (pool(j, ncodp + i1) -
                    1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) * nvar(1)
                    c1 = norder(t1, p) - wip31(t1 - 1, (pool(j, ncodp + i1) - 1), 1) + Bw31(t1 - 1, (pool(j, ncodp + i1) - 1), 0)
                    c2 = norder12(t1, p) - wip31(t1 - 1, (pool(j, ncodp + i1) - 1), 0) + Bw31(t1 - 1, (pool(j, ncodp + i1) - 1), 1)
                    semivalue = Math.Round((pool(j, schrom + t1 - maxt) / 10) * c2 + (1 - (pool(j, schrom + t1 - maxt) / 10)) *
                    Math.Max(c1, 0), 0)

                    If semivalue = 0 Then
                      semivalue = Math.Round((Math.Max(c1, 0) + c2) / 2, 0)
                    End If
                    wip31(t1, (pool(j, ncodp + i1) - 1), 1) = -1 * Math.Min(c1, 0) + semivalue - Math.Max(c1, 0)
                    Bw31(t1, (pool(j, ncodp + i1) - 1), 1) = c2 - semivalue
                    Cpur1(0) = semivalue * (Size(i4, 0) * Size(i4, 1)) * 4 * Cpumat((pool(j, ncodp + i1) - 1), u2)
                    Cpur1(1) = semivalue * (Size(i4, 0) * Size(i4, 1)) * 4 * Cpumat((pool(j, ncodp + i1) - 1), u2)
                    Totalcost(t1, 0) = Totalcost(t1, 0) + product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semivalue + Cpur1(0)
                    Totalcost(t1, 1) = Totalcost(t1, 1) + product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semivalue + Cpur1(1)
                    If ((Totalcost(t1, 0) + Totalcost(t1, 1)) / 2) <= Budget / maxt Then
                      sum(t1, 0) = sum(t1, 0) + wip31(t1, (pool(j, ncodp + i1) - 1), 0) * 4 * (Size(i4, 0) * Size(i4, 1))
                      sum(t1, 1) = sum(t1, 1) + wip31(t1, (pool(j, ncodp + i1) - 1), 1) * 4 * (Size(i4, 0) * Size(i4, 1))
                      If capacity1 - ((sum(t1, 0) + sum(t1, 1)) / 2) >= 0 Then
                        totalback(t1, 0) = totalback(t1, 0) + Bw31(t1, (pool(j, ncodp + i1) - 1), 0) * 4 * (Size(i4, 0) * Size(i4, 1))
                        totalback(t1, 1) = totalback(t1, 1) + Bw31(t1, (pool(j, ncodp + i1) - 1), 1) * 4 * (Size(i4, 0) * Size(i4, 1))
                        If backcap1 - ((totalback(t1, 0) + totalback(t1, 1)) / 2) >= 0 Then
                          sumbac(1) = sumbac(1) + Bw31(t1, (pool(j, ncodp + i1) - 1), 1) * Size(i4, 0) * Size(i4, 1) * backprice(pool(j, ncodp
                          + i1) - 1) * 4
                          sumbac(0) = sumbac(0) + Bw31(t1, (pool(j, ncodp + i1) - 1), 0) * Size(i4, 0) * Size(i4, 1) * backprice(pool(j, ncodp
                          + i1) - 1) * 4
                          suminv(1) = suminv(1) + wip31(t1, (pool(j, ncodp + i1) - 1), 1) * Size(i4, 0) * Size(i4, 1) * Cint3(pool(j, ncodp + i1)
                          - 1) * 4
                          suminv(0) = suminv(0) + wip31(t1, (pool(j, ncodp + i1) - 1), 0) * Size(i4, 0) * Size(i4, 1) * Cint3(pool(j, ncodp + i1)
                          - 1) * 4
                          Tsum(0, 0) = Tsum(0, 0) + product1(CODP1 - 1, u2, u1, u, p, 0, 0) * semivalue
                          Tsum(0, 1) = Tsum(0, 1) + product1(CODP1 - 1, u2, u1, u, p, 0, 1) * semivalue
                          Tsum(1, 0) = Tsum(1, 0) + product1(CODP1 - 1, u2, u1, u, p, 1, 0)
                          Tsum(1, 1) = Tsum(1, 1) + product1(CODP1 - 1, u2, u1, u, p, 1, 1)
                          Tsum(2, 0) = Tsum(2, 0) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)
                          Tsum(2, 1) = Tsum(2, 1) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)
                          Tsum(3, 0) = Tsum(3, 0) + semivalue * (Size(i4, 1) * Size(i4, 0))
                          Tsum(3, 1) = Tsum(3, 1) + semivalue * (Size(i4, 1) * Size(i4, 0))
                          q = q + 1
                          Sumord(0) = Sumord(0) + norder(t1, p)
                          Sumord(1) = Sumord(1) + norder12(t1, p)
                          Tsum(5, 0) = Tsum(5, 0) + price1(p) * semivalue - product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semivalue - Cpur1(1)
                          Tsum(5, 1) = Tsum(5, 1) + price1(p) * semivalue - product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semivalue - Cpur1(0)
                        Else
                          rr = 1

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For i3 = 0 To nvar(2) - 1
  If pool(j, ncodp + nvar(0) + nvar(1) + i3) = 1 Then
    For i4 = 0 To t2
      For i5 = 0 To nvar(4) - 1
        If pool(j, ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + i5) = 1 Then
          For i6 = 0 To nvar(5) - 1
            If pool(j, ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + i6) = 1 Then
              For i7 = 0 To nvar(6) - 1
                p = i7 + i6 * nvar(6) + i5 * nvar(6) * nvar(5) + i4 * nvar(6) * nvar(5) * nvar(4) + i3 * nvar(6) * nvar(5) * nvar(4) *
                nvar(3) + (pool(j, ncodp + nvar(0) + i2) - 1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) + (pool(j, ncodp + i1) -
                1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) * nvar(1)
                p9 = i7 + i6 * nvar(6) + i5 * nvar(6) * nvar(5)
                c1 = norder(t1, p) - wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) + Bw7(t1,
                (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0)
                c2 = norder12(t1, p) - wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0) + Bw7(t1,
                (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1)
                semival = Math.Round((pool(j, schrom + t1 - maxt) / 10) * c2 + (1 - (pool(j, schrom + t1 - maxt) / 10)) *
                Math.Max(c1, 0), 0)
                If semival = 0 Then
                  semival = Math.Round((Math.Max(c1, 0) + c2) / 2, 0)
                End If
                wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) = -1 * Math.Min(c1, 0) + semival
                - Math.Max(c1, 0)
                Bw7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) = c2 - semival
                Cop3(t1, 0) = ((ts3(u, i4) / (60)) + tmacmin(u) * semival * Size(i4, 0) * Size(i4, 1)) * Cbaft(u)
                Cop3(t1, 1) = ((ts3(u, i4) / (60)) + tmacmin(u) * semival * (Size(i4, 0) * Size(i4, 1))) * Cbaft(u)
                Cop8(t1, 0) = (Tope8(i6) / 8) * Cope8 * semival
                Cop8(t1, 1) = (Tope8(i6) / 8) * Cope8 * semival
                Totalcost(t1, 0) = Totalcost(t1, 0) + product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semival + Cop3(t1, 0) + Cop8(t1, 0)
                Totalcost(t1, 1) = Totalcost(t1, 1) + product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semival + Cop3(t1, 1) + Cop8(t1, 1)
                If (Totalcost(t1, 0) + Totalcost(t1, 1)) / 2 <= Budget / maxt Then
                  sum(t1, 0) = sum(t1, 0) + wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0) * (Size(i4,
                  0) * Size(i4, 1))
                  sum(t1, 1) = sum(t1, 1) + wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) * (Size(i4,
                  0) * Size(i4, 1))
                  If capacity - ((sum(t1, 0) + sum(t1, 1) / 2)) >= 0 Then
                    totalback(t1, 0) = totalback(t1, 0) + Bw7(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0) *
                    (Size(i4, 0) * Size(i4, 1))
                    totalback(t1, 1) = totalback(t1, 1) + Bw7(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) *
                    (Size(i4, 0) * Size(i4, 1))
                    If backcap - ((totalback(t1, 0) + totalback(t1, 1)) / 2) >= 0 Then
                      suminv(1) = suminv(1) + wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) * Size(i4,
                      0) * Size(i4, 1) * Cint7(pool(j, ncodp + i1) - 1)
                      suminv(0) = suminv(0) + wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0) * Size(i4,
                      0) * Size(i4, 1) * Cint7(pool(j, ncodp + i1) - 1)
                      sumbac(1) = sumbac(1) + Bw7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) * Size(i4,
                      0) * Size(i4, 1) * backprice(pool(j, ncodp + i1) - 1)
                      sumbac(0) = sumbac(0) + Bw7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0) * Size(i4,
                      0) * Size(i4, 1) * backprice(pool(j, ncodp + i1) - 1)
                      Sumord(0) = Sumord(0) + norder(t1, p)
                      Sumord(1) = Sumord(1) + norder12(t1, p)
                      Tsum(5, 0) = Tsum(5, 0) + price1(p) * semival - (product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semival + Cop3(t1,
                      1) + Cop8(t1, 1))
                      Tsum(5, 1) = Tsum(5, 1) + price1(p) * semival - (product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semival + Cop3(t1,
                      0) + Cop8(t1, 0))
                      Tsum(0, 0) = Tsum(0, 0) + product1(CODP1 - 1, u2, u1, u, p, 0, 0) * semival
                      Tsum(0, 1) = Tsum(0, 1) + product1(CODP1 - 1, u2, u1, u, p, 0, 1) * semival
                      Tsum(1, 0) = Tsum(1, 0) + product1(CODP1 - 1, u2, u1, u, p, 1, 0)
                      Tsum(1, 1) = Tsum(1, 1) + product1(CODP1 - 1, u2, u1, u, p, 1, 1)
                      Tsum(2, 0) = Tsum(2, 0) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)

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Tsum(2, 1) = Tsum(2, 1) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)
Tsum(3, 0) = Tsum(3, 0) + semivalue * (Size(i4, 1) * Size(i4, 0))
Tsum(3, 1) = Tsum(3, 1) + semivalue * (Size(i4, 1) * Size(i4, 0))
      q = q + 1
      Else
        rr = 1
totalback(t1, 0) = totalback(t1, 0) - Bw7(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0) *
(Size(i4, 0) * Size(i4, 1))
totalback(t1, 1) = totalback(t1, 1) - Bw7(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 1) *
(Size(i4, 0) * Size(i4, 1))
      Exit For
      End If
      Else
        rr = 1
sum(t1, 0) = sum(t1, 0) - wip7(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, p9, 0) * (Size(i4,
0) * Size(i4, 1)), nvar(0) + i2) - 1, i3, i4, p9, 1) * (Size(i4, 0) * Size(i4, 1))
      Exit For
      End If
      Else
        rr = 1
      Exit For
      End If
    Next
    If rr = 1 Then
      Exit For
    End If
  End If
  If rr = 1 Then
    Exit For
  End If
End If
Next
If rr = 1 Then
  Exit For
Else
  maxinvbac = Math.Max(sumbac(1), suminv(1))
  mininvbac = Math.Min(sumbac(0), suminv(0))
  Tsum(5, 0) = Tsum(5, 0) + mininvbac
  Tsum(5, 1) = Tsum(5, 1) + maxinvbac
  sumbac(1) = 0
  suminv(1) = 0
  sumbac(0) = 0
  suminv(0) = 0
End If
Next
If rr = 1 Then
  Exit For
End If
Next
If rr = 1 Then
  Exit For
End If
Next
If rr = 1 Then
  Exit For
End If
Next

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Next
ElseIf CODP1 = 3 Then
  For t1 = 1 To maxt
    Cpur1(0) = 0
    Cpur1(1) = 0
    rr = 0
    For i1 = 0 To nvar(0) - 1
      back(t1, (pool(j, ncodp + i1) - 1), 0) = 0
      back(t1, (pool(j, ncodp + i1) - 1), 1) = 0
      For i2 = 0 To nvar(1) - 1
        For i3 = 0 To nvar(2) - 1
          If pool(j, ncodp + nvar(0) + nvar(1) + i3) = 1 Then
            For i4 = 0 To t2
              For i5 = 0 To nvar(4) - 1
                If pool(j, ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + i5) = 1 Then
                  For i6 = 0 To nvar(5) - 1
                    If pool(j, ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + i6) = 1 Then
                      For i7 = 0 To nvar(6) - 1


p = i7 + i6 * nvar(6) + i5 * nvar(6) * nvar(5) + i4 * nvar(6) * nvar(5) * nvar(4) + i3 * nvar(6) * nvar(5) * nvar(4) * nvar(3) + (pool(j, ncodp + nvar(0) + i2) - 1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) + (pool(j, ncodp + i1) - 1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) * nvar(1)



p9 = i7 + i6 * nvar(6)


c1 = norder(t1, p) - wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) + Bw8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0)
c2 = norder12(t1, p) - wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0) + Bw8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1)
semivalue = Math.Round((pool(j, schrom + t1 - maxt) / 10) * c2 + (1 - (pool(j, schrom + t1 - maxt) / 10)) * Math.Max(c1, 0), 0)

          If semivalue = 0 Then
            semivalue = Math.Round((Math.Max(c1, 0) + c2) / 2, 0)
          End If
wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) = -1 * Math.Min(c1, 0) + semivalue - Math.Max(c1, 0)
Bw8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) = c2 - semivalue
Cop3(t1, 0) = ((ts3(u, i4) / (60)) + tmacmin(u) * semivalue * Size(i4, 0) * Size(i4, 1)) * Cbaft(u)
Cop3(t1, 1) = ((ts3(u, i4) / (60)) + tmacmin(u) * semivalue * (Size(i4, 0) * Size(i4, 1))) * Cbaft(u)
Cope8(t1, 0) = (Tope8(i6) / 8) * Cope8 * semivalue
Cope8(t1, 1) = (Tope8(i6) / 8) * Cope8 * semivalue
Cinv8(t1, 0) = wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0) * Cint8(i1, i5) * Size(i4, 0) * Size(i4, 1)
Cinv8(t1, 1) = wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) * Cint8(i1, i5) * Size(i4, 0) * Size(i4, 1)
Totalcost(t1, 0) = Totalcost(t1, 0) + product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semivalue + Cop3(t1, 0) + Cope8(t1, 0)
Totalcost(t1, 1) = Totalcost(t1, 1) + product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semivalue + Cop3(t1, 1) + Cope8(t1, 1)
          If (Totalcost(t1, 0) + Totalcost(t1, 1)) / 2 <= Budget / maxt Then
sum(t1, 0) = sum(t1, 0) + wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0) * (Size(i4, 0) * Size(i4, 1))
sum(t1, 1) = sum(t1, 1) + wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) * (Size(i4, 0) * Size(i4, 1))

          If capacity - ((sum(t1, 0) + sum(t1, 1) / 2)) >= 0 Then
totalback(t1, 0) = totalback(t1, 0) + Bw8(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0) * (Size(i4, 0) * Size(i4, 1))
totalback(t1, 1) = totalback(t1, 1) + Bw8(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) * (Size(i4, 0) * Size(i4, 1))

          If backcap - ((totalback(t1, 0) + totalback(t1, 1)) / 2) >= 0 Then
sumbac(1) = sumbac(1) + Bw8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) * Size(i4, 0) * Size(i4, 1) * backprice(pool(j, ncodp + i1) - 1)
sumbac(0) = sumbac(0) + Bw8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0) * Size(i4, 0) * Size(i4, 1) * backprice(pool(j, ncodp + i1) - 1)

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suminv(1) = suminv(1) + wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) *
Size(i4, 0) * Size(i4, 1) * Cint8(pool(j, ncodp + i1) - 1, i5)
suminv(0) = suminv(0) + wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0) *
Size(i4, 0) * Size(i4, 1) * Cint8(pool(j, ncodp + i1) - 1, i5)
Sumord(0) = Sumord(0) + norder(t1, p)
Sumord(1) = Sumord(1) + norder12(t1, p)
Tsum(5, 0) = Tsum(5, 0) + price1(p) * semivalue - (product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semivalue + Cop3(t1,
1) + Cop8(t1, 1))
Tsum(5, 1) = Tsum(5, 1) + price1(p) * semivalue - (product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semivalue + Cop3(t1,
0) + Cop8(t1, 0))
Tsum(0, 0) = Tsum(0, 0) + product1(CODP1 - 1, u2, u1, u, p, 0, 0) * semivalue
Tsum(0, 1) = Tsum(0, 1) + product1(CODP1 - 1, u2, u1, u, p, 0, 1) * semivalue
Tsum(1, 0) = Tsum(1, 0) + product1(CODP1 - 1, u2, u1, u, p, 1, 0)
Tsum(1, 1) = Tsum(1, 1) + product1(CODP1 - 1, u2, u1, u, p, 1, 1)
Tsum(2, 0) = Tsum(2, 0) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)
Tsum(2, 1) = Tsum(2, 1) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)
Tsum(3, 0) = Tsum(3, 0) + semivalue * (Size(i4, 1) * Size(i4, 0))
Tsum(3, 1) = Tsum(3, 1) + semivalue * (Size(i4, 1) * Size(i4, 0))
                                q = q + 1
                                Else
                                rr = 1
totalback(t1, 0) = totalback(t1, 0) - Bw8(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0)
* (Size(i4, 0) * Size(i4, 1))
totalback(t1, 1) = totalback(t1, 1) - Bw8(t1, pool(j, ncodp + i1) - 1, pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1)
* (Size(i4, 0) * Size(i4, 1))
                                Exit For
                                End If
                                Else
rr = 1
sum(t1, 0) = sum(t1, 0) - wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 0) *
(Size(i4, 0) * Size(i4, 1))
sum(t1, 1) = sum(t1, 1) - wip8(t1, (pool(j, ncodp + i1) - 1), pool(j, ncodp + nvar(0) + i2) - 1, i3, i4, i5, p9, 1) *
(Size(i4, 0) * Size(i4, 1))
                                Exit For
                                End If
                                Else
                                rr = 1
                                Exit For
                                End If
Next
If rr = 1 Then
Exit For
End If
End If
Next
If rr = 1 Then
Exit For
Else
maxinvbac = Math.Max(sumbac(1), suminv(1))
mininvbac = Math.Min(sumbac(0), suminv(0))
Tsum(5, 0) = Tsum(5, 0) + mininvbac
Tsum(5, 1) = Tsum(5, 1) + maxinvbac
sumbac(1) = 0
suminv(1) = 0
sumbac(0) = 0
suminv(0) = 0
End If
End If
Next
If rr = 1 Then

```

```

        Exit For
      End If
    Next
    If rr = 1 Then
      Exit For
    End If
  End If
Next
If rr = 1 Then
  Exit For
End If
Next
If rr = 1 Then
  Exit For
End If
Next
ElseIf CODP1 = 4 Then
  For t1 = 1 To maxt
    Cpur1(0) = 0
    Cpur1(1) = 0
    rr = 0
    For i1 = 0 To nvar(0) - 1
      back(t1, (pool(j, ncdp + i1) - 1), 0) = 0
      back(t1, (pool(j, ncdp + i1) - 1), 1) = 0
      For i2 = 0 To nvar(1) - 1
        For i3 = 0 To nvar(2) - 1
          If pool(j, ncdp + nvar(0) + nvar(1) + i3) = 1 Then
            For i4 = 0 To t2
              For i5 = 0 To nvar(4) - 1
                If pool(j, ncdp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + i5) = 1 Then
                  For i6 = 0 To nvar(5) - 1
                    If pool(j, ncdp + nvar(0) + nvar(1) + nvar(2) + nvar(3) + nvar(4) + i6) = 1 Then
                      For i7 = 0 To nvar(6) - 1


p = i7 + i6 * nvar(6) + i5 * nvar(6) * nvar(5) + i4 * nvar(6) * nvar(5) * nvar(4) + i3 * nvar(6) * nvar(5) * nvar(4) * nvar(3) + (pool(j, ncdp + nvar(0) + i2) - 1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) + (pool(j, ncdp + i1) - 1) * nvar(6) * nvar(5) * nvar(4) * nvar(3) * nvar(2) * nvar(1)



p9 = i7



c1 = norder(t1, p) - wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) + Bw9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 0)



c2 = norder12(t1, p) - wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 0) + Bw9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1)



semivalue = Math.Round((pool(j, schrom + t1 - maxt) / 10) * c2 + (1 - (pool(j, schrom + t1 - maxt) / 10)) * Math.Max(c1, 0), 0)



If semivalue = 0 Then



semivalue = Math.Round((Math.Max(c1, 0) + c2) / 2, 0)



End If



wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) = -1 * Math.Min(c1, 0) + semivalue - Math.Max(c1, 0)



Bw9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) = c2 - semivalue



Cop3(t1, 0) = ((ts3(u, i4) / (60)) + tmacmin(u) * semivalue * Size(i4, 0) * Size(i4, 1)) * Cbaft(u)



Cop3(t1, 1) = ((ts3(u, i4) / (60)) + tmacmin(u) * semivalue * (Size(i4, 0) * Size(i4, 1))) * Cbaft(u)



Cop8(t1, 0) = (Tope8(i6) / 8) * Cope8 * semivalue



Cop8(t1, 1) = (Tope8(i6) / 8) * Cope8 * semivalue



Cinv9(t1, 0) = wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 0) * Cint9(i1, i5, i6) * Size(i4, 0) * Size(i4, 1)



Cinv9(t1, 1) = wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) * Cint9(i1, i5, i6) * Size(i4, 0) * Size(i4, 1)



Totalcost(t1, 0) = Totalcost(t1, 0) + product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semivalue + Cop3(t1, 0) + Cop8(t1, 0)



Totalcost(t1, 1) = Totalcost(t1, 1) + product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semivalue + Cop3(t1, 1) + Cop8(t1, 1)


```



```

                If (Totalcost(t1, 0) + Totalcost(t1, 1)) / 2 <= Budget / maxt Then
sum(t1, 0) = sum(t1, 0) + wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 0) *
(Size(i4, 0) * Size(i4, 1))
sum(t1, 1) = sum(t1, 1) + wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) *
(Size(i4, 0) * Size(i4, 1))
                If capacity - ((sum(t1, 0) + sum(t1, 1) / 2)) >= 0 Then
totalback(t1, 0) = totalback(t1, 0) + Bw9(t1, pool(j, ncdp + i1) - 1, pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9,
0) * (Size(i4, 0) * Size(i4, 1))
totalback(t1, 1) = totalback(t1, 1) + Bw9(t1, pool(j, ncdp + i1) - 1, pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9,
1) * (Size(i4, 0) * Size(i4, 1))
                If backcap - ((totalback(t1, 0) + totalback(t1, 1)) / 2) >= 0 Then
sumbac(1) = sumbac(1) + Bw9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) *
Size(i4, 0) * Size(i4, 1) * backprice(pool(j, ncdp + i1) - 1)
sumbac(0) = sumbac(0) + Bw9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 0) *
Size(i4, 0) * Size(i4, 1) * backprice(pool(j, ncdp + i1) - 1)
suminv(1) = suminv(1) + wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) *
Size(i4, 0) * Size(i4, 1) * Cint9(pool(j, ncdp + i1) - 1, i5, i6)
suminv(0) = suminv(0) + wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 0) *
Size(i4, 0) * Size(i4, 1) * Cint9(pool(j, ncdp + i1) - 1, i5, i6)
Sumord(0) = Sumord(0) + norder(t1, p)
Sumord(1) = Sumord(1) + norder12(t1, p)
Tsum(5, 0) = Tsum(5, 0) + price1(p) * semivalue - (product1(CODP1 - 1, u2, u1, u, p, 4, 1) * semivalue + Cop3(t1,
1) + Cop8(t1, 1))
Tsum(5, 1) = Tsum(5, 1) + price1(p) * semivalue - (product1(CODP1 - 1, u2, u1, u, p, 4, 0) * semivalue + Cop3(t1,
0) + Cop8(t1, 0))
Tsum(0, 0) = Tsum(0, 0) + product1(CODP1 - 1, u2, u1, u, p, 0, 0) * semivalue
Tsum(0, 1) = Tsum(0, 1) + product1(CODP1 - 1, u2, u1, u, p, 0, 1) * semivalue
Tsum(1, 0) = Tsum(1, 0) + product1(CODP1 - 1, u2, u1, u, p, 1, 0)
Tsum(1, 1) = Tsum(1, 1) + product1(CODP1 - 1, u2, u1, u, p, 1, 1)
Tsum(2, 0) = Tsum(2, 0) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)
Tsum(2, 1) = Tsum(2, 1) + product1(CODP1 - 1, u2, u1, u, p, 2, 0)
Tsum(3, 0) = Tsum(3, 0) + semivalue * (Size(i4, 1) * Size(i4, 0))
Tsum(3, 1) = Tsum(3, 1) + semivalue * (Size(i4, 1) * Size(i4, 0))
                q = q + 1
                Else
                rr = 1
totalback(t1, 0) = totalback(t1, 0) - Bw9(t1, pool(j, ncdp + i1) - 1, pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9,
0) * (Size(i4, 0) * Size(i4, 1))
totalback(t1, 1) = totalback(t1, 1) - Bw9(t1, pool(j, ncdp + i1) - 1, pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9,
1) * (Size(i4, 0) * Size(i4, 1))
                Exit For
                End If
                Else
                rr = 1
sum(t1, 0) = sum(t1, 0) - wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 0) *
(Size(i4, 0) * Size(i4, 1))
sum(t1, 1) = sum(t1, 1) - wip9(t1, (pool(j, ncdp + i1) - 1), pool(j, ncdp + nvar(0) + i2) - 1, i3, i4, i5, i6, p9, 1) *
(Size(i4, 0) * Size(i4, 1))
                Exit For
                End If
                Else
                rr = 1
                Exit For
                End If
Next
If rr = 1 Then
Exit For
Else
maxinvbac = Math.Max(sumbac(1), suminv(1))
mininvbac = Math.Min(sumbac(0), suminv(0))

```

```

        Tsum(5, 0) = Tsum(5, 0) + mininvbac
        Tsum(5, 1) = Tsum(5, 1) + maxinvbac
        sumbac(1) = 0
        suminv(1) = 0
        sumbac(0) = 0
        suminv(0) = 0
    End If
End If
Next
If rr = 1 Then
    Exit For
End If
End If
Next
If rr = 1 Then
    Exit For
End If
Next
If rr = 1 Then
    Exit For
End If
End If
Next
If rr = 1 Then
    Exit For
End If
Next
If rr = 1 Then
    Exit For
End If
Next
End If
Tsum(0, 0) = (1 / Sumord(1)) * Tsum(0, 0)
Tsum(0, 1) = (1 / Sumord(0)) * Tsum(0, 1)
Obj1(j, 0) = Obj1(j, 0) - we1(0) * Tsum(0, 1) / maxF(0, 0)
Obj1(j, 1) = Obj1(j, 1) - we1(0) * Tsum(0, 0) / maxF(0, 0)
Obj1(j, 0) = Obj1(j, 0) + we1(1) * (1 / q) * Tsum(1, 0)
Obj1(j, 1) = Obj1(j, 1) + we1(1) * (1 / q) * Tsum(1, 1)
Obj1(j, 0) = Obj1(j, 0) + we1(4) * Size(t2, 1) / 2
Obj1(j, 1) = Obj1(j, 1) + we1(4) * Size(t2, 1) / 2
Obj1(j, 0) = Obj1(j, 0) + we1(2) * (1 / maxt) * Tsum(2, 0)
Obj1(j, 1) = Obj1(j, 1) + we1(2) * (1 / maxt) * Tsum(2, 0)
Tsum(3, 0) = Tsum(3, 0) / TD(1)
Tsum(3, 1) = Tsum(3, 1) / TD(0)
Obj1(j, 0) = Obj1(j, 0) + we1(3) * Tsum(3, 0)
Obj1(j, 1) = Obj1(j, 1) + we1(3) * Tsum(3, 1)
limit2(Tsum, 5)
Obj2(j, 0) = Obj2(j, 0) + we1(5) * Tsum(5, 0) / maxF(5, 0)
Obj2(j, 1) = Obj2(j, 1) + we1(5) * Tsum(5, 1) / maxF(5, 0)
End Sub

```

---

```

Private Sub Rankint(ByVal ns, ByRef Fr, ByRef r, ByVal m1, ByVal m2, ByVal r1, ByVal r2)
    Dim d1 As Short
    Dim np(ns - 1), rank(ns - 1), dset(ns - 1, 0), sumsp As Short
    Dim sp(ns - 1, ns - 1) As Integer

```

```

r = 0
For p = 0 To ns - 1
  For q = p + 1 To ns - 1
    If m1(p) > m1(q) And m2(p) > m2(q) Then
      sp(p, q) = 1
    ElseIf m1(p) > m1(q) And m2(p) = m2(q) Then
      If r2(p) <= r2(q) Then
        sp(p, q) = 1
      End If
    ElseIf m1(p) = m1(q) And m2(p) > m2(q) Then
      If r1(p) <= r1(q) Then
        sp(p, q) = 1
      End If
    ElseIf m1(q) > m1(p) And m2(q) > m2(p) Then
      sp(q, p) = 1
    ElseIf m1(q) > m1(p) And m2(q) = m2(p) Then
      If r2(q) <= r2(p) Then
        sp(q, p) = 1
      End If
    ElseIf m1(q) = m1(p) And m2(q) > m2(p) Then
      If r1(q) <= r1(p) Then
        sp(q, p) = 1
      End If
    ElseIf m1(q) = m1(p) And m2(q) = m2(p) Then
      If r1(q) < r1(p) Then
        sp(q, p) = 1
      ElseIf r1(q) > r1(p) Then
        sp(p, q) = 1
      End If
    End If
  Next
Next
Next

d1 = 1
While d1 = 1
  For q = 0 To ns - 1
    If rank(q) = 0 Then
      sumsp = 0
      For p = 0 To ns - 1
        If sp(p, q) <> 10 ^ 6 Then
          sumsp = sumsp + sp(p, q)
        End If
      Next
      If sumsp = 0 Then
        rank(q) = r + 1
        Fr(q) = r + 1
      End If
    End If
  Next
  d1 = check11(rank, ns)
  If d1 = 0 Then
    Exit While
  End If
  For q = 0 To ns - 1
    If rank(q) = r + 1 Then
      For p = 0 To ns - 1
        sp(p, q) = 10 ^ 6
      Next
    End If
  Next
Next

```

```

For p = 0 To ns - 1
  If rank(p) = r + 1 Then
    For q = 0 To ns - 1
      If sp(p, q) <> 10 ^ 6 And sp(p, q) = 1 Then
        sp(p, q) = 0
      End If
    Next
  End If
Next
r = r + 1
d1 = check11(rank, ns)
End While
End Sub

```

.....

```

Private Sub Crowdisint2(ByVal ns, ByVal r, ByVal Fr, ByVal g1, ByVal g2, ByRef dis, ByRef h, ByVal mean1,
ByVal mean2, ByVal var1, ByVal var2)

```

```

  Dim u, k1 As Short

```

```

  Dim dc1(u), dc2(u), nsort1(ns - 1), nsort2(ns - 1), gm1(0), gv1(0), gm2(0), gv2(0) As Single

```

```

  For i = 0 To r

```

```

    u = 0

```

```

    For j = 0 To ns - 1

```

```

      If Fr(j) = i + 1 Then

```

```

        u = u + 1

```

```

        ReDim Preserve gm1(u - 1)

```

```

        ReDim Preserve gv1(u - 1)

```

```

        ReDim Preserve nsort1(u - 1)

```

```

        gm1(u - 1) = mean1(j)

```

```

        gv1(u - 1) = var1(j)

```

```

        nsort1(u - 1) = j + 1

```

```

        ReDim Preserve gm2(u - 1)

```

```

        ReDim Preserve gv2(u - 1)

```

```

        ReDim Preserve nsort2(u - 1)

```

```

        gm2(u - 1) = mean2(j)

```

```

        gv2(u - 1) = var2(j)

```

```

        nsort2(u - 1) = j + 1

```

```

      End If

```

```

    Next

```

```

    h(i) = u

```

```

    ReDim Preserve dc1(u - 1)

```

```

    ReDim Preserve dc2(u - 1)

```

```

    If u > 2 Then

```

```

      findmaxint(gm1, gv1, nsort1, ns, u)

```

```

      findmaxint(gm2, gv2, nsort2, ns, u)

```

```

    End If

```

```

    If u = 1 Then

```

```

      dis(nsort1(0) - 1) = 10 ^ 12

```

```

    ElseIf u = 2 Then

```

```

      dis(nsort1(0) - 1) = 10 ^ 12

```

```

      dis(nsort1(1) - 1) = 10 ^ 12

```

```

      dis(nsort2(0) - 1) = 10 ^ 12

```

```

      dis(nsort2(1) - 1) = 10 ^ 12

```

```

    ElseIf u > 2 Then

```

```

      Crowdingint2(dc1, u, gm1, gv1)

```

```

      Crowdingint2(dc2, u, gm2, gv2)

```

```

    For k2 = 0 To u - 1

```

```

    For k1 = 0 To u - 1
        If nsort1(k2) = nsort2(k1) Then
            Exit For
        End If
    Next
    If Fr(nsort1(k2) - 1) = i + 1 Then
        dis(nsort1(k2) - 1) = dc1(k2) + dc2(k1)
    End If
Next
End If
Next
End Sub

```

.....

```

Private Sub crossover4(ByRef pool, ByVal ns1, ByVal m1, ByVal schrom, ByVal ncdp, ByVal nproduct, ByVal
nsupplier1, ByVal nsupplier2, ByVal nmachine, ByVal nvariety, ByVal nvar, ByVal nsource, ByVal Fr, ByVal dis,
ByVal CODP)

```

```

    Dim mc As Decimal
    Dim c1, c2, i, b1, k1, n1, n2, n3, k, u, g, h1, tl, tu, s1, sum, g2(3), g3(1), g4, y1, y2, t2, w2(1), a1, a2 As Short
    mc = 0.6

```

```

    For j = 0 To m1 - 1
        Dim of1(schrom), of2(schrom) As Short
        For i = 0 To 1
            Call Randomize()
            a1 = (ns1 - 1) * Rnd()
            Call Randomize()
            a2 = (ns1 - 1) * Rnd()
            While a1 = a2
                Call Randomize()
                a2 = (ns1 - 1) * Rnd()
            End While

```

```

            If Fr(a1) < Fr(a2) Then
                w2(i) = a1
            ElseIf Fr(a1) > Fr(a2) Then
                w2(i) = a2
            ElseIf Fr(a1) = Fr(a2) Then
                If dis(a1) > dis(a2) Then
                    w2(i) = a1
                ElseIf dis(a1) < dis(a2) Then
                    w2(i) = a2
                Else
                    w2(i) = a1
                End If
            End If

```

```

        End If
    Next
    c1 = w2(0)
    c2 = w2(1)
    putcross(of1, of2, pool, c1, c2, j, schrom, ns1, j, i)
    Call Randomize()
    g4 = Rnd() * (ncdp - 2)
    Call Randomize()
    g2(0) = Rnd() * (nvar(0) - 1) + ncdp
    Call Randomize()
    g3(0) = Rnd() * (nvar(1) - 1) + nvar(0) + ncdp
    Call Randomize()
    g3(1) = Rnd() * (nvar(1) - 1) + nvar(0) + ncdp

```

```

While g3(0) = g3(1)
  Call Randomize()
  g3(1) = Rnd() * (nvar(1) - 1) + nvar(0) + ncodp
End While
Call Randomize()
g2(1) = Rnd() * (nvar(2) - 1) + nvar(0) + nvar(1) + ncodp
Call Randomize()
g2(2) = Rnd() * (nvar(3) - 1) + nvar(0) + nvar(1) + nvar(2) + ncodp
Call Randomize()
g2(3) = Rnd() * (nvar(4) - 1) + nvar(0) + nvar(1) + nvar(2) + nvar(3) + ncodp
y1 = 0
y2 = 0
sum = 0
chek1(of1, of2, pool, ns1, j, i, ncodp, sum)
For s1 = 0 To nsource - 3
  If s1 = 0 Then
    sum = ncodp
  Else
    sum = sum + nvar(s1 - 1)
  End If
  If s1 = 0 Then
    checks123(of1, of2, c1, c2, pool, ns1, j, i)
  End If
  If s1 = 1 Then
    tl = ncodp + nvar(0)
    tu = ncodp + nvar(0) + nvar(1) - 1
    checks2(of1, of2, c1, c2, pool, ns1, j, i, tl, tu, g3)
  End If
  If s1 = 2 Then
    For k = (sum) To (sum + nvar(s1) - 1)
      If of1(k) = 1 Then
        y1 = y1 + 1
      End If
      If of2(k) = 1 Then
        y2 = y2 + 1
      End If
    Next
    tl = sum
    tu = sum + nvar(s1) - 1
    b1 = g2(s1 - 1)
    If y1 = 1 And y2 = 1 Then
      checkfeasibility(b1, of1, of2, pool, ns1, j, i, tl, tu, c1, c2)
    ElseIf y1 >= Math.Floor((nvar(s1) / 2)) + 1 And y2 >= Math.Floor((nvar(s1) / 2)) + 1 Then
      u = b1
      maincrossnew(of1, of2, pool, c1, c2, u, j, i, ns1, tl, tu)
    Else
      u = maincheck3(b1, of1, of2, tl, tu)
      maincrossnew(of1, of2, pool, c1, c2, u, j, i, ns1, tl, tu)
    End If
  End If
  If s1 = 3 Then
    tl = ncodp + nvar(0) + nvar(1) + nvar(2)
    tu = ncodp + nvar(0) + nvar(1) + nvar(2) + nvar(3) - 1
    b1 = g2(s1 - 1)
    chek1(of1, of2, pool, ns1, j, i, nvar(3), sum)
  End If
  If s1 = 4 Then
    y1 = 0
    y2 = 0
    For k1 = sum To sum + nvar(s1) - 1

```

```

        If of1(k1) = 1 Then
            y1 = y1 + 1
        End If
        If of2(k1) = 1 Then
            y2 = y2 + 1
        End If
    Next
    tl = sum
    tu = sum + nvar(s1) - 1
    b1 = g2(s1 - 1)
    If y1 = 1 And y2 = 1 Then
        checkfeasibility(b1, of1, of2, pool, ns1, j, i, tl, tu, c1, c2)
    ElseIf y1 >= Math.Floor((nvar(s1) / 2)) + 1 And y2 >= Math.Floor((nvar(s1) / 2)) + 1 Then
        u = b1
        tl = sum
        tu = schrom
        maincrossnew(of1, of2, pool, c1, c2, u, j, i, ns1, tl, tu)
    Else
        u = maincheck3(b1, of1, of2, tl, tu)
        tl = sum
        tu = schrom
        maincrossnew(of1, of2, pool, c1, c2, u, j, i, ns1, tl, tu)
    End If
End If
End If
Next
i = i + 1
Next
End Sub

```

\*\*\*\*\*

```

Private Sub mutation12(ByRef pool, ByVal m2, ByVal m1, ByVal ncodp, ByVal ns1, ByVal schrom, ByVal
nproduct, ByVal nsupplier1, ByVal nsupplier2, ByVal nmachine, ByVal nvariety, ByVal nsource, ByVal nvar,
ByVal Fr, ByVal dis, ByVal CODP)
    Dim k2, of2(schrom), c1, t1, i, k1, q, p2, y, k3, sum, a1, a2, u1, u2, dtemp(nvar(1) - 1), r3, tr1, n2, s2 As Short
    Dim pm As Decimal = 0.1
    For j = 0 To m2 - 1
        Dim of1(schrom) As Short
        Call Randomize()
        a1 = (ns1 + 2 * m1 - 1) * Rnd()
        Call Randomize()
        a2 = (ns1 + 2 * m1 - 1) * Rnd()
        While a1 = a2
            Call Randomize()
            a2 = (ns1 + 2 * m1 - 1) * Rnd()
        End While
        If Fr(a1) < Fr(a2) Then
            c1 = a1
        ElseIf Fr(a1) > Fr(a2) Then
            c1 = a2
        ElseIf Fr(a1) = Fr(a2) Then
            If dis(a1) > dis(a2) Then
                c1 = a1
            ElseIf dis(a1) < dis(a2) Then
                c1 = a2
            Else
                c1 = a1
            End If
        End If
        put1(of1, pool, c1, m1, j, ns1, schrom)
    Next

```

```

Call Randomize()
t1 = Rnd() * 5
Select Case t1
Case 0
  For i = 0 To ncodp - 1
    If of1(i) = 1 Then
      of1(i) = 0
      pool(ns1 + 2 * m1 + j, i) = 0
      Call Randomize()
      p2 = Rnd() * (ncodp - 1)
      While i = p2
        Call Randomize()
        p2 = Rnd() * (ncodp - 1)
      End While
      of1(p2) = 1
      pool(ns1 + 2 * m1 + j, p2) = 1
    Exit For
  End If
Next
Exit Select
Case 1
  sum = 4
  Call Randomize()
  k2 = Rnd() * (nsource - 2)
  If k2 > 0 Then
    For k = 1 To k2
      sum = sum + nvar(k - 1)
    Next
  End If
  If k2 = 0 Then
    Call Randomize()
    u1 = (nvar(k2) - 1) * Rnd()
    Call Randomize()
    u2 = (nvar(k2) - 1) * Rnd()
    While u1 = u2
      Call Randomize()
      u2 = (nvar(k2) - 1) * Rnd()
    End While
    If u2 < u1 Then
      r3 = u2
      u2 = u1
      u1 = r3
    End If
    tr1 = of1(sum + u1)
    of1(sum + u1) = of1(sum + u2)
    of1(sum + u2) = tr1
    For k1 = 0 To nvar(0) - 1
      pool(ns1 + 2 * m1 + j, sum + k1) = of1(sum + k1)
    Next
  End If
  If k2 = 1 Then
    Call Randomize()
    u1 = (nvar(k2) - 1) * Rnd()
    Call Randomize()
    u2 = (nvar(k2) - 1) * Rnd()
    While u1 = u2
      Call Randomize()
      u2 = (nvar(k2) - 1) * Rnd()
    End While
    If u2 < u1 Then

```



```

r3 = u2
u2 = u1
u1 = r3
End If
For i = u1 + 1 To u2
  dtemp(i - u1 - 1) = of1(sum + i)
Next
For j1 = 0 To u2 - u1 - 1
  of1(sum + j1 + u1 + 1) = dtemp(u2 - u1 - 1 - j1)
  pool(ns1 + 2 * m1 + j, sum + j1 + u1 + 1) = of1(sum + j1 + u1 + 1)
Next
End If
If k2 = 3 Then
  For i = 0 To nvar(3) - 1
    If of1(i) = 1 Then
      of1(sum + i) = 0
      pool(ns1 + 2 * m1 + j, sum + i) = 0
      Call Randomize()
      p2 = Rnd() * (nvar(3) - 1)
      While i = p2
        Call Randomize()
        p2 = Rnd() * (nvar(3) - 1)
      End While
      of1(sum + p2) = 1
      pool(ns1 + 2 * m1 + j, sum + p2) = 1
    Exit For
  End If
Next
Exit Select
End If
q = 0
If k2 = 2 Or k2 = 4 Or k2 = 5 Then
  checkone(k2, of1, nvar, sum, q, y)
  Call Randomize()
  k3 = (nvar(k2) - 1) * Rnd() + sum
  If y = 1 Then
    If of1(k3) = 1 Then
      of1(k3) = 0
      pool(ns1 + 2 * m1 + j, k3) = 0
    Else
      of1(k3) = 1
      pool(ns1 + 2 * m1 + j, k3) = 1
    End If
  ElseIf y = 0 Then
    If k3 = q Then
      Call Randomize()
      k3 = (nvar(k2) - 1) * Rnd() + sum
      While k3 = q
        k3 = (nvar(k2) - 1) * Rnd() + sum
      End While
      of1(q) = 0
      pool(ns1 + 2 * m1 + j, q) = 0
      of1(k3) = 1
      pool(ns1 + 2 * m1 + j, k3) = 1
    Else
      of1(k3) = 1
      pool(ns1 + 2 * m1 + j, k3) = 1
    End If
  End If
End If
End If
End If

```

```

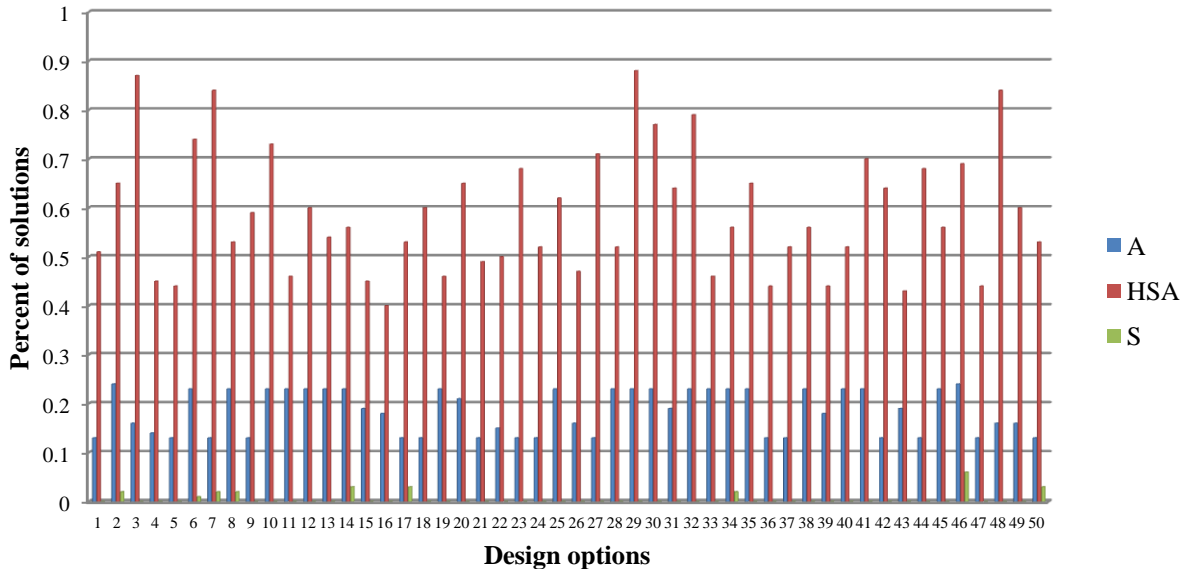
Exit Select
Case 2
For i = ncdp + nvariety To ncdp + nvariety + nsupplier1 - 1
  If of1(i) = 1 Then
    of1(i) = 0
    pool(ns1 + 2 * m1 + j, i) = 0
    Call Randomize()
    p2 = Rnd() * (nsupplier1 - 1) + nvariety + ncdp
    While i = p2
      Call Randomize()
      p2 = Rnd() * (nsupplier1 - 1) + nvariety + ncdp
    End While
    of1(p2) = 1
    pool(ns1 + 2 * m1 + j, p2) = 1
  Exit For
End If
Next
Exit Select
Case 3
For i = ncdp + nvariety + nsupplier1 To ncdp + nvariety + nsupplier1 + nsupplier2 - 1
  If of1(i) = 1 Then
    of1(i) = 0
    pool(ns1 + 2 * m1 + j, i) = 0
    Call Randomize()
    p2 = Rnd() * (nsupplier2 - 1) + nvariety + nsupplier1 + ncdp
    While i = p2
      Call Randomize()
      p2 = Rnd() * (nsupplier2 - 1) + nvariety + nsupplier1 + ncdp
    End While
    of1(p2) = 1
    pool(ns1 + 2 * m1 + j, p2) = 1
  Exit For
End If
Next
Exit Select
Case 4
i = ncdp + nvariety + nsupplier1 + nsupplier2
If of1(i) = 1 Then
  of1(i) = 0
  pool(ns1 + 2 * m1 + j, i) = 0
  of1(i + 1) = 1
  pool(ns1 + 2 * m1 + j, i + 1) = 1
Else
  of1(i) = 1
  pool(ns1 + 2 * m1 + j, i) = 1
  of1(i + 1) = 0
  pool(ns1 + 2 * m1 + j, i + 1) = 0
End If
Case 5
Call Randomize()
s2 = Rnd() * 9 + 1
of1(schrom + n2 + 1 - maxt) = s2
pool(ns1 + 2 * m1 + j, schrom + n2 + 1 - maxt) = s2
End Select
Next
End Sub

```

# E: Details of solutions for model II with constraint backorder capacity

Here, we analyze details of solutions in Pareto set and represent them with charts as follows:

The first chart (Figure 57) shows percent of solutions offering the design with different material.

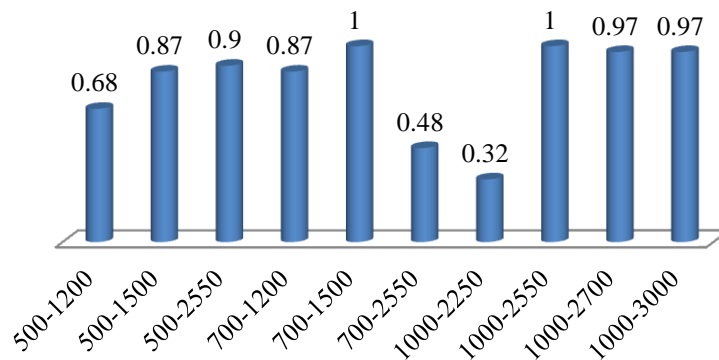


A: Acrylic; HSA: Heat Set Acrylic; S: Silk

**Figure 57:** Percent of designs options in solutions (Model II- Backorder capacity)

As chart shows, design options with material “Heat set Acrylic” include higher percent of solution. For example, 51% solutions choice design option 1 with material “Heat Set Acrylic” in order to offer to customers, while only 13% solutions propose design option 1 with material “Acrylic”. Also, only a very low percent of solutions propose design option with material Silk.

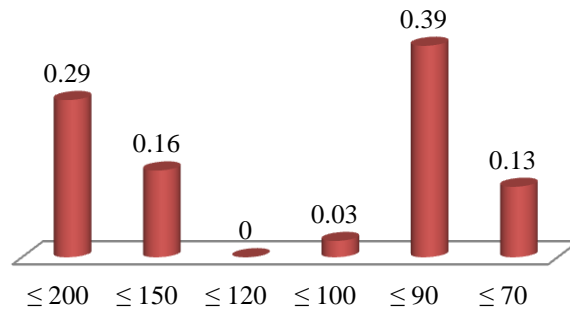
Next chart (Figure 58) shows percent of solutions offering the density options.



**Figure 58:** Percent of density options in solutions (Model II -Backorder capacity)

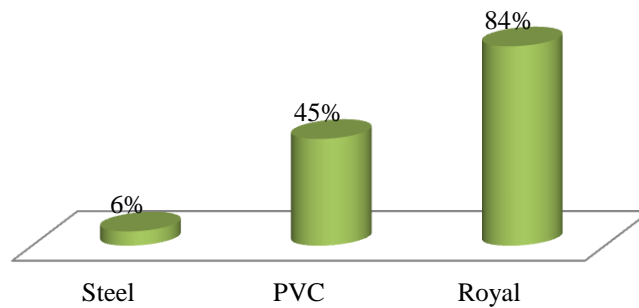
As this chart shows, 2 density options are proposed by 100% solutions.

Next chart (Figure 59) displays percent of solutions proposing different extent of feature “Size”.



**Figure 59:** Percent of size feature proposed by solutions (Model II- Backorder capacity)

The next chart (Figure 60) displays percent of solutions that propose different panels.

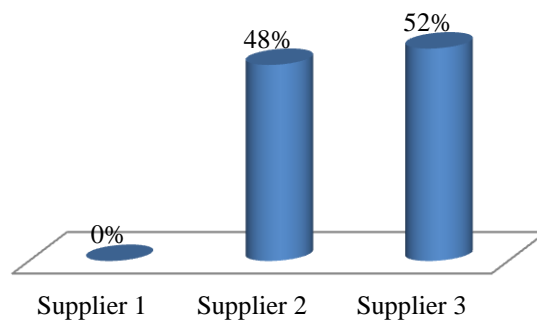


**Figure 60:** Percent of panel options in solutions (Model II- Backorder capacity)

This chart shows that more percent of solutions propose panel Royal.

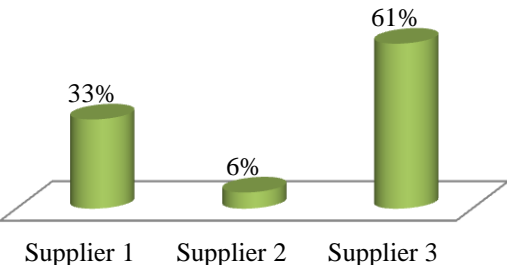
Investigation of set of solutions identify that all solution propose pack of standard and customize.

The next chart (Figure 61) displays percent of solutions that select different suppliers of panels.



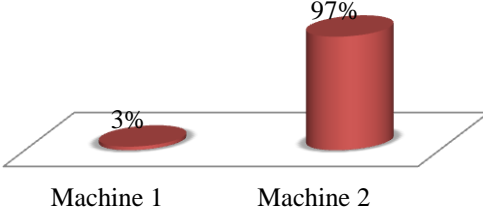
**Figure 61:** Percent of solution which select suppliers’ panel (Model II- Backorder capacity)

As this chart shows, 52% solutions prefer supplier 3 and others select supplier 2. Figure 62 identifies percent of solutions which select suppliers providing material.



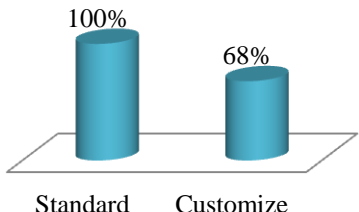
**Figure 62:** Percent of solution which select suppliers' material (Model II- Backorder capacity)

Graph 63 displays the percent of solutions that select weaving machines. Analyzing solutions shows more solutions select weaving machine 2 to weave carpet tableaus.



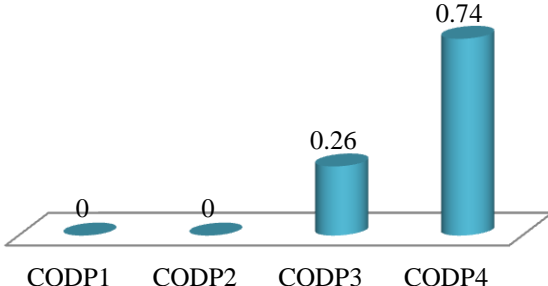
**Figure 63:** Percent of solution which select weaving machines (Model II- Backorder capacity)

Next graph (Figure 64) identifies percent of solutions that select types of packing.



**Figure 64:** Percent of solution which select types of packing (Model II- Backorder capacity)

Next chart (Figure 65) shows percent of solutions that select different CODPs.



**Figure 65:** Percent of solution which select CODPs (Model II- Backorder capacity)