

Delivery Time Uncertainty in Dynamic Supply Networks

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In the Name of Allah

تقدیم به میهن عزیزم ایران

به مادر و پدر مهربانم، همسر عزیزم فarnaz و فرزند دلبندم رادین

و به همه انهایی که دوستان دارم.

To my dear country, Iran

To my kind parents, beloved spouse, Farnaz and my dear son, Radin

&

To all those, I love.

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ABSTRAKT

Heut zu Tage verändert sich der Konkurrenzgedanke von Unternehmen untereinander hin zu einer interunternehmerischen Konkurrenz zwischen Logistiknetzwerken (Rice & Hoppe, 2001). Der Gewinn der Gunst des Kunden ist einer der primären Elemente, um am Markt zu bestehen. Die Erwartungen und Bedürfnisse der Kunden nehmen von Tag zu Tag an Diversivität zu. Um diese Bedürfnisse mit neuen angebotenen Dienstleistungen kurzfristig zu erfüllen, braucht es mehr Flexibilität auf allen Ebenen (Versorger, Hersteller, Logistikdienstleister) des Versorgungsnetzwerkes, um die Produktionskosten und Qualität im Rahmen zu halten. Deshalb ist es notwendig für jede Marktchance ein separates Versorgungsnetzwerk einzurichten (Barker & Finnie, 2004). Organisationen sind nicht länger auf Langzeitverträge mit ihren Versorgern angewiesen. Vielmehr ist die Auswahl des Versorgers damit verbunden, welche Qualifikationen dieser im Hinblick auf die Bereitstellung von Dienstleistungen und deren Kompatibilität mit den Kundenwünschen erbringt. So muss ein Versorgungsnetzwerk entsprechend der spezifischen Marktchance, mit Blick auf die Struktur und Teilnehmer, entworfen werden. Daraus resultierend muss der Aufbau von Versorgungsnetzwerken flexibler werden und bewegt sich dabei in Richtung Dynamik (Humphries & Mena, 2012). Betrachtet man die Dynamik und Kurzlebigkeit heutiger Versorgungsnetzwerke, unterscheiden sich die Managementstrategien zum Lösen dieser Netzwerkprobleme von den traditionellen Strategien (welche in den Versorgungsnetzwerken mit festen Strukturen Anwendung finden).

Die Lieferzeit ist eine der Hauptkriterien für die Evaluation der Leistung eines Versorgungsnetzwerkes. Lieferzeit und Genauigkeit in dynamischen Versorgungsnetzwerken sind, wegen ihrer Kurzlebigkeit solcher Netzwerke, die größten Herausforderungen für Netzwerkmanager (da Silveira & Arkader, 2007).

Aus einem anderen Blickwinkel betrachtet dürfen Ungenauigkeit und deren Ursachen, welche die Lieferzeit direkt betreffen, deshalb nicht ignoriert werden. Aus diesem Grund fokussiert diese Untersuchung auf die Auswirkung von Unsicherheit auf die Lieferzeit in dynamischen Versorgungsnetzwerken. Genauer gesagt untersuchen und definieren wir im ersten Schritt Versorgungsnetzwerke und Aufgaben, vor denen die Manager in entscheidungstreffenden Prozessen in Zusammenhang mit Versorgungsnetzwerken stehen. Anschließend werden die Ursachen der Unsicherheit in den Versorgungsnetzwerken aus der Sicht anderer Wissenschaftler identifiziert und gesammelt. Laut der Literatur sind Netzwerkaufbau und in diesem Zusammenhang auftretende Komplexitäten einer der Hauptfaktoren, die zu Unsicherheit in einem Versorgungsnetzwerk beitragen (Simangunsong, et al., 2012). Netzwerke mit einer höheren Komplexität (die Anzahl der Teilnehmer, wie auch der Typ der Subnetzwerke), weisen eine höhere Unsicherheit auf. In der laufenden Untersuchung besteht ein

Versorgungsnetzwerk aus einer Anzahl Versorger und einem Hersteller (die Hauptorganisation, welche die Kundenaufträge sammelt). Also beinhaltet ein Versorgungsnetzwerk Knoten, welche Netzwerkteilnehmer beinhalten, die die Möglichkeit haben zur Wertsteigerung beizutragen, wie auch Verbindungen zwischen den Teilnehmern. Nach der Diskussion der Herausforderungen und Unsicherheiten der Versorgungsnetzwerke, werden die Versorgungs Subnetzwerke (Basisnetzwerke) grafisch aufgearbeitet. Im Anschluss werden wir wiedergeben, wie durch eine Kombination von Subnetzwerken komplexe Netzwerke entstehen.

Wie gesagt, wird ein Versorgungsnetzwerk als aus zwei, oder mehr unterschiedlichen Organisationen die von einander abhängig sind, beschrieben (Harland, et al., 2001). Lieferzeitliche Unsicherheiten sind eine der Aufgaben vor denen dynamische Versorgungsnetzwerke stehen. Der Aufbau der Netze und die Mitglieder haben einen nicht unerheblichen Einfluss auf das Niveau der Unsicherheit (Safaei, et al., 2013). Jedes Mitglied des Versorgungsnetzwerkes hat sein eigenes Niveau der Unsicherheit. Die Unsicherheit der gesamten Lieferzeit hängt von der Unsicherheit jedes Mitgliedes des Netzwerkes ab. Eine Untersuchung des Einflusses der Unsicherheit jedes einzelnen Mitgliedes des Netzwerkes auf die gesamte Unsicherheit des Netzwerkes zeigt, dass dies in Verbindung, mit einer Kombination des Netzwerktyps, dem Niveau der Komplexität des Aufbaus und direkt mit den Mitgliedern, steht. Die Messung des Niveaus akkumulierter Unsicherheit im Netzwerk diese Ursachen betreffend, ist eines der Anliegen denen sich diese Untersuchung stellt. Außerdem ist es unentbehrlich Versorger mit dem höchstmöglichen Potential für die akkumulierte Unsicherheit zu identifizieren, um die Netzwerkeffizienz und Leistung zu verbessern (Safaei, et al., 2011).

Auf Grund der Kurzlebigkeit dynamischer Versorgungsnetzwerke, sollten Methoden zur Bewältigung der Forschungsaufgaben schnell und genau sein (Alkhatib, et al., 2013). Weshalb wir, auf Grund des Vorgehens welches in dieser Untersuchung vorgeschlagen wurde, nicht im Detail auf jedes Netzwerk ein gehen und betrachten lieber jeden Versorger (Mitglieder) als Quelle, dessen Lieferzeit und Unsicherheit gute Indikatoren und Schätzwerte, des ganzen Vorgangs interner Unsicherheiten, sind. Also wurde das Versogerverhalten, druch abschätzen statistischer Funktionen der Lieferzeitunsicherheit jedes Versorgers durch die Auswertung von Stichproben der Lieferzeiten ähnlicher Projekte, untersucht. Diese statistischen Funktionen bilden die Basis aller folgenden Berechnungen. Im Anschluss werden die Versorger mit dem größten Einfluss auf die Unsicherheit des gesamten Netzwerkes, durch den Einsatz, der modifizierten und angepassten PERT Methode, auf das Versorgernetzwerk, identifiziert. Im nächsten Schritt wird mittels eines angepassten GUM und einer Monte Carlo Technik, welche später erläutert werden, die akkumulierte Netzwerkunsicherheit errechnet .

Durch das Studium der Forschungsliteratur stellte sich heraus, dass die meisten Untersuchungen auf die Bereitstellung von Strategien zur Reduzierung der Unsicherheit fokussieren. Es ist aber nötig die Unsicherheit vor dem Einsatz solcher Strategien zu berechnen, was in vorherigen Untersuchungen allerdings außer acht gelassen wurde. Die vorgeschlagene Methode in dieser Forschungsarbeit hat versucht, ohne den Einsatz mathematischer Formeln, einen einfachen Weg zu beschreiben. In den Händen von Managern kann dies ein Werkzeug sein, um sie bei der Berechnung und Überwachung von Unsicherheit in ihren Versorgungsnetzwerken und der Entscheidungsfindung, zu unterstützen, bevor Kürzungsstrategien zum Einsatz kommen. Aus diesem Grund gibt es Managern die Möglichkeit kritische Versorger zu identifizieren und zu ermitteln, wo Unsicherheitskürzungsstrategien anzuwenden sind und deren Effektivität zu messen.

ABSTRACT

Nowadays, business competition turns from inter-company competition into competition between supply networks (Rice & Hoppe, 2001). Winning customer satisfaction is one of the primary elements of survival in the market. Customers' expectations and demands get more diversified day by day. Meeting customers' full satisfaction through offering them diverse services and fulfilling their varying expectations in the short term requires increased flexibility in all different levels (suppliers, manufacturers, distributors) of the supply network in order to control production costs and quality (Ari-Pekka & Antti, 2005). Therefore, it is necessary to design a separate structure of supply network for each market opportunity (Barker & Finnie, 2004). Organizations no longer are committed to long-term cooperation with suppliers. Furthermore, choosing suppliers is only based on their qualifications with regard to providing service and their compatibility with the type of customers' demands. Thus, each supply network needs to be designed according to a specific market opportunity with regard to structure and members. As a result, the structure of supply networks must be more flexible and is moving toward dynamics (Humphries & Mena, 2012). Given the dynamic and short-time nature of today's supply networks, the management strategies required to handle issues related to such networks is different from traditional strategies (which are applied in the supply networks with fixed structures.).

Delivery time is one of the main criteria for evaluating the performance of a supply network. Delivery speed and accuracy in dynamic supply networks are the main challenges ahead of network managers due to the short-time nature of such networks (da Silveira & Arkader, 2007). Therefore, from a different viewpoint, uncertainty and its sources, which directly affect delivery time, could not be ignored easily. Therefore, this study essentially focuses on the impact of uncertainty on delivery time in dynamic supply networks. In particular, we examine and define supply networks and challenges ahead of managers in decision-making processes related to supply networks in the first step. Then, the causes of uncertainty in supply networks from the viewpoint of other researchers are identified and collected.

According to the literature, network structure and relevant complexities are one of the main factors contributing to uncertainty in supply networks (Simangunsong, et al., 2012). The networks with greater complexity (in terms of the number of members as well as the type of sub-networks), will create higher uncertainty. In the current study, a supply network consists of a number of suppliers and a manufacturer (the main organization, which collects the customers' orders). Therefore, a supply network includes nodes, which cover network members who are capable of creating added value in the network as well as links between these members. After discussing supply network challenges and uncertainty, the supply sub-networks (basic networks) will be

illustrated. Then, we express how complex networks are created by combining sub-networks.

As stated, a supply network is described to consist of two or more different organizations that depend on each other (Harland, et al., 2001). Delivery time uncertainty is one of the challenges ahead of dynamic supply networks. Network structure and members have an undeniable effect on the level of uncertainty (Safaei, et al., 2013). Each member of the supply network has its own level of uncertainty. The uncertainty of the final delivery time depends on the uncertainty of each member of the network. An examination of the influences of the uncertainty of each network member on the final uncertainty of the network is related to the combination of the basic types of the network, level of structural complexity, and members directly. Measuring the level of accumulated uncertainty in the network regarding to these causes is one of the issues covered by this study. On the other hand, it is indispensable to identify suppliers with the highest contribution to the accumulated uncertainty in order to be able to improve network efficiency and performance (Safaei, et al., 2011).

Because of the short lifetime of dynamic supply networks, the methods required to deal with the research challenges should enjoy proper speed and accuracy (Alkhatib, et al., 2013). For this reason, based on the methodology proposed in this study, we will not go into the details of each network separately and will rather approach each supplier (member) as a black box whose delivery time and uncertainty outputs are good indicators and estimators of the whole event and relevant internal uncertainties. Thus, supplier behavior has been examined based on delivery time uncertainty by calculating the statistical function of each supplier's delivery time uncertainty obtained through sampling the delivery times in similar projects. These statistical functions form the basis of further calculations. Then, those suppliers with the highest effect on the total delivery time uncertainty of the network will identify through employing the modified and adapted PERT method to the supply network. In the next stage, by using adapted GUM and Monte Carlo techniques, which will be discussed later, the network's accumulated uncertainty will be calculated.

A study of the research's literature revealed that most studies had focused on offering strategies to reduce uncertainty. However, it is necessary to calculate the uncertainty before employing such strategies, something that has been overlooked by previous studies. The proposed methodology in this research, has been trying to express in a simple way and without using complex mathematical formulas. It could be a tool in the hand of managers to calculate and monitor uncertainty in their supply networks to support them in their decision before using the reduction strategies. For this reason, it enables managers to identify critical suppliers and determine where to employ uncertainty reduction strategies and measure their effectiveness.

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List of abbreviations

APICS	American Production and Inventory Control Society
CLM	Council of Logistics Management
DP	Dynamic Programming
DRP/MRP	Distribution/Material Requirement Planning
DSS	Decision support system
DT	Delivery Time
EDI	Electronic Data Interchange
GHG	Greenhouse Gas
GUM	Guide to the expression of Uncertainty in Measurement
IBM	The International Business Machines
ICT	Information and Communication Technology
IT	Information Technology
KBN	Kanban
KM	Knowledge Management
KPIs	Key Performance Indicators
MIT Press	University Press Affiliated with the Massachusetts Institute of Technology in Cambridge
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
MTS	Make to Stock
OEM	Original Equipment Manufacturer
OR	Operation Research
PERT	Program Evaluation and Review Technique
QR	Quick Response
ROP	Re-Order Point
SCC	Supply-Chain Council
SCOR	Supply-Chain Operations Reference
TPL	Third Party Logistics
TSP	Traveling Salesment Problem
USPTO	United States Patent and Trademark Office's
VIM	International Vocabulary of Metrology

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1 CHAPTER 1 – Introduction

Nowadays, supply network management is considered as one of the infrastructure foundations for implementation of a competitive business. In the global competition, various products should be available according to customers' requirements. The customers expectations on high quality and quick service have led to increase the pressures on the availability of customized products that did not exist before. Consequently, companies cannot overcome all of these pressures alone (Nagurney, et al., 2006).

Surviving in competitive markets has led companies to concentrate their activities on core products and focus on specific abilities. As a consequence, companies intend to outsource some parts of their activities. Outsourcing will increase competitive advantages of the companies with focus on special activities with more added values. Accordingly, activities such as supply and demand planning, preparation of materials, production planning, maintenance service, inventory control, distribution, delivery time (DT) and customer service, that all have been realized within a company or in a simple supply chain before, now have converted to a complex supply network.

Outsourcing as one of the characteristics of supply networks, despite its many advantages and strengths, creates a new source of uncertainty in production planning of supply networks. This new source of uncertainty in many cases is the failure factor of the supply networks (Lee, et al., 2011). Delivery time uncertainty (DTU) is thus one of the major challenges for a supply network, which may affect the goals of the network. Moreover, if the occurrences of unknown possible events (e.g. Delivery time uncertainty) are not well predicted and the appropriate strategies to deal with such occurrences are not decided, it could negatively affect the overall network performance.

1.1 Motivation

Today's business rapidly changes and has become more competitive. Organizations increasingly recognize the effective role of supply networks to compete in the global market and networked economy. Value creation within the manufacturing industry is realized in the supply networks (Baig, 2006). In general, a supply network is considered as a cooperation between suppliers and a manufacturer with the objective to realize a product and additional service.

In those industries, where batch sizes are high (series production), the supply networks usually are stable in terms of involved companies and the related processes (Guiffrida & Jaber, 2008). Due to the fact that market opportunities are more and more short-term and customer expectations are dynamic, supply networks in many cases need to be designed according to a specific market opportunity. In consequence, the configuration of supply networks becomes dynamic.

Therefore, quantities, delivery times, due dates, start times, etc., in the network may change at any time. Consequently, supply network systems must

be updated accordingly, so that decisions are based on dynamic information (Barker & Finnie, 2004). The objective of these dynamic supply networks is to realize individual demands in a reliable way with short reaction times to the market need.

Agility and accuracy in delivery time, product final cost and quality are the fundamental characteristics of competitiveness. The enterprises have to be able to provide consumer demands just in time, with desired quality at reasonable price (Toukko, 2010). Nowadays, a firm in the supply network can outsource different functions. Different degrees of commitment and integration between the company and the contractors follow accordingly. Outsourcing in the supply network creates a new source of uncertainty in delivery time and other quantity and quality factors. This uncertainty influences supply network performance by affecting delivery time reliability (Vanany, et al., 2009). The importance of delivery time as a strategic parameter has been recognized in the arena of global competition (Christopher, 2000; Lerder, 1997). The strategic importance of delivery time uncertainty has been identified by many researchers and practitioners, and it has emerged as a key competitive factor in a supply network. Thus, many manufacturers are adopting the use of delivery-time guarantees as part of their market positioning strategy (Urban, 2009).

An important precondition to reach reliable deliveries is the consideration of delivery time uncertainties due to the fact that a predictable reaction time is a main success factor in the global competition. Delivery time uncertainty within a supply network can be understood as the lack of ability of the network to guarantee a certain percentage of deliveries within a defined time-frame.

Backlogs, delay in demand delivery, demurrages and increase in product total price result from higher uncertainty in delivery time. The way that enterprises interact with their partners and type of relations has a large impact on the uncertainty in delivery time. Appropriately designing, controlling, and organizing the supply network structure and its relationships leads to control and in the following, reduction of delivery time uncertainty.

In order to improve the performance of the supply network and control of the delivery time uncertainty, it is required to define a methodology to identify the suppliers with the highest influence on this uncertainty (critical suppliers). Moreover, to ensure reliable deliveries of a supply network, a method to identify and to control potential uncertainties regarding the delivery is needed.

1.2 Gap of knowledge and research problem

In this chapter, a brief description of the research problem is presented, which will be explained in further detail within chapter 4.

As mentioned before, achieving maximum customer satisfaction has turned into a key success factor in today's competitive market. Consequently, the need for delivery of services to meet increased diversity in customer demands has compelled organizations to focus on increasing flexibility in offering services as well as controlling costs. One of these flexibilities is related to the structure of

the networks and ability of the network to reconfigure itself for different orders. Supply networks with fixed structures (called traditional supply networks in the following), cannot meet organizations' demands anymore. For this reason, to succeed in today's business environment it is necessary to make organizations turn to dynamic supply networks. Hence, dynamic supply networks need to be designed in accordance with the dynamic short-term customers' demands (Ari-Pekka & Antti, 2005). Providing a secure way to meet every single demand of customers in the shortest possible time is the main goal behind designing short-term dynamic supply networks.

Adapting the methods and techniques of traditional supply networks to dynamic networks has been another cause of concern for managers. Due to their short-term nature, dynamic networks are not able to benefit from older techniques, which were applied in the decision making of traditional supply networks regarding to the continual improvement. Therefore, it is important that the methods must have high capability to provide required information for managers in the shortest period of time, with the highest level of accuracy as well as speed. Uncertainty is one of the challenges associated with supply networks. Uncertainty originates from different factors such as structural complexity and type of relationship among network members. These factors will be discussed in detail in chapter 3.

Formally, a supply network can be described by nodes representing the companies and the links (relationships) between these nodes (companies). From this perspective, a network type is defined as the structure indicating how the different nodes are linked with each other. In this point of view, there are several basic network types (see figure 4-2). Accordingly, complex networks can be configured from a combination of basic or conventional networks. In other words, conventional networks, as introduced above, can be individually complex or in combined forms. As Zhao et al. defined, those networks with irregular, intrinsic, and in time dynamically evolving structures can be considered as complex (Zhao, et al., 2011).

The structural complexity of today's dynamic supply networks is among the main factors contributing to uncertainty (Cheng, et al., 2013). Higher complexity in terms of the number of network members and the type of structure, will create a higher level of uncertainty. A literature review has revealed gaps in some cases. They showed that most of the models and strategies proposed by previous studies on supply network uncertainty focused on uncertainty reduction inside companies separately, or they were implemented into the traditional supply network environment. The first gap is related to the need for adapting the methods to dynamic networks (Pishvaei, et al., 2009).

There is much research on strategies and methods to decrease the uncertainty in the literature. In most studied cases, researchers investigated the internal factors of uncertainties, e.g., machine breakdown and the external factors like demand uncertainty, which most of them are created by the customers (Käkia, et

al., 2013; Simangunsong, et al., 2012). A survey on evaluating the uncertainty, which is caused by the suppliers under consideration of the network configuration, is still a gap in this area.

As for the third gap, first it is necessary to determine in which section(s) or supplier(s) uncertainty reduction is more effective, as shown in figure 3-8. Hence, prevention or reduction models could be introduced accordingly. In other words, the location for implementing the model should be determined first. Then, the model should be designed based on that location. Literature review indicated the need for a model that could calculate and monitor uncertainty with high speed and accuracy to show these locations.

As mentioned above, the role of delivery time and its effectiveness in increasing customer satisfaction in dynamic supply networks is undeniable. Hence, the current study focuses on how to control and monitor supply network uncertainty in dynamic supply networks.

The delivery time uncertainty of a supply network is caused by the individual delivery time uncertainties of the members of the network (Zimmer, 2002). To be able to estimate the delivery time uncertainty of the entire supply network, the influence of these individual uncertainties on the total uncertainty level has to be understood. The way how the individual uncertainties need to be accumulated depends on the network type.

Uncertainty in delivery time depends on the type of network and relationship between the constituent. Manufacturers have to evaluate the individual delivery time uncertainties of each single supplier. The problem is to understand how the individual uncertainties influence the total uncertainty of the network. The knowledge about the interdependency between a network type and the accumulation of the individual uncertainties is essential to identify those parts of the network, which have the highest potential for improving the total delivery time uncertainty.

The research problem addressed in this thesis comprises an identification of the amount of uncertainty transferred from the suppliers to the manufacturer, search for a model to accumulate the uncertainties of individual suppliers and finally determination of those suppliers which have most influence on delivery time uncertainty.

1.3 Purpose and procedure of the dissertation

In fact, there are no boundaries and borders in today's business, and the market economy proceeds toward globalization, a fact that has led to an increase in complexities and uncertainties observed in all business aspects. Dealing with such complexities and uncertainties has turned into a serious challenge for organizations (Ellis, 2008).

Consequently, companies are seeking higher performance of their supply network by managing these new challenges. One of these problems is controlling the uncertainty in the supply network regarding the delivery time. The objective of this research is to adapt a hybrid methodology to calculate the

accumulation of delivery time uncertainty in supply networks and to show the effective role of the network configuration on it. The hybrid methodology is able to find those suppliers who have highest influence on the accumulation of delivery time uncertainty (critical suppliers). Furthermore, to find the network behavior to transfer the individual uncertainties to the Original Equipment Manufacturer (OEM) by a statistical and mathematical formula is the next goal of this research.

Knowledge about the influences of the different basic network types on the delivery time uncertainty of the supply network is crucial to supply networks' structure planners: It assists them in designing the network with more efficiency and effectiveness than before in order to control and decrease uncertainty. Thus, they could increase their supply network performance. Additionally, finding the critical suppliers in the supply network could be used as an index of supplier selection methods with regard to the delivery time. Moreover, accumulated delivery time uncertainty generates more confidence of managers to discuss about the delivery time of the contracts, resulting in a higher degree of control.

Since most of the quantitative models, regarding the literature (see chapter 3), have used complicated mathematical models to represent, analyze, and solve uncertain situations in supply networks the role of quantitative models has become ambiguous in practice. Accordingly, a proper comprehension and application of complex mathematics for practitioners and managers is abstruse and time-consuming. For these reasons, a combination of both quantitative and qualitative approaches is required to benefit from both in a heuristic method. Another objective is, to introduce a hybrid method by employing mathematical and stochastic techniques: firstly, the complexity of network under uncertainty is reduced and, secondly, the accumulative uncertainty of the corresponding network is calculated. Given the accumulated uncertainty an analytical tool is developed that precisely measures the effect of alternative strategies against delivery-time uncertainty in every node of the network. Therefore, managers can easily evaluate their own policies.

In order to achieve the mentioned objectives, first, all the suppliers must be identified and according to the relationships between them, the structure of supply network should be drawn. After determining the network structure, the mathematical model of the behavior of the suppliers based on samples collected from the supplier delivery time must be found separately by a probability function. This function is entitled 'probability density function' (pdf) in this research. According to the probability density function of each supplier and the methods presented in chapter 5 as well as the types of network that we will introduce in the future, critical suppliers will be identified. The detection of critical suppliers allows us to spend less time to calculate the uncertainty that can be transferred from suppliers to manufacturers. Based on the methodologies GUM¹ and Monte Carlo method and an adaptation of these models within

¹ Guide to the Expression of Uncertainty in Management

supply network's field, which will be detailed in Chapter 5, a comprehensive methodology to calculate the accumulated uncertainty for any networks will be presented.

1.4 Structure of the dissertation

Given the objective of the study, the current thesis is compiled in seven chapters. The first chapter presents an introduction to familiarize readers with the topic. This short introduction is followed by a brief explanation about the motivation conducting the research. Then, the existing gap in the literature as well as the research questions are discussed briefly. Finally, the goals of the research and the procedure employed to achieve the goals are determined. At the end, the research's structure is interpreted and the relevant diagram (figure 1-1) is presented in order to clarify the path of the research.

Chapter 2 has been entirely dedicated for introducing supply networks since the term “supply network” is one of the principal keywords of the research. At the beginning of the chapter, supply network management is defined, following an introduction to the need for network activity. Then, the most important applicable definitions provided by the literature are discussed. Subsequently, the history of the development of supply networks from their appearance until today is presented. Following that, the general structure of today's supply networks, and that structural parameters are interpreted. The next part, most common challenges ahead of supply network managers, according to the literature are introduced. The following section is dedicated to introducing measures required for creating an effective and efficient supply network. The last section of the chapter explains the need for rapid responses, given the importance of delivery time in our research.

Since uncertainty has been introduced as one of the key challenges ahead of supply network managers in chapter 2, the third chapter provides a detailed explanation of uncertainty, its sources, and relevant techniques applied in the literature and discussed in this regard. At the end of the chapter, the strengths and weaknesses of those techniques as well as the gaps associated with uncertainty-related methods are mentioned.

Chapter 4 focuses on the research questions. At the beginning, the dynamic term in supply networks is defined. Then, the importance of controlling and monitoring delivery time and preventing delays are explained. In the next section, the motivation of the research is stated and the supply network from the viewpoint of the current research is defined. In this regard, sub-networks are primarily introduced. And then the complex supply networks regarding to these sub-networks are described. The next section explains the main questions of the current study. For this reason, it is necessary to introduce some measurable quantitative parameters in order to be able to define the problem, that is why, they are explained after describing the main questions. Finally, the features of a method (or methodology) that should be designed to solve the problem have been introduced.

A hybrid methodology for solving the problem has been introduced in chapter 5. Due to the importance of probability density functions in this methodology, a number of the most important probability density functions are illustrated in the first step. Then, the following section shows, how to simplify complex supply networks and the relevant formulas that will be employed by the methodology, are presented. This methodology is developed by combining and modifying three different methods, namely PERT² (from the project control field), GUM (from the calibration field) and Monte Carlo Method (from the simulation field), and adapting them to supply networks. For this purpose, the adapted PERT and its algorithm, the adapted GUM and its algorithm, and the adapted Monte Carlo Method and its algorithm are presented respectively. The hybrid methodology is finally developed by combining and harmonizing these methods and presenting a final algorithm.

Chapter 6 examines the methodology introduced in chapter 5 and evaluates its accuracy, efficiency and applicability through examples and solving sample questions. This chapter is divided into two parts in terms of content. The first part provides a numerical example of a complex supply network and introduces two scenarios. The first scenario seeks to establish the effectiveness of the adapted Monte Carlo Method through the use of the adapted GUM, while the second scenario tests the final methodology on a more complex supply network. The second part of the chapter introduces three real-life supply networks and applies the hybrid methodology to them in order to measure the efficiency and applicability of the method in real life.

Chapter 7 is dedicated to conclusions and suggestions for future research. The chapter starts with a general summary of the thesis and continues with the capabilities and innovations of the research. Following that, suggestions on real-life applications of the research are presented. The research limitations as well as suggestions for future research are included at the end of the thesis.

Figure 1-1 illustrates the outlines of the research introduced in this section.

² Program Evaluation and Review Technique

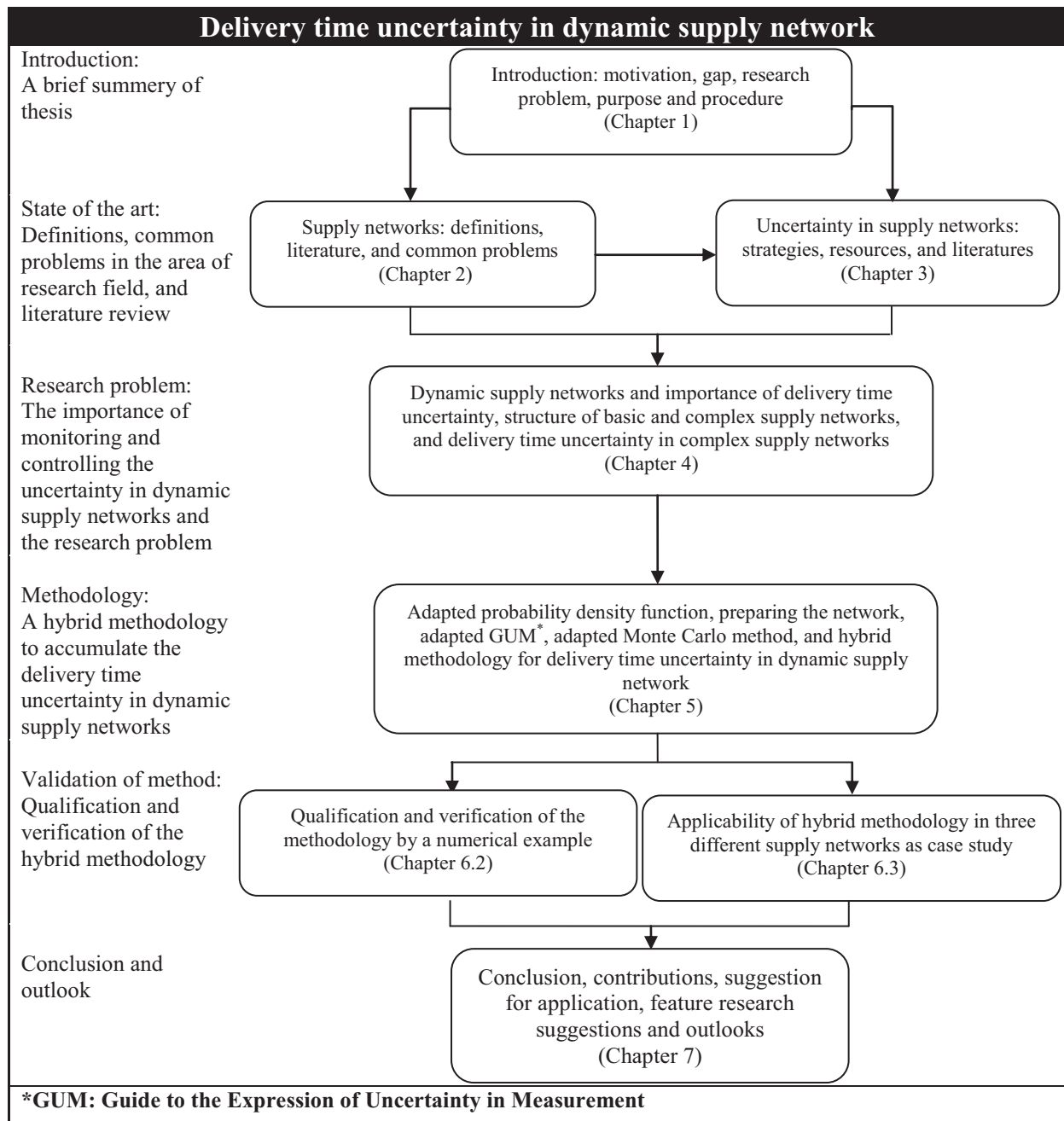


Figure 1-1: Structure of dissertation

2 CHAPTER 2 – Supply networks: definition and literature

In the current competitive market, manufacturing and productive agencies need to manage and monitor external organizations and resources as well as internal resources and their organization to achieve a competitive advantage with the aim of gaining a greater share of the market (Bhatnagar & Sohal, 2005). Accordingly, some activities such as supply and demand planning, procurement, production planning, goods maintenance services, inventory control, delivery time and customer service, which have already been carried out in the company, have moved to the level of supply networks. Key issues in a supply network are managing, controlling and coordinating all these activities (Hoppe, 2001). Supply network management is a phenomenon that carries out this issue in such a way that the costumers can receive reliable and fast services with high quality products at the lowest cost (Ayers, 2000).

In general, a supply network consists of two or more organizations that are legally separated and are related to each other by material flows, information and financial flows. These organizations could be the agencies that produce the raw materials, components, finished products, or services such as distribution, storage, wholesale and retail. Even the final consumer can also be considered as one of these organizations (Christopher, 2005).

This chapter examines the concepts, definitions, general design, and problems of supply networks. Then the history of the formation of supply networks (from the beginning of independent activity of plants and becoming a chain and finally the development towards a supply network) is discussed. Finally, the management principles to make the network more efficient, the importance of speed and the accuracy in responding are examined. The purpose of this chapter is to familiarize the reader with the concept of supply networks.

2.1 Supply network management: introduction and definitions

A supply network consists of different entities, such as suppliers, manufacturers, distributors, retailers and customers who work together to reach a common objective (Hu, et al., 2013). In today's competitive environment of business, companies and organizations are taking advantage of technology and management science. Their aim is to create a competitive benefit through data-management tools, KM³, and optimization of enterprise processes such as the production or communications. Supply network management is one of the most important management sciences, which proposed very useful topics in this area (Cao & Zhang, 2010). By using the supply network management as a management tool, the organization is able to develop its business relationships by exchanging data with trading partners such as raw material suppliers, distributors of products, and transportation contractors. Thus, the business agency will be able to reduce the delivery time and waste costs (Roebuck, 2011). According to Christopher (Christopher, 1998), today the most efficient solution

³ Knowledge Management

to achieve cost advantages is not necessarily the size of the products and economic scales, but a supply network management. He believes that the supply network is a network of upstream and downstream organizations, which are involved in the processes, and activities that make a value in the form of products and services for the final customer.

The concept of supply network management has been described and analyzed by many researchers, and they considered it with the synonyms of logistics, operations management, supplies, or a combination of these three concepts (Chopra & Meindl, 2012; Monczka, et al., 2011; Lambert, et al., 2005). There are three main approaches: Within some research works, they limited the supply-chain relations between the buyers and sellers. Such an attitude focuses only on the first-stage purchase operations in an organization (Meehan & Wright, 2012; Esmaeili & Zeepongsekul, 2010). Another group has a wider view towards supply-chains, and considers it as consisting of all sources of supply of an organization (Morita & Nakahara, 2004). By this definition, the supply-chain includes all stages of suppliers. Such an approach to the supply-chain leads to the definition of the supply-network.

The third attitude is the value chain approach in which the supply network includes all the functions needed to provide a product or service to the final customer (Cóccola, et al., 2013). Within this approach to the supply-network, manufacturing and distribution functions are added to the network as part of the flow of goods and services. In fact, with such an approach, the supply-chain and supply-network includes all three fields of procurement, production, and distribution. Shukla et al. in 2011 expressed that “*supply network management is management of material, money, men, and information within and across the supply network to maximize customer satisfaction and to get and edge over competitors*” (Shukla, et al., 2011).

A comprehensive definition by the Global Supply Chain Forum can be cited: “*supply network management is the integration of key business processes from the final customers to the main suppliers and is responsible for the products, services and information that create value for customers and interested parties*” (Supply chain council, 2006). In the next section, we provide a literature review on supply networks.

2.2 Literature review on supply network process

In the 1960 and 1970, organizations have struggled to increase their competitiveness by standardizing and improving their internal processes to make a higher quality and lower price for the products. At that time, the prevailing thought was that strong engineering, design, and coordinated production operations are prerequisites for achieving the demands of the market and gaining more market shares. For this reason, organizations focused all their efforts on increasing efficiency (Goldratt, et al., 2012). In the 1980s, by increasing diversity in the expected patterns of customers, organizations became interested in increasing the acceptance flexibility in production lines and developing new

products to satisfy customers' requests. In the 1990s, along with the improvements in manufacturing processes and the use of re-engineering patterns, many industry executives found that improving internal processes and flexibility in the company's capabilities were not sufficient to continue the participation in the market (Shukla, et al., 2011). Moreover, the suppliers of components and materials needed to produce materials with best quality and lowest cost, and the distributors had to be closely associated with the development policies of the producer's market. With such an attitude, the supply-chain management and supply-networks came into existence (Goldratt, et al., 2012). Here we describe a brief history of production systems, logistics, and supply network from 1898 to present.

2.2.1 Evolution of supply network: yesterday, today, and tomorrow

Formation processes of supply network management and its evolution to the present time may be classified in five steps (Shukla, et al., 2011):

- Step one: decentralization of procurement
- Step two: cost management
- Step three: integration of functions
- Step four: supply chain management
- Step five: towards supply networks and their data electronic management

It can be said that the concept of supply network management is a combination of the five-step management (see figure 2-1). The first step can be described as the field of internal logistics. In the second step, the attitude towards the organizational decentralization changes to the centralization of core functions, which are derived from the new attitudes associated with cost optimization and customer service. In the third step, the supplies significantly expand and cover warehousing, internal shipping, and the relationship of inside operations with the functional areas of business partners. As the concept of channel relationships grew, in the fourth step, the concept of supplies transformed to the supply-chain management. With the growth of complexity in supply chain structures, they cannot be named as “chain” anymore. They were transformed into complex networks, and the management of these networks, became one of the main concerns of researchers (Serdarasan, 2013). Today's, one of the efforts in this field is the use of information technology (IT) applications in supply network management. It can be said that the supply network management is entering into the fifth step, namely the electronic supply network management and the complex supply network management (Fritz & Hausen, 2009). In the next section, history of each of the five steps is briefly described.

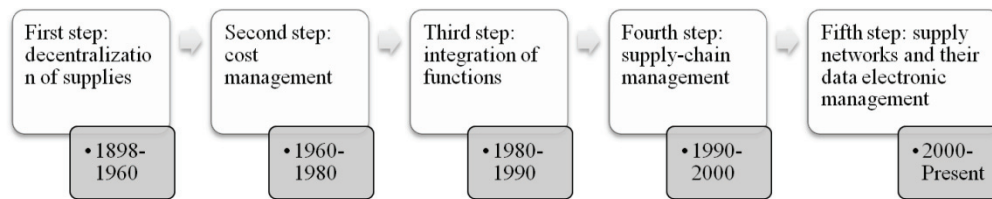


Figure 2-1: History of supply network process (with some modifications) (Shukla, et al., 2011)

○ **Step one - Decentralization of supplies**

This stage was developed from the late nineteenth century to the early 1950s. During this period, the area of logistics was not known as an important source of competitive advantage. Basically, logistics were known as a mediator's duty with inventory and delivery management. Agencies believed that logistics cannot make profits and are therefore not worthwhile to be invested in (Johnson & Leenders, 2004). Here we examine the major events of this period:

The word "logistics" was seen for the first time in the Oxford English dictionary of Simpson and Weiner (Simpson & Weiner, 1989), to be used in military activities in military science journals, to introduce the packaging and storage techniques (Lummus, et al., 2001). In 1919, transport and traffic researchers and professors of Syracuse University carried out their initial researches on the supply of goods (Whitman, 2012). At that time; the companies suffered from the low work efficiency, until, Henry Ford in 1927 made some changes in the layout of the machines allocation, as chain-shaped (Line-shaped), and decentralized supplies to reduce the production costs of the car "class A". Finally, he managed to invent the mass production system (NSF, 2003).

Mass production system of Ford not only revolutionized the industry in Europe and America, but also the combination of the mass production of goods with high wages for workers and lower prices, created such an effect on the economy and society of the twentieth century that it was called "Fordism" (Hudson, 2009). The growing trend of research towards increasing efficiency in manufacturing firms continued until in 1950, Wroe Alderson, then presented the "strategy of postponement". This strategy was the next step, in order to avoid errors in estimating demand and reducing costs. The strategy of postponement is based on the fact that *"the business entities postpone changes in form and identity of products to the latest possible point in the marketing flow and postpone changes in inventory location to the latest possible point in time"* (Schultz, 2003).

After the successful implementation of mass production at Ford's plant and the increase of products, the next concern of manufacturers and factory owners was identifying and tracking the products. In 1952 Norman Woodland and Bernard Silver managed to provide "the bar-coding system", they registered the strategy as an invention with the code no. 2612994 in the United States Patent and Trademark Office's (USPTO) (USPTO, 1952). Then in 1957, an organization was established to develop a scientific framework for performance

management in America - the American Production and Inventory Control Society (APICS). At the time, companies went to the APICS for training, prestigious international certifications and a comprehensive resource and a global network of industries. Today, APICS continues its work; as a leader and academic primary source in the scientific body of the supply chain, manufacturing operations management, inventory control, material management and logistics (APICS, 2011). After providing the bar-coding system, most of the managers focused on the control and management of production and warehousing costs. Thus, the second stage of development began.

○ **Second step - Cost management**

In the mid-50s, it was found that existing the structure and purpose for logistics, and its management can be a competitive advantage for the company. The second step in the supply network management emerged in order to evaluate the two main points. The first focus is the efforts of companies to focus on the logistics activities in an independent management system. It can be examined by the combination of a series of activities distributed through an independent section. Thus, the separate costs associated with transportation, physical distribution and inventory can be decreased. Thereupon, simultaneously, the efficiency throughout the logistics system can be increased as a whole. The second critical point is the centralization of companies to use the concept of total cost in logistics. The strategy attempts to minimize the total costs of logistics by decreasing the costs of one or two specific functions of logistics such as transportation or warehousing (Kulmala, 2004). The main activities during this period are stated below:

In 1961, Forrester could identify the “Forrester Effect” in the supply-chain management to increase control and enhance demand in his book entitled “Industrial dynamics, MIT Press⁴ 1961”. Forrester's research showed that demand could be erratic with peaks and troughs, commonplace within most organizations. These variations in requirements and supply are amplified within the supply chain when re-orders are made (Forrester, 1961).

In the same year, Gene Thomas in IBM⁵ Company managed to develop the concept and application of “Bill of Material” or the basic version of “MRP” (Linkedin, 2011).

With increasing interest in the supply-chain issues, Proctor and Gamble Company held a contest titled “Traveling Salesment Problem (TSP)” in 1962 and asked the participants to solve this problem for 33 different cities. The winner was Professor Gerald Thompson of Carnegie Mellon University and he presented the first solution to reduce the cost of a TSP (TSP, 2005).

Researchers felt that there is a need for a community to develop and improve the skills of companies in the field of logistics, increase the theoretical and

⁴ University Press Affiliated with the Massachusetts Institute of Technology in Cambridge

⁵ The International Business Machines

practical knowledge and also an efficient scientific source to teach the concepts of production and logistics. To this end, the Council of Logistics Management (CLM), that began its work as the National Council of Physical Distribution Management was established in 1963 (CLM, 1996).

The importance of the relationship between supply chains was examined for the first time by Shaw and colleagues in 1969 in a paper entitled Customer-Supplier relationship (Shaw, et al., 1969). Their study can be considered as the start point of analyses associated with the relationship between supply networks. In 1971, Zicmund and Stanton stated that a production system cannot be considered as a result of a one-sided and linear relationship. They presented the initial idea of “Reverse Logistic” in order to reduce costs. In this theory, the relations of production machinery and logistics are considered as circular and rotational and good flows can also occur in the opposite direction and create a backflow. Reverse logistics, including the process of returned goods and a suitable deal with these items and all operations related to the reuse of products and materials to increase productivity and profitability of efficiency of the producer. Reverse logistics is one of the ways to reduce costs and increase revenue and customer service levels (Wrigh, et al., 2011). The term “Supply-Chain Management ”, emerged for the first time in an interview of Keith Oliver, the consultant of the Booz Allen Hamilton Company, with the Financial Times in 1982 (Blanchard, 2010).

With the growing research interest in the field of reducing production costs, the researchers found that it needs the integration of functions and thus they entered the third step.

○ ***Third step - Integration of functions***

During the 1980, corporate executives realized that focuses on the total cost of logistics is a positive way to manage the distribution channels (Simchi_Levi, et al., 2000). Until this time, most corporate executives looked at logistics as a tactical activity that has a very little effect on the company's strategic planning. In the mid-70s, the companies realized that due to the continuous improvement and integration with logistics, partners can provide great strategic values. The main activities carried out in order to improve logistics system and supply networks are expressed below:

“Theory of constraints” is one of the new approaches within the field of continuous improvement that was introduced for the first time by Dr. Goldratt in 1984. Perhaps the basis of this theory can be expressed in one sentence: limitations of each system, determine its function (Goldratt, et al., 2012). Goldratt defines the constraint as anything that limits the system performance relative to its target. He also defines the goal of a business agency as “making money, now and in the future”. Goldratt describes the concepts of constraint theory as a story in the book entitled “goal”. This book gradually revealed the philosophy and applications of this theory in the form of daily production. Until about ten years ago, the theory of constraints was limited to the production.

However, today this theory is used in a wide range of organizational topics such as finance, project management, production management, supply-chain management, marketing, sales, and strategic management (Bhatnagar & Sohal, 2005).

In 1985, due to strong growth in the competitive environment of textile and apparel industries around the world, the leaders of these industries in America established “Kurt Salmon Associates” Group in order to recover the chain activities. In the same year, this group analyzed the supply chains of textile and apparel industries in order to accelerate the response time. Previous studies showed that the delivery time for the apparel supply chain, from raw materials to consumer is generally 66 weeks of which, 40 weeks are spent in the storage or in transportation (Ferne & Sparks, 1999). This time causes major damage to the chain goals. The results of this research became the trigger of Quick Response (QR) strategy. In QR strategy, suppliers and distributors work together in order to reduce the response time to the needs of consumers by sharing the necessary information (Lummus, et al., 2001). In the same year, Ken Ackerman and Dean Wise, published an article on the “Third Party Logistics (TPL)” in the Council of Logistic Management Annual Conference and examined for the first time the issue of outsourcing in key activities of a supply chain to external companies. One of the main advantages of the outsourcing of logistics activities is the focus of plants on their key competencies through which they can increase their production efficiency (Cai, et al., 2013; Hertz & Alfredsson, 2003).

After implementing the system of mass production by Henry Ford and the first revolution in manufacturing industry, John Krafcik, published an article entitled “Triumph of the lean production system” in 1988 and introduced the new system of “Lean Production” that reduces costs and enhances the efficiency to the mass production (Krafcik, 1988). The introduction of this system after its implementation in the Production Systems of Toyota Company can be considered as the “Second Industrial Revolution”. Lean production uses the continuous improvement philosophy, and tries to analyze the losses during the production process using teamwork culture (Black & Hunter, 2003). Following a lean system reduces production time, increases staff efficiency and product quality, generates greater flexibility to market, reduces inventory levels, increases life expectancy of machinery and equipment and reduces the overhead costs (Pettersen, 2009).

Due to the outstanding principles and systems such as Lean Production and QR strategies, researchers found that they need an expertise to handle them in the entire chain levels. Thus, the supply-chain management concepts were formed.

○ ***Fourth step - Supply-chain management***

During the 1980s, companies developed concepts of integrated logistics and supply channel management to exploit new market realities. Supply chain goes beyond the logistics and includes other activities such as handling multiple

manufacturing companies, setting goals, determining internal and external buying strategies, enhancing the quality of manufacturers marketing and customer service to multiple clients (Shukla, et al., 2011). During this decade, some activities were carried out in order to improve the supply network management. A history of some important activities is stated below:

Michael Hammer in 1993 introduced a new management system called “Reengineering” in a book entitled "Reengineering the Corporation: A Manifesto for Business Revolution". He stated that the old methods of management were no longer useful to succeed in the competitive market, and that new methods were needed to have the simultaneous successful ability in the four areas of fast delivery, high quality, high flexibility and low cost. He introduced the re-engineering method as a fundamental idea business process to improve the four criteria of critical management (Hammer & Champy, 1993).

With the rise of using supply-chain management in production, the Supply-Chain Council (SCC), in 1996 started its activities with 69 volunteer companies to promote the objectives of supply-chain management (Supply chain council, 2006).

The problem, which is not managed in the supply chains due to the instability, is the bullwhip effect (Costantino, et al., 2013). This effect causes a fluctuation in the supply chain, by changes in the level of demand. In other words, a minor change in the customer side of demand, make a major fluctuation in the first level of suppliers demand. As a result the network will face large fluctuations (Delhoum, 2008). Each organization and member in the supply chain tries to solve the problem from its own perspective. The "bullwhip effect" is considered in all industries and shows its effects by increased costs and poor service levels. Lee and colleagues published a paper in 1997 entitled "Information Distortion in a Supply Chain: The Bullwhip effect", and presented ways to reduce and control this effect (Lee, et al., 1997).

With the increasing development of research on supply-chain management, supply chains converted to complex networks. One of the most basic needs prevailing in these networks was making relations in order to maintain integrity. With the advancement of science, researchers began to think of supply network problems and e-supply network management.

○ ***Fifth Step: Towards supply networks and their electronic data management***

Over the past two decades, due to the increase of customers’ expectations and consequently increasing industrial competitiveness, there was a belief that not only competition between the companies and even the supply chains but also cooperation among several integrated supply chains are needed (Anatan, 2006). This collaboration which is called “supply network” is done between several chains and is no longer like a simple linear collaboration. The quality, delivery time and services to the customer are widely dependent on the factories and plants which have been involved directly and indirectly (Blanchard, 2010). So,

these issues create challenges for legally separated companies, coordination of material flows, information and so on, which did not occur before. In the end, the IT extended the functional area of supply-chain management. The aim of e-supply network management is to reduce the data-transfer and product's costs on the one hand and extend the business opportunities and cooperation between companies on the other hand (Lancaster, et al., 2006).

In the early twentieth century with the rise in need for specialists who are able to handle the logistics management, the United States Department of Labour in 2000, released its new category of professional as “Logistician” and introduced this expertise formally as a profession **Invalid source specified..**

Due to the increasing potential risks of greenhouse gases (GHG), a protocol was adopted in 1997 to reduce its emission. Until 2001, more than 1000 companies and organizations following the protocol of GHGs, developed and improved the environmental conditions in order to reduce emission. This was the first step towards a green supply network (GHG, 1997).

supply network management became gradually an expertise until O*Net, one of the main contributors to the American Job Center, presented the job class to the supply network managers in 2010 and introduced supply network managers officially as a career (O*Net, 2010). Given today's competitive business market and also satisfying the demands and expectations of customers, the managers mostly use the complex supply networks rather than linear supply chains to enhance their flexibility. Most current researchers deal with cost reduction, increase quality and delivery time reduction in these networks (Shukla, et al., 2011).

2.3 A general view of a supply network

supply network includes all activities associated with the flow and transformation of goods from the raw material's stage (extraction) to delivery to the final consumer as well as the associated information flows. It is composed of the following components (Singer & Donoso, 2008):

- **Upstream supply network**

This section contains the primary suppliers (they can be assemblers or manufacturers) and their suppliers, and all directions come from the material. The main activities in this section are purchasing and delivery.

- **Internal supply networks**

It covers all the processes used by an organization to convert the carried data and materials into the organization by the suppliers from when the materials enter the organization until the final product moves to the outside of the organization. Activities here include material handling, inventory management, manufacturing, quality control.

- **Downstream supply network**

It covers all the processes used by an organization to convert the data and materials carried into the organization by the suppliers until the final product exits the organization. Activities here include packing,

warehousing and transporting. These activities may be carried out using several distributors such as retailers or wholesalers.

supply networks occur in all shapes and sizes and may be very complex. Supply network for an automobile manufacturer includes hundreds of suppliers, thousands of workshops and assembly workshops, warehouses, brokers, direct commercial vendors, wholesalers, customers and supportive functions such as product engineering, procurement agencies, banks and transportation companies (Serdarasan, 2013). In general, the supply network is a network of organizations that are involved with upstream and downstream processes and activities (Monczka, et al., 2011).

In fact, a supply chain or in the more complex cases, a supply network, consists of two or more organizations that are legally separated but are interrelated by the flow of material, information and finance. (Shukla, et al., 2011). Figure 2-2 is shown the main components of a supply chain.

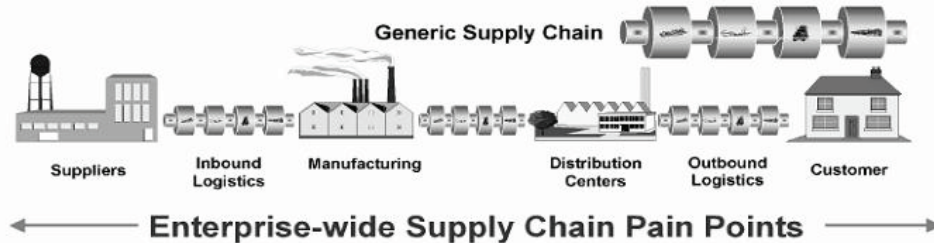


Figure 2-2: The main components of a supply chain (Chopra & Meindl, 2001)

supply network management includes all the integrating activities related to the materials' flow and transportation of goods from the raw material (extraction) to the final product (for consumers) and the related information flow. This is done by improving the relationship within the network and chains to achieve the reliable and ongoing competitive advantage. This management philosophy aimed at reducing costs, and delivery times take place (Huang, 2013).

For a better analysis of the supply network, its aspects must first be understood. In general, as shown in figure 2-3, the supply network can be measured in two dimensions (Li, et al., 2009);

- Horizontal dimensions: it represents the number of horizontal cells in a network (a supply network consists of several cells (e.g. Suppliers, manufacturers, distribution centers, and customers)).
- Vertical dimensions: it represents the number of each cell separately (e.g. Number of suppliers, manufacturers and customers).

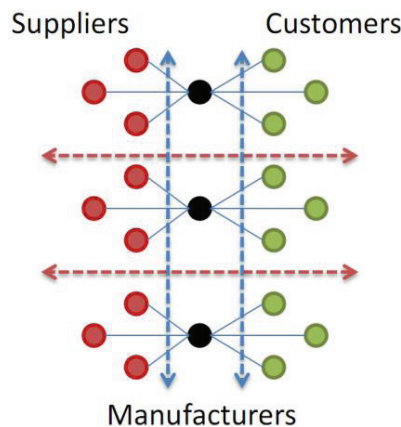


Figure 2-3: Dimension of supply network

2.4 Common challenges in supply network and their sources

In the business world, there are many examples of companies that are not able to reach their demand level and thus, suffer from the costly inventories. In this section, we describe these problems and their causes. Generally, the problems of supply network arise from two sources: Uncertainty and Lack of coordination (Arshinder, et al., 2011).

○ Uncertainty

A major source of uncertainty for the supply network is predicting demand (van Donk & van der Vaart, 2005). Predicting demand is affected by several factors such as competition, price, current conditions, technological development and the general level of customer commitment. Another factor of uncertainty in the supply network is delivery times (Safaei, et al., 2011). They dependent on some factors such as the breakdown of machines in the production process, traffic density, which is involved in transportation, quality problems of materials that may cause production delays, and the network structure and network partners.

○ Lack of coordination

These types of problems occur when one sector of the company has not a good relationship with other sectors, when the communications and messages are incomprehensible to business partners, and the company departments are not aware of some issues or when it is too late to become aware of what should happen (Xiangtong, et al., 2004).

As it was pointed out, numerous problems can occur during the supply network, from these sources. Two of the most persisting problems are cited here (Balan, 2008):

• Bullwhip effect

This effect was observed for the first time by Procter & Gamble (PSG) in relation to one of their products. The "bullwhip effect" means that small change in product demand by the consumer that occurs at the beginning of the supply network is converted to larger

fluctuations in demand during the reverse route through the supply network (Delhoum, 2008). The bullwhip effect refers to the fact that the variability of orders received by suppliers is larger than the variability in consumer demand. Because of this, the companies that are in various stages of the supply network will have a different idea of the market demand and this issue creates challenges for the supply network (Buchmeister, et al., 2008). Companies with this type of behaviour in response to fluctuations of demands will face product shortage and then will be forced to provide additional products (refer to figure 2-4).

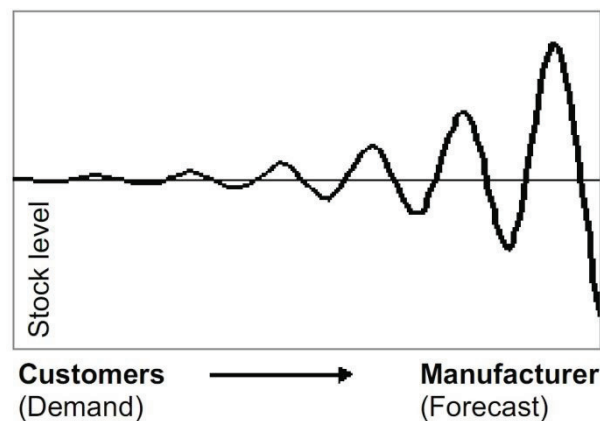


Figure 2-4: Stock variability amplification in a supply network due to bullwhip effect (Buchmeister, et al., 2008)

- Deceptive Stock

This problem occurs when the customers want a product that is not available to them, but generally is. This happens for example, when a product is placed at the wrong place or the wrong value is stored (Naghadeh, 2012).

There are three main types of techniques to deal with the network management problems:

- The first are techniques, which are associated with the design and supply of products, suppliers, management of relationships between suppliers and the relation of organization with the suppliers (Simchi_Levi, et al., 2000).
- The second set of techniques is associated with production systems, inventory management and internal issues within the organization to solve the problems (Basnet, 2013).
- The third category of techniques considers distributors, buyers, buyer's fidelity and their coordination throughout the organization (Balan, 2008).

2.5 Toward an effective and efficient supply network

Definitions of supply networks cover some issues such as information systems management, sourcing and procurement, production scheduling, order

processing, inventory management, warehousing and customer service (Ayers, 2000). Thus, it is necessary for the suppliers and customers to work in a coordinated way and share their information. The rapid flow of information between customers and suppliers, distribution centers and transportation systems, enables some companies to build highly efficient supply networks. Suppliers and customers should have the same goals and mutual trust. Customers rely on their suppliers about the product's quality and services. In addition, the suppliers and customers must cooperate with each other to achieve the common goals and facilitated communication and information flow (Sahay, 2003).

Some companies try to gain supply network control using the acquisition and integration of all components along the supply network from the procurement of materials and services to the final product delivery and customer service (Huang, 2013). But even with this type of organizational structure, operational activities and units may be inconsistent. The organizational structure of the company must focus on the coordination of activities to achieve the overall goals within the company (Ayers, 2000).

To achieve efficiency and effectiveness in the management of supply networks, five functions are considered. These five functions are partly a factor in the organization. Skills and effectiveness of supply network management will depend upon the accuracy of these five functions (Emam, 2003).

- The structure of supply network partners

The supply network is designed according to the efficiency of strategic factors and customer requirements, So that it covers the range of available products, services, and new products (Humphries & Mena, 2012).

- Implementing a participatory communication

This section refers to the kinds of essential partnerships for the company. This function expands the performance of supply network communications to partnerships with outside factors. Partners need to be notified of any changes in the supply network, which must be implemented in the whole network. Supply network management requires the effective partnership of factors outside the company. Even so, the company's relationship with the outside firms is problematic (Safaei, et al., 2011). Some issues such as the center of competition, partners' motivations and their structure are described about the partners.

- supply network design for strategic profitability

Supportive operations of the supply network processes comprise:

- Organizing changes in the supply network
- Collaborative process to redesign the supply network
- Evaluations and their roles
- Position of the supply network management function within the company

- supply network management information

The role of information systems should not be ignored in the improvement of the supply network. This section shows the role of technology in the improvement of the supply network. Systematic changes must affect the changes (modifications) of the company's processes and strategies (Hoppe, 2001). The main concepts in this area include:

- Elements of supply network system
- Technological innovation
- Using the software complements
- Difficulties in the implementation process
- Reducing the cost of the supply network

The main indicator of supply network improvement is the cost reduction. This effort is part of effective strategies and policies. The five main reasons of costs are (Pettersen, 2009):

 - Lack of clarity in the supply network process
 - Changes in domestic and foreign policy of the company
 - Weaknesses in the design of production
 - Insufficient information for decision-making
 - Weaknesses in the network design and lack of definition in relationship between partners of the supply network

2.6 Importance of quick response (QR) in supply networks

When accelerating the delivery time is considered as a winner strategy for growth or survival of organizations, choosing a control approach of delivery time in the supply network seems a logical step (Sharifi, et al., 2006). Response speed in the supply network is directly related to the ability of the network to line up the members with the dynamics and fluctuations in customer requirements (Christopher, 2000).

Christopher, one of the first advocates of the concept of agility in the supply network, described four main characteristics of a network, to speed up the delivery times as follows:

- Sensitivity to the market

The ability of a supply network to understand and respond to the actual demand in the market
- Virtual space (Cyberspace)

Using the IT for sharing information between buyers and suppliers of virtual supply networks by applying advanced electronic devices such as Electronic Data Interchange (EDI), which improve the speed and clarity of information.
- Process integration

Such as: cooperation between buyers and suppliers, the development of common principles and common systems and shared information
- Being a network

Recognizing that the company cannot be successful alone and must collaborate with other companies as a member of a production network. Lin and colleagues presented a conceptual model of the agile supply network. In this conceptual model, the dimensions of agility in the supply network such as stimulants, abilities, enablers and objectives are discussed (Lin, et al., 2006).

Van Hoek presented two operations of the supply network for agility such as the management and use of variations and deviations, and QR (van Hoek, 2005). Swafford in his thesis presented a framework for the agility of supply network based on flexibility and stated that agility is highly influenced by flexibility in different parts of the supply network, including new-product development, procurement and sourcing, manufacturing and distribution (Swafford, 2003). Gunasekaran and colleagues presented the concept of “Responsive Supply Network (responsive supply network)” as a competitive strategy in the network economy and tried to analyze a new dimension of responsiveness, speed and flexibility in the supply network (Gunasekaran, et al., 2008).

Similar studies have been conducted primarily by researchers. The most important literatures relevant to the agility indicators of supply network are as follows:

Yusuf and colleagues considered the agile supply network activities as follows (Yusuf, et al., 2004):

- Cooperation with competitors,
- Long-term cooperation with customers and suppliers,
- Levering of basic resources by networking with other firms
- Cooperation with other companies due to difficult operational conditions
- Alliances with business counterparts,
- Integration of information with other companies based on computer systems,
- And giving higher priority to the integration than to market penetration.

Swafford and colleagues and also Lin with colleagues considered the agility capabilities with terms of responsiveness, competence, flexibility and speed (Swafford, et al., 2006; Lin, et al., 2006).

Agarwal et al., used the research literature and brainstorming sessions to present fifteen variables for agility. These variables include: Market sensitivity, speed, accuracy of data, new product introduction, collaborative planning, process integration, use of technology, reducing delay, improving service levels, cost minimization, customer satisfaction, quality improvement, uncertainty minimization, development of trust and reduction of resistance to change (Agarwal, et al., 2007). The most important criteria for evaluation of the agility based on the supply-chain operations reference models (SCOR) are responsiveness and flexibility in delivery time (Supply chain council, 2006).

Given the importance of agility in the supply networks, the speed and accuracy of delivery time is one of the inseparable principles to have an agile supply network. The uncertainty in the supply network is a major contributor to reduce the accuracy and speed in delivery time. Therefore, much research has been done on the causes and sources of uncertainty, and each of these studies has tried to control and manage this uncertainty. The next chapter examines the uncertainties and their sources in the supply networks.

2.7 Summary

Due to the importance of the term “supply network” as one of the main keywords of the current research, this chapter deals with introducing and explaining supply networks. First, definitions offered in the literature review so as to become familiar with supply networks were examined. Then, the history of the development of supply networks since their appearance was expressed. The history was divided into five stages: (1) decentralization of procurement, (2) cost management, (3) integration of function, (4) supply-chain management , and (5) supply networks and their electronic data management. Following that, a general view of supply network structure was provided, and its parameters and structural aspects were introduced. Later, the literature review was examined to categorize and explain problems and issues, which most of the supply network researchers are facing. Solutions for creating an effective and efficient supply network were presented in the next step. The last part of this chapter deals with the importance of rapid responses in supply networks since our research has focused on time, and especially delivery time.

3 CHAPTER 3 – Uncertainty in supply networks: Strategies and resources

Despite great research efforts, the adequate utilization of all possible network capacities remains a challenge due to uncertainties in supply networks. Understanding the causes of uncertainty makes it possible to find appropriate solutions to deal with them and eventually manage networks more efficiently. In this chapter, first general classification methods of uncertainty are introduced by defining the general concept of uncertainty and its difference to Error concept. Second, the concept of uncertainty in supply networks and its management is investigated in the scope of supply networks. Third, classifications of uncertainty sources are investigated and a general classification is presented. Fourth, management and control strategies are surveyed, and a brief summary is provided. Finally, the limitations of each strategy are discussed in general.

3.1 Error and uncertainty

In summary, error is the difference between a measurement and the true value of the measurand (the quantity being measured). However, uncertainty is simply the possible range, which the quantity being measured is on it. Therefore, Error may be represented as positive or negative (+ or -) while these signs are not used for Uncertainty (mostly represented by \pm). On Uncertainty, this sign (\pm) indicates the possible range of values within which the true value is asserted to lie. In other words, Error can be measured only after the occurrence of events while uncertainty is measurable before the occurrence of events where there is a specific probability.

VIM 6 : 2008 has defined the measurement error and measurement uncertainty as follows (VIM, 2008):

“Measurement error is defined as a nonnegative parameter that the measured quantity value minus a reference quantity value.”

“Measurement uncertainty is defined as a parameter associated with the result of a measurement that characterizes the dispersion of the values attributed to the measurand.”

It should be noted that uncertainty may be, for example, a standard deviation (or a given multiple of it) or a half width of an interval associated with a specific coverage probability (JCGM, 2008).

Uncertainty definition with some changes in VIM: 2008 version (Guide to the Expression of Uncertainty in Management (GUM), 1999; VIM: 1993) is defined as follows. The most important change is that the new definition of uncertainty focuses uncertainty evaluation on available data. It means that the reported uncertainty may change in future with access to new information.

According to the definition of measurement of uncertainty in VIM: 2008, it is generally composed of several components. Some of these components may

⁶ International Vocabulary of Metrology

be evaluated from the statistical distribution of the results from a series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviation, are evaluated from assuming probability distributions based on the analysis or other information (JCGM, 2008).

3.2 Classification of uncertainty

Before the 1980s, uncertainty components were classified as the two categories, “systematic” and “random”. The systematic component of uncertainty is associated with the known systematic effects, while the random component of uncertainty is associated with random effects that can influence the measurement. However, recommendation INC-1 (1980), which was developed by the working group consists of 11 national standards laboratories convened by the International Bureau of Weights and Measures (BIMP⁷) on the Statement of Uncertainties. The recommendation INC-1 refers to different classifications of uncertainty as “Type A” and “Type B”. In other words, the suggested new classification is based on uncertainty evaluation method rather than on its components. Moreover, it is better to use the terms “Type A” and “Type B” instead of “systematic” and “random” (Muller, 2009).

Classification under type A and B is selected because it represents two evaluation methods of uncertainty components with a conventional aspect of uncertainty. This classification does not mean that there is a difference between the natures of components obtained in the two evaluations. Both types of evaluations are based on “probability distribution” while both uncertainty components are assigned by statistical measures such as variance and standard deviation. Estimated variance and standard deviation for uncertainty components evaluated by “Type A” method are calculated by a set of repetitive observations and measurements. This estimated standard deviation is called “standard uncertainty of Type A”. The estimated value of variance and standard deviation for uncertainty components evaluated by type B method will use available knowledge. This estimated standard deviation is called “standard uncertainty of Type B” (JCGM, 2008).

3.3 Uncertainty in supply networks

Management in the supply network always points to the improvement. Furthermore, it can be described the same quality, to an endless road, as a valuable tool, that makes human life more efficient. There are various reasons why companies do not obtain ideals in the supply network management. However, definitely one of the reasons is related to the network inconsistency that is sometimes out of the scope of the company authorities. For some reasons such as sudden changes in demand, or changes in production and changes in the supplier delivery time, there is always an inconsistency between the members.

⁷ BIPM: Bureau International des Poids et Mesures

According to the reasons mentioned, Towill and Christopher, and Lee proved that supply network strategy is nothing but responding to the uncertainty in demand and supply (van Donk & van der Vaart, 2005).

Considering the importance of the supply network, its efficient management is of particular importance for organizations. Davis believed that the first step to improve the supply network is accurate understanding of uncertainties and their reduction in the supply process (van Donk & van der Vaart, 2005).

One of the main reasons for using the supply network and its management in the companies is the assignment of the construction and design processes to the suppliers. This would be also possible only by creating a close relationship with them. All members within the network should be integrated and organized, so that the members will strengthen the positive effects of the network. A flexible and transparent network is required to achieve strong and consistent relationship between the members. Therefore, the basis of the management of supply networks is nothing but the coordination among units and members of the network. Uncertainty in the supply networks is considered as one of the major causes of failure in network management, which directly influences the coordination and integration of the network and reduced performance of the supply network.

In practice, every manager encounters uncertainty in the supply network (Hult, et al., 2010). The level of uncertainty increases due to the increasing complexity of the supply networks and it also raises the delay potential in delivery time and quality problems (Jiraporn, et al., 2005). Uncertainty has a considerable impact on the supply network design and operation. In other words, risks and uncertainties make the meaning of the business. Because if there is no risk involved in the business, it contains no economic value since the activity will create no added value (Simchi-Levi, et al., 2004). Davis (1993), suggested the need to understand and control the uncertainty in the supply networks and called it as “supply networks Disaster” (Davis, 1993). In recent years, many studies have been conducted on uncertainty. Scientists and researchers referred to a variety of sources as uncertainty factors and provided many different classifications (Prater, 2005). First, it is necessary to examine the given definitions to better understand and study uncertainty in the field of supply networks:

3.3.1 Definitions of uncertainty in supply networks

There are many appropriate definitions in the areas of finance, insurance, marketing, decision theory, etc., but little studies are conducted on uncertainty in supply networks (Tang, 2006). In most investigations, the term “uncertainty in supply networks” is synonymous with the word “risk”, and the two terms sometimes are used interchangeably (Ritchie & Brindley, 2007; Peck, 2006). To this end, it is necessary to investigate the differences in this section. Some researchers in order to distinguish between the two terms of risk and uncertainties determine the differences (Hillson & Murray-Webster, 2006;

Courtney, et al., 1997). The main point on the difference of these definitions is related to the expected output type. Some researchers believe that the term “risk” should be used only on issues that may have a negative output (Wagner & Bode, 2008; Peck, 2006; Hillson & Murray-Webster, 2006), but both positive and negative outputs may be obtained in uncertainty issues. For example, the risk caused by natural disasters will only lead to problems in the supply network while the uncertainty in customer demand can be better or worse than what is expected. According to this definition, one could argue that the term “uncertainty in supply networks” is more general and that uncertainties (can sometimes include definitions of risk) may occur across a supply network. As can be seen, this definition is consistent with the definition in Van der Vorst and Beulens (2002) studies:

“Decision-making situations in the supply-network in which the decision-maker does not know definitely what to decide as he [or she] is indistinct about the objectives; lacks information about (or understanding of) the supply-network or its environment; lacks information processing capacities; is unable to accurately predict the impact of possible control actions on supply-network behavior; or, lacks effective control actions (non-controllability)”

Generally, uncertainty in supply networks is defined as “imminent but uncertain events or conditions” that may have a positive or negative impact on the organization's objectives in the event of occurrence (Queensland government, 2003). In the following sections, sources of uncertainty in supply networks will be examined from the other researchers and scientists' viewpoint:

3.4 Sources of uncertainty in supply networks

Management of uncertainty starts with an accurate evaluation of uncertainty, and develops with an appropriate and timely response to uncertainty. In fact, effective management of uncertainty reduces the network vulnerability to changes by making a flexible supply network (Bogataja & Bogataja, 2007). Deloach points out the dynamic concept of uncertainty and believes that classifications of uncertainty sources are interdependent. Therefore, some uncertainties can be considered as a source of uncertainty in future events (Tang, 2006). On the other hand, Juttner, suggested that uncertainty should be distinguished from uncertainty sources, outputs or effects of the uncertainty. Sources of uncertainty include environmental and organizational variables also affiliate with the supply network which they are not definitely predictable and influence the supply network output variables (Juttner, 2005). According to Juttner (Juttner, 2005), sources of organizational uncertainty are divided into three types: sources outside supply networks (such as political, natural, social, market and industry resources), sources within the supply network (ranges from a strike of labor supply, machine failure to uncertainty related to the IT systems) and network related resources (interrelationships between organizations within a supply network).

Complex and dynamic interactions, among the components of the network lead to uncertainty in planning. This uncertainty has an effect on the performance of the supply network, oscillatory and continuously (Bhatnagar & Sohal, 2005).

Sources of uncertainty can be studied in two tactical levels (short-term and long-term). Some cases such as demand for a good or set of goods can be cited as short-term uncertainty. However, the long-term uncertainties include factors such as market expansion and development of the production line (Mosavi & Khalili, 2007).

Davis (1993) presented the first categories related to the uncertainty in supply networks. He introduced demand, supply and production process as three sources of uncertainty. He reviewed the three factors and noticed the influence of the demand and supply uncertainty on the uncertainty of the production process. He suggested that this effect directly influences the timely delivery of orders. He also introduced demand uncertainty as the most important factor in the prediction problems. This study was approved by other researchers such as Bhatnagar et al., (2003); van der Vaart et al., (1996), Gupta and Maranas (2003).

Supply uncertainty is the result of the supplier's performance in incomplete responses of good's delivery. The results of the process uncertainties are due to the lack of production process reliability and machinery breakdown. Demand uncertainty, introduced by Davis, is obtained by inaccurate prediction, incorrect prediction or instantaneous demand. The demand uncertainty will cause the "Bullwhip Effect" too (van Donk & van der Vaart, 2005). The main factors of inconsistency in the supply network can be outlined as follows:

- Bullwhip
- Organizational dynamics of supply networks
- Determination of appropriate technology for data transmission
- Changes in produced goods
- The buyer and seller conflict
- Type of product
- Time gap between order and delivery of goods and delivery time issues

Bullwhip theory is not related to specific agencies, and all organizations encounter this phenomenon. Consider a bullwhip, a small fluctuation at the beginning of it, lead to a big swing at the end. This property is simply used in the management systems. In fact, bullwhip is a small fluctuation across the network created by the end-customer. In periods of rising demand, down-stream participants increase orders. Initial signal stimulates each member to act against fluctuations and store more inventory or make more orders in higher levels. Therefore, excess inventory will be raised falsely, heavy costs will be created and consequently, the efficiency of the whole network will be reduced (Turban, et al., 2008; Sameer, et al., 2007; Gunasekaran & Ngai, 2004; Zhao, 2002; Lowson, et al., 1999; Simchi_Levi, et al., 1999).

This interesting term (Bullwhip) can be used to understand that even the slightest change in any uncertainty factors (demand, delivery time, etc.) faced by members of the network may lead to various fluctuations that affect organizational performance.

The second factor is “organizational dynamics of supply networks” that consists of risk and power. Risk is used in this sense that the success of any organization not only is dependent upon the network performance but also on the information of the other units or members. Power concept means that some members of the network are preeminent in strength than others. Network members must identify their position within the network and perform their functions in order to transfer data in a clear and rational form. Any incorrect information will be a major problem for the entire system.

Another issue that is of particular importance is to determine the appropriate technology to transfer data within the organization. Since each organization uses a different approach and a technology to transfer data, it especially affects integration between organizations.

Another reason for inconsistencies among members is the changes of the produced goods. If the goods' model changes, the main organization may be forced to contact new suppliers, or cut-off its relations with some existing suppliers. Naturally, this can create problems and inconsistencies in the members' performance.

Sometimes the problems are different. There are always both buyer and seller in the supply network as the main members with apparently conflicting interests (hereafter manufacturer and supplier). They have different interests because the buyer is willing to make the products with cheapest price, highest quality and most favorable terms, while the seller hopes to sell his products in low-quality and more expensive. Meanwhile, the network management tries to make users understand that their interests are not only in contradiction with each other, but are in line with each other so that the interests of one member definitely make the other member a winner. However, it is not easy to make companies to believe in this truth.

The much broader and larger network, i.e. more members, increases the probability of making mistakes. For example, the manufacturing company (OEM) may work with numerous suppliers, and each supplier in turn be in touch with multiple other suppliers. The mistakes of the different parts of the company could negatively affect the overall system. Therefore, the uncertainty of these systems is due to the type of cooperation, and it is extremely high. This kind of uncertainty ranges from incorrect predictions to late delivery, low quality of delivered parts or raw materials, faulty machinery in the production process, uncontrolled orders, misinformation, etc. All these factors result in system failure or reduce the probability of success (Salvendy et al., 2001; Lummus et al., 2003; Bhutte et al., 2002; Chakravarty et al., 2001; Lambert et al., 1998; Gupta

et al. 2003). (Gupta & Maranas, 2003; Lummus, et al., 2003; Bhutta & Huq, 2002; Salvendy, 2001; Chakravarty, 2001).

Another point is related to “time gap between order and delivery of goods and delivery time issues”. Christopher considered this issue as one of the most important scales to measure uncertainty in supply networks (van Donk & van der Vaart, 2005). Many solutions have been proposed by researchers to deal with this problem, including the use of a safety stock system in warehouses or increased system accuracy in prediction methods.

Different mathematical methods have been proposed at different levels to solve the uncertainty management problems across the network. For example, Bose and Penky suggested MPC (Model Predictive Control). Some models, which are often at the operational level, are suggested to maximize organization's profit. Some researchers, like Sakawa offered “Fuzzy models”, mostly used at the strategic level. Moreover, the third group of researchers with a number of activities focuses on mathematics and statistics-based approaches to reduce uncertainty (Guillén, et al., 2005).

Another noteworthy issue is environmental forces, including factors such as changes in customer demand, uncertainty in supplier delivery time, uncertainty in supply quantity, lack of quality certainty, price fluctuations, unpredictable competitive reactions which may lead to, rapid changes in the production process and short product life cycles.

In the next classification, called "uncertainty circle model" by Simangunsong (2012), Mason-Jones and Towill (1998) added a new factor to the basic model provided by Davis (1993). They classified four factors of uncertainty as follows: Uncertainty in control that refers to the ability of an organization to use the information to take decisions related to production orders, production schedules, as well as required raw materials (Geary, et al., 2006). From this perspective, uncertainty in supply networks includes three other groups in addition to uncertainty in controlling: Demand uncertainty, supply uncertainty and the uncertainty in the manufacturing process. Moreover, they offered a new model to minimize uncertainty in the four areas and introduced a tool to deal with uncertainties in integrated supply networks. The primary advantages of this sort of classification compared with basic classifications are its comprehensive property due to the addition of a fourth factor (control), better performance and more adaptive supply networks (Lockamy-III, 2008; Childerhouse & Towill, 2004).

Wilding (1998) divided the complexity of the supply network into three categories (Figure 3-1), and used the categories to introduce the fifth source of uncertainty in complex networks called “uncertainty based upon the interaction of suppliers”. This kind of uncertainty results from the cooperation of one leading member with several other sections of the network, the effect of member's interaction on each other and uncertainty of the main member. As you can see in Figure 3-1, Wilding's complexity triangle includes three angles:

amplification; deterministic chaos and parallel interaction. He considered “amplification” as the main factor of bullwhip effect, while “deterministic chaos” was related to control systems such as an information system.

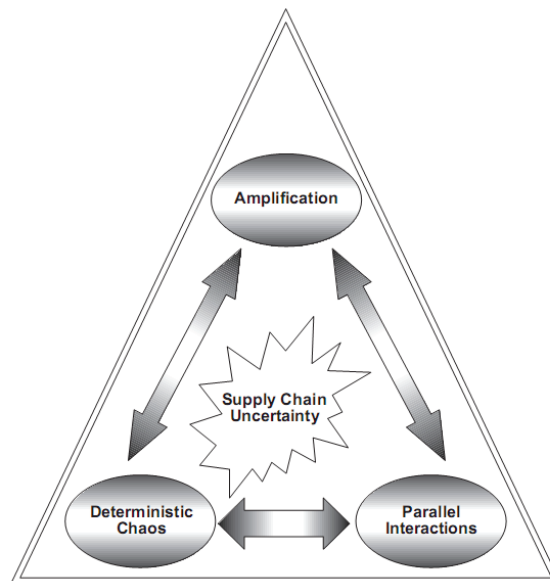


Figure 3-1: The supply chain complexity triangle (Wilding, 1998)

Prater (2005), updated and developed the “Wilding model” and other previous models, to provide a micro/macro model. He also introduced eight sub-sources of uncertainty in addition to four main sources of uncertainty. New and important source of uncertainty created by this model added two other sources of uncertainty: “uncertainty of the complexity of decision-making” (Which is related to the multi-objective decision according to the uncertainty of weight and importance of each objective and its constraints.) and “contingent models” created for specific objectives. For example, Van der Vorst and Beulens (2002), investigated on the network redesigning and uncertainty within the food industry. Fisher (1997) provided a model to define uncertainty in supply networks of innovative products.

Donk and van der Vaart (2005) made a distinction between two uncertainty factors of “volume of uncertainty” and “the combination and separation of uncertainty”. These models, led to the identification of additional resources of uncertainty. Moreover, Donk and van der Vaart and Beulens (2002) introduced five other reasons for uncertainty and suggested another classification. They suggested uncertainty sources in 2002 as follows: The structure of the network, infrastructures and equipment, orders anticipation, complexity in IT and information systems, as well as human behavior and characteristics. Moreover, by considering a review on the Van der Vorst et al. (2002, 2005) and Fisher (1997) studies, a common property of the three studies can be found, which is related to the characteristic of a particular product, and we introduce it as the twelfth factor.

Miller (1992, 1993), investigated the risk identification and control models and suggested an integrated risk management framework to deal with uncertainty in the companies working at the international level. In this study, the uncertainty is defined with respect to the three factors of public organizations, industries or enterprises. Werner et al. (1996), applied and developed the framework to improve it in the probability conditions. Afterwards Juttner et al. (2003) as well as Christopher and Peck (2004), suggested different sources of risk and uncertainty called internal uncertainty (process and control), the uncertainty of the network (supply and demand) as well as external uncertainties. They introduced and offered a framework to monitor and manage uncertainty. The main result from the studies mentioned in this paragraph is that a new source of uncertainty is added to the 12 previous sources. The thirteenth source of uncertainty is called environmental uncertainty (politics, government and society policy) and the final source of uncertainty is related to catastrophes and natural disasters.

Fourteen main sources of uncertainty can be classified into three groups:

- Group 1:
Organization internal uncertainties: uncertainty that occurs within the company, including the sources of uncertainties such as:
1- The characteristics of the product, 2- Production processes, 3- Control/chaos, 4- Complexity in decision making, 5- Issues related to organizational behavior 6- IT and information flow.
- Group 2:
supply network internal uncertainties: the uncertainties that occur in the supply network, and are not confined to any particular company. This type of uncertainty is due to companies' impact on each other and creation of new uncertainty composed of the following sources:
7- The customer demand, 8- Demand amplification, 9- Supplier, 10- Interaction between suppliers, 11- Order anticipation, 12- Network structure.
- Group 3:
supply network external uncertainties which are out of network control and include the following points:
13- Environmental resources, for example governmental regulations, or other sources of macroeconomic uncertainty, 14- Natural disasters, such as earthquakes and hurricanes that cause network activity interference.

These fourteen sources are considered as the main sources of uncertainty in supply networks. In other words, each source either alone or in collaboration with other sources creates uncertainty in delivery time, quality and quantity of demand and other factors affecting network performance. Figure 3-2, illustrated these 3 groups.

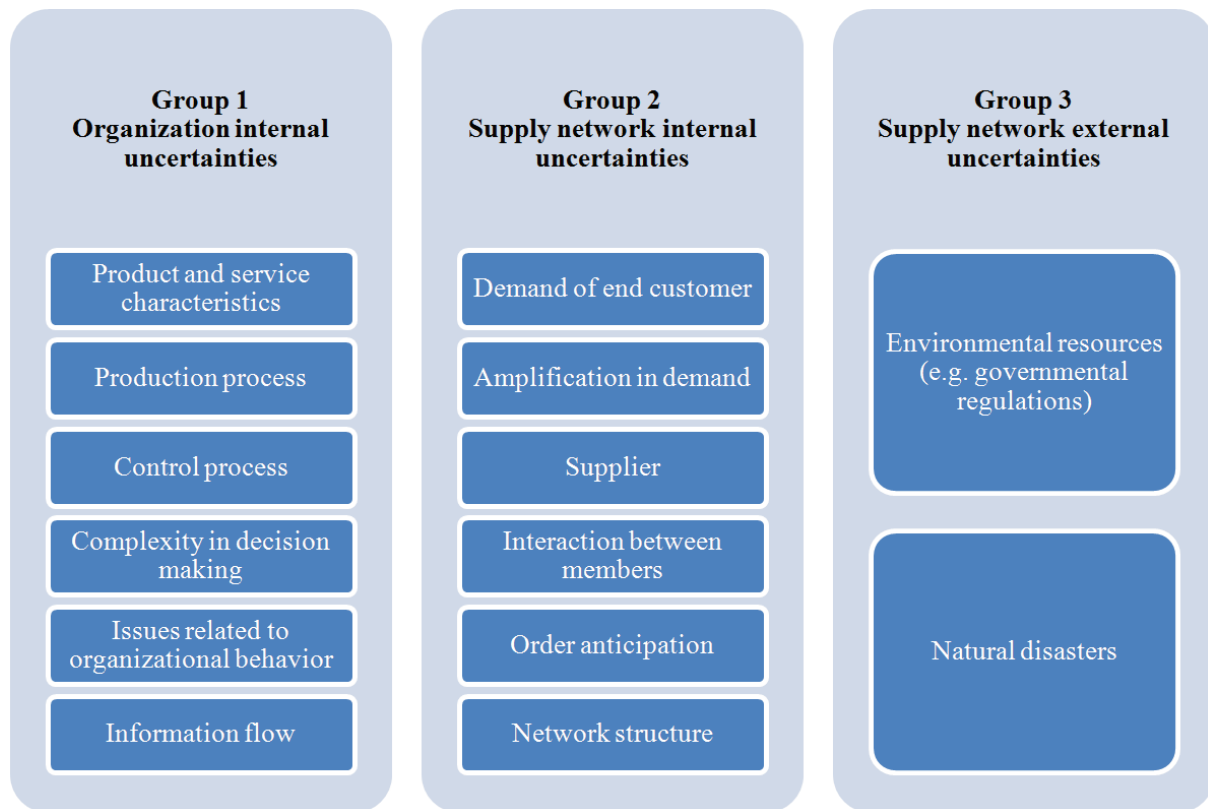


Figure 3-2: The sources of uncertainty in supply networks

After examining the sources of uncertainty and an overview of research conducted in this area, the literature review on managing and controlling uncertainties in the supply network will be provided in the next part of this study.

3.5 Literature review on managing and controlling uncertainties in supply networks

There are many researchers conducted on uncertainties and risks in supply networks. A group of these studies used a qualitative model to identify the uncertainty in supply networks while others represented quantitative models of uncertainty to define uncertainty (Peidro, et al., 2009). However, no extended and comprehensive method is suggested so far to manage uncertainty in supply networks (Simangunsong, et al., 2012).

The words “uncertainty and risk” are considered as keywords of many studies conducted on supply networks and business management. The term “uncertainty” in supply networks has been investigated in many studies in quantitative (mathematical modelling) and qualitative form (conceptual modelling) and, mostly aimed at identification of the sources of uncertainty, management strategies and representation of experimental observation. By quantitative models we mean models that use mathematical formulas and functions to evaluate uncertainty. For example, Wilson (2005), investigated the impact of transportation disruptions on supply network performance using simulation of the system dynamics (Wilson, 2006). However, qualitative models

generally represent the subjective or conceptual frameworks to evaluate and reduce the expression of uncertainty in the supply network.

Simangunsong (2012), pointed out that there are two types of decreasing and coping strategies in the field of management strategies. He suggested that strategies to reduce uncertainty can be defined as follows:

“Each utilized management concept that enables organizations to reduce uncertainty, for example, using an appropriate pricing strategy to reduce changes in customers' demand”

He also defined the coping strategy in the uncertainty strategies as a prevention strategy with no effect on the source of uncertainty. Rather, this strategy means to find a method to adapt and reduce uncertainty. For example, organizations must provide effective methods to predict uncertainty and try to reduce its errors by coping strategies in order to cope with changes in customer demand. In these conditions, the uncertainty of demand does not change, rather organizations will be able to better estimate the effects of changes in demand and thus, reduce the uncertainty (Simangunsong, et al., 2012).

Provided guidelines on the management of uncertainty in supply networks can be classified into four categories:

- **Designing an efficient information management system and controlling of supply network information**

As mentioned before, a supply network consists of the flow of information in all up and down sides of the network. Poor information flow across the network is the most important factor in creating uncertainty. Information is often incorrect, inaccurate and inappropriate, and worst of all; the relevant information is badly managed. Ability to manage the flow of information is a vital tool for organization's management (Min & Zhou, 2002). IT has a high potential to affect many aspects of network management such as cost, amount, power in timely delivery, flexibility and the organization. As mentioned above, the main part of the problem is related to the bullwhip effect due to inadequate flow of information. Walton and Miller, argue that uncertainty is mainly caused when organizations do not have the proper information (Prasad & Sounderpandian, 2003).

- **supply network integration and cost reduction**

Network management's focus is on the integration between the components of the supply network. Moreover, the supply network can be defined as a network of connections between components (Prasad & Sounderpandian, 2003), naturally, much greater integrity of the network leads to higher efficiency and reduces uncertainty. Supply network integration, at the first step requires to have internal integration within each member separately, i.e. the integration between the different parts of a member, but the next step is to create integration of all network components.

○ **Implementation of cooperative communication**

According to what was mentioned above, supply network management includes a collaboration, coordination and communication between the main manufacturer and suppliers so that each member may have complete trust in other members. This is considered as one of the important steps that companies should consider. Regardless of economic pressures and problems, this principle of trust and confidence should be formed as a good social relationship between the members. For example the OEM shall not use several suppliers in an incorrect competitive environment in order to receive raw materials at the cheapest price, highest quality and within a lowest time interval. This is disadvantageous because none of the suppliers (due to the lack of security in their relationship with the OEM) is willing to invest more in order to improve technology in the field of supply. Consequently, the manufacturer will eventually be affected. Another point about the healthy collaborative relationship is that members shall be informed about any changes in the network before implementation of those changes (Ayers, 2006; Qi, et al., 2004; van Hoek, et al., 2002).

○ **The structure of the network partners**

The supply network requires effective partnerships outside the company, but for any company, it is very difficult to make external relationships. Following points are considered in partners' selection:

- OEM
- Partner motivation
- Partner structures

According to the conducted researches in the field of uncertainty in supply networks and the variety of applied strategies (e.g., quantitative or qualitative), the structure of the uncertainty literature review in this study is shown in Figure 3-3:

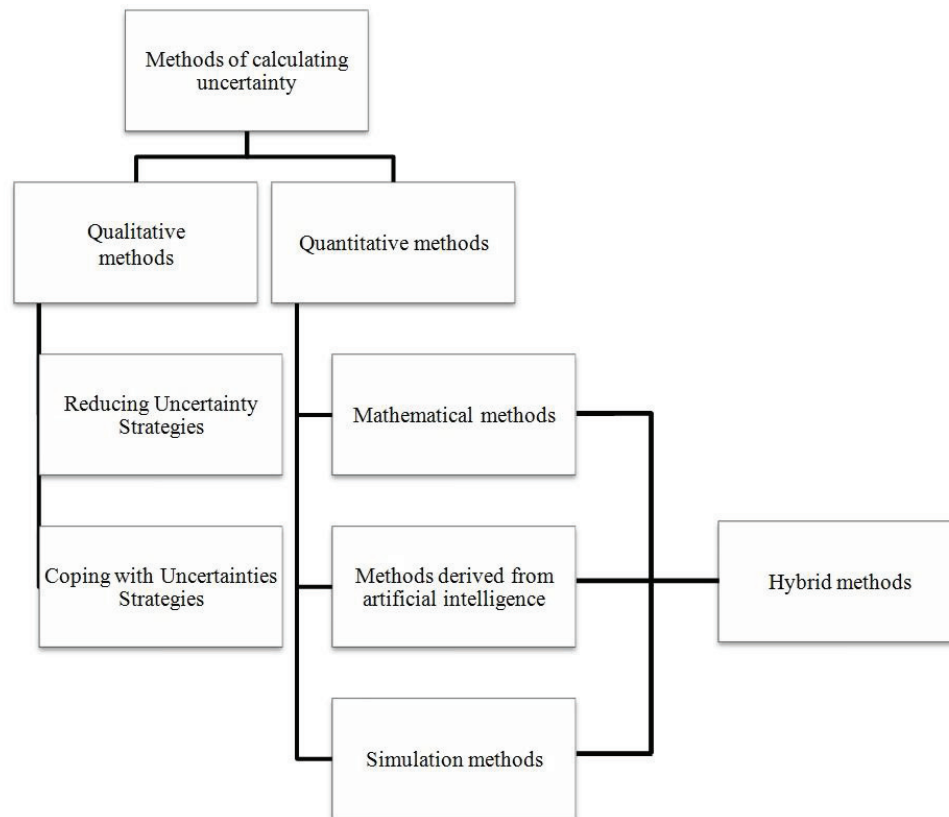


Figure 3-3: Structure plan of literature review

3.5.1 Qualitative models

○ Literature review on reducing uncertainty strategies

Management strategies to reduce uncertainty were introduced in 1992 by collaboration based studies by Miller. He used a vertically integrated system to control the uncertainty of supply and demand. Vertical integration is the amount of one company or organization ownership to the upstream (suppliers) and downstream (buyers). In the strategy provided by Miller, it is necessary to make a cooperation contract between suppliers and buyers to reduce uncertainty. This contract is based on the principles of a voluntary refrain from competing with one another, joint venture, license using each other's technology, as well as participation in the common consortium (Miller, 1992).

Davis (1993) went beyond these principles and provided triple strategies to reduce and control uncertainty in the process of manufacturing, demand and supply. His strategy was based on three principles of total quality control, new-product design and the supply network redesign. The first two strategies were used to reduce uncertainty in the production process (Geary, et al., 2002; Gerwin, 1993) and the third strategy was used to reduce the uncertainty related to demand and supply. Davis, in his second strategy based on product design, argues that a good initial design or proper changes in product design can make a better and stronger production process, which in turn has a significant impact on reducing uncertainty.

Meanwhile, Davis in his third strategy for the first time provided the idea of production network redesign to reduce uncertainty. The main question in his third strategy was “*To what extent each company should be close to its key customers?*” This work was considered as the basis of redesign principles. Key factors provided in the Davis's supply network redesign are shown in Figure 3-4:

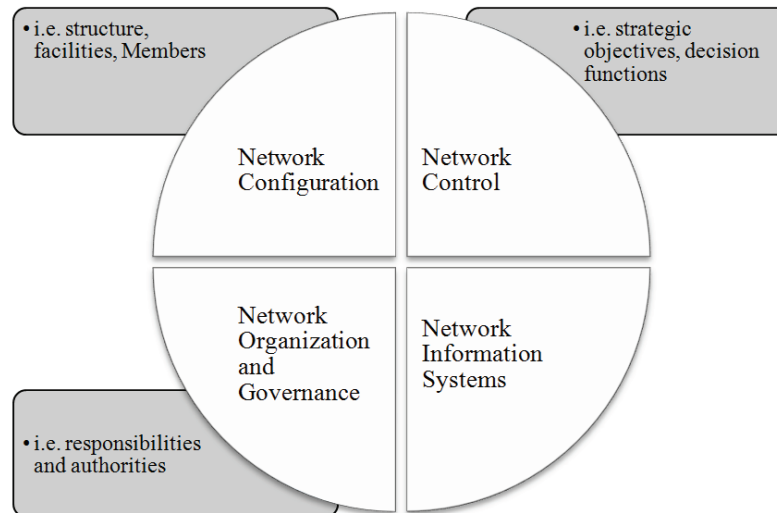


Figure 3-4: The key factors of redesign of a supply network structure (Bhatnagar & Sohal, 2005; van der Vorst & Beulens, 2002)

The supply network redesign and restructuring were considered by other scientists in the following years. This issue will be discussed further later.

Another study was conducted by Fisher (1997) to reduce uncertainty. He offered “the stock replenishment” system for supply networks with shorter planning time than the estimated time. He attempted to reduce the uncertainty for products with a short lifetime. Fisher successfully offered the “shorter planning period” strategy. He suggested that shorter time for planning of system performance than estimated time for completion of the work led to higher prevention of sudden changes of the scheduled program which in turn reduces uncertainty (Fisher, 1997).

Van der Vorst et al (1998) believed that one possible method to reduce uncertainty is finding a proper way to make correct decision policies. They believed that this strategy can improve supply network processes. For example, the bureaucracy involved in policy decisions requires registering and obtaining signatures of several people which in turn create more complicated problems. Therefore, the decision-making process redesigns to reduce the number of required signatures leads to reduced complexity of the decision and thereby reduced inherent uncertainty (van der Vorst & Beulens, 2002; van der Vorst, et al., 1998).

Mismanagement of information and communication networks (such as inaccurate reception or sending of information) is one of the fundamental problems in decision making leading to increased uncertainty in controlling. For this reason, researchers suggested “good decision support system” (DSS)

strategy to support and assist managers in making complex decisions (Shim, et al., 2002; Muckstadt, et al., 2001). In the following, Deane et al (2009) studied different methods such as staff training courses to raise awareness, retesting and reviewing the processes, process monitoring and backup creation to protect sensitive data. They successfully studied these new methods to facilitate the implementation of strategies, reduce complexity and uncertainty. Finally, they provided effective strategies (Deane, et al., 2009).

The role of redesigning to reduce the supply network's uncertainty was inevitable for researchers. Harrison considered supply network design in the context of other questions such as the number of plants required for a network, technologies needed for different processes or design based on the selection of appropriate suppliers. He also considered effects on network flexibility in the case of adding a new product or process. He believed that the network structure redesign including for example manufacturers, distribution centers, transportation networks, production processes and network relationships will attract customers and has a significant impact on reducing uncertainty (Harrison, 2001). Later, other researchers pursuing this idea provided concepts of “outsourcing systems” and used “third-party logistics” company concepts (Sun, et al., 2009; Lee, 2002). Another study was carried out in this field by Van der Vorst and Beulens (2002). They also offered two other strategies to reduce uncertainty in addition to redesign of supply network structure and configuration. They focused on collaboration with clients and key suppliers as a requirement to reduce uncertainty in supply networks and also to reduce the problems associated with their decisions. They made their first strategy based on this basic principle. Their second strategy to reduce uncertainty was by decreasing the role of humans in the production process that was i.e. possible through the use of automation in the processes.

After Miller's (1992) studies, many researchers were interested in using concepts such as collaboration. At the beginning of the twentieth century, researchers believed in closer collaboration with suppliers and customers for joint planning and correct or accurate decision making. This led to company ability to reduce uncertainty (Holweg, et al., 2005; Christopher & Peck, 2004). Van der Vorst and Beulens (2002) used cooperative principles and considered internal integration as an important factor for better decisions and to reduce uncertainty in organizations. Other investigations in this field in 2002 led to provide the theory of an “integrated supply network”. All network members in the integrated supply network work together as one single organization and therefore avoid uncertainty, because more coordination of members causes more uncertainty reduction in the manufacturing process, supply, demand and control (Childerhouse & Towill, 2004; Geary, et al., 2002). Integrated strategy means to extend management systems to the upstream (to suppliers) and downstream (customers). Thus, integrated strategy seems useful to reduce uncertainties in the integrated supply networks. For example, Geary et al (2002) introduced the

“well-trodden path” system as a systematic control method in integrated supply network control that successfully reduced the uncertainty in supply and demand. This issue requires the removal of waste products by lean strategies and implementation of a coordinated flow of materials throughout the network. Boyle et al. (2008) used “E-intermediation”, in order to facilitate the flow of information in the integrated supply network and reduce uncertainty by receiving key business information in the network (Boyle, et al., 2008).

Geary et al. (2006) presented the strategy of “performance measurement process” that is considered as another step in the management of uncertainty. They used this strategy in areas such as quality measures, machine performance indicators, and key performance indicators (KPIs) for uncertainty reduction (Geary, et al., 2006).

Methods provided for reduction of uncertainty in demand were also considered by many researchers. Some of them suggested “pricing strategies/promotion incentives” to improve the uncertainty (Gupta & Maranas, 2003). Gupta and Maranas believed that marketing activities can be used to change the orientation of the end-customer demand to the tendencies of the organization. Therefore, marketing impact on seasonal demand changes can help to manage the demand uncertainty. Research conducted in this area showed that improved pricing methods and controlled marketing may have a significant effect on the bullwhip effect.

Scientists attempted to improve the network performance followed by studies conducted in the field of strategic cooperation and supply network design. They developed and adapted previously successful systems (used within the company to reduce costs and enhance the quality) and applied these systems in the network to improve its performance. They found that the “lean production” system should be implemented in the supply network for easy material flow across the network as well as enhancing members' coordination factor. After implementing the system, they discovered a direct impact on reducing the uncertainty. For example, they found out that by making a process leaner, it became more simplified with lesser uncertainties (Tracy & Knight, 2008; Taylor, 2006; Hines, et al., 2004).

However, determination of proper lean supply network design is dependent on the system of sharing information among members as a requirement of cooperation strategy. Therefore, Gunasekaran and Ngai (2004) suggested “Information and Communication Technology” (ICT) systems to address this problem (Gunasekaran & Ngai, 2004). ICT systems provide an appropriate infrastructure for DSS strategies to reduce uncertainty (Childerhouse & Towill, 2004).

○ Literature review on coping with uncertainty strategies

One of the strategies to cope with uncertainty is a “postponement” strategy. Lee and Billington (1995) for the first time introduced this strategy to control the demand uncertainty. This hypothesis is based on delaying the activities and

processes as much as possible for more adaptation to the demand determined, rather than using demand forecasting systems (Yang & Yang, 2010; Yang, et al., 2004). A practical example of this strategy can be seen within the Toyota Company. It has been very successful in delaying the decision makings as much as possible to obtain all market information and cope with demand uncertainty (Yang, et al., 2004).

The flexible supply network is considered as another method to tackle uncertainty studied by many scientists (Gosling, et al., 2010; Sawhney, 2006; Prater, et al., 2001). These strategies are provided to the three phases of input, processing and output. Flexibility strategies include input flexibility, volume and delivery time flexibility, process flexibility and customer flexibility.

At the input phase, an organization must manage multiple suppliers to create flexibility in the input (Sawhney, 2006). Although added suppliers may increase uncertainty in delivery time or quality, a balance is needed to be among them (Lee, 2002). The use of available potential suppliers and their willing for assistance is considered as a factor to manage and cope with uncertainty. For example, working with multiple suppliers enables organizations to compensate for damages resulting from production plan changes by using a selection of those suppliers, which supply raw materials immediately (Sawhney, 2006).

In the process phase, flexibility in the amount of staff and equipment is possible through management of equipment, personnel and infrastructure (Sawhney, 2006). At this phase, two strategies are examined: Flexibility in volume and delivery time and flexibility in the process. The strategy of flexibility in volume and delivery time is based on companies' ability to enhance the speed of services and production despite constant volume changes (Braunscheidel & Suresh, 2009). It is possible only if the specific production equipment and multifunction equipment (van Donk & van der Vaart, 2005) or multi-skilled workforce (Miller, 1992) to be used. Strategy of flexibility in the process is the second approach to cope with uncertainty. This strategy calls for the creation of plant-level flexibility (flexibility in labour, equipment) that is required to deal with the uncertainty caused by frequent changes in the product at the workshop level. Multi-skilled workers, for example, may allow flexibility in the process (Miller, 1992). Moreover, the process flexibility may result from the use of multipurpose machinery, equipment and technologies (Ulrich, 1995).

The last strategy is the customer's flexibility in this category. The main principle is to use clients who have a lower sensitivity and higher adaptability. For example, the uncertainty caused by the breakdown of the machine can be removed by changing the contracted delivery time with customers who are less sensitive (Sawhney, 2006).

Other strategies to cope with uncertainty may include:

- The use of safety stock, which is called “strategic stocks” (Wong & Arlbjorn, 2008; Helms, et al., 2000).

- Delivery time management strategy: agreeing on customer delivery times longer than the originally required time (Prater, et al., 2001)
- Financial management strategy: This strategy refers to a method of reducing the financial risk including insurance (Ritchie & Brindley, 2007; Tomlin, 2006).

Quantitative techniques and mathematical tools are used as another tool to cope with uncertainty. Applying the research techniques in operation, mathematical principles of forecasting, simulation and modeling are among examples of this category (Peidro, et al., 2009). The history of the use of quantitative techniques to deal with uncertainty in supply networks will be explained in the next section.

3.5.2 Quantitative models

According to the literatures related to the growth and development of quantitative issues in supply networks, it can be concluded that in traditional supply networks or the so-called supply chain most researchers focus was on quality control, time and cost. Until 2000, the focus was turned toward coordination between these three elements. Therefore, network quantitative issues at that time changed into resolving issues related to the integration of these three parameters. Nowadays, with the development and growth of definitions and concepts of uncertainty and risk in supply networks, researchers found an important element or parameter that may directly impact each of the three previous parameters. For this reason, the focus of most researches (at least in quantitative models) is changed into providing methods for reducing uncertainty, which has a direct impact on each of these three parameters. For better understanding of this concept, see the conceptual model of supply network problems by Norrman and Jansson (2004) in figure 3-5.

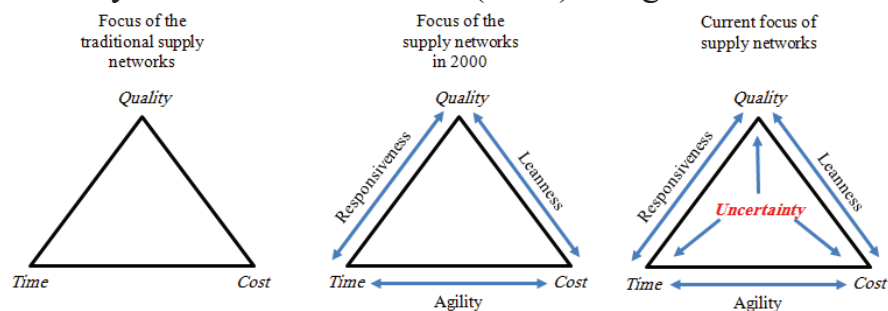


Figure 3-5: The evaluation of key focus area of supply network management (Micheli, et al., 2008; Norrman & Jansson, 2004)

As the economy changes, as competition becomes more global, it's no longer company vs. company but supply network vs. Supply network (Fawcett & Magnan, 2001). Thus, companies can no longer enter competitive markets as a unique company, and they must work as an integral part of the integrated supply network (Min & Zhou, 2002). Therefore, the ultimate success of a company depends on its ability to manage the integration and coordination with

a network (Lambert & Cooper, 2000). Moreover, network activities can reduce the effects of unexpected events (Guillén, et al., 2005). However, the complexity of supply networks and dynamic and changing relationships between network members is considered as one of the major causes of uncertainty in the supply network (Bhatnagar & Sohal, 2005). In the process of decision-making within the supply network, uncertainty is a major factor that has a direct impact on the effectiveness of network coordination and structure (Davis, 1993). This factor influences the whole network performance.

In this chapter, fourteen sources of uncertainty are introduced. With study of providing quantitative models to reduce uncertainty, it can be found that the models mostly focus on metric factors and criteria such as demand uncertainty, supply uncertainty, delivery time uncertainty, and process uncertainty. Review of the literature shows that so far little has been done to study network design and network structure as a source of uncertainty. Now this issue is recognized as a serious gap in the literature related to this field (Klibi, et al., 2010).

Quantitative models proposed to reduce the uncertainty in supply networks can be divided into four categories (See figure 3-6).

- Mathematical models
- Models derived from artificial intelligence
- Simulation models
- Hybrid models

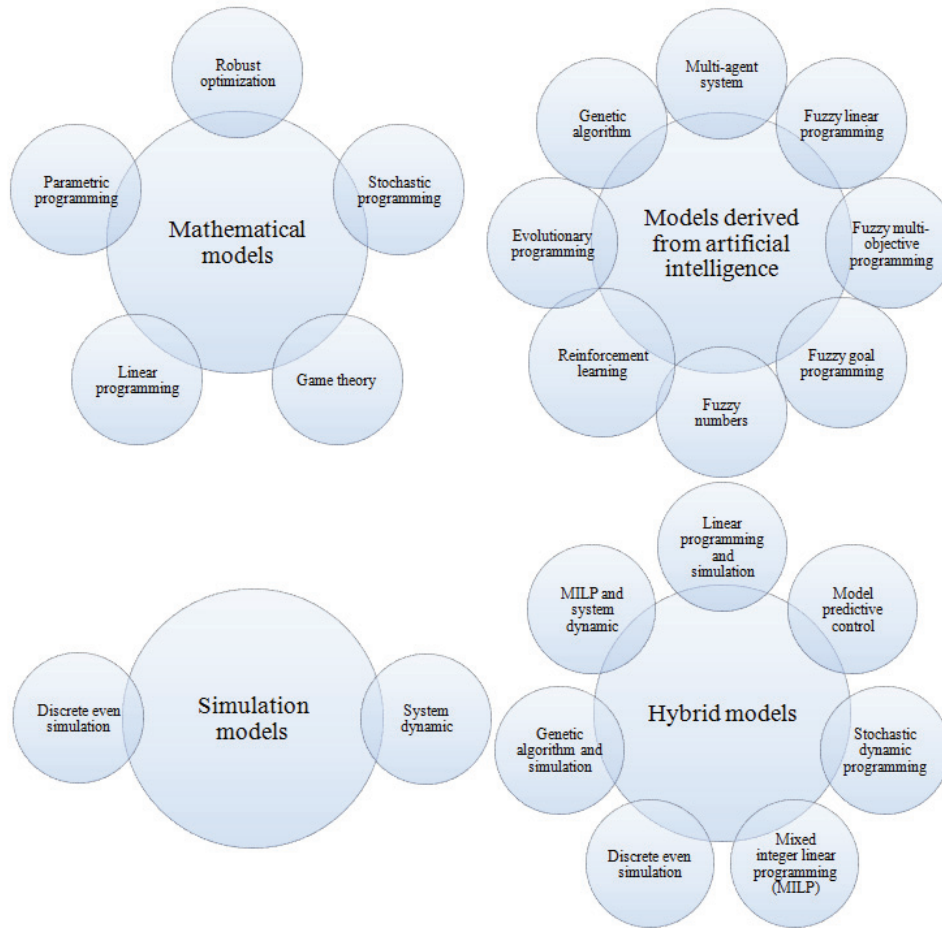


Figure 3-6: Subcategories of quantitative models

This section introduces some studies as examples of each of these four models:

○ Mathematical models

These models are mostly based on operation research (OR) and probability. The purpose of most models is to control costs and uncertainties associated with the demand, supply, lead-time, and process. The mathematical techniques used in such studies are :

Robust optimization, stochastic programming, games theory, linear programming and parametric programming (Stein & Ziemba, 2005). Due to the high number of provided mathematical models in this area, in this section just some of them briefly explained as follows:

Cohen and Lee (1988) presented a simple statistical model to measure the cost of a supply chain. They took the first steps in this direction with a manufacturer and a distributor. Their model was capable of calculating supply network cost in terms of demand and supply uncertainty. This model is the first model of optimization in terms of uncertainties (Cohen & Lee, 1988). Svoronos & Zipkin, followed by Cohen & Lee, continued in 1991 with the completion of their model for a production system with a manufacturer and several distributors as next steps of these models. Considering the possible transporting time in the

network, this model provided a plan to control inventory at the lead-time uncertainty (Svoronos & Zipkin, 1991).

In order to optimize the design process in the supply chain, one year later, Lee et al., developed the inventory control model of Svoronos & Zipkin and added state of uncertainty in demand and supply of goods. The main objective was product design and its production process for different markets with the lowest cost and the highest customer service (Lee, et al., 1993). In the same year, he provided a heuristic statistical model in cooperation with Billington, in order to manage the flow of material presented in a decentralized supply chain (Lee & Billington, 1993). The main objective was planning and controlling of supply chain inventory in order to achieve the appropriate level of service. On the other hand, at the same time, Pyke and Cohen, succeeded in presenting a probability model for a production-distribution supply chain. They studied a supply chain including a manufacturer, a product warehouse, and a retailer. This model was designed to control inventory and cost under conditions of uncertainty in demand (Pyke & Cohen, 1993). In 1994, they completed their previous model by considering the network with the multi-products (Pyke & Cohen, 1994). Altiok and Ranjan (1995) developed mathematical models to calculate the optimal production level for each product of a multi-product supply chain, taking into account the uncertain demand (Altiok & Ranjan, 1995).

Blanchini et al. (1997) suggested the first non-probabilistic model in terms of uncertainty by considering the uncertainty in demand and resolving it under non-probabilistic condition based on a game dynamics between two players (controller and demand). On the other hand, in the same year Lee et al., developed their previous model and suggested a mathematical probability model by considering the uncertainty in prices and potential demand and investigated its influence on bullwhip effect (Lee, et al., 1997). McDonald and Karimi in the same year designed a Mixed Integer Linear Programming (MILP) model for a multi-product production planning in a supply chain by taking into account several consecutive periods of uncertainty in demand (McDonald & Karimi, 1997).

Two years later, Escudero et al., developed McDonald and Karimi model based on probable planning to optimize production planning and assembly under uncertainty conditions in demand and supply (Escudero, et al., 1999). In 2000, Applequist et al., provided a method to identify supply chain design under demand and supply uncertainties. To this end, they developed the concept of risk to provide a tool to investigate risk and uncertainty of the chain. Their method was based on the proper balance between the expected performance of a series of decisions and the related risks and uncertainties (Applequist, et al., 2000). Gupta and Maranas, in the same year, developed McDonald and Karimi's model to provide a two-stage probabilistic scheduling model based on potential demand (Gupta & Maranas, 2000). Three years later they developed their model for a multi-product supply network with multiple different suppliers for

uncertainty demand conditions in order to complete their previous model. By establishing the balance between the service level of the customers and the related costs, their model tried to propose a suitable production planning (Gupta & Maranas, 2003).

With the growing complexity of supply chains and structural changes to the network and also increases in uncertainty with the complexity of the network, researchers in the supply networks fields are getting every day more interested in this issue. In 2004, Lababidi et al., designed a cost optimization model for the petroleum supply network entitled "demand and process uncertainty". The main objective of their model was optimization of using resources by minimizing the total cost involved in the production, raw materials, transportation and storage (Lababidi, et al., 2004). In the same year, Miranda and Garrido provided a mixed integer non-linear programming model and took another step in this direction in probabilistic demand conditions. They solved their model with a heuristic model based on Lagrangian relaxation. Their model was designed to control inventory levels (Miranda & Garrido, 2004).

Ryu et al.(2004), used a bi-level parametric programming model and by its adaptation to supply network conditions, they created a new method for network planning in this area. Their model, by considering two factors of uncertainty of demand, and process, performed the production planning (Ryu, et al., 2004).

Aghezzaf et al. (2005), suggested a model for inventory planning and optimal use of warehouse's capacities under probabilistic demand conditions. His model was designed based on robust optimization method, then solved by Lagrangian relaxation. In the same year, Santoso et al., suggested a stochastic programming model with algorithms to solve problems with large-scale supply network under conditions of uncertainty. Their model was considered the demand, supply, and process as sources of uncertainty.

Leung et al. (2006), presented a model in order to solve production planning problems in a multi-site supply network. They used stochastic programming approach for mid-term production planning in order to deal with the uncertainty of demand. In 2007, they completed the previous model and developed a robust optimization model in an attempt to reduce the overall cost of the network, such as production costs, labor and inventory.

Zhao et al., used game theory to consider the coordination issue in a manufacturer–retailer supply chain using option contracts for solving conflicts between retailers and manufacturers under uncertainty in demand (Zhao, et al., 2010).

Hua Xu et al., addresses the lead time uncertainty problem in supply chain systems. He adopted a two-echelon supply chain model, in which a Markovian lead time model is combined with control theory to consider uncertainty in stochastic processes (Xu & Rong, 2012). Cardoso et al., proposed a MILP for design and planning of supply networks with reverse flows and reverse logistics activities. He considered products' demand uncertainty in his model. The model

is applied to a representative European supply chain case study and its applicability is demonstrated (Cardoso, et al., 2013).

○ **Models derived from artificial intelligence**

Another approach in quantitative models is artificial intelligence and fuzzy models to recognize the uncertainty and improve the operations in order to control and reduce it. Usually, these intelligent techniques are used in combination with mathematical programming for semi-optimization purposes.

Among the techniques used in this research are:

Multi-agent system, fuzzy linear programming, fuzzy multi-objective programming, fuzzy goal programming, fuzzy numbers, reinforcement learning, evolutionary programming and Genetic algorithm.

Petrovic et al. (1998 and 1999), for the first time presented a fuzzy model to simulate uncertainty conditions in a simple supply chain. They determined the level of inventories and orders in a specified time interval to obtain an appropriate performance of the delivery process and acceptable cost. Uncertainty in the demand and supply of raw materials was defined as a fuzzy set in their model (Petrovic, et al., 1999; Petrovic, et al., 1998). In 2001, they developed a supply chain simulation tool, to conduct analysis of supply chain models in fuzzy uncertainties (Petrovic, 2001).

Hu et al. (2000), presented a mathematical programming model solved by Genetic algorithms. Their model was capable of considering uncertainties to determine the product inventory levels (using probabilistic parameters), and also to define the percentage of sales (by a fuzzy parameter).

Giannoccaro and Pontrandolfo (2002), introduced a decision making method for inventory in an integrated supply network. Three techniques of Markov decision process, reinforcement learning, and simulation were used in their method (Sutton & Barto, 1998) to control demand and supply uncertainty in supply networks (Giannoccaro & Pontrandolfo, 2002).

Chen and Peng (2003), evaluated uncertainty in a multi-agent supply network. They provided a theoretical framework based on Bayesian Network. The proposed framework, controls the activities of the network, which could be configurable to the uncertainties. They called this method “Extended Bayesian Network” (Chen & Peng, 2003).

Chen et al. (2003), in two consecutive papers, provided a model at a distribution level on planning model for multi-product multi-stage, and multi-period supply network. Their model objectives were to maximize the benefit of every member of the network, and the level of customer service, along with keeping a balanced level of stored inventory. Their model type was mixed integer non-linear programming with multi objective, which used a fuzzy set to define the uncertainty (Chen, et al., 2003; Chen, et al., 2003). One year later, Chen and Lee completed the previous model and added demand uncertainty to investigate the model with several scenarios. They used fuzzy principles to define uncertainty (Chen & Lee, 2004).

In the next stage of these researches, Kumar et al., provided a fuzzy goal programming method used in the problem of vendors' selection and controlled the network uncertainty in the supply and process conditions. Their model obtained by a combination of mixed integer and fuzzy goal programming models. The main purposes of this model were, minimization of the vendor's costs in the network, and also minimizing the uncertainty in the delivery. For this purpose, one triangular membership function was defined for each fuzzy goal (Kumar, et al., 2004). Later, Kumar et al. (2006), offered the same problem, solved with another method based on multi-objective fuzzy programming (Kumar, et al., 2006).

Other models also were found based on Genetic algorithm to control the uncertainty, such as Truong and Azadivar model provided in 2005. They combined Genetic algorithm, mixed integer programming, and simulation to offer a model for allocation of equipment in the supply network. They used Genetic algorithm in the interpretation of uncertainty in supplier selection and production planning. They also used mixed integer programming as an approximate solution to the demand uncertainty (Truong & Azadivar, 2005).

Lieckens and Vandaele (2007), developed a MILP model for supply network and combined it with queues theory in order to control dynamic aspects of network (such as delivery time) and demand uncertainties in reverse logistics. They solved the model by using Genetic Algorithm (Lieckens & Vandaele, 2007).

Hnaïen et al. studied a two-level assembly system in supply chain planning under lead-time uncertainty by minimizing the total expected cost at level 2 of the assembly. For solving this problem, they employed Genetic algorithm as an intelligent technique (Hnaïen, et al., 2009). Mula et al., proposed a fuzzy mathematical programming model, which was used for representing demand uncertainty in a supply chain production planning problem. They employed possibilistic programming for their experiment (Mula, et al., 2010).

○ **Simulation models**

These models were initially suggested by Towill's studies (Towill, 1991) to handle uncertainty. He used simulation method to investigate the effect of changes in demand on the different strategies of the supply chain. He suggested five scenarios for this purpose: (1) elimination of the distribution links and creation of a direct relationship between manufacturer and customers, (2) integration of the information flow in the chain, (3) establishing strategies to reduce delays, (4) changes in lot-size to have easy movements in material flow in the supply chain, and (5) changes in lot-sizing procedure definition parameters. He eventually investigated the uncertainty of demand in all these scenarios and found that (3) and (4) strategies are the best strategies to cope with changes in demand in the supply chain. We refer to just a few of latest researches as examples in this category.

Suwanruji and Enns (2006), performed a simulation of the inventory control system in the supply network considering the uncertainty in the demand, as a discrete event. Their supply network model was a multi-echelon model covering two parts of manufacturer and distributor. In this simulation, they compared three systems of distribution/material requirement planning (DRP/MRP), the re-order point (ROP), and Kanban (KBN) at inventory replenishment. They performed the mentioned model with two scenarios in the seasonal demand changes (demand uncertainty), and stable demand. In the case of uncertainty in demand, DRP/MRP strategies, provided better results than the other three cases (Suwanruji & Enns, 2006).

As an example in another research we can refer to the dynamic simulation system provided by Low and Chen model in 2013 (Low & Chen, 2013). They simulated a system of production-distribution and provided some scenarios for demand and delivery time uncertainty conditions. They showed that how uncertainty in delivery time, can affect network performance. Finally, they offered a series of strategies to deal with uncertainty.

○ Hybrid models

The hybrid models can be considered as a combination of the above methods used to reduce uncertainty. Various types of these models in the studied literatures have been classified in figure 3-6. In this section, an example of each of these categories are mentioned.

Newhart et al. (1993) model, could be considered as one of the first hybrid models to control the uncertainties of supply networks. They proposed a two-stage mathematical model to minimize the amount of inventory stored in different parts of the network. Next, in the following step they provided an inventory management model, based on the spreadsheets to estimate the required safety stock to cope with the probabilistic demand and delivery time. This model is classified as linear programming and simulation (Newhart, et al., 1993).

Seferfis and Giannelos (2004), conducted another study in the field of hybrid models, which resulted in a model for optimization of controlling procedures, in the multi-product supply networks. The purposes of this model were increasing customer satisfaction, and reducing the cost of the network model with consideration of the potential demand. This model is created by the combination of the mathematical optimization and simulation models, which belongs to the predictive control of the hybrid model group (Seferfis & Giannelos, 2004).

Lim et al. (2006), offered a hybrid model to use a combination of Genetic algorithms and simulation for solving distribution planning problems, in supply networks under uncertainty conditions, and they took another step in this direction. Among the model aims, were minimizing costs and maximizing customer satisfaction. Uncertainty parameters considered in the model included machinery breakdowns and their repair time. One of the results of their model

was providing a program for distribution with optimization of operation time consistent with the random nature of the supply network (Lim, et al., 2006).

Choi et al. (2006), suggested a hybrid model of stochastic Dynamic Programming (DP) to optimize price and demand uncertainty for a multi-product supply network. In their model, in which the Markov chain was used to define the network and its probabilities, a DP approach was introduced uncertainty controlling. They used this model and invented a new method called “DP in a heuristically restricted state space”. Choi et al., used a simulation of several scenarios under dynamic concentrated inventory to provide strategies to cope with fluctuations in demand (Choi, et al., 2006).

A typical example of hybrid models is related to discrete event simulation, which proposed by Lim et al. (2006). They developed a hybrid model for production planning of the production - distribution system to control the uncertainty in the process. They provided a mathematical programming model to make decisions about the production volumes and storage in each member of the networks, and the presented mathematical model was investigated with simulated scenarios (Lim, et al., 2006).

Villegas and Smith (2006), offered a hybrid model to analyze the impact of different policies on safety stock to reduce uncertainties in demand. They implemented this study as a case study in a food company and analyzed obtained results and effects. They used real demand for their simulation model inputs. The results of their study led to the formulation of the policies in the company, and their mathematical model used for reducing the effects of the demand uncertainty in the production planning. The hybrid model of Villegas and Smith is considered in MILP and system dynamic classification (Villegas & Smith, 2006).

As a final example of this type of research, we refer to Wang and Durugbo model in 2013. They provided a model of hybrid fuzzy methodology and combined fuzzy and simulation models to provide a theoretical framework in the field of controlling metric parameters of uncertainties in the supply networks. Their main focus was to analyze how knowledge of professionals and managers affects the reduction of uncertainty and appropriate decision making in the process. Their model controlled uncertainty of the process and demand (Wang & Durugbo, 2013).

3.6 Advantages and limitations of the approaches

Based on the quantitative models investigated, the strengths and functional limitations of each model are presented briefly in Table 3-1. Mathematical and stochastic models have a high accuracy, responsiveness and adaptability. Moreover, the application of these types of models is easy, because it is not dependent on large amounts of data. These models are mostly used to address optimization problems. The main limitation is the complex calculations, that make it difficult to be used for the supply networks due to lack of mathematical and statistical theorems for some special cases.

Artificial intelligence and fuzzy models are based on fuzzy logic. These models are a good alternative to the models in the first group and are used effectively in the fuzzy optimizations. One method to solve these models is to use meta-heuristics techniques to find an optimal approximate solution. The weakness of these models is a large number of data needed to consider the uncertainty compared with the first type of models, a limited area of response and solutions due to the limitations of these models to solve problems. Multi-agent systems are also in this group of models and their major limitation is that they are only applicable for decentralized supply networks. The main disadvantage of these models is that they leave doubts about the quality of the proposed solution due to the lack of consideration of the entire network and separate focus on each network segment.

The third group of models relates to simulation techniques. Effectiveness when using these models in solving complex networks is obvious. However, solving the complex problems with extensive optimizations requires a very challenging program. Moreover, sometimes it takes too much time to find solutions and implement the system.

Limitation	Advantage	Model
Mathematics and stochastic models	<ul style="list-style-type: none"> - Right adaptation for managing random uncertainties (based on probability distributions) - Appropriate for solving optimization problems - High accuracy - Easy to apply 	<ul style="list-style-type: none"> - Not powerful enough to model complex scenarios. Solutions provided could be limited in their application fields because of preliminary restricting hypotheses - There are not enough statistical formula to solve all scenarios
Intelligent artificial and fuzzy models	<ul style="list-style-type: none"> - The fuzzy set theory could provide an alternative approach for dealing with supply network uncertainties whenever statistical data are unreliable or even are not available - Appropriate for solving optimization problems (fuzzy) - Multi-agent systems constitute a very useful solution for the decentralized management of the supply network - The application of techniques based on meta-heuristics, evolutionary and bio-inspired algorithms to obtain valid approximations with a right computational efficiency 	<ul style="list-style-type: none"> - The application of fuzzy set theory requires defining more input data for considering uncertain parameters - Solutions provided could be limited in their application fields because of preliminary restricting
Simulation models	<ul style="list-style-type: none"> - More capable of capturing scenarios of complex system behaviour 	<ul style="list-style-type: none"> - The application of fuzzy set theory requires defining more input data for considering uncertain parameters - Solutions provided could be limited in their application fields because of preliminary restricting

Table 3-1: Advantages and limitations of the quantitative models groups

Considering strengths and weaknesses of the three techniques, we are looking for a hybrid model that uses the strengths of each single type of models in order to calculate network uncertainty (in simple or complex networks).

3.7 Possible mathematical methods in explanation of uncertainty

According to literature review presented in the context of quantitative models for the uncertainty, it can be found that all these models generally use one of three methods of the interval bound, membership function (for fuzzy approaches), and probability density function to define uncertainty. See figure 3-7 for diagram provided for each of them.

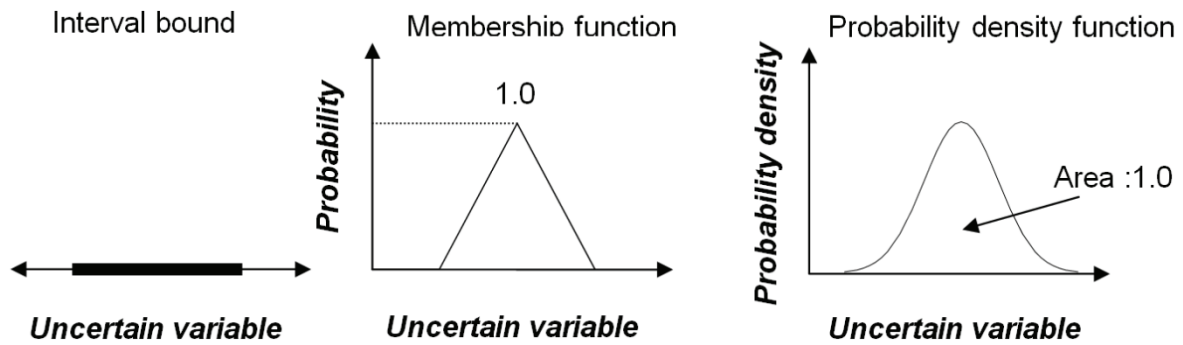


Figure 3-7: Three different ways of characterizing the uncertainty in the quantitative models (Safaei, et al., 2011)

Interval bound is the simplest way of characterizing of the uncertainty in the input variables by specifying upper and lower limits. The definition of "membership functions" requires more information than the Interval bound methods. This information can be propagated through the use of fuzzy logic methods. If there is enough information about the input variables to define probability density functions, then analysis methods of "probabilistic" uncertainty can be used. These methods are also called "stochastic" methods.

The main challenge in mathematical definitions of uncertainty is between the fuzzy method (membership function), and probability density function due to the higher accuracy of the method definition (Yen, 2009). The fuzzy methods to define fuzzy uncertainty, should create a membership function based on the assumptions given by experts' experience and there is no particular system based on actual data (Zhu, et al., 2010). That's why, so many errors in estimations may be obtained in the model results. The question that arises here is that despite these problems, why have many scientists and researchers used this model to define uncertainty? To answer this question, we should refer to the limitations of the method rivals (Pdf). In probability density function method, because it is directly dependent on probability formulas to define uncertainty, there is no obvious solution presented for the probabilities of combining multiple probability density functions with different names and formulas (Montgomery, 2008). That's why, scientists have preferred to deal directly with the probability density function constraints by fuzzy systems. But, the probability density function method has a property that cannot be easily ignored, i.e., its consistency with the real-life conditions compared with its fuzzy competitor. The reason of this issue is that probability density function method directly uses previous data to define uncertainty and fully represent the true state of the measured variable.

According to the advantages and disadvantages of each of these two methods, we can conclude that if it was possible to remove probability density function method limits for definition of uncertainty, then it may be claimed that no other system can be provided to express the uncertainty as good as in this method. Therefore, in this study, the uncertainty is defined based on a

probability density function method. Additionally, we tried to remove its restrictions by a hybrid methodology.

3.7.1 Most common probability density functions

As noted above, to define and specify the uncertain parameters, the fuzzy methods require more inputs than the other two methods. Moreover, according to limiting assumptions in the fuzzy method to obtain the response as well as acceptable access to the accuracy in the probability density function methods, we choose probability density function to define uncertainty. The behavior of a random variable is described by its probability distribution function. It can be expressed in the form of figure, histogram, Table, or a mathematical formula. Sometimes, the results of statistical experiments associated with a continuous sample space have a certain type of behavior. Consequently, these variables have the same probability, by which density of the random variable can be explained. By a given probability density, called continuous probability models, it will be possible to explain the behavior of many continuous random variables. A brief overview of the major distribution functions used to estimate uncertainties, will be presented in the next part. Chapter 5, will discuss them in more details and represent how to make them consistent with problems of supply network.

- **Rectangular distribution**

If the probability of events falling within an interval is consistent with interval length, with inevitable location in the interval, it is followed by the continuous uniform distribution or rectangular distribution (Montgomery & Runger, 2010).

- **Triangular distribution**

If the probability of events in a point between interval to be more than other points with zero probability of its occurrence outside of this interval, the event is based on triangular distribution (Montgomery & Runger, 2010).

- **Normal distribution**

One of the most important statistical distributions is a normal distribution, which has many applications, and most events in nature are following this distribution. The main reason for this phenomenon is the role of normal distribution in the central limit theorem (Montgomery & Runger, 2010). “*The central limit theorem is a statistical theory that states that given a sufficiently large sample size from a population with a finite level of variance, the mean of all samples from the same population will be approximately equal to the mean of the population. Furthermore, all of the samples will follow an approximate normal distribution pattern, with all variances being approximately equal to the variance of the population divided by each sample's size* (Machkouri, et al., 2013)”. Therefore, most researchers in dealing with unknown distributions try to

increase statistical population to use the normal distribution for providing estimations. The probability function of this distribution has two parameters that determine the location and scale of distribution. Moreover, the mean of this distribution equals with location parameter, and its dispersion equals with scale parameter. The probability function curve is symmetric around the distribution mean. Also, because of the form of the probability function of this distribution, it is also known as a bell curve (bell-shaped) (Montgomery & Runger, 2010). The probability density function of the random distribution is single mode, and its peak located at it's the mean point. The median and mean of this distribution are similar.

- **Exponential distribution**

Considering the duration of a probable event, the event can be estimated by an exponential distribution. Among the applications of the exponential distribution, is in the theory of queues and waiting times for getting service (Montgomery & Runger, 2010). Information related to calculations of this distribution is given in the section 5.2.

- **Gamma distribution**

Gamma distribution is one of the continuous probability distributions with two scale parameter of " θ ", and shape parameter of " s ". If " s " to be considered as a natural number, then the gamma distribution is equal to the sum of " s " random variable, with exponential distribution of " $1/\theta$ ", parameter. Unlike, normal distribution function, this distribution function is not symmetric and its interval starts from zero and goes to infinity (Montgomery & Runger, 2010).

3.8 The gap in the literature review

According to guidelines of Project Management Institute entitled "a guide to the project management body of knowledge" in 2009, six steps should to be taken to manage uncertainty properly in order to claim that uncertainty of supply network has been controlled. The six steps are given in figure 3-8.

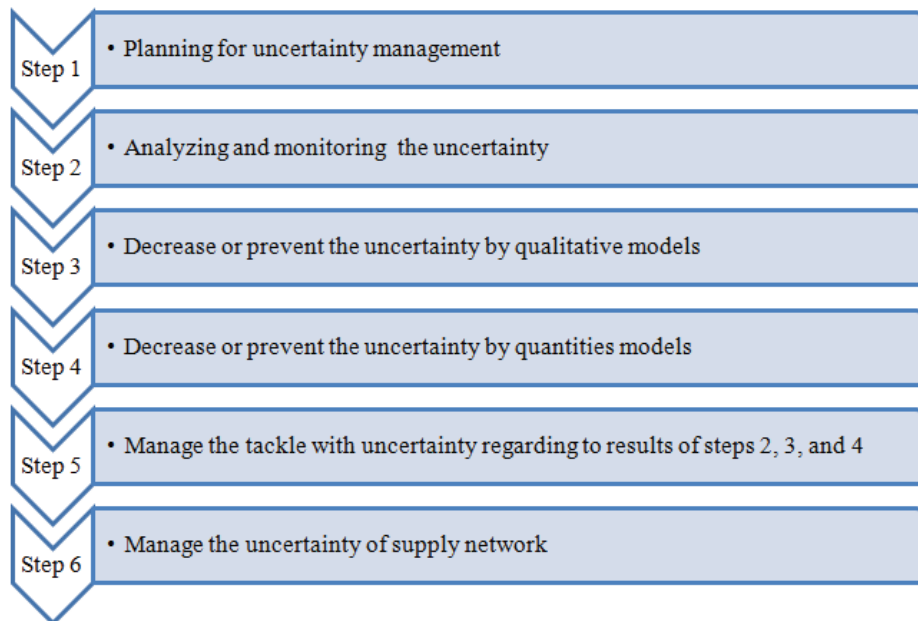


Figure 3-8: Managing the uncertainty process (Institute standards committee, 2009)

According to what presented in the literature, many researchers focus on providing quantitative and qualitative models in order to reduce the uncertainty, but as shown in figure 3-8, providing models to reduce uncertainty are in stages 3 and 4. Therefore, for targeted management of uncertainty first, it should determine the place of reducing the uncertainty, or find those members of the network which have higher influence on the delivery time uncertainty. Next, preventive or reduction models can be provided. In other words, initially model performance should be located followed by reducing models designed based on the location.

After extensive study of the literature related to the uncertainty of supply networks, a missing part was found, i.e., lack of adequate research sources to identify and monitor uncertainty before implementation of the reducing models as a prerequisite of this model. Monitoring and analysis of uncertainty in supply networks are considered as a tool to reduce and prevent the uncertainty, which increases productivity and causes a greater impact on the overall activity of the network along with saving much time and money.

Another issue that needs to be mentioned at the end of this chapter is increased tendency of companies to join the dynamic supply network due to the increasing competitiveness (dynamic supply network will be investigated in details in chapter 4). Variations in customer demands and manager's tendency to customer satisfaction, caused network managers to use supply networks with dynamic structure in order to reduce production costs and increased flexibility (Ari-Pekka & Antti, 2005). High accuracy and rapid response are becoming the most important features of models in such dynamic networks in short-term projects. Most current supply network models are time-consuming (established based on continual improvement), and using continual improvement is

impossible (due to the short-term structure of the networks and projects). Therefore, new methods with mentioned abilities should be provided for them. According to the importance of time in such networks, this study focuses on analyzing and monitoring the delivery time uncertainty. The next chapter describes a more detailed investigation of the study problem and its motivational factors.

3.9 Summary

Uncertainty of supply networks is one of the management challenges, which is mentioned in chapter 2. It is impossible to manage the supply networks without a proper strategy to deal with the uncertainty of the network (Arshinder, et al., 2011). For this reason, and because of the uncertainty as a key term in this study, this chapter presents and interprets this issue in the best possible way.

Considering the definition of uncertainty, we found very close meaning of two terms of uncertainty and error. For this reason, a number of researchers in their studies, sometimes mistakenly use the word error as uncertainty. Therefore, this chapter was started with different definitions of uncertainty and error. Then uncertainty in supply networks was investigated, as the main objective of this thesis. After the definitions provided in the literature on uncertainty, sources of uncertainty were identified and classified. Next, studies and models of uncertainty were classified in two qualitative and quantitative groups that some important examples of them were represented. In the next step, quantitative models as a part of the uncertainty model were analyzed and their advantages and limitations introduced. After that, by a summary of the obtained results of the literature, this study investigated all mathematical and quantitative methods of defining uncertainty and reasons for choosing probability density function method. Then, the reason for their selection were described, followed by a brief description of some of the most common probability density functions.

At the end of this chapter, gaps in the literature were represented to create a bridge to the following analysis. As mentioned in chapter 3, a study of the research's literature revealed that most studies had focused on offering strategies to reduce uncertainty. Therefore, lack of a methodology to determine the place of using of the reducing uncertainty, find those members of the network, which have higher influence on the delivery time uncertainty and calculation of accumulated delivery time uncertainty in the networks are some existed gaps in this field which in this research is trying to fill these gaps.

4 CHAPTER 4 – Dynamic and complex supply networks: Delivery time and uncertainty challenges

Nowadays, supplying a variety of products according to the customers' expectations is recognized to one of the critical issues for survival in competitive markets. On the other hand, company's inclination towards participation in supply networks in order to keep or improve competitive capabilities has increased the role of managers in performance evaluations. Due to the importance of the subject, various research has been conducted to evaluate the performance of supply networks by managers, and they have used different qualitative and quantitative criteria like on-time delivery, rate of inventory shortage, rate of order fulfillment, manufacturing flexibility, costs of network managing and the net asset value (Cetinkaya, et al., 2006; Gregor & Hartmut, 2005).

The main aim of this chapter is to present and elucidate/elaborate the research subject in detail and express the motivation of the researcher for performing the investigation. Hence, by introducing dynamic supply networks and expressing the importance and necessity of analysis and monitoring of delivery time uncertainty, the motivation behind this research is shown. Due to the necessity to synchronize the readers' and the researcher's perspective, the supply networks and different structures from the author's point of view are described in the next section. In this regard, the basic networks that are the primary structures of all supply networks are introduced. It will then be shown, how the structures of the complex networks will be created based on them.

The research subject is fully introduced in section 4.4. Regarding the developed mathematical solution, the author found it necessary to introduce some mathematical definitions of the specified subject in section 4.5. Finally, the expected features, which a method or methodology must have to solve the research question are developed to create a link to the next chapter.

4.1 Dynamic supply networks

Today managers and researchers have discovered the importance of the role of supply networks in creating merits for production companies. Generally, a supply network is considered as the cooperation of suppliers and producers to actualize the final product and service.

Strategic planning in supply networks in order to take advantage of today's market opportunities is becoming more and more short-term. Customers' expectations are also getting more diverse and dynamic. Therefore, it is a necessity to create the supply network due to the specific market opportunity and customer expectation (Ari-Pekka & Antti, 2005). Consequently, the structure of supply networks is continually changing and hence they should be designed dynamically. The aim for this short-term and dynamic planning is to achieve certain and reliable ways to respond to every single customer's order. In this situation it is impossible for supply networks to achieve the targets with fixed

structures and definite members. Furthermore, due to the quick changes in customers' expectations and their request for various products in shortest time, achieving success in today's time oriented, competitive market is impossible with continuous improvement of traditional networks with fixed structures. Hence it is essential to add some features to the decision taking methods which were previously applied in those traditional networks (Ivanov & Sokolov, 2012).

Speed and accuracy are the main and inseparable elements of such methods in dynamic supply networks. Thus, evaluation potentials in shortest time and with suitable responding and quality are considered to be among the important characteristics of these methods. The results obtained from the methods designed for fixed networks, caused to create some information that is neither correct nor appropriately precise (Li & Chan, 2013). Clearly, managers need the tools and methods for their major decisions that could ensure the ability to provide high speed and accurate information. Also, these methods should have high conformity to today's dynamic environment. Hence, creating such tools and techniques in today's dynamic supply networks has been transformed into one of the most vital studies that has occupied a lot of researchers in that field (Ivanov & Sokolov, 2012; Liu & Brookfield, 2000).

As stated before, due to the fact that customers relish variety, supply networks require the creation of a short-term structures for satisfaction of each customer. In other words, project structures are created product specifically. Hence, the network structure is continuously changing. Consequently, such kinds of supply networks are called “**Dynamic supply networks**” (Humphries & Mena, 2012; Ivanov & Sokolov, 2012; Ivanov, et al., 2010; Fritz & Schiefer, 2002). The purpose of these dynamic networks is obtaining satisfaction of customers having different orders, in a permissible time frame. As the name "supply network" defines, it is consisting of a group of suppliers and manufacturers, which are carrying out their activities besides each other to reach a common objective. The main factory (OEM), takes the orders from the customers, selects the suppliers required and designs the configuration of the supply network, especially for the purpose (Ari-Pekka & Antti, 2005). In the next section, the importance of delivery time in dynamic supply networks and the necessity of controlling and monitoring delivery time uncertainty will be discussed.

4.2 The importance of monitoring and controlling delivery time uncertainty

Mainly speaking about supply networks, we will undoubtedly face "outsourcing" of activities as one of the main specifications in the supply network. Outsourcing means giving a part or all of the activities within the production processes of a product to the suppliers and manufactures selected by the OEM, and it is one of the features of supply networks (Liu & Nagurney, 2013). Despite all the advantages that outsourcing has, it is one of the elements creating uncertainty in supply networks. Moreover, with increasing complexity

and number of members within supply networks, the rate of uncertainty increases as well. One of the inevitable effects of this source of uncertainty is on the delivery time (Liu & Nagurney, 2011).

Time is quite important in delivery performance of supply networks in today's competitive markets. The delivery process and time related is one of the known processes (plan, source, make, deliver, and return) in supply chain operations reference-model (SCOR) (Stephens, 2001). The delivery time in a supply network can be specified as the time spent from receiving the customer's order up to the moment of delivering what was ordered to him. This time is the result of combining some internal delivery times (production and process) and external delivery times (distribution and transportation) for any of the network members at different levels (Bushuev & Guiffrida, 2012).

Delivery with the least uncertainty (under best conditions, on-time delivery) is one of the customers' and managers' main concerns. Moreover, lots of studies have expressed the point that reducing uncertainty within delivery time plays a key role in the general performance of the network (da Silveira & Arkader, 2007; Iyer, et al., 2004; Salvador, et al., 2001). Nowadays, researchers believe that the importance of analyzing the process of delivery and time has three main reasons.

The first and main reason is related to creating the competitive advantage that researchers such as Porter (1980) and Stalk (1988) have dealt with as one of the main keys to success in today's business market. The second motivation of researchers lays in the importance of customer satisfaction, as one of the key principles of success in supply networks (Fan, 2011). And finally the last reason is related to the importance of evaluating and measuring the performance of a supply network and its relations to the reliability of the delivery performance (Whicker, et al., 2009; Gunasekaran, et al., 2004). For instance, the analysis of the delivery time performance and selection of the suppliers could be pointed on the general performance of the supply network (Shin, et al., 2009) or analyzing the control systems and production planning on the delivery time performance (Lane & Szwejczewski, 2000) are some cases of it.

Speed and accuracy on delivery time, cost and quality, are the fundamental specifications of today's competitive market. Organizations should have the ability to arrange for customer requests within the shortest delivery time with appropriate price and quality. The rate of the work in process, delay in delivery, rate of the backlog, increase in total cost, are all results of uncertainty in the supply network (Alkhatib, et al., 2013). Finding solutions to these problems is one of the concerns of a supply network and its members. Designing and organizing the structure and proper relationships among the members of the supply network, identifying the most efficient members, with the highest effective factors and using appropriate members, have great effects in reducing the uncertainty (Safaei, et al., 2013).

Regarding the recognized dynamic networks' definition and the importance of fast response by them, the existence of uncertainty during the delivery time

and finding of rapid ways to determine its rates and even controlling it has concerned the network managers. Relevant research is conducted by Hnaïen et al. (2010) and Richardson & Domingos (2006).

Timely delivery of tasks and activities of the network, have always had special and important direct consequences such as earning customer loyalty, increasing the market share, acquiring new customers, victory over competitors, increase in customer satisfaction and obtaining the confidence of public communities. It also indirectly affects increasing the production, boost up productivity, increasing income and financial profits, reducing project risks (failure, fines, delays, transport costs, costs for untimely deliveries such as storage and shortage costs). Hence, the most important part of the supply network literature has indicated that extensive research has been conducted in that field (Huang, et al., 2005; Gustafson, et al., 2004).

Due to differences in requirements and diversification of products requested by customers, companies and suppliers are always looking for definition of products with higher life cycle, guaranteed and high quality. In a research by Asgari and Farahani (2008), the importance of being on-time is clearly indicated. For instance, in their research they found, in case of possibilities for a buyer not to consider on-time delivery but to pay attention to increasing the savings of the network, what should be the total difference to being on-time? To answer the question, a curve with the time difference to on-time delivery against the obtained savings costs has been drawn, that is shown in the figure 4-1. As it can be observed by this graph, with increasing the difference from on-time delivery, the total costs for the network are increased. So it can be concluded that being "on-time" is a very important factor and that deviation from it is by no means recommended (Asgari & Farahani, 2008).

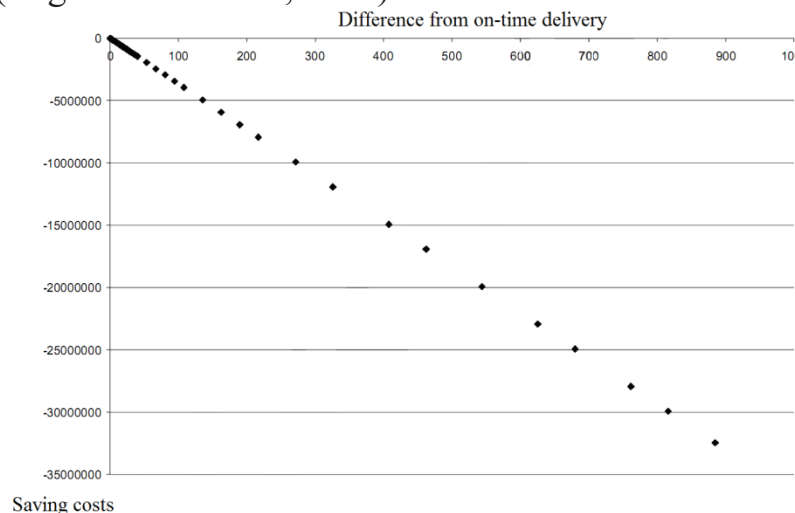


Figure 4-1: Percentage of deviation from on-time delivery against saving costs in the whole supply network (Asgari & Farahani, 2008)

Similar results can be picked up from the research of Karpak et al. and Stadtler & Kilger (Stadtler & Kilger, 2005; Karpak, et al., 2001). These analyses indicate the importance of "on-time delivery" well. The importance remains,

even if the costs for fluctuations from on-time delivery, including delays or earlier deliveries that appear as storage or shortage costs, are low. Hence, if the optimization of the integrated network is considered, "on-time delivery" should not be ignored, and it is considered as the first and most important element of measuring the performance of networks.

Despite the very important aspect of "on-time delivery", we can see that on-time delivery does not occur in a lot of cases. It has for example, in the report prepared by Rogerson -the strategic manager of Object Watch Company- been shown that 30% of the projects are cancelled before finishing and the corresponding cost, time and labor is diminished or wasted. Due to incorrect estimation for the delivery time and costs, the rest of the projects are often facing failures (Demeulemeester & Herroelen, 2002).

Furthermore, another research that was done by Assaf (2006) on 57 network suppliers, found that 76% of them had delays between 10-30% as compared to the allocated delivery times. He also found that 45 projects out of 76 supply network projects had faced delays in a year, and that 10-30% of delays of suppliers had caused 70% of delay in all projects within a supply network (Assaf & Al-Hejji, 2006).

Due to the given statements about the importance in preventing delays in projects and production orders and the importance of speed and accuracy in delivery times in today's dynamic networks and instability of production networks, the need to review the methods for calculating uncertain delivery time resulting from the production networks has increased. Thus, to reach the assured delivery in supply networks, we require new techniques that can calculate the rate of uncertainty in delivery time for each network with a certain speed and accuracy. The relevant information should be provided to the network managers, to support them in decision making.

4.3 Structure of supply networks and complex supply networks

As mentioned in the paper which is extracted from this thesis (Safaei, et al., 2014):

In general, a supply network consists of two or more organizations that are legally separated and are related to each other by material flows, information and financial flows. These organizations can be the agencies that produce the raw materials, components, finished products, or services such as distribution, storage, wholesale and retail. Even the final consumer can be considered as one of these organizations (Knight & Harland, 2005).

supply networks encompasses a mass of nodes and complex sub-networks involving lateral links, reverse loops, and bi-directional exchanges, and include a broad strategic view of resource acquisition, development, management, and transformation (Harland, et al., 2001). In literature various classifications of supply networks' types have been introduced, but the structure of the networks in the generic form is discussed in this section. Simply said, a supply network can be described by nodes, which represent the companies and the edges

(relationships) between these nodes. From this perspective, a network's type can be represented as a structure that shows how different nodes are linked with each other. Basic structures of related nodes have to be recognized and fundamental types are introduced in figure 4-2.

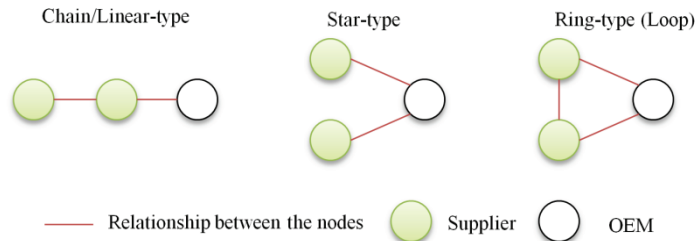


Figure 4-2: Basic network types (Pathak, et al., 2007; Thoben & Jagdev, 2001)

In figure 4-2, the simplest topology is the linear-type, in which the partners' interaction pattern mainly follows a chain. The maximum number of input and output degree for any node (firm) in this network is one. Here multiple tiers are possible, but every firm has at most one predecessor and one successor or either of them. In this type only a progressive process can be accomplished. The second topology is star-type that consists of at least three firms of which just one is directly connected to the rest (Liu & Brookfield, 2000). In the star topology all suppliers interact with one central node, called OEM. In this type, only the OEM is supplied by the rest of the nodes as suppliers. The maximum depth layer of the star is one, and it includes a single tier. The best example of this network type is eBay (Pathak, et al., 2007). The third topology is a ring-type that includes at least three nodes, each with exactly two edges. Each node has a direct relationship with its neighbor nodes. In the ring-type, every firm simultaneously plays multiple roles, and they can share some resources with each other. As Pathak (2007) expressed, this is found frequently in the defense supply industry where a firm can simultaneously compete, cooperate, be supplied by and be a supplier to another firm. In this research, supply networks are considered as networks with an OEM and its suppliers.

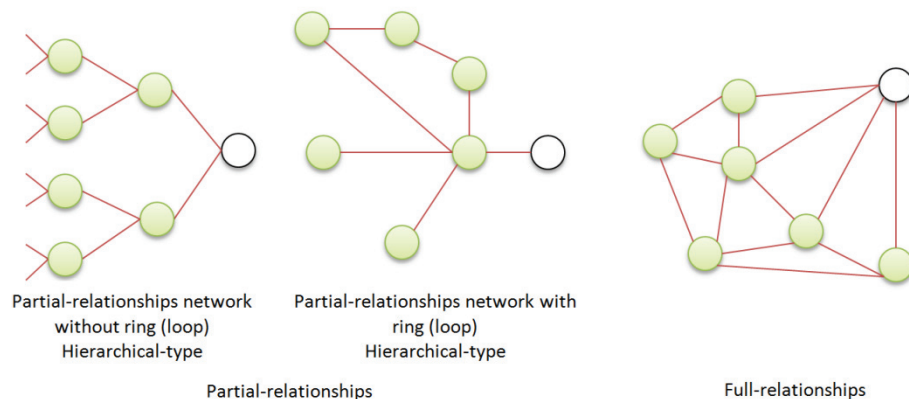


Figure 4-3: Complex network types (Boccaletti, et al., 2006)

As a matter of fact every type of network is a combination of one or more basic networks introduced above. The most famous complex networks include

the partial-relationship networks, and the full-relationship networks. The partial-relationship networks are the most prevalent and assumed as normal structure for supply networks. Sometimes, when there is no loop within the network, it becomes much like the star topology except that it does not use a central node and it is a kind of directed acyclic graph (DAG) (Imani & Sarbazi-Azad, 2010). Moreover, the partial-relationships topology is a combination of several stars and rings in a network which in those cases when there is no ring-type (loop) inside, are called hierarchical-type. The goods' flow is generally from downstream to upstream towards the OEM. Automobile industries and most assembly firms are the best example of the hierarchical-type (Pathak, et al., 2007). In generalized-type complex interactions between nodes are configured and we called them full-relationship networks. The full-relationship network connects every single node and OEM may take the place of each node. The maximum of relationships (edges) in this network can be calculated by $(n \times (n-1))/2$ in case the network is fully connected (n is the number of nodes) (Gross, 2003).

Accordingly, complex networks can be configured from a combination of several basic or conventional networks. In the other words, the conventional networks, as introduced above, can be individually complex or in combined forms. As Zhao et al. defined, those networks with irregular, intrinsic, and dynamically evolving in time structures can be considered as complex (Zhao, et al., 2011).

In other words, the complexity in networks can be divided into two dimensions:

Structural complexity: investigating the structure of networks, including the number of members and the amount of basic networks which created this complex structure.

Operational complexity: Investigating the dynamic logistics of collaboration networks, including the degree of connection and the degrees of predictability and uncertainty within the system. A known and unchanged supply network structure is used to analyze the relationship between those dimensions and the uncertainty of dynamic logistics or information flow of the supply network, which managers can refer to to manage supply chain (Cheng, et al., 2013).

Each complex network is created from the combination of several basic network types shown in figure 4-2. The degree of complexity in a network depends on the number of members, and number of basic network types, participating to create it. As mentioned before in chapter 3, the complexity in the network is one of the sources creating uncertainty in supply networks.

This subject will be followed in the next chapter with some examples of supply networks provided with two, three and four nodes and specification of the direction of each relationship and link. The author will thereby deal with classifications derived from the basic supply networks in six categories. Also by

giving some examples, it will be shown how complex networks are created from combining basic networks.

4.4 Delivery time uncertainty in complex supply networks

The complex and dynamic nature of supply networks imposes a high rate of uncertainty to the final delivery times of the networks, considerably affecting the total performance of the networks. Clearly, the affecting rate of the uncertainty on major decisions such as designing the network is relatively larger than the decisions of minor levels (Pishvaei, et al., 2009).

According to the literature of Chapter 3, the uncertainty in delivery time can be classified into two main categories as follows (Mula, et al., 2007; Mula, et al., 2006):

First category: Uncertainty of delivery time occurring randomly (Randomness delivery time uncertainty).

Second category: Epistemic delivery time uncertainty or the knowledge that we face due to lack of information about the data required.

Simultaneously, the uncertainty of delivery time in the dynamic supply network can be classified into two categories of another dimension (Klibi, et al., 2010) as follows:

First category: "Business-as-usual uncertainty" that includes normal uncertainties in delivery times, demands and supplies.

Second category: uncertainty with little possibility to occur but with high effect that is interpreted as "disaster". This type of uncertainty is either due to natural disasters such as earthquakes and tornados, or due to unexpected events like electric cut-off.

By combining the two point of views about the nature of the delivery time uncertainty, different conditions can be shown as a matrix such as in figure 4-4.

Randomness uncertainty in delivery time	a	d
Epistemic uncertainty in delivery time	b	c
	Business-as-usual uncertainty in delivery time	Disaster uncertainty in delivery time

Figure 4-4:The nature of delivery time uncertainty in dynamic supply networks

According to figure 4-4, there are four different types of conditions for delivery time uncertainty in dynamic supply networks. However, a review on literature and the logic of uncertainty in critical states shows that the 4th state that is practically a combination of the randomness and disaster states revealed a vague situation. This is due to the disorders that have no regular historical data and the probability distribution functions for them not having suitability. Now the existence of uncertainties in delivery time with the state "a", "b" and "c" are considered as the main factors of delays in orders and network services.

Today, supply networks are specialized in their products, and every particular component requires its own supply network. On this basis, synchronization of delivery times between members in such a dynamic network is crucial. In other words, delivery times of each particular product and its uncertainty definition plays a decisive role (Kevin Weng & McClurg, 2003).

Generally, in our study delivery time in supply networks can be described as the time estimated by suppliers to deliver their products to (internal/external) customer. According to Janat Shah (2009), “delivery time is the time taken by supply network to complete all the activities from order to delivery. This dimension of customer service has a significant impact on the way a supply network is designed and operated.” (Shah, 2009). The importance of delivery time as a strategic “weapon” has been recognized in the arena of global competition (Christopher, 2000; Lerder, 1997). Thus, many manufacturers are adopting the use of delivery-time guarantees as part of their market positioning strategy (Urban, 2009).

Generally, industrial supply networks have a direction of material flow as well as a direction for information flow. By taking into account the importance of delivery time uncertainty, the direction of physical material flow has to be considered for recognition and analysis of delivery time uncertainty. Nevertheless, in the following methodology, information flow in the process is essential.

Moreover, outsourcing in supply networks creates a new source of uncertainty in delivery time affecting the final node in the network. This uncertainty creates impact on supply network performance by influencing the delivery time reliability (Vanany, et al., 2009).

Basically, delivery time uncertainty of a supply network is recognized by aggregation of the individual delivery time uncertainties of the members in the network. Indeed, to be able to estimate delivery time uncertainty of the entire supply network, the influence of these individual uncertainties on the total uncertainty level has to be understood. However, the way how the individual uncertainties need to be accumulated depends on the network type and the relationship between the constituents of that (Guiffrida & Jaber, 2008). As mentioned before, supply networks are constituted of suppliers, manufacturers, distribution centers (Persson, 2011). However, in this study the nodes within a network are classified in three modes: beginner node(s), intermediate node(s), and the final node (OEM). The beginner node(s) are those which have no predecessor and may be more than one, the intermediate node(s) are those nodes with both predecessor and successor, and the final node is the only node of the network which has no successor and terminates the flow of material.

The knowledge about the interdependency between a network type and the accumulation of the individual uncertainties is essential to identify those parts of the network, which have the highest potential for improving the total delivery time uncertainty.

The problem addressed in this thesis is to identify how much uncertainty is transferred from the suppliers to the manufacturer. The aim is to find a methodology to accumulate the uncertainties of individual suppliers and finally to understand the influence of the network type on this accumulation.

For estimating delivery time uncertainty of the entire supply network, the impact of individual suppliers' uncertainties on the overall network's uncertainty must be understood. In doing so, for each node its confidence interval and confidence coefficient have to be estimated.

4.5 Mathematical definition of delivery time uncertainty

From the author's point of view, it is necessary to have a mathematical and a schematic definition of delivery time uncertainty, before considering the method of solutions. An example of a mathematical and schematic definition of delivery time uncertainty for a normal probability distribution (to be introduced in section 5.1) is brought in figure 4-5.

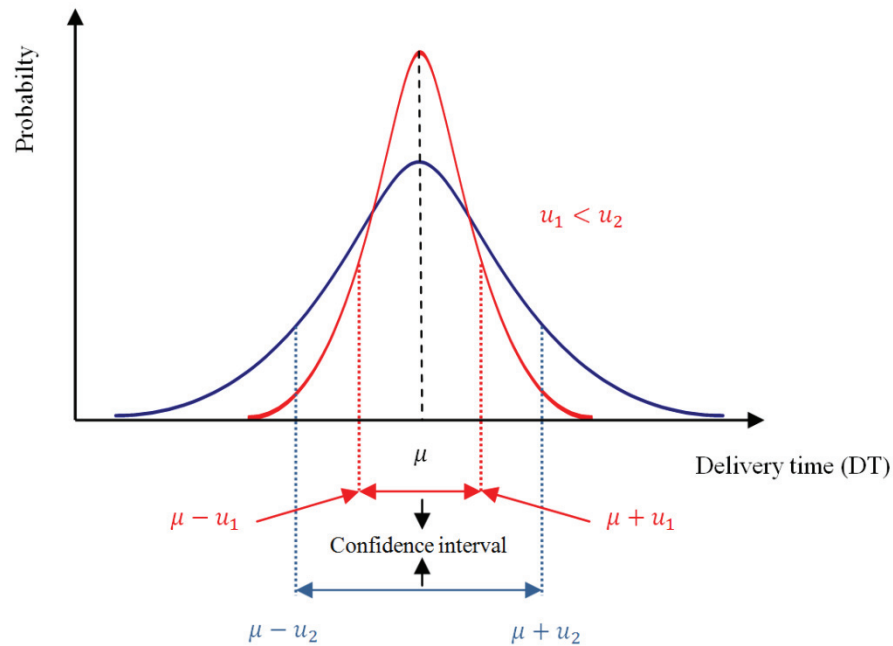


Figure 4- 5: A sample of mathematical definition of delivery time uncertainty and its parameters for normal probability density function

For better understanding the delivery time; first of all, a brief description of used mathematical symbols and parameters in figure 4-5 is provided. Then the definition of delivery time uncertainty is expressed.

The horizontal axis in figure 4-5, presents the delivery time and the vertical axis shows the probability of delivery for each specific time. In this figure, simultaneously, two behavioral examples of uncertainty in delivery time (red and blue curves) are compared. Both of them have a similar delivery time mean " μ ". The main difference of them is in the interval time frame, which is derived from the different uncertainties in the delivery time. The red curve has " u_1 " uncertainty and blue curve has " u_2 ". As it is mentioned, on the figure 4-5, the

uncertainty of the red curve is less than that of the blue curve. This is why the behavioral curve of the delivery time of the red curve, is towards the mean line, and it is going upwards at the mean point. The integral (the surface under each curve) of the probability curves is equal “1”.

Two mathematical parameters for defining the uncertainty in delivery time are required, which will be discussed in detail in the next chapter. The first parameter is the "confidence interval" that is referred to the interval and the time frame between the two dotted red lines for the red curve and two dotted blue lines for the blue curve. The total area under the curve between the determined confidence interval is called "confidence coefficient". It has been tried for the curves that the confidence intervals to be shown in both conditions have equal confidence coefficients in both states, to show how we could observe the improvement for the time frame of the delivery time with equal probability or even better probability.

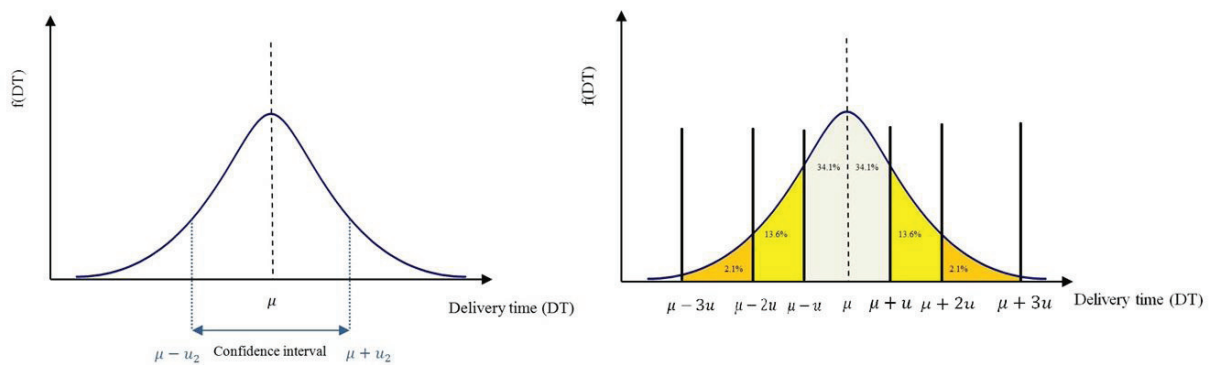


Figure 4- 6: Confidence interval and confidence coefficient

The confidence interval on the left side of the figure 4-6, introduces the confidence interval which is the time frame, that a supply network is able to deliver a certain percentage of orders. The confidence coefficient introduced on the right side of the figure represents the percentage of orders which are delivered within the confidence interval.

Overall, a delivery time and its uncertainty are defined by two confidence interval parameters that indicate the time frame within which a supplier could deliver the orders and a confidence coefficient, which shows the rate of the certainty of supply network for delivery in the defined time frame. Additionally, the delivery time of each order introduced by an interval and a probability of delivery in this interval, then, in consequence, the delivery time uncertainty can be defined as the combination of the confidence interval with the related confidence coefficient. The time related objective of planning and controlling strategies in supply networks is to reach a low level of delivery time uncertainty of the entire network - in other words, to reach a low confidence interval in combination with a high confidence coefficient.

4.6 Features of expected method

Lots of efforts have been done by researchers regarding on-time delivery of a project or products in the supply network, and each researcher has dealt with expressing his/her own views in that field. As stated in the previous chapter, there are four quantitative methods all together for coping with and decreasing the uncertainty that have been developed by researchers, which include:

- Mathematical models
- Models derived from artificial intelligence
- Simulation models
- Hybrid models

Nevertheless, the basis for all of these methods is calculation, analysis, and monitoring of the rate of uncertainty in the supply network. There is no possibility to have proper strategic decisions for the uncertainties without calculating the uncertainties in the network. These methods have a possibility to consider uncertainty regarding one of three measurable natures of uncertainty (see figure 4-4). Hence, proposing a method that can calculate uncertainty in supply networks by considering all three measurable natures of uncertainty is quite another gap.

Due to the importance of speed and accuracy in the dynamic supply networks, the need for reviewing old methods (methods, which are applied in the fixed and traditional supply networks to support managers in decision making) seems to be necessary as well. Hence, to reach highly reliable delivery in dynamic supply networks and increased efficiency of the methods for decreasing uncertainty, we need new ways that have the ability to calculate network-based uncertainty (due to the dynamism of the network structures). Moreover, they must have an ability to measure uncertainty with all three natures in a great speed and proper accuracy. The information obtained from this adapted method with dynamic networks could be helpful as a supporting tool, for the network managers in making appropriate decisions, having better recognition of network performances in delivery and creating a reliable delivery time frame. Thus the simplicity of using this method in the real world, to be understandable, is another characteristic, which we are following. A hybrid methodology will be presented in the next chapter for calculation and monitoring of the uncertainty of dynamic networks with the revealed specifications.

4.7 Summary

By defining the dynamic networks and their characteristics, the necessity of on-time delivery with high certainty was first pointed out in this chapter. It was also tried by introducing general basic networks and complex networks definitions to synchronize the views of readers for better understanding of the supply networks. The author then deepened the research subject. Two questions were considered within the section related to describing the research subject. The first question was related to the calculation of delivery time uncertainty in

dynamic supply networks. Subsequently, the second one looked at finding suppliers who have high influence in the supply network uncertainty. Then, since the aim of this research is to provide a hybrid quantitative methodology, it was necessary to introduce the mathematical parameters briefly that are used for defining the delivery time and its uncertainty. In other words, the mathematical definition of uncertainty for the delivery time was expressed in this section from the viewpoint of the author. To help simplicity and better understanding of the definitions and their schematic views, the normal probability density function diagram (as an example) was used. At the end, we dealt with introducing and stating the features of a method necessary to solve the research problem.

In the next chapter, we will propose a hybrid methodology according to the features which are discussed in the chapter 4. This methodology will be able to calculate the accumulated delivery time uncertainty. Furthermore, by this methodology networks managers will have a possibility to find the place of applying the reduce uncertainty strategies (which are presented in the chapter 3). Therefore, it will cause to save time and increase the productivity of the performance of these strategies by introducing the best places to be run.

5 CHAPTER 5 – A hybrid methodology for delivery time uncertainty in dynamic supply networks

As shortly stated before, the introduced methodology for recognizing and analysis of delivery time uncertainty in supply networks is a hybrid procedure formed from three individual statistical tools and techniques. The PERT is a technique for simplifying complex networks by defining their critical path according to delivery time uncertainty. The GUM is a mathematical tool for calculating an aggregated uncertainty in an entity out of several sources of uncertainties in a system. The Monte Carlo Method can be used as a simulation mean to model and calculate uncertain systems (Calvet, et al., 2010). Furthermore, a combination of these three techniques is favorably developed to be adapted for solving complex supply networks. However, this combined framework offers two alternative combinations encountering alternative uncertainty distributions within a network. If it is ensured that all distributions follow the normal distribution, the framework employs the combination of PERT and GUM as the developed solving tool. Nevertheless, if alternative distributions other than normal are recognized in the network, then the combination of PERT and Monte Carlo Method has to be applied.

In this chapter, due to extensive usage of probability density function in the adapted methods of PERT, GUM and Monte Carlo Method, we first provide a brief description of five distribution functions that have more applicability as compared to other distributions. It has been tried in this part to use the interpreting literature of the distributions in accordance with the research subject and the type of distribution behavior to be interpreted according to the suppliers of a supply network. Then, to simplify and make the networks conform for calculation of PERT model, different basic types of production networks are defined and the simplification techniques of them are analyzed. In the next section, it has been tried to adapt the PERT method to the research problem. The descriptions regarding the use of the adapted GUM follow. In the next section, the Monte Carlo Method model is designed for the indicated case and in the end, the final hybrid methodology is presented.

5.1 Probability density function

The future could be regarded as the uncertainty domain. Thus, considering the main difference between past and future, different methods should be used for evaluating and modeling each one. Due to lack of independence of future from the past and countless effects of past events on the future, we find that inspired from past events, more or less accurate forecasts can be made for future events, if and only if the past is considered thoroughly (van Collani, 2008). As one of the characteristics of probability density functions, they can estimate the behavioral function of the delivery time of a supplier in a project regarding to the delivery times of past similar projects. Moreover, another characteristic of

probability density functions is the defined standard formulas to calculate the mean and standard deviation of each of them. In this research, we are using the standard deviation of probability density functions as the standard uncertainty of delivery time. Due to these characteristics they could be used as one of the statistical methods to define uncertainty of future events inspired by past occurrences, we are going to deal with the states and adaptation of probability density function's used in the calculation of uncertainties. Noteworthy, the related methodology could identify “65” cases of the existing probability density functions in the real life, and we have dealt in this section with introducing five examples of the most important probability density functions. In case the probability density functions, related to the calculated results of accumulated uncertainties, which are not conform with this five examples, complementary descriptions about the relevant probability density functions are shown in the appendix.

5.1.1 Adapted probability density functions

As stated before, the rate of delivery time uncertainty in the supply network depends on factors such as individual uncertainties of delivery times of the network suppliers. To estimate the delivery time uncertainty, it is first necessary to determine the standard delivery time uncertainty of each of the suppliers, and subsequently, by combining them according to the structure of the supply network, to calculate the final uncertainty of delivery time from suppliers to the OEM.

For estimating uncertainty, it is essential first to gain acquaintance of statistical distributions and calculation of statistical parameters such as mean, standard deviation, and standard uncertainty. Hence, regarding the most common probability density functions, which were introduced in chapter 3, we deal in this section, with adaptation of the formulas and probability density functions definitions for calculation of uncertainty in the supply network.

Meanwhile, it has been tried to avoid mathematical formulas in this section as much as possible, but we have pointed to the brief equations required for calculating delivery time uncertainty. It is noticeable that all the definitions in this section are based on the Montgomery books entitled “Applied statistics and probability for engineers” and “Introduction to statistical quality control”, with little modification (Montgomery & Runger, 2010; Montgomery, 2008). Subsequently, we are going to introduce the conformed probability density functions:

○ Rectangular distribution

This statistical distribution is applicable in many of the uncertainties evaluations. If it is likely to distinguish the upper bound “b” days and the lower bound “a” days, for the delivery time of the supplier, and in case it can be claimed that the probability for the delivery time of the supplier from “a” to “b” is 100% and the possibility of being out of the interval is zero, it may be used. Therefore, selecting the rectangular probability density function for the delivery

time of the supplier is an appropriate choice. Likewise, if no adequate knowledge and information exists for the probabilistic values of the delivery time between the lower and upper limits, the best estimation is rectangular distribution. In other words, if a supplier defines a time frame for the delivery time of an order and there is the fixed and equal possibility of delivering the goods on each day during this time frame, the delivery time of the supplier obeys rectangular (Uniform) distribution. The introductory symbol of the distribution is $U(a,b)$. The diagram related to this distribution is shown in figure 5-1.

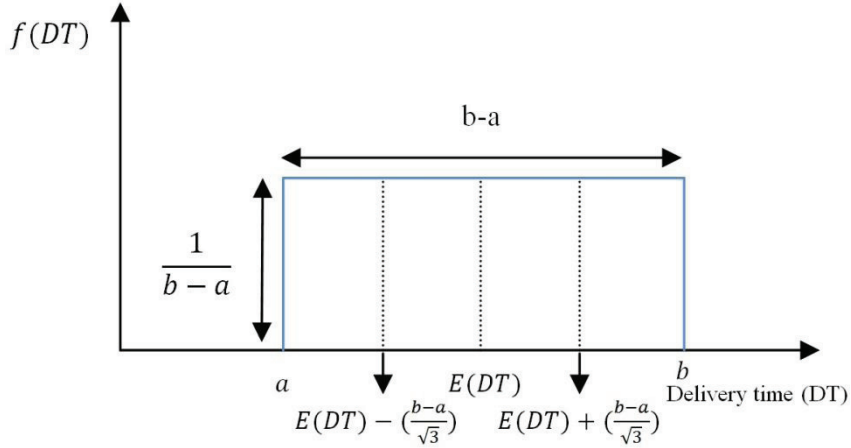


Figure 5-1: Rectangular distribution (Montgomery & Runger, 2010)

The related probability density function to this distribution is:

$$f(DT) = \begin{cases} 1/b - a & , \quad a \leq DT \leq b \\ 0 & , \quad \text{Otherwise} \end{cases} \quad 5-1$$

Where the mean of delivery time is exposed by $E(DT)$ as an expected value of delivery time, $f(DT)$ is the value of the probability density function per delivery time of the supply network and the variance of delivery time is demonstrated by u^2 . Equations 5-2 and 5-3, are the mean and variance formulas for the suppliers the probability density function of delivery time of which follows the rectangular distribution.

$$E(DT) = \frac{(a + b)}{2} \quad 5-2$$

$$u^2 = \frac{(b - a)^2}{12} \quad 5-3$$

○ Triangular distribution

Like the rectangular distribution, the triangular distribution is functional in many evaluations of uncertainties. Similar to rectangular distribution, this distribution is considered as a continuous distribution.

In case of estimating the upper bound “b” (days) and the lower bound “a” (days) for the delivery time of the supplier, if it could be assumed that it is more likely to deliver at the “ c^{th} ” day (absolutely laying between the specified time frame between “a” and “b”), and the probability of zero to be out of the time

frame, selecting triangular distribution to model the supplier's delivery time is an accurate choice.

It can be used in case a supplier defines a time frame for delivery of an order and the probability that goods are delivered within that interval time is 100% (between “a” to “b” days), and there exists a day with the highest probability of delivering of the order that lies in this interval. This supplier delivery time obeys triangular distribution. The introductory symbol of this distribution is T(a,b,c). Figure 5-2, denotes the diagram of this distribution.

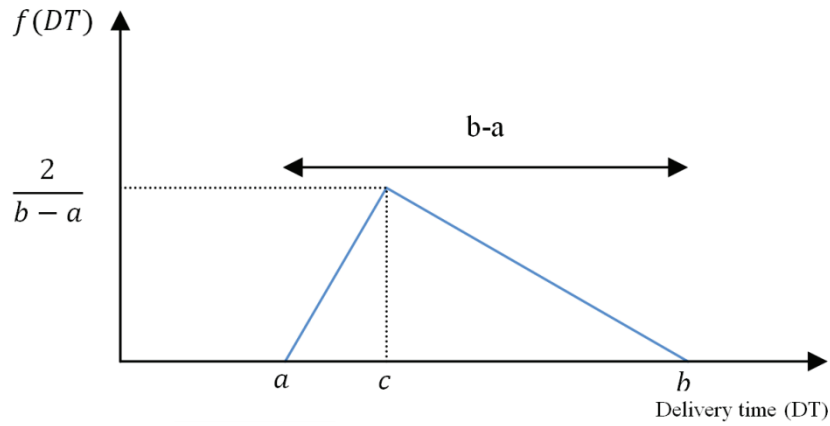


Figure 5-2: Triangular distribution (Montgomery & Runger, 2010)

Therefore, the equations (5-3), (5-4), and (5-5), respectively express probability density function, mean and variance of delivery time for this distribution.

$$f(DT) = \begin{cases} 0 & , \quad DT < a \\ \frac{2(DT - a)}{(b - a)(c - a)} & , \quad a \leq DT \leq c \\ \frac{2(b - DT)}{(b - a)(b - c)} & , \quad c \leq DT \leq b \\ 0 & , \quad DT > b \end{cases} \quad 5-3$$

$$E(DT) = \frac{(a + b + c)}{3} \quad 5-4$$

$$u^2 = \frac{a^2 + b^2 + c^2 - ab - ac - bc}{18} \quad 5-5$$

○ Normal distribution

If the observations and sampling of the supplier's delivery time uncertainties are independent from each other and employ similar conditions (e.g. for comparable orders), usually, the effects of different factors of uncertainty due to randomized sources, cause the results to be distributed symmetrically, as shown in figure 5-3.

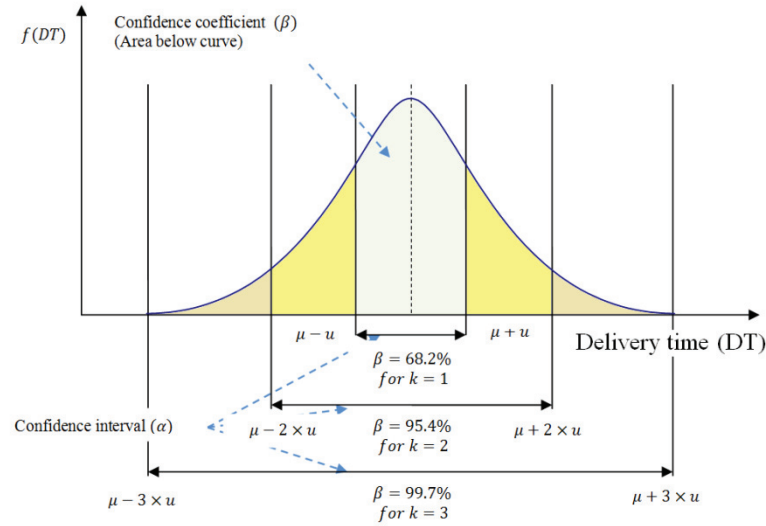


Figure 5-3: Normal distribution

As mentioned, in figure 5-3, the confidence interval (α) introduces the time frame within which a supply network is able to deliver the ordered. The confidence coefficient (β) introduced in figure 5-3, represents the percentage of certainty of a supplier to deliver the orders in the specific time frame (confidence interval).

This distribution curve, which is showing the relation between the deviation from the mean rate of delivery time, and the delivery probability is known as "normal" or "Gaussian" distribution and " μ " is the mean of the supplier delivery time. The shape of this distribution is bell-shaped, and it is expressed by the following equation:

$$f(DT) = \frac{1}{u\sqrt{2\pi}} e^{-\frac{(DT-\mu)^2}{2u^2}} \quad 5-6$$

Where " μ " is the mean delivery time or $E(DT)$, and " u " indicates the standard deviation (standard uncertainty) of the delivery time. In equation (5-6), the DT considers each of the observed delivery times, and it is independent of the other observations. Also, " μ " is the mathematical mean value for infinite times of similar observations. Thus, $(DT - \mu)$ is the deviation from the actual value. The normal distribution is represented in statistical subjects with $N(\mu, u^2)$ and hence, we are going to use this symbol for presenting this distribution.

Regarding the probability theories (Montgomery & Runger, 2010), and by using the distribution function of $f(DT)$ in equation (5-6), we can provide a probability of occurrence of a DT in the specified interval time frame. This probability is exactly equal to the area under the normal distribution curve in the specified interval.

One of the verified specifications of this statistical distribution, which has many applications in uncertainty calculations is usage of "coverage factor (k)" in calculations. This factor has a special role in determining the range of uncertainty. In mathematic point, this " k " has a \pm coefficient, which, multiplied

to the standard uncertainty, will make the coefficient interval for the delivery (see figure 5-3).

In other words, to present the rate of uncertainty in delivery time by this distribution function, it can be stated that: 68.3% of the delivery will fall in $\pm 1u$, interval of the mean of delivery time ($k = 1$), which indicates that the total area under the normal distribution curve is 68.3% within this boundary. For $k = 2$, the area will be 95.5% and for $k = 3$, it will have 99.7% confidence coefficient. Noteworthy the total area under a normal curve is 100% (i.e. =1). Refer to figure 5-3.

Another feature of the curve for this distribution indicates that if the uncertainty of delivery time decreases, the normal curve will be more compact for the mean and will have a higher altitude on mean delivery time. Thus, the best case for the delivery time is when the curve gets the shape of a vertical line. It is known as “Just in time (JIT)”, meaning delivery without standard deviation and uncertainty (see figure 5-4).

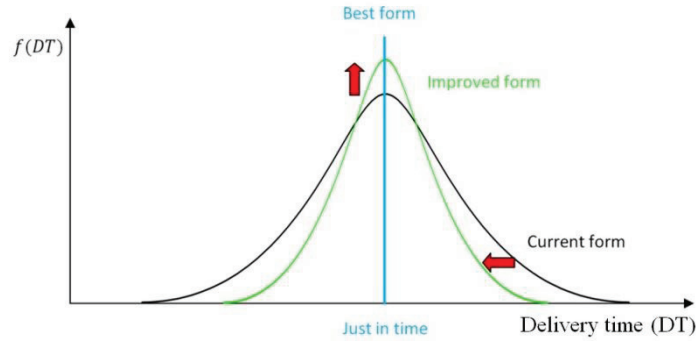


Figure 5-4: Delivery time uncertainty in different situations (Montgomery & Runger, 2010)

○ Exponential distribution

When the probability of delivery gets the highest value at the time of ordering or when a supplier uses his production program according to “Make to Stock (MTS)” strategy and the capacity of the warehouse is limited in such a way that there is the possibility of shortages, the exponential distribution could be a proper representation of the supplier behavior in delivering the material (Montgomery, 2008). The probability density function for the exponential distribution is indicated in equation (5-7):

$$f(DT) = \begin{cases} \lambda e^{-\lambda(DT)} & , \quad DT > 0 \\ 0 & , \quad \text{Otherwise} \end{cases} \quad 5-7$$

The diagram for the exponential probability density function can be observed in figure 5-5.

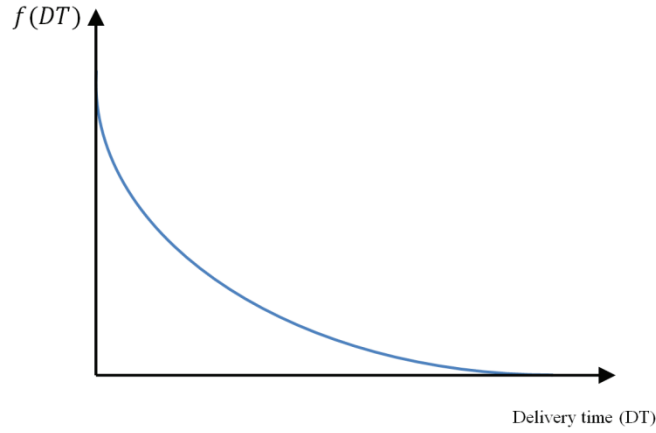


Figure 5-5: Exponential distribution

The mean of delivery time and the variance for such suppliers attain from equations (5-8) and (5-9), respectively:

$$E(DT) = \frac{1}{\lambda} \quad 5-8$$

$$u^2 = \frac{1}{\lambda^2} \quad 5-9$$

The symbol of this distribution is $EXP(\lambda)$, where “ λ ” is the time gap between two consecutive deliveries.

○ Gamma distribution

As it has already been pointed out in chapter 3, Gamma distribution is one of the continuous probability distributions. This statistical distribution is proposed by two parameters, one “scale parameter”, which is shown by θ , and the second one is “shape parameter (s)”. If “ s ” is a number from the set of natural numbers, then Gamma distribution will be equivalent to the sum of “ s ” random variables, followed by the exponential distribution with parameter “ $1/\theta$ ” ($\lambda = 1/\theta$). This distribution function is not symmetrical as in normal distribution and its time frame starts from zero to infinity.

If a supplier uses the MTS strategy like the exponential distribution function and he is obliged to deliver the goods in ordered packages at different times, and “ s ” is the number of ordered packages and θ is the probability of success in on-time delivery of the material, the delivery time will follow Gamma distribution function. The symbol of this probability density function is $G(s, \theta)$. Equations 5-10, 5-11 and 5-12 indicate probability density function, mean and variance of the delivery time, respectively, for such suppliers.

$$f(DT) = \frac{1}{\Gamma(s)\theta^s} \times DT^{s-1} e^{-\frac{DT}{\theta}}, \quad \Gamma(s) = \int_0^\infty DT^{s-1} e^{-DT} \partial DT \quad 5-10$$

$$E(DT) = s\theta \quad 5-11$$

$$u^2 = s\theta^2 \quad 5-12$$

5.2 Preparing the network

The first step in calculating the network uncertainty and using the adapted PERT method is to identify various networks and analyze each basic situation of

the networks and their primary calculations for making the network ready to use the PERT method. Since one of the drawbacks of PERT is lack of ability to calculate for the networks having cycles and loops, we are going to provide a solution in this section to eliminate that problem.

For these reasons, this section is started by analyzing the simplest and most basic network forms (networks with two nodes with a supplier and an OEM). Finally the more complicated networks are considered. The designed scenarios for this case include analysis of networks with two nodes, three nodes and in addition networks with four nodes, and we consider all the related situations for them. The reason for not considering the networks with over four nodes is that no new situations occur in them and the obtained information for the networks with two, three and four nodes could cover the conditions for the ones with over four nodes. The aim for simplification and doing the calculations is to direct the networks towards simple linear networks.

Before analyzing the networks, it is necessary for terms such as input and output degrees of the supplier and the total degree of the supplier to be defined. In this research, the input degree “ i ” of the supplier is the number of suppliers which supply the “ i ” node of the network. In other words, it is the number of suppliers that are the predecessors of “ i ” node and the “ i ” supplier needs them directly to provide its own services. The output degree of the “ i ” supplier indicates the suppliers that after the “ i ” supplier have direct relations with it and form its predecessors straight. The general degree of a supplier in the network indicates the total input and output degrees of a supplier. In other words, it is the sum of the total number of relations which a supplier enters or leaves.

Each network needs primary (beginner) node(s) and a final node for the calculations, and it is called OEM. One of the features of a primary node is that it is having the least input degree among all the suppliers and members of the network (mostly it is 0). It is noticeable the number of connected oriented graphs is given by 5-1.

n	1	2	3	4	5
Number of oriented graphs	1	1	5	34	535

Table 5-1: The numbers of connected oriented graphs (Weisstein, 2003)

Where n denotes the numbers of nodes.

As shown in table 5-1, all possible connected oriented graphs for basic types of network with 4 nodes are 34. Most common shapes of basic types of network are shown in figure 5-6. Moreover, all possible types of network with 4 nodes are presented in the appendix 9.6.

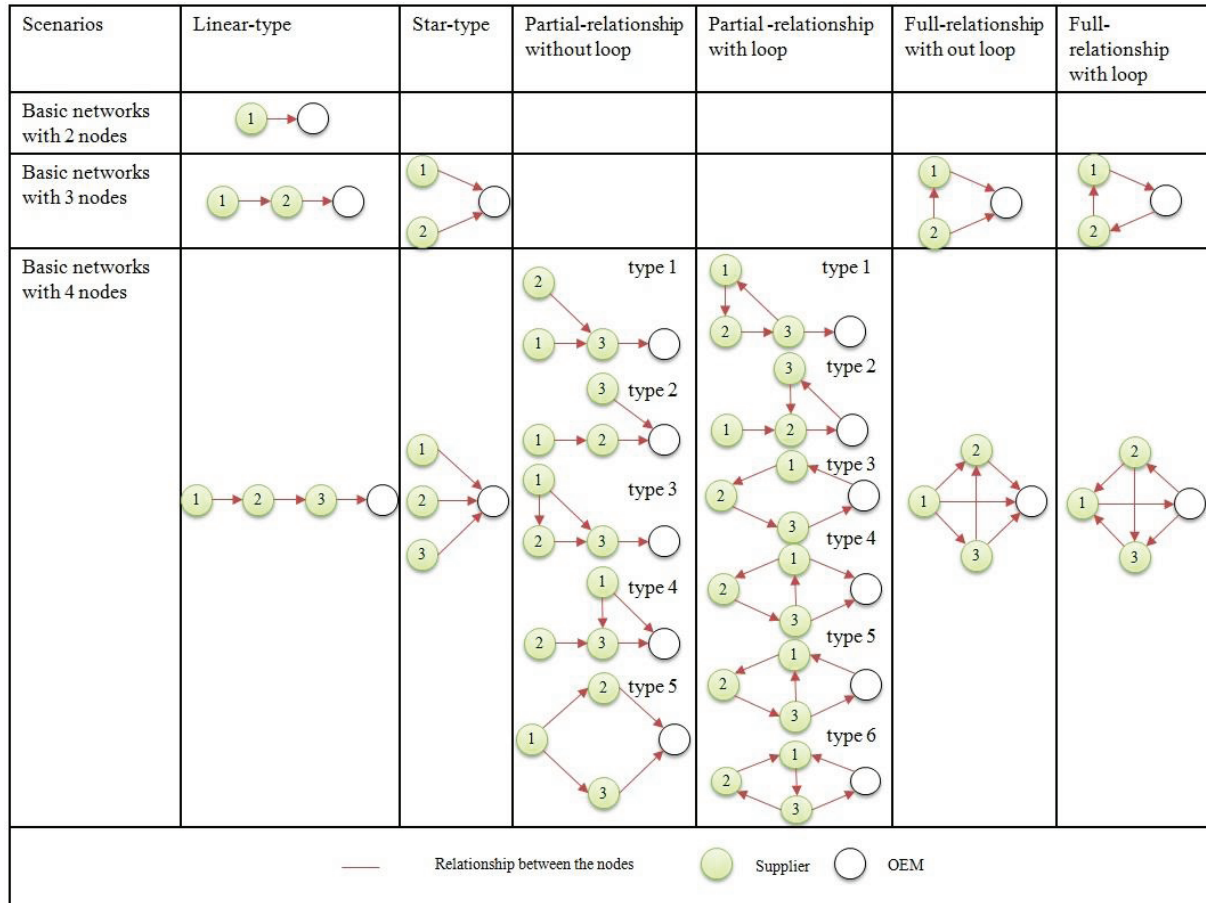


Figure 5-6: Most common shapes of basic network types within two, three, and four nodes

As demonstrated in figure 5-6, most common basic networks have been divided into six groups: linear-type, star-type, partial-relationship networks with loop, partial-relationship networks without loop, full-relationship networks without loop and finally full-relationships networks with loop. Since the aim has been the analysis of basic networks, we have started the scenarios by analyzing the networks with two nodes (a supplier and an OEM) and finished by four nodes (three suppliers and an OEM). The reason for not considering basic networks with over four nodes is coverage of all the six classified groups by the scenario of networks with four nodes and considering other cases (with more than four nodes) equals repeating of the classification. To continue, we are going to consider separately each of the cases:

5.2.1 Basic networks with two nodes

As shown in figure 5-6, a simple linear network is the only possible state of this scenario. Therefore, it can simply be said that if the mean of delivery time of supplier “1” is μ_1 and if μ_c is the mean of the combination of delivery times of the network up to the OEM, the relation between them will be $\mu_1 = \mu_c$, and the transferred uncertainty from the network to OEM (u_c), is the uncertainty of supplier “1” ($u_c = u_1$). Additionally, if “f(y)” represents the relationship function between the relations of this network and $f(DT_i)$, shows the probability

density function of the i^{th} supplier, the relationship function of the network will be calculated as follows:

$$f(y) = f(DT) = f(DT_1) \text{ and } Y = DT_1 \quad 5-13$$

5.2.2 Basic networks with three nodes

According to figure 5-6, this scenario includes 4 groups of networks out of 6 conditions (linear-type, star-type, full-relationships networks without loop, full-relationship network with loop).

In case μ_1 shows the mean of the delivery time of supplier 1, μ_2 shows that of supplier 2 and μ_c is the mean of the combination of delivery times of the network up to the OEM, the following rules are used for calculating μ_c of the basic networks in this scenario:

- In “linear-type” scenario, the mean of the combination of delivery times of the network, up to OEM is equal to the total of the mean of delivery times of both suppliers ($\mu_c = \mu_1 + \mu_2$).

$$f(y) = f(DT) = f(DT_1) + f(DT_2) \text{ and } Y = DT_1 + DT_2 \quad 5-14$$

- In “star-type” scenario, the average of the combination of delivery times of the network, up to OEM is equal to maximum mean of delivery times of both suppliers ($\mu_c = \max(\mu_1, \mu_2)$).

$$f(DT) = \max(f(DT_1), f(DT_2)) \text{ and } Y = \max(DT_1, DT_2) \quad 5-15$$

- In “full-relationship networks without loop”, the following actions should be applied:

The simplified state of the network for this category is shown in figure 5-7.



Figure 5-7: Simplified types of full-relationship networks without loop in three nodes scenario

As shown in figure 5-7, the supplier 2 is introduced as the primary (beginner) supplier (node) of the network due to having the least input degree (0) in comparison to the input degree of supplier 1, that is (1). Finally, to simplify the stated “full-relationship” network, we have changed it into two linear networks with two and three nodes. The calculations for these two linear networks are exactly similar to linear networks in 2 and 3 node states, the relationship function of the network will be calculated as follows:

$$f(DT) = \max(f(DT_2), f(DT_2) + f(DT_1)), \mu_c = (\mu_2 + \mu_1) \text{ and } Y = DT_2 + DT_1 \quad 5-16$$

- In “full-relationship networks with loop”, the loop should first be eliminated in the network, and then the scenario should be simplified. The method for eliminating the loop in the network is as follows: First, the total degrees of uncertainty of all the suppliers of the loop are calculated and the supplier that has the highest total degree should be determined. Then by creating a dummy supplier, the loop problem is eliminated as shown in figure 5-8. It is to note that the dummy supplier is made by the supplier with the highest total degree of uncertainty. Furthermore, the created relations between the main and dummy suppliers are only for maintaining the network structure and have no other applications. Whenever the total grades of supply of all the nodes are equal, such as in figure 5-8 (e.g. in this case the total degree of all the nodes is two), one can create a dummy supplier, optionally. The only condition in this situation is that for more simplicity of the network, if OEM is itself one of the establishing members of the loop, and the total degrees of the nodes are equal, one should create a dummy node from that OEM. This is the only exceptional state, by which the OEM is calculated in the network. According to the special created situation and the mentioned condition, since OEM exists in the loop in this special situation, shown in figure 5-8, one should create a dummy member out of the OEM named “M” in the simplification process.

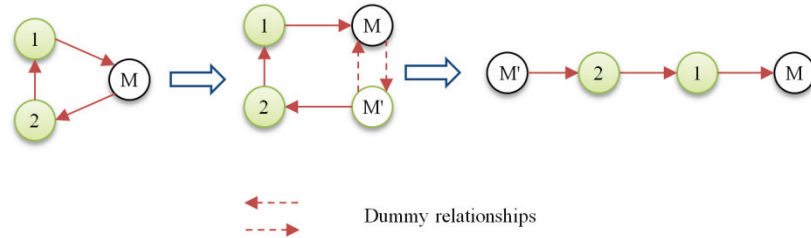


Figure 5-8: Simplification process of networks with loop

If μ_M is related to the mean of delivery times of OEM, then regarding the fact that dummy members have no identities and have the same characteristics of the main member, the mean of delivery times of dummy and main OEM are equal. Hence $\mu_c = \mu_M + \mu_2 + \mu_1$.

$$f(y) = f(DT) = f(DT_M) + f(DT_2) + f(DT_1) \text{ and}$$

$$Y = DT_M + DT_2 + DT_1 \quad 5-17$$

5.2.3 Basic networks with four nodes

As shown in figure 5-6, the scenario for the basic networks formed by four nodes consists of all of the six groups of basic networks. Therefore, it is selected as the last case. If μ_1 , μ_2 and μ_c bear the same as earlier mentioned concepts and μ_3 is the mean of delivery time for the 3rd supplier, we should obey the following rules for calculating μ_c of the basic networks in this scenario:

- In “linear-type” case, the mean of the combination of the delivery times up to the OEM is equal to the sum of means for delivery times of three suppliers $\mu_c = \mu_1 + \mu_2 + \mu_3$
- In “star-type” case, the mean of the combined delivery times up to OEM is equal to the maximum mean of delivery times of three suppliers $\mu_c = \max(\mu_1, \mu_2, \mu_3)$.
- In “partial-relationship without loop”, there are five possible states, and we are going to explain all the 5 states, in order to calculate more complicated and complex networks. Since the purpose of the calculations is analyzing the shapes, patterns and topology of the networks, we found it sufficient to express about these five states, but in overall conditions, by switching the number of suppliers, the other situations with the same patterns could be established, but they were not considered by the author. All the five states are shown in simple forms in figure 5-9. As it is shown in this figure, the effort has been to simplify states of the network, by transforming them to linear networks, for reasons of simplified calculations. Hence, for the relevant calculations, the rules presented for linear networks in scenarios 2, 3 and 4 can be referred to.

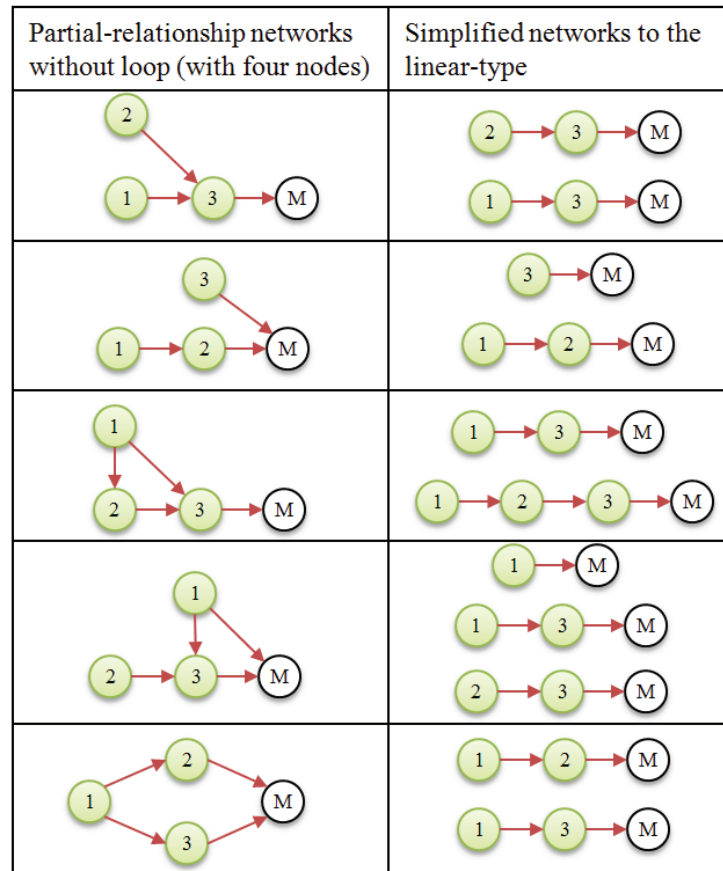


Figure 5-9: Simplified networks of partial-relationships without loop category with four nodes scenario

- In “partial-relationship with loop”, the network should first be transformed to a network without loop and then transformed to a linear network. As stated before, the calculations of simplified linear networks in figure 5-10 are similar to the past calculations for linear networks.

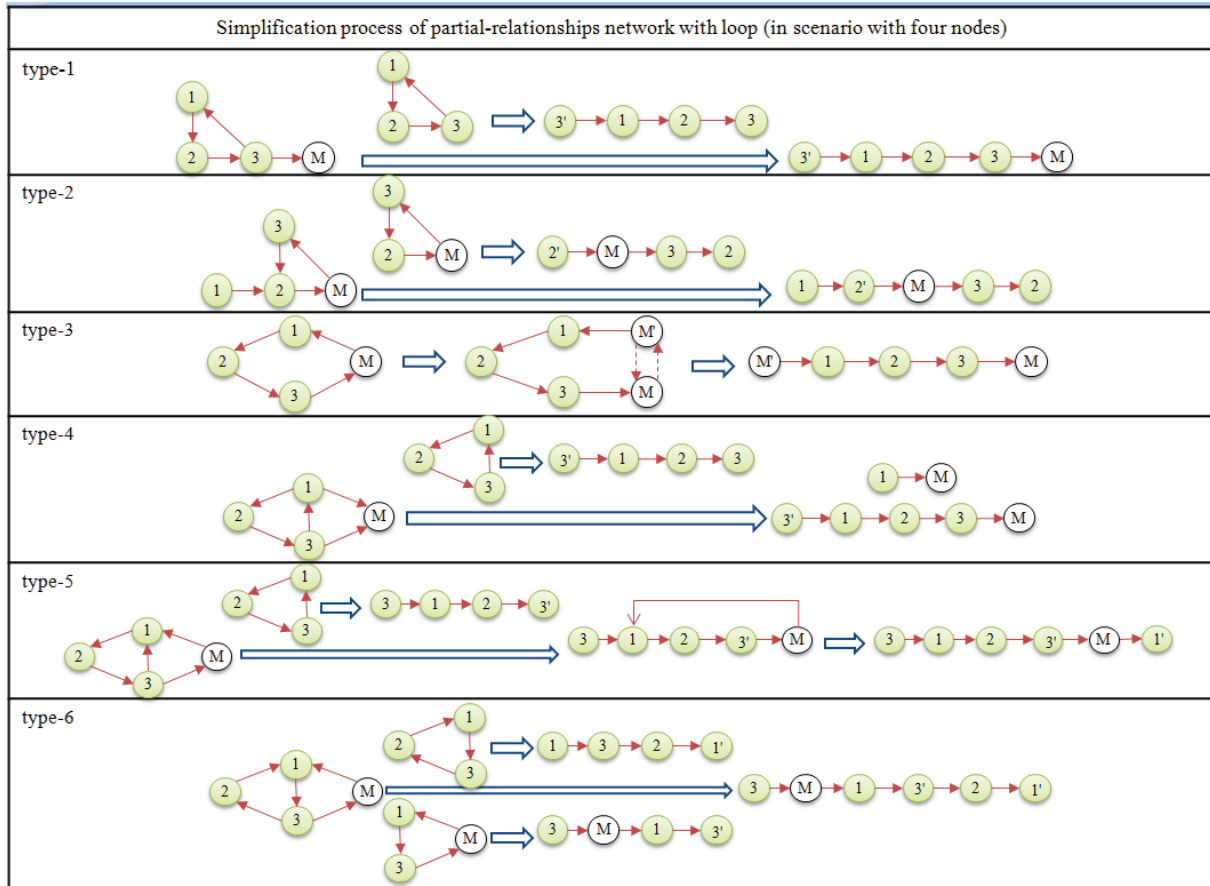


Figure 5-10: Simplified networks of partial-relationships with loop category with four nodes scenario

- In “full-relationship without loop” the simplified network is transformed to linear network, as in figure 5-11 and the calculations are similar to simple linear networks for the scenarios with linear patterns. Since the supplier 1 in figure 5-11 has the lowest input degree, it is introduced as the primary node. Figure 5-11 shows the simplification process of these types of networks.

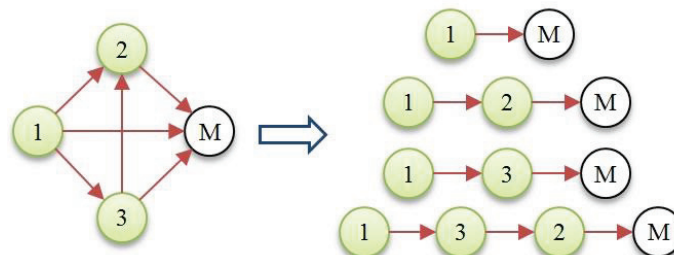


Figure 5-11: Simplified networks of full-relationships without loop category with four nodes scenario

- In “full-relationship with loop”, due to the existence of two loops in this network, it forms the most complicated base network that has all possible relations. To eliminate both of the loops, we introduce two dummy nodes of M' and M'' due to existence of OEM in the cycles (figure 5-12).

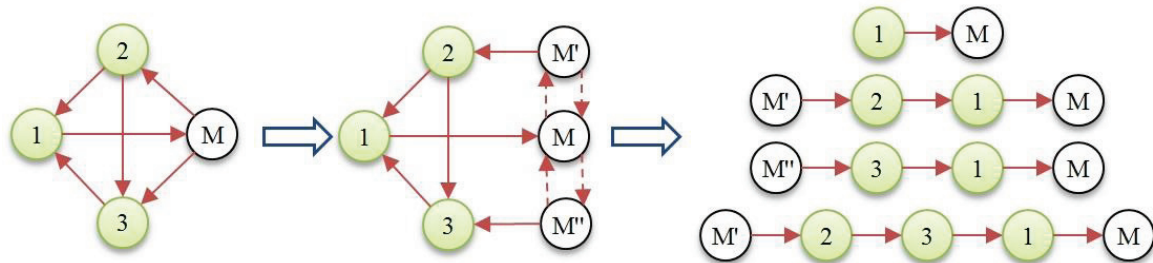


Figure 5-12: Simplification process for full-relationships network with loop in scenario with four nodes

As it is shown in the extracted article from this thesis (Safaei et al., 2014), the descriptions regarding the methodology are as follows:

5.3 Program (or Project) Evaluation and Review Technique (PERT)

In 1958, the USA navy was analyzing the activities for manufacturing “Polaris” rocket. The responsibility of this project lay with a navy officer “Roburn”. About 3,000 contractors were occupied in this project and the number of components that were to be manufactured and assembled and put together for the final system were 12,000. A review on the number of projects by the navy that were performed before, shows in the most of them, the indicated time and needed budget, exceeded what was predicted. The time was 45 percent longer on average, and the budgets were 250 percent higher than the predictions.

Regarding the relevant records and considering the volume of the project, the Polaris project manager decided to establish a research group for planning the project to provide an effective and scientific method for the project. With the cooperation of an office related to the navy and Lockheed airlines Co. and a consulting company for management affairs named "Booz& Hamilton", the team was established to present PERT method by the first half of 1958. The application of this method began for the Polaris project in October 1958. The PERT relied upon the principle that the key events (essential to occur in a definite date for the project to be completed) should be determined. These events were named "Milestones" and their circumstances were considered at defined dates for the project conditions to be determined with regard to progress in activities. By applying PERT for management and project control in the Polaris, that project was successfully completed earlier than the foreseen date (Sapolsky, 1972).

Notably, though the studies and research for achieving CPM⁸ and PERT methods were carried out almost simultaneously, neither of the research groups knew about the activities of the other group. Anyhow, the principle of both methods relied on the network graphs and both methods were completely similar with respect to calculation instructions. Application of PERT and CPM methods was rapidly expanded to building and industrial companies. Probabilistic estimation of the time of performing the activities is considered in PERT. The main difference of PERT and CPM is in probabilistic and certain time estimations. Hence it can be said that when the time of doing the activity could not be expressed with certainty, the PERT method should be used for identifying the critical path of the network (Demeulemeester & Herroelen, 2002).

Research and studies for development of these methods are continued and considerable achievements have been achieved so far. Today, calculation of durations, matters such as assigning and allocating resources, costs, workforce and equipment as well as adjusting time and cost can be considered by applying these methods.

5.3.1 Adapted PERT

A principle to consider is the lack of necessity in taking uncertainty for all the network suppliers into account. The reason behind is the uncertainty rate, and that the average delivery times of some suppliers are shadowed by others. The rate of their delivery times may not have any effects on the uncertainty of the delivery time of the whole network. Since one of the aims of this search is speeding up the calculations, we found it necessary to identify the group of suppliers being in the bottleneck of the network as so called "critical suppliers". In order to avoid any unnecessary calculations, calculations of uncertainty are in accordance to them. Thus, the aim of adapted PERT method is identifying such critical suppliers and also simplifying the network to speed up the calculations.

Conventionally, the PERT is a statistical tool for controlling and management of activities running during a project horizon. PERT is essentially used to manage activities with time probability by means of defining a unique critical path throughout the project steps. Vital nodes with most sensitive time frames, critical to finalization time of the project, define an underlined route, starting from the beginner's node and ending with the final node, which is called critical path. Adoption of PERT in this methodology is a promising way for simplifying complex networks to pure linear networks with easy load of calculation. Therefore, for calculating an accumulated delivery time uncertainty for any type of complex supply networks, only the corresponding critical path has to be considered that reduces the cost of computations (Safaei, et al., 2014).

To estimate the delivery time instead of giving a definite time, different durations are given in the method of PERT. The relevant times are introduced as: In case everything is OK, the earliest time for delivery (Optimistic delivery

⁸ Critical Path Method

time), the most possible case (Most likely delivery time) and finally the worst case (Pessimistic delivery time). The time estimations are done by managers or the people who are quite familiar with the suppliers. There are two main hypotheses in doing PERT calculations:

- The time distribution of each activity follows Beta distribution in figure 5-13.
- The time for doing an activity is independent from the time of other activities.

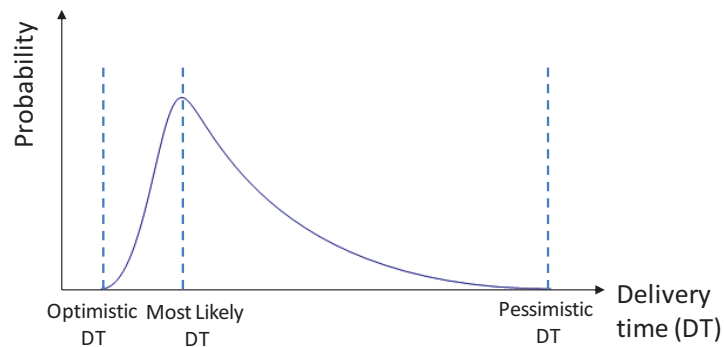


Figure 5-13: Beta probability density function for PERT

The expected value of delivery time, $E(DT)$, is calculated from the following formula for each supplier separately, in case the delivery times follow "Beta distribution" function:

$$E(DT) = (\text{Optimistic DT} + 4 \times \text{Most likely DT} + \text{Pessimistic DT}) / 6 \quad 5-18$$

Also the variance of the delivery time is calculated by equation (5-19):

$$u^2 = (\text{Pessimistic DT} - \text{Optimistic DT})^2 / 36 \quad 5-19$$

The question to be considered is: "If the probability density function of the delivery time of a network member does not obey Beta distribution, how could the method of PERT be used, where the estimation of the probability density functions to Beta distribution is not needed to be responsive?"

The adapted method for PERT has tried to change the situation of the old method from the project control management environment and to be responsive to adjustment to the supply networks. Moreover, by providing some changes and the relevant formulas, it was tried to add the capability of considering distribution functions other than the Beta distribution. In the adapted PERT, the expected value (mean) for the delivery time is used instead of considering the three mentioned times after finding the probability density function related to the delivery time of each one of the suppliers (see appendix 9.1).

The adapted procedure of PERT for defining the critical path of complex supply networks is the following:

Step 1: Calculation of the expected value of delivery time for each supplier

The first step in adapted PERT method is calculating the expected value of delivery time ($E(DT)$) for all suppliers separately. Formally PERT for

calculating $E(DT)$ assumes only Beta distribution for delivery time, which is calculated by

$$E(DT) = (\text{optimistic } DT + 4 \times \text{most likely } DT + \text{pessimistic } DT) / 6$$

However, if the suppliers' delivery time uncertainty follows other types of distributions, then it requires an adaptation in PERT calculation procedure. As a contribution, the author adopted new formulas for other likely distributions as in Table 9-1 in the appendix 9.1. It is noticeable that all calculations to find probability density function of delivery time, and its parameters (e.g. $E(DT)$) have been done by EasyFit software and that there is no need to calculate all of them.

Step 2: Calculation of the forward pass

For this purpose one calculates the following values:

- 1 Earliest start date for supplier i , ES_i and ES_m is earliest start date for the manufacturer
- 2 Earliest finishing date for supplier i , $Ef_i = ES_i + E(DT_i)$
- 3 Forward pass necessities two rules. Rule 1: put $ES_1 = 0$, for the supplier at the beginning (If there are more than one, put all of them equal to zero). Rule 2: if there are K suppliers which are the predecessors of supplier i , ES_i is calculated as: $ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$. Do the calculation of the forward pass until the earliest finish date for the last node is defined. In order to find the critical path backward pass calculation is required, too.

Step 3: Calculating backward pass

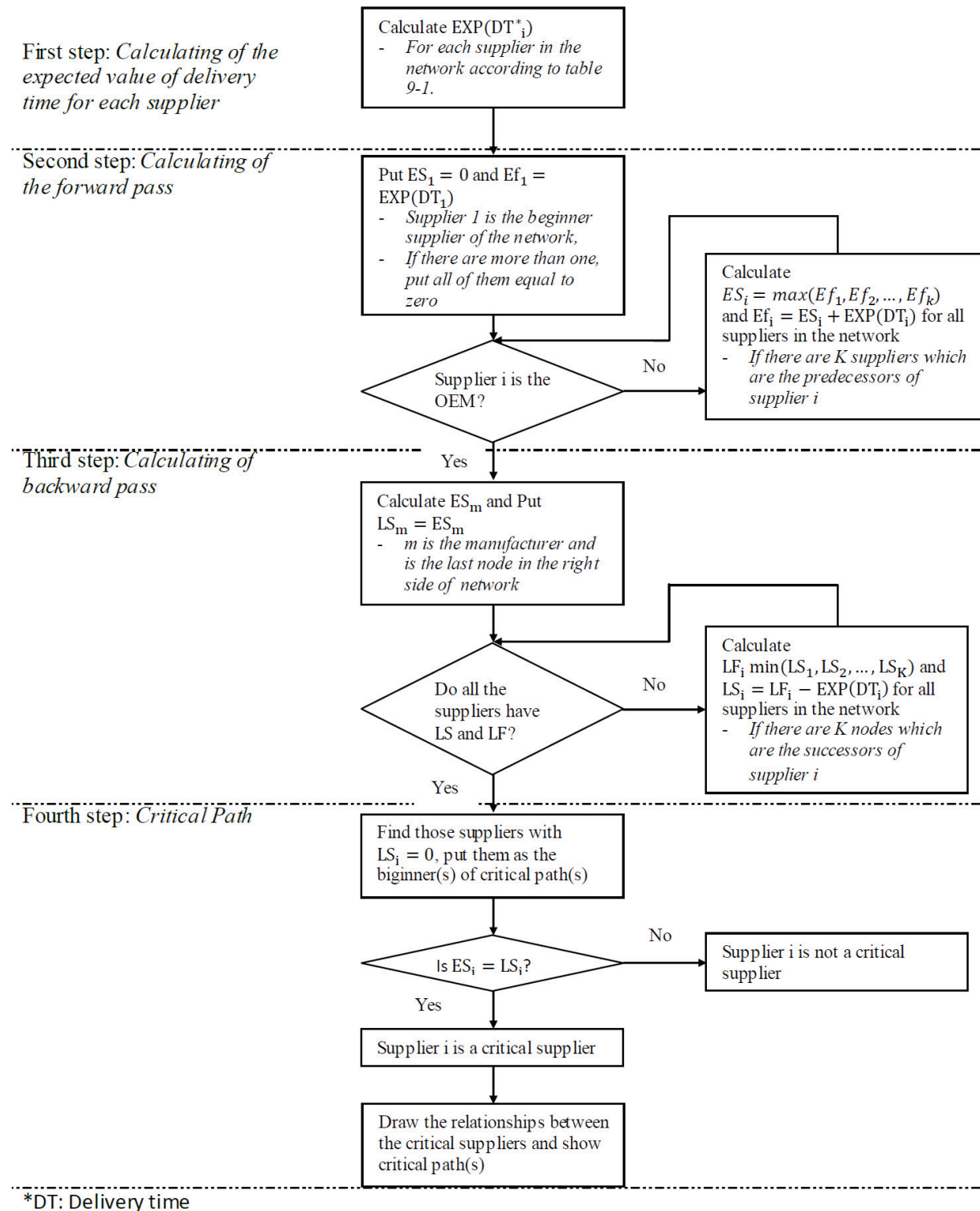
For this purpose one calculates the following values:

- 1 Latest start date for supplier i , LS_i , and LS_m is latest start date for the manufacturer (last node), put $LS_m = ES_m$.
- 2 Latest finished date for supplier i , LF_i , and if there are K nodes which are the successors of supplier i , LF_i is calculated by: $LF_i = \min(LS_1, LS_2, \dots, LS_K)$ and $LS_i = LF_i - E(DT_i)$.
- 3 Calculate all LS_i and LF_i from manufacturer (last node) towards the beginner's node(s). If there are more than one beginner node then the node with $LS = 0$, is the beginner node of the critical path.

Step 4: Critical Path

All in all the nodes i with $EF_i = LF_i$ and $ES_i = LS_i$, configure the critical path of the corresponding network. Moreover, sometimes there may be more than one critical path in a network. In this case, the delivery time uncertainty of each individual critical path as a linear route has to be calculated separately.

Conclusively, the entire adapted algorithm to find the critical path is as figure 5-14.

**Figure 5-14:** PERT algorithm

5.4 Guide to the Expression of Uncertainty in Measurement (GUM)

The GUM could be considered as a tool or a guide that is established by ISO to provide common and coordinated laws for defining and measuring uncertainty for the researchers in calibration, standardization and servicing laboratories related to methodology. Since GUM is a guide for reaching the standards, it is today recognized as an acceptable reference for measuring

uncertainty in calibration by various organizations (Attivissimo, et al., 2012). The most important aims for establishing GUM are as follows:

- To provide synchronization in definitions linked to uncertainty
- To provide a measurement basis for common international uncertainty in calibration

Herewith the history of GUM is described:

Due to lack of existence of a common notion for uncertainty and its measurements and also the disagreement between the researchers and international organizations, Comité International des Poids et Mesures (CIPM) that was one of the most powerful organizations of the time in metrology asked for the establishment of "Bureau International des Poids et Mesures (BIPM)" in 1977 to provide a common guideline to solve the relevant problems in national standard laboratories. It took 16 years until the first edition of GUM was published by ISO in 1993. Two years later, in 1995, the second and modified edition was also published (van Collani, 2008). By the publication of this guide, uncertainty was recognized as a measurable feature and one of the new concepts in the history of measurement. After that, it officially separated its path from the errors and analysis of errors in measurements.

5.4.1 Adapted GUM

As mentioned, one of the well know techniques for calculating uncertainty in the calibration field, widely applied in mechanical and electrical systems, is GUM. This is a guideline introduced by the JCGM member organizations (JCGM, 2008).

The uncertainty of delivery time in a supply network is the result of the uncertainties of every individual member in that network. Now, in order to estimate the uncertainty of the individual members, two categories are possible concerning the way that their numerical values are estimated (Jones, et al., 2001). These two types are the following:

Type A: those uncertainties which are evaluated by statistical methods based on observation

Type B: those uncertainties which are conventionally given by other means of measurement like uncertainty certificate or experience.

However, the major difference between both types A and B returns to the nature of data acquisition regarding either conventional or observational data inference. Therefore, the calculation of uncertainty in the system is similar for both types. Nevertheless, regarding the characteristics of supply networks type A is a practical way for our purpose. In order to calculate delivery time uncertainty with GUM method, following notations and introductions are necessary.

In the type A the estimated variance of the series of the repeated observations is denoted by u^2 . As known, the standard deviation of the samples is easily the square root of variance. This standard deviation of observation (u) represents delivery time uncertainty in each node of a supply network. Therefore,

delivery time uncertainty of type A is obtained from probability density function, derived from the observed frequency distribution, whereas delivery time uncertainty of type B is obtained from a given probability density function, concerning the validity of the standard certainty certificate.

The set of $\{DT_1, DT_2, DT_3, \dots, DT_n\}$, represents delivery times of the members of a network. The relationship function between these variables is expressed as:

$$f(DT) = f(DT_1, DT_2, DT_3, \dots, DT_n) \text{ and } Y = (DT_1, DT_2, DT_3, \dots, DT_n) \quad 5-20$$

Where Y is the accumulated delivery time at the entrance of the final node of a network (OEM), as the process uncertainty inside this node is not required to be considered. This is because delivery time uncertainty has only effect up to the entrance of the final node, the OEM. According to the concept of critical path inside any type of complex networks, the relationship between the nodes in the critical path is linear; therefore the function Y can be calculated by (5-21).

$$f(y) = f(DT) = \sum_{i=1}^n f(DT_i) \text{ and } Y = \sum_{i=1}^n DT_i \quad 5-21$$

The output of GUM tool is by itself a normal probability density function that represents accumulated uncertainty of the network. Now, the variance of this accumulated probability density function can be calculated by (5-22).

$$u_c^2(y) = \sum_{i=1}^n \left(\frac{\partial f}{\partial DT_i} \right)^2 \times u(DT_i)^2 \quad 5-22$$

Where u_c is the combined uncertainty for all parameters (suppliers in our case). The indexes of $1 \leq i \leq n$ and $1 \leq j \leq n$ are used to represent to sequential nodes. And $\frac{\partial f}{\partial DT_i}$ is the sensitivity coefficient for the variable DT_i , which is the partial derivative of the function f with regard to DT_i . The amount of this coefficient is between -1 and 1. And it is related to the relationships and influence of the supplier to the supply network (e.g. If a supplier has more influence on the delivery time uncertainty and the supply network is highly dependent on it, this sensitivity coefficient must be higher than others and in the maximum cases, it could be 1.). There is not a special way to calculate this sensitivity factor, and it could be achieved based on the experts and network managers' opinion. For this thesis, we consider 1, if the supplier belongs to the critical path and 0 otherwise.

Conclusively, the entire adapted algorithm for calculating an accumulated uncertainty for a complex network is as indicated in figure 5-15.

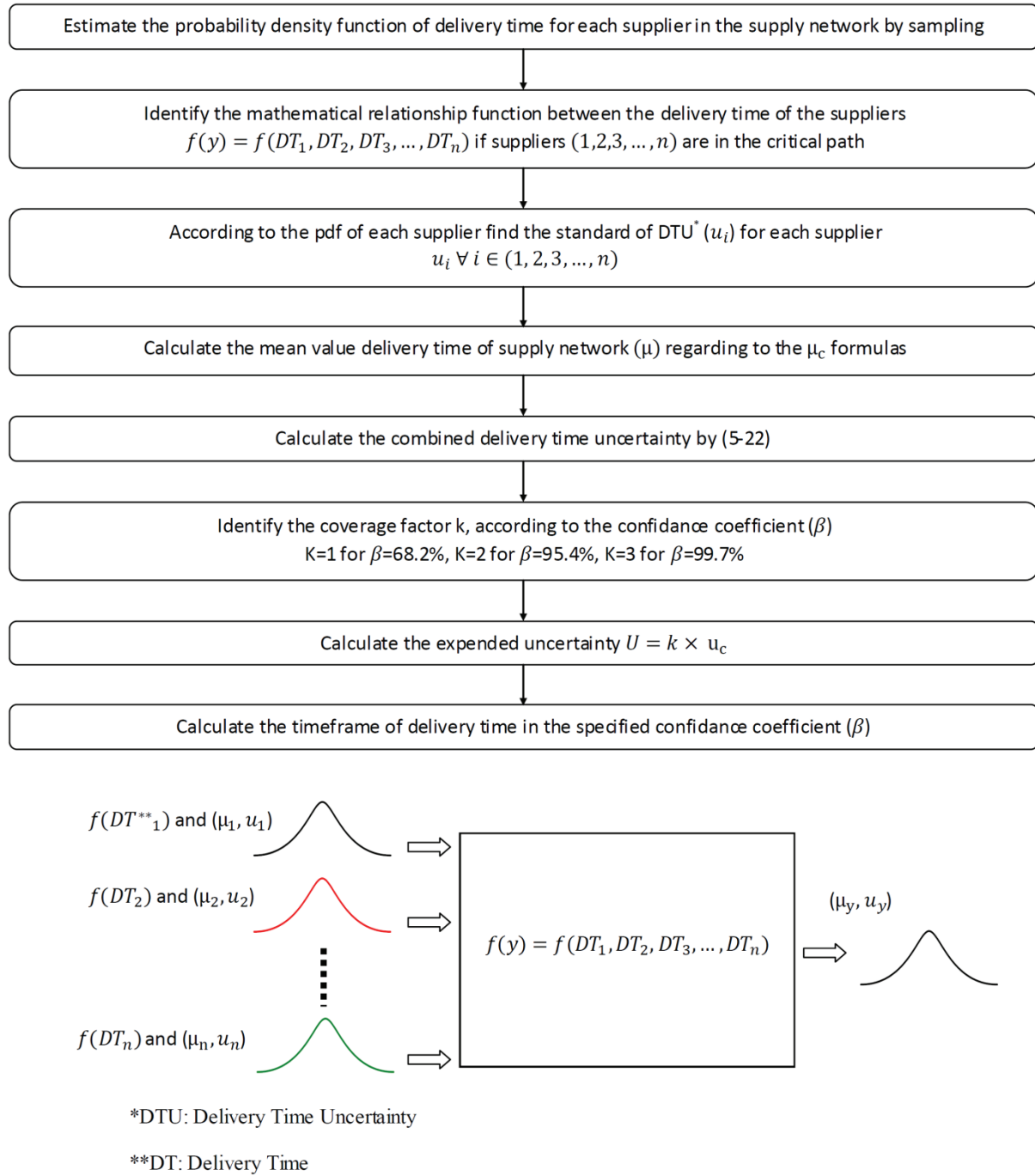


Figure 5-15: Adapted algorithm of GUM for calculating delivery time uncertainty

However, GUM has some pros and cons which moderate its application in calculating delivery time uncertainty of supply networks. GUM is a exact mathematical tool for calculating any types of uncertainty and compared with other alternative mathematical tools (e.g., Bayesian network and Markov chain) has a simpler calculation algorithm and formulas (Richardson & Domingos, 2006). Nevertheless, the calculation complexity of GUM grows as the complexity of the network arises. Thus, for calculating rather complex networks this technique is computationally expensive. Moreover, this technique is developed for calculating uncertainty of networks with only normal distribution.

5.5 Monte Carlo method

Monte Carlo method is a practical technique for substituting GUM in calculating uncertainty. In contrary to GUM, Monte Carlo method has the ability to calculate any form of uncertainty distributions and therefore, brings a great advantage to practical networks. In other words, Monte Carlo models uncertain situations by mean of numerical estimation method, using probability density function and data generation with some repetitions (Alkhatib, et al., 2013). In comparison to GUM, Monte Carlo method has various applications in practice, some of which include:

- In case of nonlinear relationship functions
- In case of asymmetrical probability density functions
- In case of complex supply networks

The adapted Monte Carlo method for delivery time uncertainty calculation seeks for the distribution function of accumulated delivery time of the last node (OEM) in a supply network, which is denoted by (F_Y). If probability density function of delivery time in the last node is denoted by $f(y)$ and the cumulative distribution function of it is defined by F_Y , then the relation between them is as follows:

$$F_Y = \int_{-\infty}^Y f(y) dy \xrightarrow{\text{yields}} f(y) = \frac{\partial F_Y}{\partial Y} \quad 5-23$$

The technique of Monte Carlo method is based on sampling repetition of each probability density function of DT_i and evaluation of the linear mathematical model of $f(y) = f(DT_i)$ in every repeat and estimation of Y which is called a model's value. The more sampling number, the better quality of results for F_Y can be achieved. If the number of independent samplings is M , then $\{y_1, y_2, y_3, \dots, y_M\}$ are the outputs of the method. Based on it, the expected value of the relationship function $E(Y)$, and the $\text{var}(Y)$ can be easily calculated. Accordingly, the general algorithm of Monte Carlo method can be described as below:

- 1 Input M : Input the number of independent samplings of delivery time.
- 2 Create M vectors out of generated independent sampling of delivery time, by considering probability density function for each supplier separately: as a result M vectors with dimension n will be produced, in which n is the number of nodes within the critical path before the last node (OEM). Regarding the equation (5-21), calculate $\{Y_1, Y_2, \dots, Y_M\}$.

$$\begin{bmatrix} y_1 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} DT_{11} & \cdots & DT_{1n} \\ \vdots & \ddots & \vdots \\ DT_{M1} & \cdots & DT_{Mn} \end{bmatrix} \quad 5-24$$

- 3 Draw the histogram of the resulted vector: from the sampling frequency of vector $[y_1 \cdots y_M]^T$, configure this histogram in order to define the curve of frequency distribution $f(y)$, representing the probability density function of delivery time in the last node.

- 4 Calculation of the uncertainty in the last node u_c : from the probability density function of the last node derive its variance and combined uncertainty (standard deviation) u_c .
- 5 Define the coverage factor k , according to the confidence coefficient (β): $k = 1$ for $\beta = 68.2\%$, $k = 2$ for $\beta = 95.4\%$, and $k = 3$ for $\beta = 99.7\%$.
- 6 Calculate the expended uncertainty $U = k \times u_c$.
- 7 Calculate the time frame of delivery time: $\mu_y \pm U$.

For better understanding of the algorithm of Monte Carlo method figure 5-16 provides an overview.

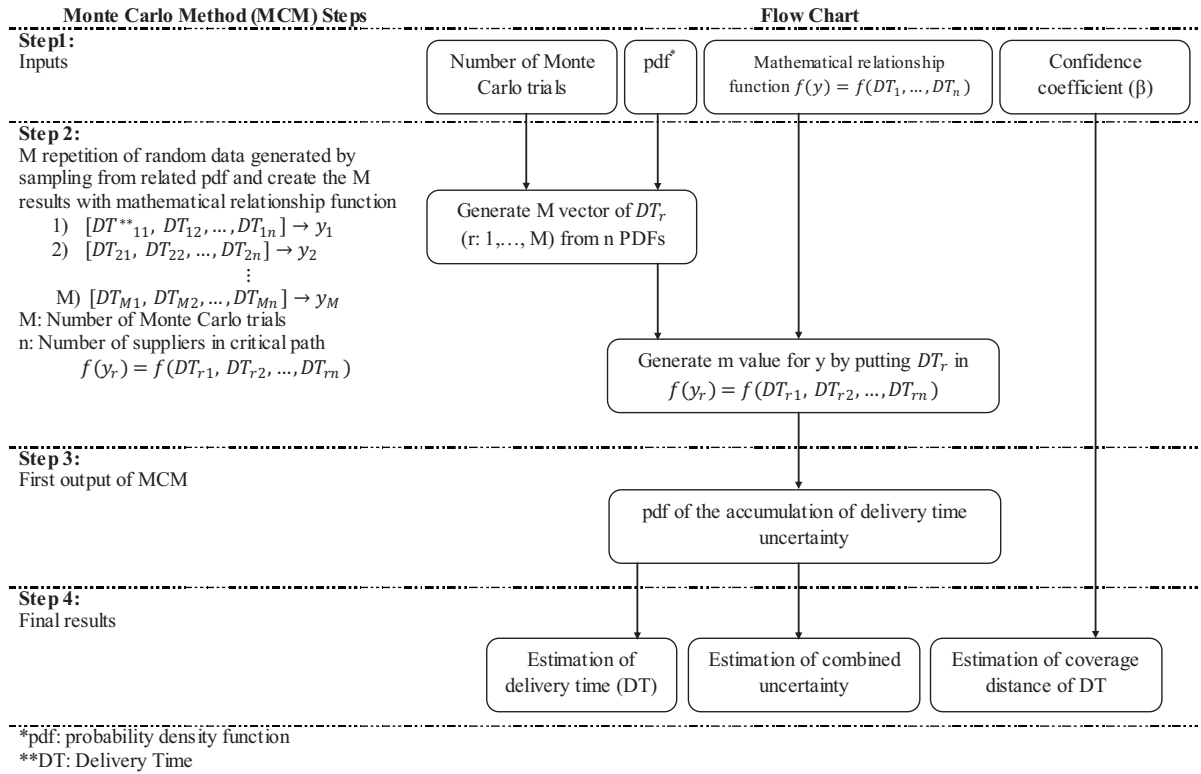


Figure 5-16: Adapted algorithm of Monte Carlo method for calculating delivery time uncertainty

5.6 Hybrid algorithm

As explained earlier and as pointed out in the extracted article from this thesis (Safaei, et al., 2014), the function of hybrid methodology is as follows:

First the supply network structure should be determined for the specific order.

Then the data, samples and observations related to the delivery time regarding to the past projects must be collected. These data are the delivery time of past projects for every supplier who are involved in the network. Afterward, put all the collected data into the EasyFit software, for each supplier separately. Therefore, the EasyFit software by using the MLE (Maximum Likelihood Estimates) method find the best fitted probability density function for each

supplier (Mathwave, 2013). The EasyFit software has a capacity to conform the samples to 65 existing probability density functions in mathematics and the real world, that is an exclusive feature, and then by prioritizing from 1 to 65, the nearest probability density function function could be identified.

As mentioned before, The PERT method is able to find the critical path of the network. This critical path is contained of several suppliers who are bottlenecks in the network. In other words, regarding to the individual mean and standard uncertainty of each supplier, which are obtained by its probability density function, they are introduced as critical suppliers. These critical suppliers have highest influences on the delivery time uncertainty of the network. Because each small change in the mean or standard uncertainty can change the mean and standard uncertainty of the whole network. Then, by using the adapted PERT algorithm, find the critical suppliers. The links between critical suppliers are drawn and hereafter the critical path through the network can be determined.

As mentioned in the characteristics of GUM, because in some cases of probability density functions, there is no mathematic formula to find the summation several different probability density functions (except the normal probability density function). Therefore, the GUM is unable to find the delivery time accumulation of several suppliers with different probability density function. For this reason, In case all the members of the critical network have a normal distribution, GUM could be selected as the calculating engine. Otherwise, when there is another probability density function is considered or in case the relationship function is complex or nonlinear, the Monte Carlo method will be a proper replacement for the calculations. In the programming of the adapted Monte Carlo method, we are able to consider the nonlinear relationship functions, while in the more complex network because GUM is a mathematical method it is becoming more difficult to apply GUM for calculation. Therefore, it makes a possibility for our methodology to consider the nonlinear relationship function.

This hybrid methodology can calculate and expand every complex network with any number of suppliers by using the given formulas and laws in section 5.2 in connection to making the networks ready and with the fact that all the complex supply networks have been created from combining the 6 categories of basic networks. In this methodology, PERT is presented to challenge complexities of the networks, and GUM and Monte Carlo method are the algorithm calculation engines. Refer to the algorithm given in figure 5-17 for more information.

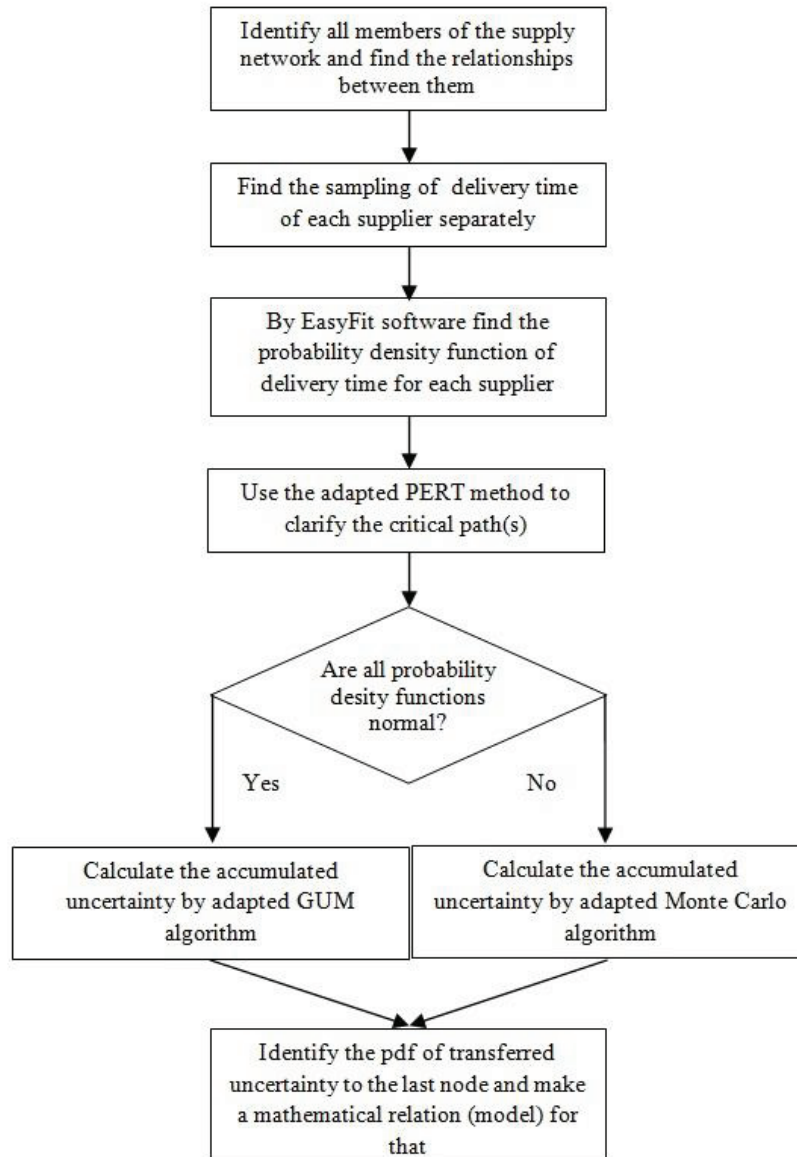


Figure 5-17: The adapted algorithm for calculating delivery time uncertainty out of PERT, GUM, and Monte Carlo method

5.7 Summary

This chapter dealt with a hybrid methodology to calculate accumulated delivery time uncertainty in dynamic supply networks. First, the reader was familiarized with the concepts of the most important and probabilistic probability density function's. Their adaptation with the production world and supply networks, and their performance as well as their conformities, were studied. Then by introducing and dividing basic networks, 6 categories were shaped: linear-type, star-type, partial-relationships networks with loop, partial relationships networks without loop, full-relationship networks with loop and full-relationships networks without loop. All the complex networks are established by combination of two or more of the mentioned basic networks. Thus, by introducing the 6 categories and their classifications, as well as providing calculations and calculating formulas, it has been tried to simplify the

calculations for more complex networks. Then by introducing PERT method and comparing it with the relevant case, suppliers that were most relevant to the uncertainty of the network were spotted, and the critical path of the network was determined by this technique. Afterwards, the adapted GUM and Monte Carlo method, and their performances and algorithms were specified. By the end of this chapter, the main methodology of the case was presented by providing a hybrid method out of the other adapted methods.

6 CHAPTER 6 – Qualification and verification of the hybrid methodology

This chapter examines the methodology introduced in chapter 5 and evaluates its accuracy, qualification and applicability through providing example and case studies. This chapter has been divided into two parts in terms of content. The first part provides a numerical example of a complex supply network and introduces two scenarios. The first scenario seeks to establish the effectiveness of the adapted Monte Carlo method through the use of the adapted GUM, while the second scenario tests the final methodology on a more complex supply network. The second part of this chapter introduces three real-life supply networks and applies the hybrid methodology to them in order to measure the efficacy of this method in the real world.

6.1 Qualification and verification of the methodology by a numerical example with complexity

In this section, a typical complex supply network is presented as a numerical example in order to show the qualification and verification of the methodology proposed in this thesis. As a favorable contribution, this supply network is employed to verify the authenticity of the GUM and Monte Carlo techniques in calculating delivery time uncertainties. In other words, this issue has been raised at the beginning of this chapter in a bid to verify the efficiency and accuracy of the methodology through applying it to two different scenarios provided by the numerical example. There is no doubt about the accuracy of the answers provided by GUM since GUM is an established mathematical calculation method, the adapted GUM has used the same rules employed to calculate supply network uncertainty, and the traditional GUM has been adapted to dynamic networks. Since Monte Carlo method is a simulated model, it is necessary to verify its accuracy first. Consequently, all the probability density functions have considered as normal in the first scenario and solved the related problem using the adapted GUM and Monte Carlo methods. The first scenario seeks to verify the accuracy and efficiency of Monte Carlo method's response. In the second scenario, the model's capability to solve problems related to very complex networks through the use of various probability density functions has been examined. Having verified the accuracy and efficiency of Monte Carlo method in the first scenario, the model's ability to solve problems using different probability density functions has examined. Showing the model's ability to solve complex problems and networks was another goal behind presenting a numerical example, because this ability is not properly demonstrated in a case study appearing in the second part of this chapter. The considered supply network is a complex network out of eight nodes that defines seven suppliers and an OEM. See Figure 6-1.

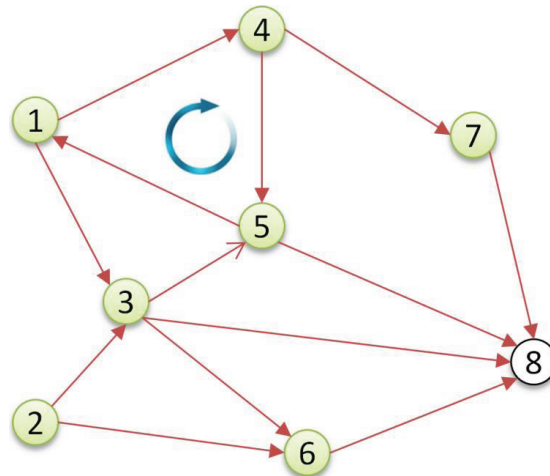


Figure. 6-1: The exemplary complex supply network

In order to deal with this network the beginner node, the last node, and the critical path have to be defined. Since this network has a loop between nodes 1-4-5, according to the section 5.2, it has to be simplified like figure 6-2. The node 5, is selected to take a dummy pair because it has the higher node total degree (the most input and output) and OEM doesn't belong to this loop. After recognizing the node 2 as the beginner (because there are no predecessors for it and it has minimum input degree) and node 8 as OEM the new shape of network is as figure 6-3.

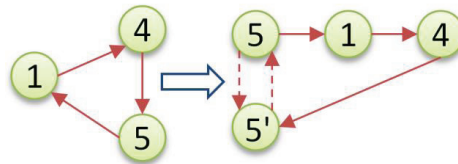


Figure. 6-2: The simplification of a loop in the network

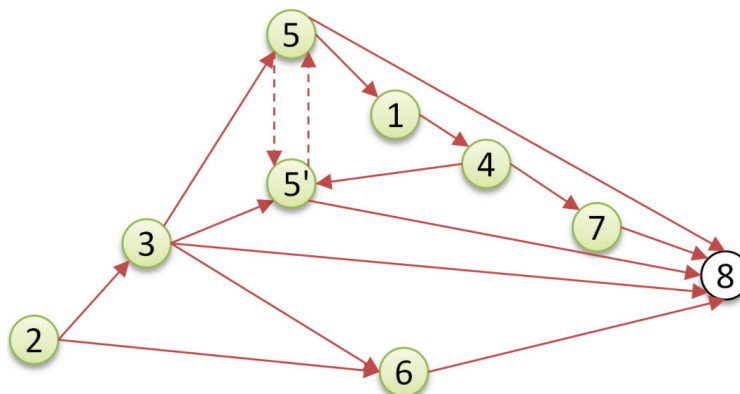


Figure. 6-3: The final shape of the exemplary network

At this moment, to solve this network problem for the two scenarios some assumptions are required. Here all calculation is based on coverage factor 2 ($k = 2$) and confidence coefficients $\beta = 95.4\%$.

Assumptions made in this problem are as follows:

- Each supplier has a unique delivery time probability density function for each product obtained through observing and sampling the delivery times of that product. All these probability density functions have been assumed in the numerical example. The probability density functions should have been obtained through sampling the previous delivery times of the supplier, but they have rather been assumed due to the numerical nature of the example.
- All the calculations are based on a coverage factor equal “2” ($K=2$), and confidence coefficient=95.4% ($\beta = 95.4\%$). The confident coefficient will reach to 99% if the calculations are based on $K=3$. All the calculations related to $K=1$ and $K=3$ are similar to those related to $K=2$. So, they are not mentioned here.

6.1.1 Accuracy and efficiency of Monte Carlo method

As mentioned before, GUM is an applicable and proven method used by calibration experts to calculate the uncertainty. There is no doubt about the accuracy of this method. But the point is that GUM can provide accurate calculations only when all the samples enjoy normal statistical distribution. Otherwise, a normal distribution is estimated in order to find the answers, reducing the accuracy of the method subsequently. Thus, efforts have been made to make the best use of the final methodology proposed in this thesis by adapting GUM to supply networks and using it for situations in which all the members enjoy normal distribution. However, GUM cannot conduct calculations in other situations or produce approximate answers through numerous estimations. Therefore, the adapted Monte Carlo method in order to cover also for the adapted GUM has been presented. Now, it is necessary to establish that the adapted Monte Carlo method could be trusted. Applying both methods to the same problem is the best way to do it. Since we were sure about the performance of GUM in normal situations and sought to examine the accuracy of Monte Carlo method, all delivery time probability density functions for each supplier were supposed as normal in the first scenario. These functions are solved by applying both methods, and the results are examined ultimately. In the second scenario, a more complex situation was examined, and different distribution functions were assigned to the delivery time of each supplier after the efficiency of the adapted Monte Carlo method was established. The two scenarios will be examined below.

- ***supply network with normal probability density functions***

This scenario has been presented to examine the accuracy and efficiency of Monte Carlo method. Therefore, firstly, we have tried to solve the same problem by both methods (the adapted GUM and adapted Monte Carlo method), then the results are compared. If there is little difference between the results produced by these two methods, the adapted Monte Carlo method could replace the adapted

GUM in situations in which the latter acts through estimation. In this numerical example, all the probability density functions of the delivery time of the suppliers are supposed to enjoy a normal distribution pattern. Table 6-1 contains the assumed probability density functions of each supplier.

Node	Probability density function	Mean (μ_i)	Variance (σ_i^2)
Supplier 1	Normal	10	1
Supplier 2	Normal	5	1
Supplier 3	Normal	20	4
Supplier 4	Normal	8	2
Supplier 5	Normal	15	3
Supplier 6	Normal	15	2
Supplier 7	Normal	9	2

Table 6- 1: The probability density functions of suppliers in scenario 1

Now, finding those members of supply network who have most influence on delivery time uncertainty is the next step, for this aim, the critical path of the network must be identified. According to the PERT the critical path of the network has to be calculated by the values in Table 6-2 (see appendix 9.1) in order to achieve the values in Table 6-3. Conclusively, Table 6-4 defines the critical nodes to configure the critical path as in figure 6-4. To observe the details of forward and backward calculations see appendix 9.4.1.

Node	Optimistic DT*	Most likely DT	Pessimistic DT	E(DT)
Supplier 1	7	10	13	10
Supplier 2	2	5	8	5
Supplier 3	14	20	26	20
Supplier 4	3.757	8	12.243	8
Supplier 5	9.804	15	20.196	15
Supplier 6	10.757	15	19.243	15
Supplier 7	4.757	9	13.243	9

*DT: Delivery Time

Table 6- 2: Calculation of expected value of delivery time

Node	Calculation of forward pass		Calculation of backward pass	
	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + EXP(DT_i)$	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - EXP(DT_i)$
Supplier 2	$ES_2=0$	5	5	0
Supplier 3	5	25	25	5
Supplier 6	25	40	73	58
Supplier 5	25	40	40	25
Supplier 1	40	50	50	40
Supplier 4	50	58	58	50
Dummy supplier 5'	58	73	73	58
Supplier 7	58	67	73	64
OEM (8)	73	-	-	$LS_8=ES_8=73$

*DT: Delivery Time

Table 6- 3: Calculation of forward and backward pass

Node	$LS_i - ES_i$
Supplier 2	0
Supplier 3	0
Supplier 6	33
Supplier 5	0
Supplier 1	0
Supplier 4	0
Dummy supplier 5'	0
Supplier 7	6
OEM (8)	0

Table 6- 4: Calculation of critical path

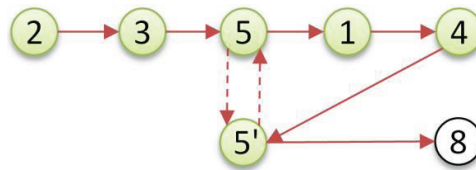


Figure. 6-4: The critical path of the network

It is noticeable that the dummy relationships have to be not considered in a critical path. The critical path is 2-3-5-1-4-5'-8.

- **Mathematical calculations of GUM for the considered network**

Following are the mathematical calculations of GUM for the considered network. Regarding to the GUM process algorithm in figure 5-15 and equations (5-20), (5-21), and (5-22) the GUM calculations are as follows:

First, the relationship function should be calculated based on sample calculations related to simple linear networks presented in section 5.2 and relation (5-20). As seen in figure 6-4, the calculated network is a linear network consisted of nodes (suppliers) 2-3-5-1-4-5' and 8. Thus, its relation is:

$$f(y) = f(DT_2) + f(DT_3) + f(DT_5) + f(DT_1) + f(DT_4) + f(DT_{5'}) \text{ and}$$

$$Y = DT_2 + DT_3 + DT_5 + DT_1 + DT_4 + DT_{5'} \quad 6-1$$

Then, the sensitivity coefficient of each supplier in the network in relation with the relationship function should be calculated through the use of the adapted GUM. This methodology is capable of choosing any number between -1 and 1 as a sensitivity coefficient. To avoid complexity in explaining the research; however, the number will be 1 if there is a critical supplier in the critical network. Otherwise, the number will be 0.

$$\frac{\partial f}{\partial DT_1} = \frac{\partial f}{\partial DT_2} = \frac{\partial f}{\partial DT_3} = \frac{\partial f}{\partial DT_4} = \frac{\partial f}{\partial DT_5} = \frac{\partial f}{\partial DT_{5'}} = 1$$

$$\frac{\partial f}{\partial DT_6} = \frac{\partial f}{\partial DT_7} = 0$$

Given relation (5-21), the standard uncertainty of the assumed network will be calculated as follows:

$$u_c^2(Y) = u(DT_2)^2 \times \left(\frac{\partial f}{\partial DT_2}\right)^2 + u(DT_3)^2 \times \left(\frac{\partial f}{\partial DT_3}\right)^2 + u(DT_5)^2 \times \left(\frac{\partial f}{\partial DT_5}\right)^2 + u(DT_1)^2 \times \left(\frac{\partial f}{\partial DT_1}\right)^2 + u(DT_4)^2 \times \left(\frac{\partial f}{\partial DT_4}\right)^2 + u(DT_{5'})^2 \times \left(\frac{\partial f}{\partial DT_{5'}}\right)^2 = 14 \text{ days}$$

$$u_c = 3.74 \text{ days}$$

According to the proved probability theorem, summation of some independent normal variable is normal (Montgomery & Runger, 2010) and because all of probability density functions in this example are normal, therefore the calculated standard uncertainty is a value with a normal probability distribution rather than a fixed value, showing the limits on both sides (it is a time frame). Obviously, for the lower of this value, the network has shown a better behavior in terms of uncertainty. Based on the GUM algorithm shown in figure 5-15, an extended uncertainty with confidence coefficient= 95.4% and K=2 will be a value with the below tolerance:

$$U = k \times u_c = 2 \times 3.74 = 7.48$$

After calculating uncertainty, the average delivery time of the network should also be calculated based on the relations introduced in section 5.2, which deal with network simplification. This calculation is conducted as follows:

$$\mu_c = \mu_2 + \mu_3 + \mu_5 + \mu_1 + \mu_4 + \mu_{5'} = \text{EXP}(DT_2) + \text{EXP}(DT_3) + \text{EXP}(DT_5) + \text{EXP}(DT_1) + \text{EXP}(DT_4) + \text{EXP}(DT_{5'}) = 73 \text{ days}$$

As a result for $\beta = 95.4\%$ time frame of delivery time up to OEM is 73 ± 7.48 days.

• **Monte Carlo method results and assumption for scenario1**

Following are Monte Carlo method results and assumption for scenario1. For calculating the Monte Carlo method followings hold true:

- Number of Monte Carlo trials (M):10000
- Probability density functions are follow Table 6-1,
- Mathematical relationship function: $f(y) = f(DT_2) + f(DT_3) + f(DT_5) + f(DT_1) + f(DT_4) + f(DT_{5'})$ and $Y = DT_2 + DT_3 + DT_5 + DT_1 + DT_4 + DT_{5'}$
- Confidence coefficient (β): 95.4% and coverage factor $k = 2$
- Results: accumulated probability density function is followed as a normal distribution function with $\mu_c = 72.96$ days and combined uncertainty $u_c = 3.71$ days. The time frame of delivery time is 72.96 ± 7.42 days. To examine the details of forward and backward calculations see appendix 9.5.1.

- ***Compare the results of GUM and Monte Carlo method***

Since, the precision of GUM as a mathematical tool is recognized and the difference in the calculation of accumulated uncertainty is only 0.08% (see Table 6-5), the capability assumption of Monte Carlo method is approved.

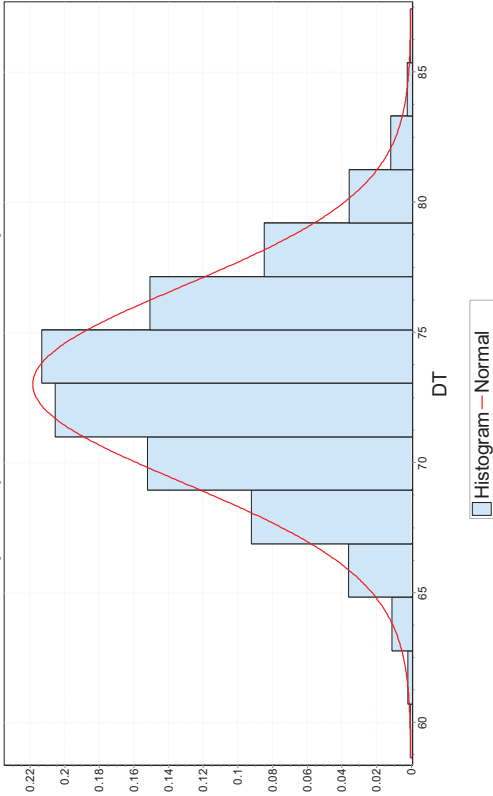
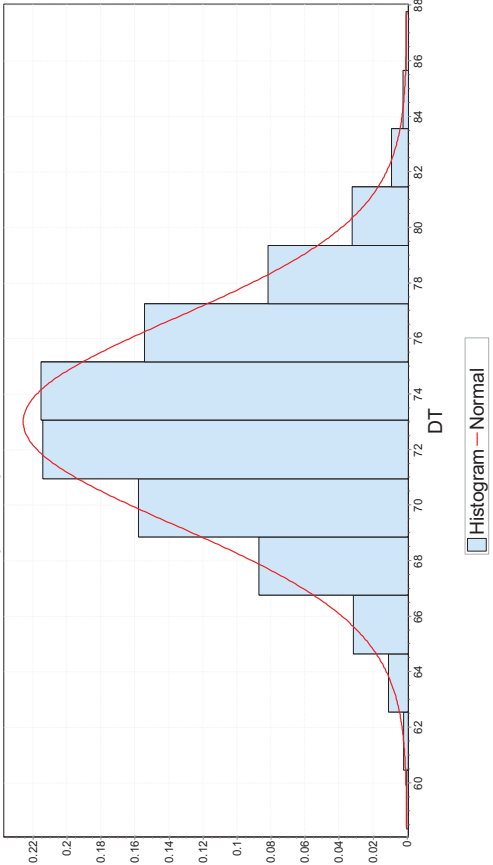
GUM [*] results	Monte Carlo method results
<div><p>Probability Density Function for scenario 1 by GUM</p><p>DT</p><p>Legend: Histogram (blue bar), Normal (red line)</p><p>Probability density function: Normal $\mu_c = 73.00$ days $u_c = 3.74$ days Difference in the calculation of accumulated uncertainty: 0.08 % *GUM: Guide to the Expression of Uncertainty in Measurement</p></div>	<div><p>Probability Density Function for scenario 1</p><p>DT</p><p>Legend: Histogram (blue bar), Normal (red line)</p><p>Probability density function: Normal $\mu_c = 72.96$ days $u_c = 3.71$ days</p></div>

Table 6- 5: Comparing the results of GUM and Monte Carlo method

6.1.2 Applicability of methodology in high complex supply network with alternative probability density functions

In case of alternative probability density functions for the nodes of the network the values represented in Table 6-6 are considered in a way that the critical path stays the same. Table 6-7 shows the expected values of delivery time for calculating the critical path.

Node	Probability density function	Indexes (day)
Supplier 1	Normal	$\mu_1 = 10, u_1^2 = 1$
Supplier 2	Rectangular	Lower bound: $a = 4$ Upper bound: $b = 6$
Supplier 3	Triangle	Lower bound: $a = 19$ Upper bound: $b = 21$
Supplier 4	Gamma	Shape parameter: $a = 4$ Scale parameter: $\theta = 2$
Supplier 5	Normal	$\mu_5 = 15, u_5^2 = 3$ $\mu_{5'} = 15, u_{5'}^2 = 3$
Supplier 6	Rectangular	Lower bound: $a = 12$ Upper bound: $b = 18$
Supplier 7	Triangle	Lower bound: $a = 7$ Upper bound: $b = 11$

Table 6- 6: The probability density functions of suppliers in scenario 2

Node	Optimistic DT	Most likely DT	Pessimistic DT	E(DT)
Supplier 1	7	10	13	10
Supplier 2	4	5	6	5
Supplier 3	19	20	21	20
Supplier 4	4	8	12	8
Supplier 5	9.804	15	20.196	15
Supplier 6	12	15	18	15
Supplier 7	7	9	11	9

*DT: Delivery Time

Table 6- 7: The expected value of delivery time

Due to the fact that, all probability density functions of delivery time in this case are not a normal function GUM can not used, for this reason, the adapted Monte Carlo method is the method which can find the accumulated delivery time uncertainty regards to the hybrid methodology algorithm (see figure 5-17).

For calculating Monte Carlo method the following steps hold true:

- Number of Monte Carlo trials (M):10000
- Probability density functions are follow Table 6-6,
- Mathematical relationship function: $f(y) = f(DT_2) + f(DT_3) + f(DT_5) + f(DT_1) + f(DT_4) + f(DT_{5'})$ and $Y = DT_2 + DT_3 + DT_5 + DT_1 + DT_4 + DT_{5'}$
- Confidence coefficient (β): 95.4% and coverage factor $k = 2$

- Results: the accumulated probability density function of the network can be estimated by “generalized extreme value” probability density function (see appendix 9.2) with ($k = -0.03694$, $u = 5.196$, $\mu = 68.82$). Regarding to the excel formulation (see appendix 9.2, and Table 9-2), which we had for this function, the mean of this delivery time and combined uncertainty are as follows: $\mu_c = 71.6356$ days and combined uncertainty $u_c = 6.3653$ days (See figure 6-5). Look at the appendix 9.5.2 to see the details of the calculations in Monte Carlo method and EasyFit.

The details of the results are in the appendix 9.5.

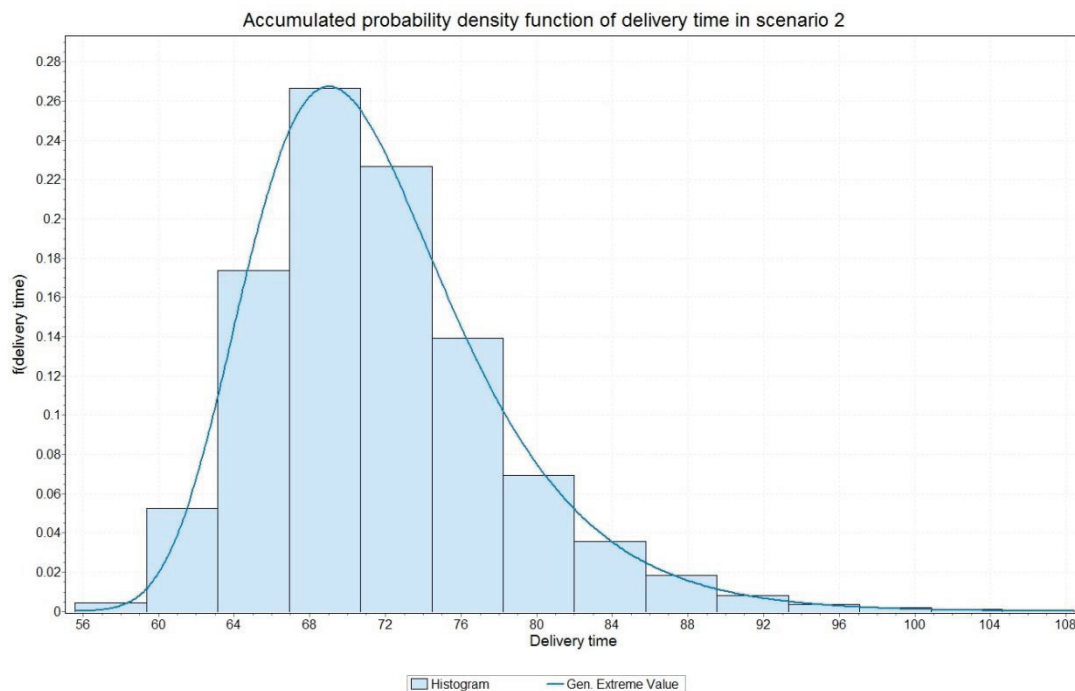


Figure. 6-5: Accumulated probability density function of delivery time for scenario 2

In conclusion, the adopted hybrid algorithm showed its potential in calculating delivery time uncertainty of supply networks with relatively simple calculation load. It was already recognized that GUM is reliable in precisely estimating uncertainty of delivery time in case of normal or t-student probability density functions. Accordingly, in the solved example the result of Monte Carlo method presented very similar values to GUM, so that its capability is also approved. With this regard, Monte Carlo method is a reliable technique in estimating of the types of delivery time uncertainty.

6.1.3 Validation of hybrid methodology by cross –validation

Cross-validation is an evaluation technique that determines the generalizability of the outcome of a statistical analysis on a data set. This technique is usually applied to estimate the accuracy of a predictive model in practice. In general, one round cross-validation includes dividing the data into

two subsets (train data and test data). It analysis on one of its subsets (train data) and validate this analysis by using the test data.

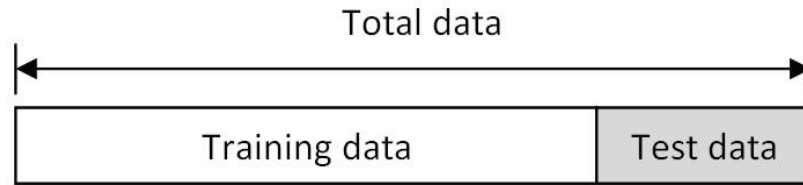


Figure. 6-6: A division of the data set into subsets (Borovicka et al. 2012)

To reduce variability, cross-validation procedure performs several rounds with different divisions, so that the validation results are averaged over the rounds. The cross validation technique is applied when the data collection is more difficult, costly or impossible (Fleet, 2002).

○ **K-fold validation:**

In this case of validation, the data are randomly partitioned into K equal size subsets. From this K subsets, each time, a single subset is selected as the test data for validation and other $(K-1)$ subsets are used as train data. This procedure is repeated K times, and all data are used exactly once for training and once for validation. The average of these K validations shows the final accuracy of the estimating model (Browne, 2000).

A single round of K -fold cross validation proceeds as follows:

- 1 Arrange the data in a random order
- 2 Partition the train data into K -folds

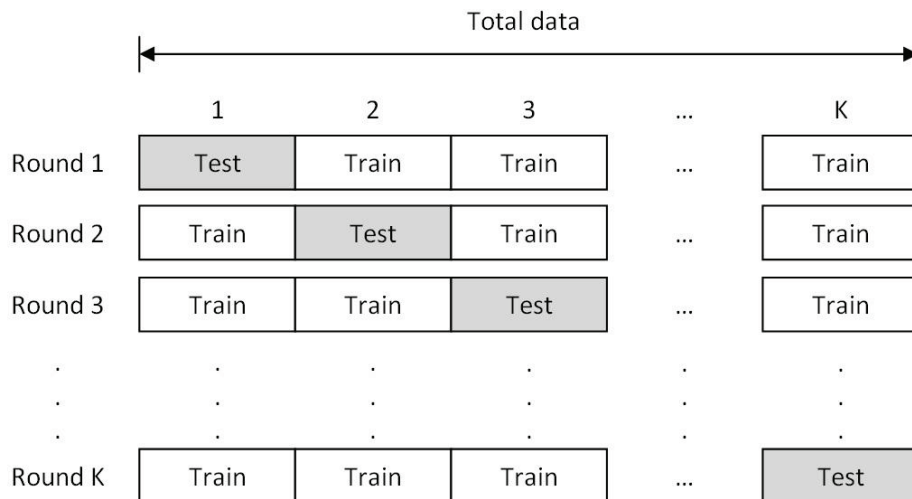


Figure. 6-7: K-folds cross-validation

- 3 For each K experiment, use $(K-1)$ folds for training and the left one for testing and validating.

- 4 In each round ($i = 1, 2, 3, \dots, K$), fit the model according to the $K-1$ folds and test and validate the model by the test data. Find the error of each round (E_i).
- 5 Calculate Error of the model (E).

$$E = \frac{\sum_{i=1}^K E_i}{K} \quad 6-2$$

○ **Validation of the hybrid algorithm by cross-validation technique:**

To validate the hybrid algorithm, we applied cross-validation technique to show the accuracy of the estimated probability density function for the delivery time uncertainty of the supply network. To this end, the error of the estimated function for the numerical example of section 6.1.2, is calculated by cross-validation technique.

In the numerical example of section 6.1.2, after simplification of the network the critical path was a linear network of the suppliers 2, 3, 5, 1, 4, 5', and 8. The relationship function of this network regarding to the introduced strategies in chapter 5, is the same of equation (6-1).

According to the introduced probability density function of each critical supplier, by Monet Carlo method, 10000 random data are generated and by relationship function 10000 times of Y are created. Then, by using the combination of Monet Carlo's method and EasyFit software the best probability density function for Y is estimated. This function is the result of hybrid method, and all of decision after that (like calculating of the accumulated uncertainty) is made based on it. For this reason, calculating the error of this created probability density function can show the error of the hybrid algorithm. In order to have more clearly imagination of this discussion, please look at Table 6-8.

$f(Y) = f(DT_2) + f(DT_3) + f(DT_5) + f(DT_1) + f(DT_4) + f(DT_{5'})$ and $Y = DT_2 + DT_3 + DT_5 + DT_1 + DT_4 + DT_{5'}$							
Row	DT_2^{**} (Random number according to probability density function*)	DT_3 (Random number according to probability density function)	DT_5 (Random number according to probability density function)	DT_1 (Random number according to probability density function)	DT_4 (Random number according to probability density function)	$DT_{5'}$ (Random number according to probability density function)	Y
1	Random number	Random number	Random number	Random number	Random number	Random number	Y1
2	Random number	Random number	Random number	Random number	Random number	Random number	Y2
3	Random number	Random number	Random number	Random number	Random number	Random number	Y3
...
9998	Random number	Random number	Random number	Random number	Random number	Random number	Y9998
9999	Random number	Random number	Random number	Random number	Random number	Random number	Y9999
10000	Random number	Random number	Random number	Random number	Random number	Random number	Y10000
*probability density function: Probability density function							
**DT: Delivery time							

Table 6-8: Generated random numbers by adapted Monte Carlo

As introduced before, the probability density function of delivery time uncertainty of the proposed network in the numerical example of section 6.1.2 was “**generalized extreme value**” indicated by $k = -0.03694$, $u = 5.196$, and $\mu = 68.82$. To validate the hybrid methodology, error of fitting the probability density function is calculated by the 10-folds cross-validation technique. Table 6-9, shows the subsets.

Subset 1	Subset 2	Subset 3	Subset 4	Subset 5	Subset 6	Subset 7	Subset 8	Subset 9	Subset 10
Y_1	Y_{1001}	Y_{2001}	Y_{3001}	Y_{4001}	Y_{5001}	Y_{6001}	Y_{7001}	Y_{8001}	Y_{9001}
Y_2	Y_{1002}	Y_{2002}	Y_{3002}	Y_{4002}	Y_{5002}	Y_{6002}	Y_{7002}	Y_{8002}	Y_{9002}
Y_3	Y_{1003}	Y_{2003}	Y_{3003}	Y_{4003}	Y_{5003}	Y_{6003}	Y_{7003}	Y_{8003}	Y_{9003}
.
.
.
Y_{1000}	Y_{2000}	Y_{3000}	Y_{4000}	Y_{5000}	Y_{6000}	Y_{7000}	Y_{8000}	Y_{9000}	Y_{10000}

Table 6-9: Organization of subset data for 10-folds cross-validation in hybrid methodology

Afterward, 10 rounds and experiments are designed (see figure 6-8).

Round 1	Train data (Y_1, \dots, Y_{9000})	Test data ($Y_{9001}, \dots, Y_{10000}$)
Round 2	Train data (Y_1, \dots, Y_{8000}) and ($Y_{9001}, \dots, Y_{10000}$)	Test data ($Y_{8001}, \dots, Y_{9000}$)
Round 3	Train data (Y_1, \dots, Y_{7000}) and ($Y_{8001}, \dots, Y_{10000}$)	Test data ($Y_{7001}, \dots, Y_{8000}$)
Round 4	Train data (Y_1, \dots, Y_{6000}) and ($Y_{7001}, \dots, Y_{10000}$)	Test data ($Y_{6001}, \dots, Y_{7000}$)
Round 5	Train data (Y_1, \dots, Y_{5000}) and ($Y_{6001}, \dots, Y_{10000}$)	Test data ($Y_{5001}, \dots, Y_{6000}$)
Round 6	Train data (Y_1, \dots, Y_{4000}) and ($Y_{5001}, \dots, Y_{10000}$)	Test data ($Y_{4001}, \dots, Y_{5000}$)
Round 7	Train data (Y_1, \dots, Y_{3000}) and ($Y_{4001}, \dots, Y_{10000}$)	Test data ($Y_{3001}, \dots, Y_{4000}$)
Round 8	Train data (Y_1, \dots, Y_{2000}) and ($Y_{3001}, \dots, Y_{10000}$)	Test data ($Y_{2001}, \dots, Y_{3000}$)
Round 9	Train data (Y_1, \dots, Y_{1000}) and ($Y_{2001}, \dots, Y_{10000}$)	Test data ($Y_{1001}, \dots, Y_{2000}$)
Round 10	Train data ($Y_{1001}, \dots, Y_{10000}$)	Test data (Y_1, \dots, Y_{1000})

Figure. 6-8: 10 rounds of designing cross validation for hybrid methodology

In each round we fit a probability density function according to the train data. After the probability density function is created ($g(y_{\text{Train}})$), put the test data into the $g(y_{\text{Train}})$ and calculate the amount of probability density function of test data $g(y_{\text{Test}})$ according to the probability density function, which is created by train data and compare this number with the original probability density function $f(y)$, which is obtained by hybrid model for the test data $f(y_{\text{Test}})$. Afterward, by the equation (6-3), the error of each fitted function for each round (E_{round}), must be calculated individually. The final error of fitted probability density function for hybrid model is obtained by the average of round errors (see equation (6-4)). Table 6-10, illustrates the process of error calculation for each round.

$$E_{\text{round}} = \sqrt{\frac{(g(y_{\text{Test}}) - f(y_{\text{Test}}))^2}{1000}} \quad 6-3$$

$$E = \frac{\sum_{\text{round}=1}^{10} E_{\text{round}}}{10} \quad 6-4$$

Round	$f(y)$	$g(y_{Test})$	E_{round}
1		Generalized extreme value ($k = -0.03533$, $u = 5.1907$, $\mu = 68.818$)	5.66306×10^{-5}
2		Generalized extreme value ($k = -0.03644$, $u = 5.2075$, $\mu = 68.807$)	0.000133537
3		Generalized extreme value ($k = -0.0438$, $u = 5.2316$, $\mu = 68.827$)	0.000321858
4		Generalized extreme value ($k = -0.04319$, $u = 5.2199$, $\mu = 68.831$)	0.000249367
5	Generalized extreme value ($k = -0.03694$, $u = 5.196$, $\mu = 68.82$)	Dagum 4p ($k = 5.6433$, $\alpha = 566$, $\beta = 2606.4$, $\gamma = -2540$)	0.002108412
6		Generalized extreme value ($k = -0.03981$, $u = 5.2134$, $\mu = 68.829$)	0.000167645
7		Dagum 4p ($k = 6.57$, $\alpha = 160.11$, $\beta = 748.33$, $\gamma = -687.95$)	0.001150483
8		Generalized extreme value ($k = -0.03714$, $u = 5.1793$, $\mu = 68.841$)	0.000193058
9		Generalized extreme value ($k = -0.03857$, $u = 5.195$, $\mu = 68.845$)	0.000173351
10		Generalized extreme value ($k = -0.03345$, $u = 5.2063$, $\mu = 68.821$)	0.000123987

Table 6-10: Process of error calculation for each round

$$E = \frac{\sum_{round=1}^{10} E_{round}}{10} = 0.000468$$

The calculation of the 10 folds cross-validation shows that the error of the fitted probability density function is approximately 0.05%. This amount shows the function is fitted with high accuracy and it validates the hybrid methodology results.

6.2 Applicability of hybrid methodology in three different supply networks as case study

As mentioned before, calculating delivery time uncertainty for custom products is one of the main goals of the hybrid methodology. Each product requires its own supplier. Therefore, a supply network is designed for each specific product, since the relevant OEM does not have a fixed supply network. Given the importance of timely delivery and the need for delivering goods with the lowest deviation from the guaranteed delivery time and highest confidence coefficient in today's competitive market, this methodology provides quick and accurate information to help managers decide about delivery time uncertainty. This section has introduced real-life supply networks (provided by literature) and calculated time delivery uncertainty for each of them through the use of the adapted hybrid methodology in order to show the methodology's application in real life. Unfortunately, normal probability density functions for delivery time were assigned to all the cases since there was no proper method to assign different probability density functions to each delivery time. To further challenge the hybrid methodology, probability density functions assigned to the delivery times were assumed as different, replacing normal conditions in some cases. Each network will be discussed in detail below:

6.2.1 A case study from the commodity supply networks for custom products

To challenge the proposed hybrid methodology, the first supply network to which the methodology is applied is a notebook supply network extracted from studies conducted by Graves and Willems (2005) and Li and Womer (2008). This network supplied two types of notebooks dubbed here as notebook “A” (gray cover) and notebook “B” (blue cover), both of them assembled by the same OEM. Notebook “A” has been targeted both U.S. and foreign markets, while notebook B is for the U.S. market only.

The supply network has been designed after conducting a survey on 100 notebook manufacturers. It consists of fourteen suppliers manufacturing two types of notebooks based on the orders offered by customers. A notebook computer is consisted of three main components, namely a liquid crystal display (LCD), a circuit board and a housing. In the mentioned supply network, LCDs are a standard component supplied by a foreign supplier (supplier 5). The housings are supplied by another foreign supplier (supplier 6). Also, all components of the circuit boards are supplied by foreign suppliers (suppliers 1, 2, 3, and 4) and assembled by a factory which is a member of the network (supplier 7). Production of notebook batteries, which is a time-consuming process, is also assigned to a foreign supplier (supplier 8).

Graves and Willems examined all the notebook supply networks and assumed all suppliers of notebook sub-components as a single supplier (supplier 9). The assembly process of supplier 11 consists of assembling all the components, conducting relevant quality tests and creating generic notebooks, all of which take place in a factory. Afterward, the generic notebook is customized by providing it with a blue or gray cover. The supplier of gray-covered notebooks is called "supplier 10", while the supplier of blue-covered notebook is called "supplier 12". Gray-covered notebooks are assembled by supplier 13 and the blue-covered ones are assembled by supplier 14. All of these notebooks are shipped to the OEM to undergo final tests. The gray notebooks target both U.S. and foreign markets while the blue ones are presented in the U.S. market only. This supply network has been illustrated in figure 6-9.

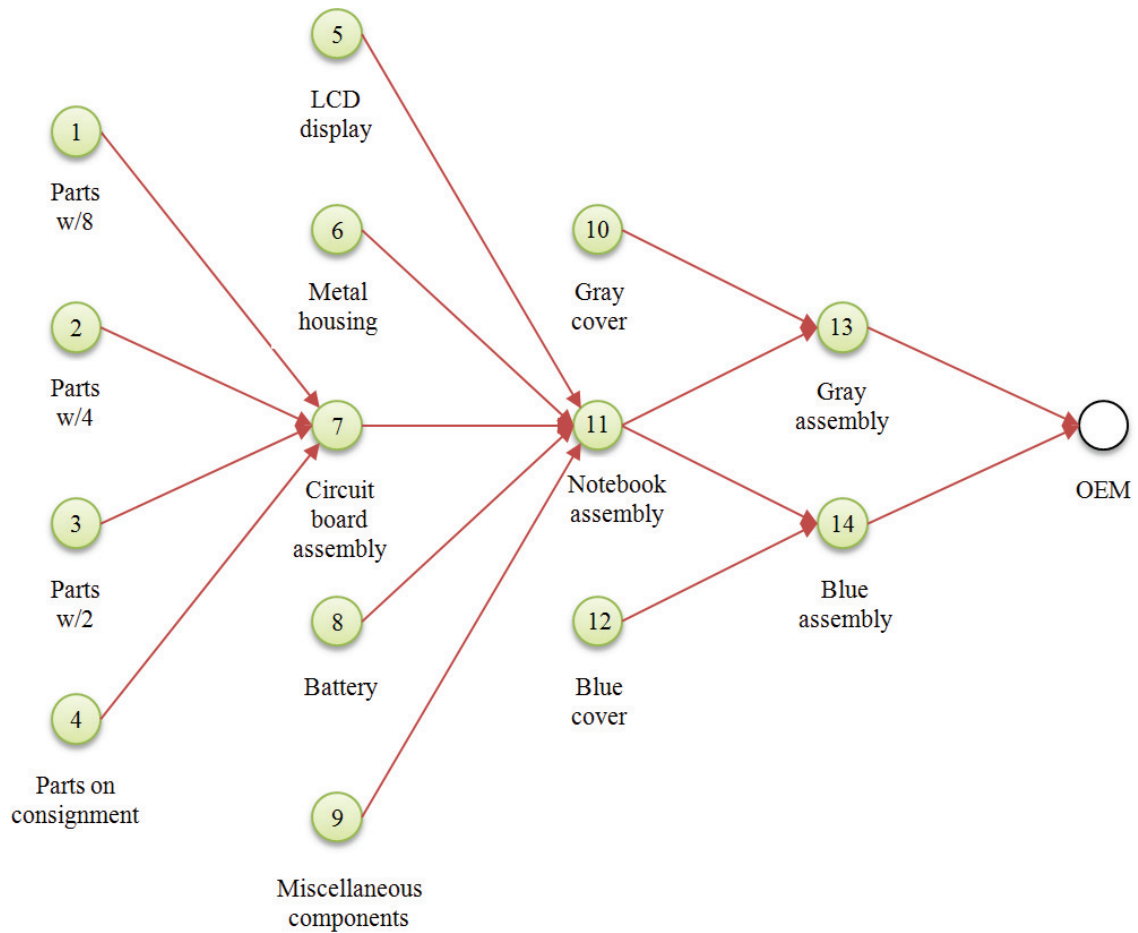


Figure. 6-9: Notebook computer supply network

Since this supply network has been designed to provide two products, it is necessary to demonstrate the supply network of each product separately so as to be able to implement the hybrid methodology. Accordingly, we have illustrated the separate supply networks of these two products in figure 6-10. The network on the left belongs to the blue-covered notebooks, while the one on the right belongs to Gary-covered notebooks.

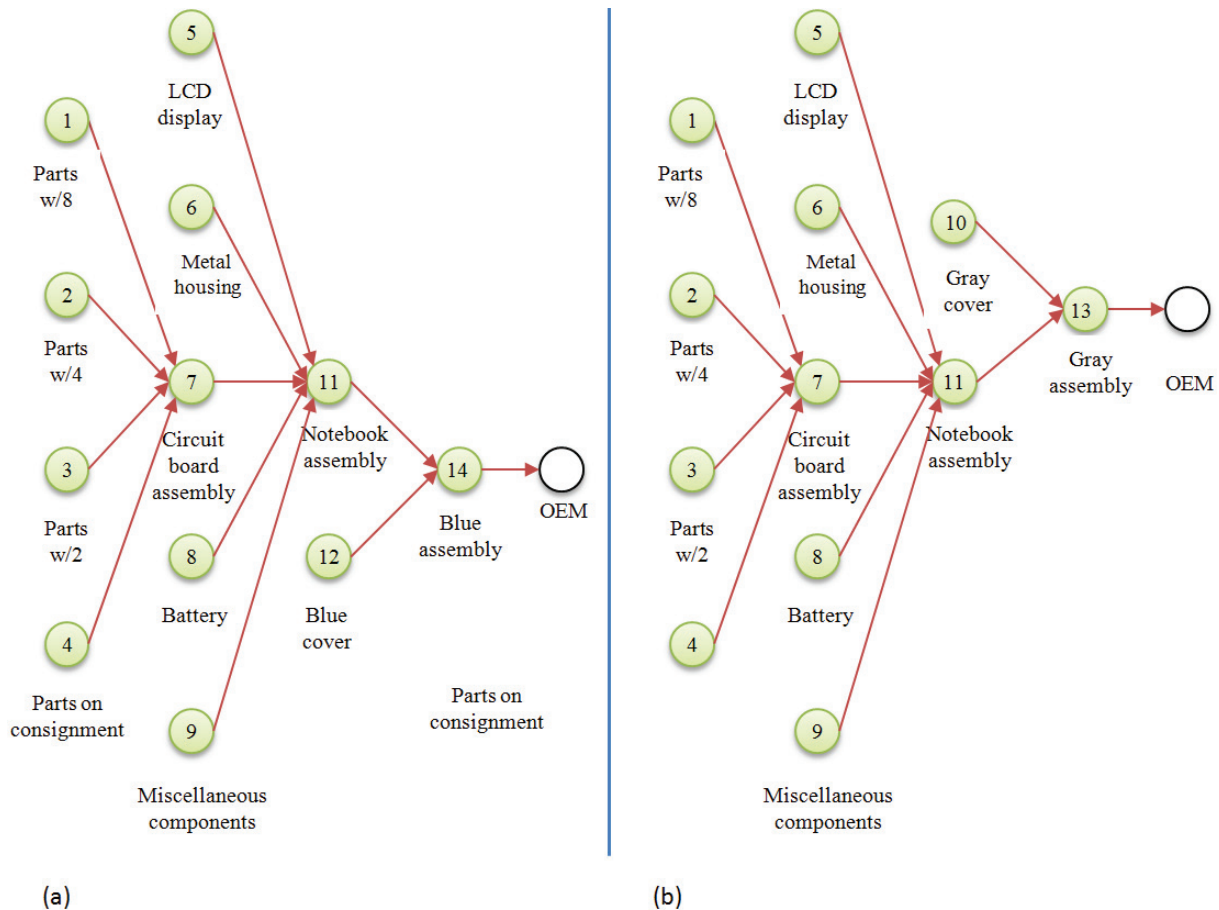


Figure. 6-10: Instance supply networks for two variant notebook computers

The probability density functions of all the suppliers have been presented in Table 6-11 based on the delivery times for the suppliers in this case study as well as the delivery time observed by Graves and Willems (2005).

Node	Stage name	Probability density functions	Mean (μ_i) = EXP(DT _i) (Day)	Variance (u_i^2)(Day)
Supplier 1	Parts w/8	Normal	40	6
Supplier 2	Parts w/4	Normal	20	8
Supplier 3	Parts w/2	Normal	20	4
Supplier 4	Parts on consignment	Normal	5	0
Supplier 5	LCD display	Normal	60	3
Supplier 6	Metal housing	Normal	70	2
Supplier 7	Circuit board assembly	Normal	20	4
Supplier 8	Battery	Normal	60	5
Supplier 9	Miscellaneous components	Normal	30	4
Supplier 10	Gray cover	Normal	40	5
Supplier 11	Subassembly	Normal	5	2
Supplier 12	Blue cover	Normal	40	5
Supplier 13	Gray assembly	Normal	1	0
Supplier 14	Blue assembly	Normal	1	0

*DT: Delivery Time

Table 6- 11: **The probability density functions of suppliers in notebook computer supply network (Graves & Willems, 2005)**

Then, the adapted hybrid methodology is applied to the above-mentioned supply network to calculate its delivery time uncertainty. Since the mean of delivery time, standard uncertainty, and probability density functions are equal for suppliers 12, 13 and 14, which produce two different products, the level of uncertainty will be equal for both products. Hence calculate the uncertainty of one of them only namely the blue-covered notebooks will be calculated. In the following, the adapted hybrid methodology will be examined:

Critical supply networks whose delivery time fluctuations have the highest impact on their uncertainty are identified after the E(DT) and probability density function of each network is determined. The network is simplified and prepared for further calculations by identifying these suppliers through the use of the adapted PERT and data extracted from Table 6-11. Forward pass and backward pass calculations for network (a), illustrated in figure 6-10, have been presented in Table 6-12. Suppliers 1, 2, 3, 4, 5, 6, 8, 9 and 12 are identified as beginner nodes since they enjoy the lowest input degree and are not preceded by any suppliers, while the OEM is considered the last node in the network. Calculation details for Table 6-9 have been presented in appendix 9.4.2.

Node	Calculation of forward pass		Calculation of backward pass	
	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + EXP(DT_i)$	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - EXP(DT_i)$
Supplier 1	$ES_1=0$	40	50	10
Supplier 2	$ES_2=0$	20	50	30
Supplier 3	$ES_3=0$	20	50	30
Supplier 4	$ES_4=0$	5	50	45
Supplier 7	40	60	70	50
Supplier 5	$ES_5=0$	60	70	10
Supplier 6	$ES_6=0$	70	70	0
Supplier 8	$ES_8=0$	60	70	10
Supplier 9	$ES_9=0$	30	70	40
Supplier 11	70	75	75	70
Supplier 12	$ES_{12}=0$	40	75	35
Supplier 14	75	76	76	75
OEM (15)	76	-	-	$LS_{15}=ES_{15}=76$

*DT: Delivery Time

Table 6- 12: **Calculation of forward and backward in notebook computer supply network**

In this stage, we need to find the critical network. The results of calculations related to the critical network, obtained through the use of the PERT algorithm illustrated in figure 5-14, have been presented in Table 6-13.

Node	$LS_i - ES_i$
Supplier 1	10
Supplier 2	30
Supplier 3	30
Supplier 4	35
Supplier 7	10
Supplier 5	10
Supplier 6	0
Supplier 8	10
Supplier 9	40
Supplier 11	0
Supplier 12	35
Supplier 14	0
OEM (15)	0

Table 6- 13: **Calculation of the critical path in notebook computer supply network**

As shown in Table 6-13, suppliers for which the difference between the earliest and latest start times is zero are considered critical suppliers of the network. The path of the critical network has been drawn in figure 6-11.

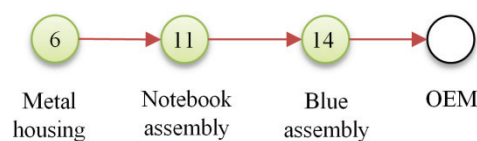


Figure. 6-11: Critical path network for notebook computer

At the next stage, the computational engine of the algorithm should be determined. As mentioned in chapter 5, the GUM model is employed to conduct the calculations since all the suppliers in the critical network enjoy normal probability density functions, the number of suppliers is low, and the network's form and structure are the linear one. Regarding the adapted GUM illustrated in figure 5-15 and equations (5-20), (5-21) and (5-22), the calculations are as follows:

First, the relationship function of the suppliers is defined as follows since the critical network of notebooks has been turned into a single line (see section 5.2):

$$\begin{aligned} f(y) &= f(DT_6) + f(DT_{11}) + f(DT_{14}) \text{ and} \\ Y &= DT_6 + DT_{11} + DT_{14} \end{aligned} \quad 6-5$$

In other words, the uncertainty for suppliers 6, 11 and 14, will have the highest effect on the delivery time uncertainty of the whole network. That is why, the relationship function for these three critical suppliers of the network is more important than the others, because the uncertainty of other suppliers will be in the shadow of these three suppliers uncertainties.

One of our assumptions in the hybrid methodology is that the confidence coefficient of the delivery time uncertainty for supplier “i” will be equal to “1” into the relationship function ($\frac{\partial f}{\partial DT_i} = 1$) if this supplier is a member of the critical network. Otherwise, the value will be zero ($\frac{\partial f}{\partial DT_i} = 0$). In that case, the assumption will be as follows:

$$\begin{aligned} \frac{\partial f}{\partial DT_6} &= \frac{\partial f}{\partial DT_{11}} = \frac{\partial f}{\partial DT_{14}} = 1 \\ \frac{\partial f}{\partial DT_1} &= \frac{\partial f}{\partial DT_2} = \frac{\partial f}{\partial DT_3} = \frac{\partial f}{\partial DT_4} = \frac{\partial f}{\partial DT_5} = \frac{\partial f}{\partial DT_7} = \frac{\partial f}{\partial DT_8} = \frac{\partial f}{\partial DT_9} = \frac{\partial f}{\partial DT_{12}} \\ &= 0 \end{aligned}$$

Given the relationship function, the assumptions and equation (5-22), the standard uncertainty for the notebook network (u_c) is calculated as follows:

$$\begin{aligned} u_c^2(Y) &= u(DT_6)^2 \times \left(\frac{\partial f}{\partial DT_6}\right)^2 + u(DT_{11})^2 \times \left(\frac{\partial f}{\partial DT_{11}}\right)^2 + u(DT_{14})^2 \times \\ &\left(\frac{\partial f}{\partial DT_{14}}\right)^2 = 4 \text{ days} \\ u_c &= 2 \text{ days} \end{aligned}$$

The standard uncertainty of delivery time for this network is 2, namely a numerical range with the maximum tolerance of 2 days. Because of the normalcy of delivery time for all network members, the delivery time of the whole network is also normal, with its mean of delivery time being determined by adding up the mean delivery times of all the members since the critical network is a linear one (see section 5.2).

$$\text{EXP}(\text{DT}_c) = \mu_c = \text{EXP}(\text{DT}_6) + \text{EXP}(\text{DT}_{11}) + \text{EXP}(\text{DT}_{14}) = \mu_6 + \mu_{11} + \mu_{14} = 76 \text{ days}$$

The expanded uncertainty with a confidence coefficient=95.4% and coverage factor=2 have been calculated as shown below. This expanded uncertainty indicated that the managers of the notebook networks will be able to deliver notebooks within the pre-determined delivery time range, by 95% of confidence.

$$U = k \times u_c = 2 \times 2 = 4$$

As a result for $\beta = 95.4\%$ time frame of delivery time up to OEM is 76 ± 4 days.

The final diagram of the delivery time probability density function and its uncertainty has been illustrated in figure 6-12.

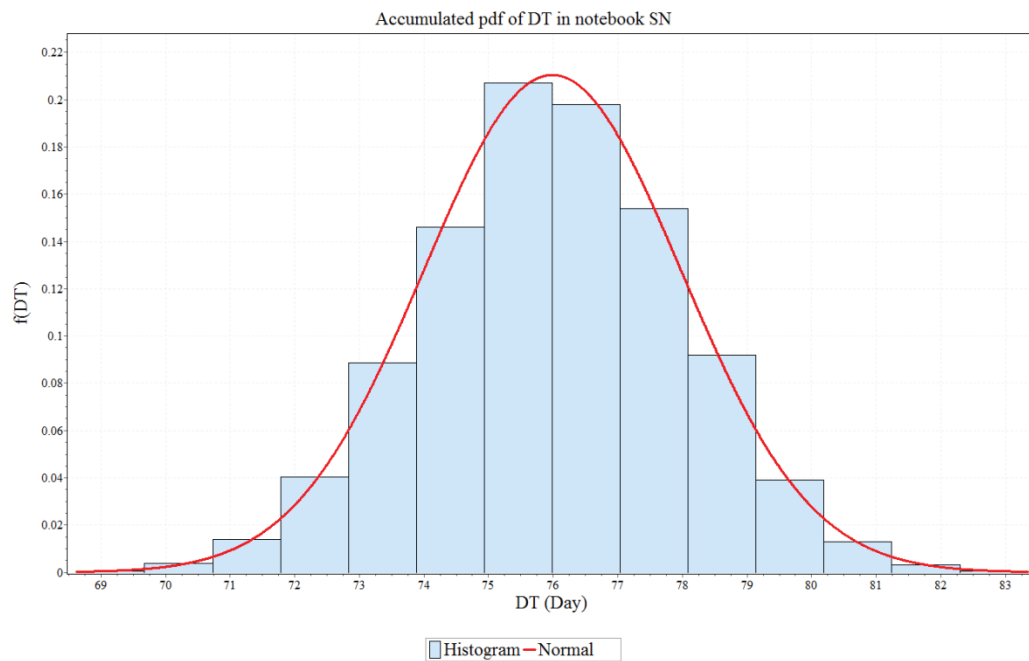


Figure. 6-12: Accumulated probability density function of delivery time uncertainty in the supply network

6.2.2 A case study for supply networks with more than one OEM

In this section, the hybrid methodology is applied to another type of supply network. In the real world, not all of the supply networks have a single OEM, and some networks provide goods based on orders placed by several OEMs. The hybrid methodology is applied to the supply network of Noramco's spray nozzles here in order to see how it works for such networks. This case study has been taken from a study conducted by Kumar (2001).

General Pump (GP) started operating as a distributor of high pressure positive displacement plunger pumps in the US market. It embarked on manufacturing products such as high pressure spray tips (nozzles) and pump thermal protectors (PTPs) through its subsidiary (Noramco). Normaco's supply

network of high pressure spray tips (nozzles) has been illustrated in figure 6-13. Nozzles consist of three main components: an orifice, a body and a plastic cap. About sixty six types of orifices with different current rates and spray angles are available presently. The body of these sprays is available in four types: quick connect body (Q), $\frac{1}{4}$ national pipe thread (NPT) male (M), $\frac{1}{8}$ NPT male (S) and $\frac{1}{4}$ NPT female (F). Also, caps are produced in four colors showing type of the spray angle. Normaco has four major OEMs among which the above-mentioned products are distributed by GP. The supply network of these products has been illustrated in figure 6-13.

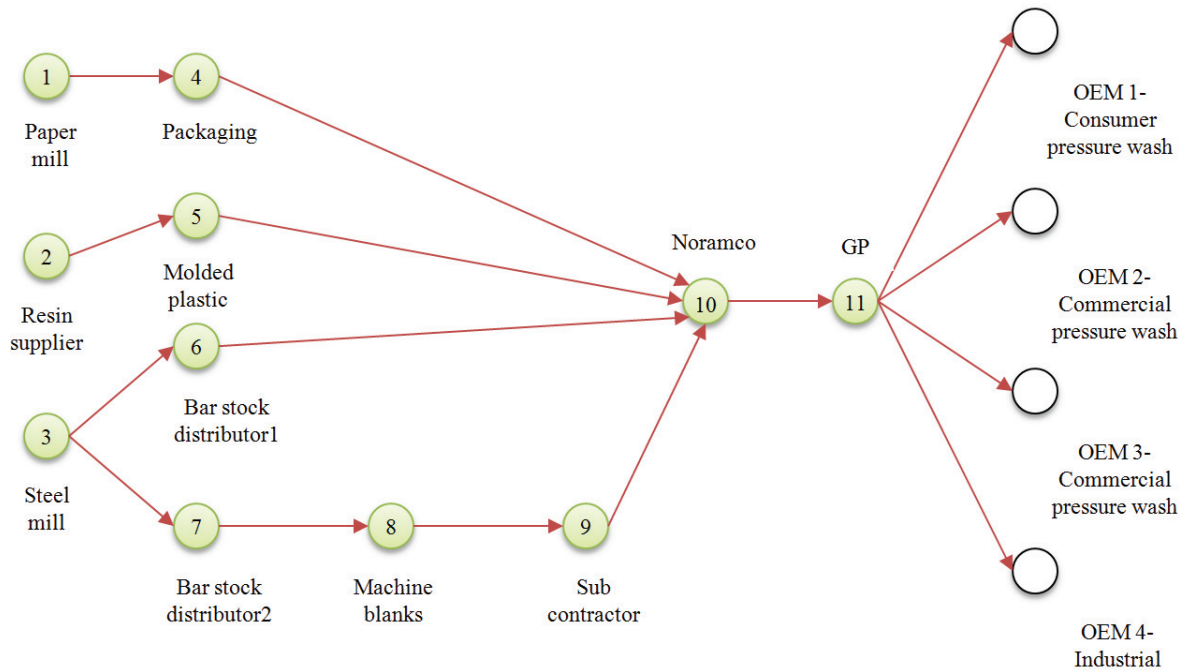


Figure. 6-13: Noramco's spray nozzles supply network

Since the hybrid methodology could be applied only to the supply network of one product with one OEM, the network of each OEM should be drawn separately, and its delivery time uncertainty should also be calculated individually. For this purpose, the supply network illustrated in figure 6-13 is divided into four separate supply networks, which have been shown in figure 6-14.

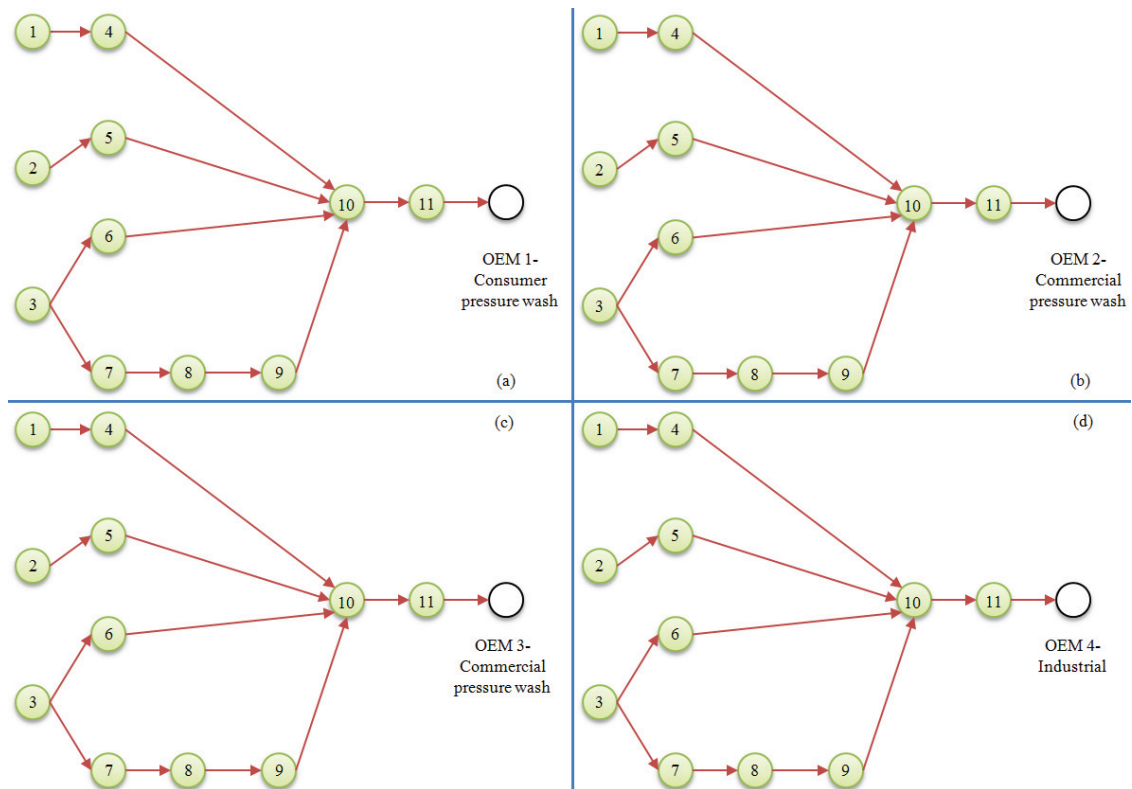


Figure. 6-14: Four different supply networks of Noramco's spray nozzles for each product and each OEM separately

As seen in figure 6-14, the suppliers of the four networks are the same and the only difference between these networks is that each of them has a different OEM. The response of all the four networks to the methodology is similar, and their uncertainty is equal since the accumulated delivery time uncertainty does not take OEMs into consideration in this methodology. Thus we will examine only one of these networks, namely network (d). The delivery times mentioned in this case study have been taken from Kumar's study (2001). Pdfs of all the suppliers have been presented in Table 6-14.

Node	Stage name	Probability density function	Indexes (day)
Supplier 1	Paper mill	Normal	$\mu_1 = 95, u_1^2 = 5$
Supplier 2	Resin supplier	Normal	$\mu_2 = 65, u_2^2 = 4$
Supplier 3	Steel mill	Normal	$\mu_3 = 95, u_3^2 = 4$
Supplier 4	Packaging	Normal	$\mu_4 = 32, u_4^2 = 3$
Supplier 5	Molded plastic	Normal	$\mu_5 = 32, u_5^2 = 2$
Supplier 6	Bar stock distributor1	Normal	$\mu_6 = 12, u_6^2 = 4$
Supplier 7	Bar stock distributor2	Rectangular	Lower bound: $a = 10$ Upper bound: $b = 20$
Supplier 8	Machine blanks	Normal	$\mu_8 = 15, u_8^2 = 5$
Supplier 9	Subcontractor	Rectangular	Lower bound: $a = 42$ Upper bound: $b = 48$
Supplier 10	Noramco	Triangular	Lower bound: $a = 12$ Upper bound: $b = 16$ $c = 14$
Supplier 11	GP	Rectangular	Lower bound: $a = 3$ Upper bound: $b = 9$

Table 6-14: The probability density functions of suppliers in supply networks of Noramco's spray nozzles (Kumar, et al., 2001)

Table 6-15 contains optimistic delivery time, most likely delivery time, pessimistic delivery time and EXP (DT) calculations for each supplier, required to calculate the critical path of the adapted PERT. These calculations have also been presented in Table 9-1, in the appendix 9.1. It is noteworthy that all the calculations were conducted through assuming coverage= 95.4% and K=2.

Node	Optimistic DT	Most likely DT	Pessimistic DT	E(DT)
Supplier 1	91	95	99	95
Supplier 2	61	65	69	65
Supplier 3	91	95	99	95
Supplier 4	29	32	35	32
Supplier 5	29	32	35	32
Supplier 6	8	12	16	12
Supplier 7	10	15	20	15
Supplier 8	11	15	19	15
Supplier 9	42	45	48	45
Supplier 10	12	14	16	14
Supplier 11	3	6	9	6

*DT: Delivery Time

Table 6-15: Calculation of expected value of delivery time for suppliers of Noramco's spray nozzles

In the next step, backward pass and forward pass calculations should be calculated through the use of the adapted PERT to identify the critical suppliers of the network. Therefore, data related to the expected delivery time for each supplier are extracted from Table 6-15 to conduct these calculations, which have been presented in Table 6-16. Suppliers 1, 2 and 3 are selected as beginner nodes since they have the lowest input degrees (0), and backward pass as well as forward pass are calculated using the adapted PERT illustrated in Table 6-17. Like the previous example, details of calculations presented in Table 6-16 could be found in appendix 9.4.3.

Calculation of forward pass			Calculation of backward pass	
Node	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + EXP(DT_i)$	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - EXP(DT_i)$
Supplier 1	$ES_1=0$	95	138	43
Supplier 2	$ES_2=0$	65	138	73
Supplier 3	$ES_3=0$	95	95	0
Supplier 4	95	127	170	138
Supplier 5	65	97	170	138
Supplier 6	95	107	170	158
Supplier 7	95	110	110	95
Supplier 8	110	125	125	110
Supplier 9	125	170	170	125
Supplier 10	170	184	184	170
Supplier 11	184	190	190	184
OEM-4 (12)	190	-	-	$LS_{12}=ES_{12}=190$

*DT: Delivery Time

Table 6-16: Calculation of forward and backward pass for Noramco's spray nozzles supply network

As seen in Table 6-16, the LS_i of the third supplier is equal to 0, meaning that this supplier is the beginner node of our critical network, while the OEM is its last node naturally. Now, we need to continue with the calculations presented in Table 6-17 in order to identify the remainder of critical suppliers.

Node	$LS_i - ES_i$
Supplier 1	43
Supplier 2	73
Supplier 3	0
Supplier 4	43
Supplier 5	73
Supplier 6	73
Supplier 7	0
Supplier 8	0
Supplier 9	0
Supplier 10	0
Supplier 11	0
OEM-4 (12)	0

Table 6-17: Calculation of the critical path in Noramco's spray nozzles supply network

Results of Table 6-17 indicate that all the suppliers for which the difference between the earliest start time, and the latest start time is equal to zero are regarded as critical suppliers. The path of the critical network has been illustrated in figure 6-15.

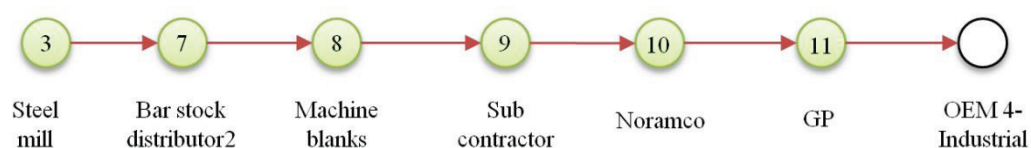


Figure. 6-15: Critical path network for Noramco's spray nozzles supply network

The importance of probability density function type is highlighted when trying to identify the method for calculating the standard delivery time

uncertainty of the supply network of Noramco's spray nozzles. Monte Carlo method is a good method for calculating the network's delivery time uncertainty since suppliers 7, 9, 10, and 11 do not have normal distribution functions. Introducing the number of Monte Carlo method trials (M) is the first step in this regard, as mentioned in the section dealing with the adapted Monte Carlo method (figure 5-16). The "M" value compels the engine to produce "M" random numbers for delivery time depending on the probability density function type of the supplier. In this research, M=10,000 is considered in all the cases. In the next step, the probability density function of all the suppliers, presented in Table 6-14, should be determined. Then, the relationship function should be created. This function has been presented in the form of equation (6-6) given the linear nature of the critical network and the method of calculations for linear networks mentioned in section 5.2.

$$f(y) = f(DT_3) + f(DT_7) + f(DT_8) + f(DT_9) + f(DT_{10}) + f(DT_{11}) \text{ and} \\ Y = DT_3 + DT_7 + DT_8 + DT_9 + DT_{10} + DT_{11} \quad 6-6$$

After determining the relationship function, it is needed to measure the confidence coefficient (β). Since the coverage factor (K) is equal to 2 for all the cases, the confidence coefficient is decided to be 95.4%. Now, all the input data required during the implementation of the adapted Monte Carlo method are available. Data are added to an Excel program using software such as EasyFit, which serves as an engine to produce random numbers. The output will be as follows:

Monte Carlo method results indicate that the standard uncertainty is equal to 4.91 days ($u_c = 4.91$ day), the expected delivery time is equal to 190.02 days ($E(DT) = 190.02$ day), and the best probability density function for calculating accumulated uncertainty for this network, which has an Error distribution function, has the following features: $k=2$, $u_c=4.91$, and $m=190.02$. To perceive more details of the calculations in Monte Carlo method and EasyFit see appendix 9.5.3. Additionally, the error distribution goes by a variety of names: Exponential Power Distribution, Generalized Error Distribution (GED), Generalized Gaussian distribution (GGD), and Subbotin distribution. More details about this probability density function are available in appendix 9.3. Figure 6-16 illustrates the accumulated delivery time uncertainty diagram for the supply network of Noramco's spray nozzles.

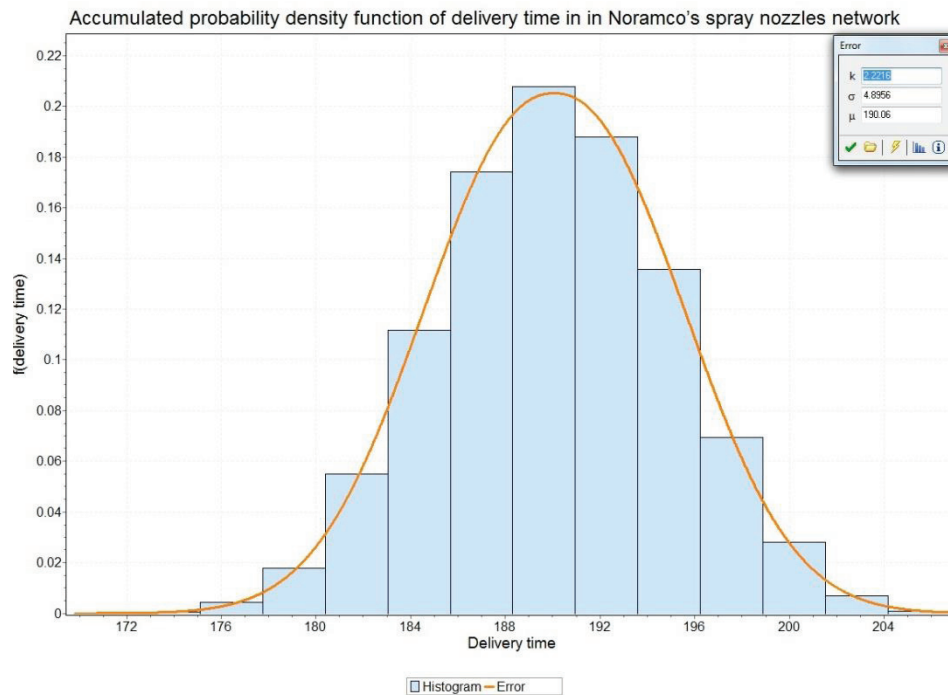


Figure. 6-16: Accumulated probability density function of delivery time uncertainty in Noramco's spray nozzles supply network

6.2.3 A case study for supply networks with more than one critical path

In this section, the supply, assembly and production network of bulldozers presented by Graves and Willems (2002) will be examined. In higher supply levels, a bulldozer consists of fourteen major stages: frame assembly, case, brake system, drive, plant carrier, platform, fender, rollover, transmission, engine, fan, bogie assembly, pin assembly, and track-roller frame (Nepal, et al., 2012). In the frame assembly process, the chassis and the engine are assembled as the output of the supplier of the common subassembly stage. Finally, track and suspension are mounted. The main supply network, which is consisted of suppliers of small parts, has about one thousand suppliers and sub-suppliers. Graves and Willems have combined the small suppliers with the main suppliers due to the importance of the main processes in the supply network and in order to avoid complexity and confusion, introducing the final supply network illustrated in figure 6-17. Another assumption by Graves and Willems was that this network targets general bulldozer production only. All the delivery times, presented in Table 6-18, were also assumed to be normal.

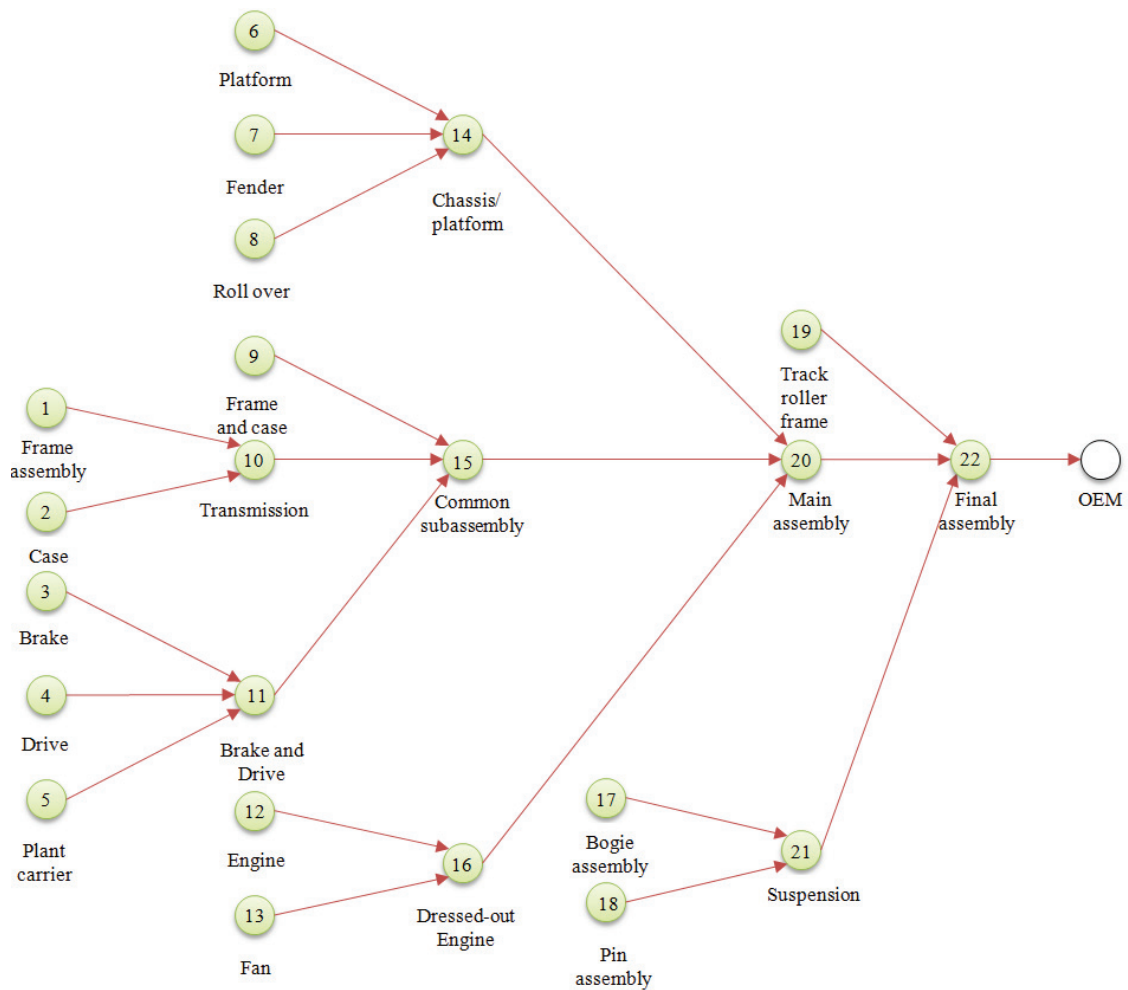


Figure. 6-17: Bulldozer supply network (Nepal, et al., 2012; Graves & Willems, 2003)

Table 6-18 also contains the probability density functions of all the suppliers in this case study, which are based on the delivery times of the suppliers and observations made by Graves and Willems (2003).

Node	Stage name	Probability density functions	Mean (μ_i) = EXP(DT _i) (Day)	Variance (σ_i^2)(Day)
Supplier 1	Frame assembly	Normal	19	4
Supplier 2	Case	Normal	15	3
Supplier 3	Brake group	Normal	8	4
Supplier 4	Drive group	Normal	9	2
Supplier 5	Plant carrier	Normal	9	5
Supplier 6	Platform group	Normal	6	2
Supplier 7	Fender group	Normal	9	4
Supplier 8	Roll over group	Normal	8	3
Supplier 9	Frame and case	Normal	24	8
Supplier 10	Transmission	Normal	15	5
Supplier 11	Brake and Drive	Normal	6	3
Supplier 12	Engine	Normal	7	1
Supplier 13	Fan	Normal	12	3
Supplier 14	Chassis/platform	Normal	10	3
Supplier 15	Common subassembly	Normal	10	5
Supplier 16	Dressed-out Engine	Normal	14	4
Supplier 17	Bogie assembly	Normal	11	3
Supplier 18	Pin assembly	Normal	35	5
Supplier 19	Track roller frame	Normal	10	2
Supplier 20	Main assembly	Normal	8	3
Supplier 21	Suspension	Normal	17	7
Supplier 22	Final assembly	Normal	7	3

Table 6-18: **The probability density functions of suppliers in supply networks of Noramco's spray nozzles (Nepal, et al., 2012; Graves & Willems, 2003)**

After determining probability density functions of delivery time for all the suppliers through the use of Graves and Willems' theories, the adapted PERT should be calculated. First, we need to calculate optimistic delivery time, most likely delivery time, pessimistic delivery time and E (DT) for each supplier based on the Table presented in appendix 9.1. The results of these calculations have been presented in Table 6-19.

Node	Optimistic DT	Most likely DT	Pessimistic DT	E(DT)
Supplier 1	17	19	21	19
Supplier 2	13.3	15	16.7	15
Supplier 3	6	8	10	8
Supplier 4	7.6	9	10.4	9
Supplier 5	6.8	9	11.2	9
Supplier 6	4.6	6	7.4	6
Supplier 7	7	9	11	9
Supplier 8	6.3	8	9.7	8
Supplier 9	21.2	24	26.8	24
Supplier 10	12.8	15	17.2	15
Supplier 11	4.3	6	7.7	6
Supplier 12	6	7	8	7
Supplier 13	10.3	12	13.7	12
Supplier 14	8.3	10	11.7	10
Supplier 15	7.8	10	12.2	10
Supplier 16	12	14	16	14
Supplier 17	9.3	11	12.7	11
Supplier 18	32.8	35	37.2	35
Supplier 19	8.6	10	11.4	10
Supplier 20	6.3	8	9.7	8
Supplier 21	14	17	20	18
Supplier 22	5.3	7	8.7	7

*DT: Delivery Time

Table 6-19: Calculation of expected value of delivery time for suppliers of Bulldozer supply network

Forward pass and backward pass calculations come next. These calculations have been presented in Table 6-20. Given the structure of the supply network shown in figure 6-17 as well as the rules for calculating the input value of each supplier, the input degree for suppliers 1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 13, 17, 18 and 19 is zero, meaning that all of them could be considered a beginner node for the critical network. Therefore, all of them are chosen as beginner nodes, while the OEM is introduced as the finisher node.

Node	Calculation of forward pass		Calculation of backward pass	
	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + EXP(DT_i)$	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - EXP(DT_i)$
Supplier 1	$ES_1=0$	19	19	0
Supplier 2	$ES_2=0$	15	19	4
Supplier 3	$ES_3=0$	8	28	20
Supplier 4	$ES_4=0$	9	28	19
Supplier 5	$ES_5=0$	9	28	19
Supplier 6	$ES_6=0$	6	34	28
Supplier 7	$ES_7=0$	9	34	25
Supplier 8	$ES_8=0$	8	34	26
Supplier 9	$ES_9=0$	24	34	10
Supplier 10	19	34	34	19
Supplier 11	9	15	34	28
Supplier 12	$ES_{12}=0$	7	30	23
Supplier 13	$ES_{13}=0$	12	30	18
Supplier 14	9	23	44	34
Supplier 15	34	44	44	34
Supplier 16	12	26	44	30
Supplier 17	$ES_{17}=0$	11	35	14
Supplier 18	$ES_{18}=0$	35	35	0
Supplier 19	$ES_{19}=0$	10	52	42
Supplier 20	44	52	52	44
Supplier 21	35	52	52	35
Supplier 22	52	59	59	52
OEM (23)	59	-	-	$LS_{23}=ES_{23}=59$

*DT: Delivery Time

Table 6- 20: Calculation of forward and backward pass for the Bulldozer supply network

Based on the calculations presented in Table 6-20, the latest start time for two suppliers has been equal to zero ($LS_{18} = 0, LS_1 = 0$), meaning that there are two critical paths in the network and that these networks serve as beginner nodes in the critical paths. To identify the two critical paths through final calculations presented in Table 6-21 is needed.

Node	$LS_i - ES_i$
Supplier 1	0
Supplier 2	4
Supplier 3	20
Supplier 4	19
Supplier 5	19
Supplier 6	28
Supplier 7	25
Supplier 8	26
Supplier 9	10
Supplier 10	0
Supplier 11	19
Supplier 12	23
Supplier 13	18
Supplier 14	25
Supplier 15	0
Supplier 16	18
Supplier 17	14
Supplier 18	0
Supplier 19	42
Supplier 20	0
Supplier 21	0
Supplier 22	0
OEM (23)	0

Table 6- 21: Calculation of critical path in Bulldozer supply network

Suppliers for which the difference between the earliest start time and the latest start time is equal to zero are critical suppliers affecting the network. Data extracted from Table 6-21 indicate that suppliers 1, 10, 15, 18, 20, 21, 22 are critical suppliers, with the OEM serving as the last node of the path. The two critical paths have been illustrated in figure 6-18 based on the structure of the bulldozer supply network shown in figure 6-17. Suppliers 1 and 18 are the beginner and finisher nodes of the two paths.

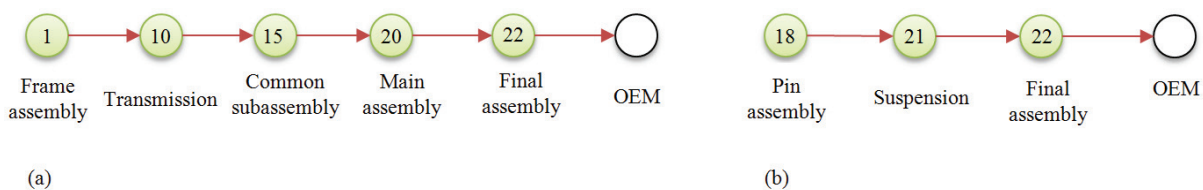


Figure. 6-18: Two critical paths of bulldozer supply network

After identifying the critical suppliers and paths, the standard uncertainty should be calculated separately for both critical paths based on the details presented in section 5.3 in order to select the maximum uncertainty as the standard uncertainty for the whole network. The adapted GUM illustrated in figure 5-15 has been employed to calculate the standard uncertainty of the network since all suppliers on both critical paths enjoy normal pfd.

First, the standard uncertainty of the critical path (a) will be calculated. Since this critical network is a linear one, the relationship function of the suppliers will be a total of probability density functions based on the explanation

provided in section 5.2. The relationship function is demonstrated in the form of equation (6-7).

$$f(y) = f(DT_1) + f(DT_{10}) + f(DT_{15}) + f(DT_{20}) + f(DT_{22}) \text{ and } Y = DT_1 + DT_{10} + DT_{15} + DT_{20} + DT_{22} \quad 6-7$$

The assumptions applied to this case study based on the principles of the hybrid methodology are as follows:

- $\beta = 95.4\%$ and $k=2$ for all the calculations
- The sensitivity coefficient of delivery time uncertainty in relation with the relationship function is equal to 1 for suppliers belonging to the critical network and 0 for other suppliers, as shown in relation 6-14:

$$\frac{\partial f(y)}{\partial f(DT_i)} = \frac{\partial Y}{\partial DT_i} = \begin{cases} 1 & i \in \{1, 10, 15, 20, 22\} \\ 0 & \text{for other suppliers} \end{cases} \quad 6-8$$

Then, calculation of the standard uncertainty for the critical path (a) is needed:

$$u_{ca}^2(Y) = u(DT_1)^2 \times \left(\frac{\partial Y}{\partial DT_1}\right)^2 + u(DT_{10})^2 \times \left(\frac{\partial Y}{\partial DT_{10}}\right)^2 + u(DT_{15})^2 \times \left(\frac{\partial Y}{\partial DT_{15}}\right)^2 + u(DT_{20})^2 \times \left(\frac{\partial Y}{\partial DT_{20}}\right)^2 + u(DT_{22})^2 \times \left(\frac{\partial Y}{\partial DT_{22}}\right)^2 = 20 \text{ days}$$

$$u_{ca} = 4.47 \text{ days}$$

The accumulated probability density function for this network is normal since the probability density function of all the critical suppliers is normal, and its standard uncertainty is 4.47 days. The expected DT is calculated through the use of the following relation:

$$\begin{aligned} EXP(DT_{ca}) &= \mu_{ca} \\ &= EXP(DT_1) + EXP(DT_{10}) + EXP(DT_{15}) + EXP(DT_{20}) \\ &\quad + EXP(DT_{22}) = \mu_1 + \mu_{10} + \mu_{15} + \mu_{20} + \mu_{22} = 59 \text{ days} \end{aligned}$$

Also, the expanded uncertainty with $\beta = 95.4\%$ and $k=2$ is calculated as follows:

$$U = k \times u_{ca} = 2 \times 4.47 = 8.94 \text{ days}$$

As a result for $\beta = 95.4\%$ time frame of delivery time up to OEM is 59 ± 8.94 days.

The final diagram of the probability density function for delivery time and the relevant uncertainty has been illustrated in figure 6-19.

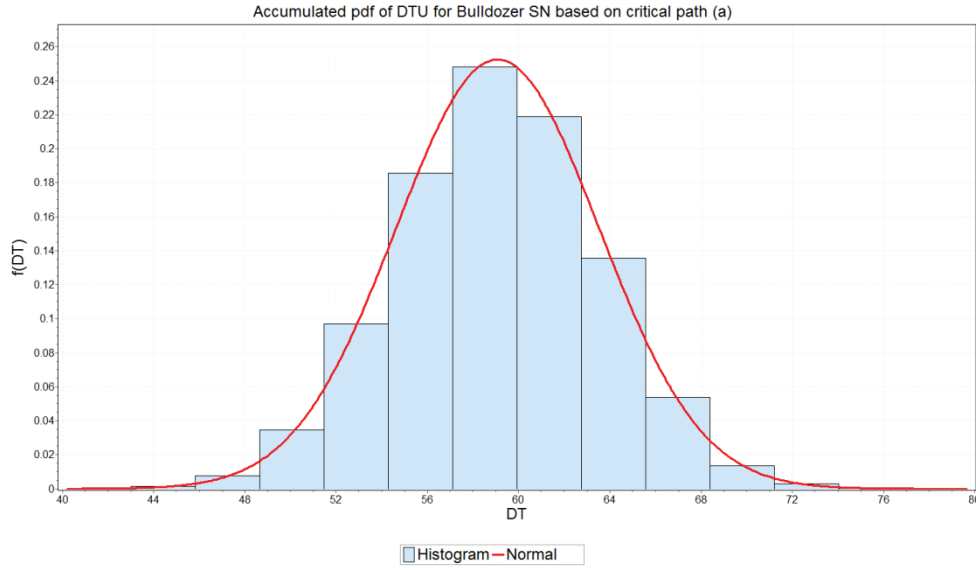


Figure. 6-19: Accumulated probability density function of delivery time uncertainty for Bulldozer supply network according to the critical path (a)

In the next step, the same calculations will be applied to the critical path (b). To avoid repeating the above process, only relevant calculations and equations are mentioned here.

$$f(y) = f(DT_{18}) + f(DT_{21}) + f(DT_{22}) \text{ and } Y = DT_{18} + DT_{21} + DT_{22} \quad 6-9$$

$$\frac{\partial f(y)}{\partial f(DT_i)} = \frac{\partial Y}{\partial DT_i} = \begin{cases} 1 & i \in \{18, 21, 22\} \\ 0 & \text{Others} \end{cases} \quad 6-10$$

The standard uncertainty, mean of delivery time and the extended uncertainty are calculated as follows:

$$u_{cb}^2(Y) = u(DT_{18})^2 \times \left(\frac{\partial Y}{\partial DT_{18}}\right)^2 + u(DT_{21})^2 \times \left(\frac{\partial Y}{\partial DT_{21}}\right)^2 + u(DT_{22})^2 \times \left(\frac{\partial Y}{\partial DT_{22}}\right)^2 =$$

15 days

$$u_{cb} = 3.87 \text{ days}$$

$$EXP(DT_{cb}) = \mu_{cb}$$

$$= EXP(DT_{18}) + EXP(DT_{21}) + EXP(DT_{22}) = \mu_{18} + \mu_{21} + \mu_{22}$$

$$= 59 \text{ days}$$

$$U = k \times u_{cb} = 2 \times 3.87 = 7.74 \text{ days}$$

The accumulated probability density function for this critical path is a normal function with mean of delivery time= 59 days and accumulated uncertainty= 3.87 days. The relevant diagram has been illustrated in figure 6-20.

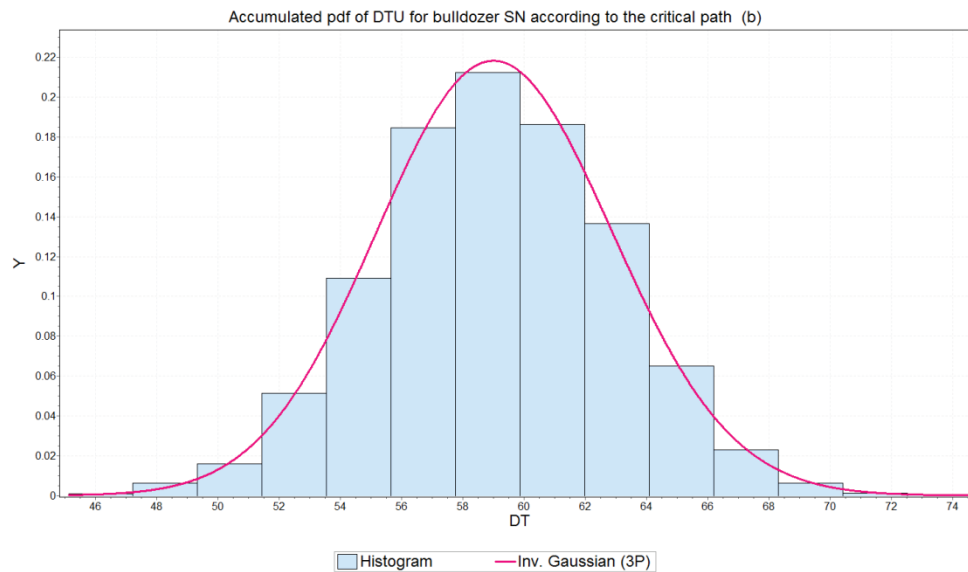


Figure. 6-20: Accumulated probability density function of delivery time uncertainty for Bulldozer supply network according to the critical path (b)

Since the standard uncertainty for path (a) is higher than that of the path (b), it is considered as the uncertainty of the whole network.

6.3 Summary

This chapter examined the hybrid methodology and its performance by providing a numerical example and three case studies dealing with networks with different structures. Since the real cases presented in this chapter had simple supply networks compared to the methodology's capability, the numerical example was designed to have a complex structure so as to duly demonstrate the methodology's capabilities in solving more complex problems. Besides, we tried to establish the efficiency and accuracy of Monte Carlo method, which is the simulation part of the methodology, through the use of the adapted GUM (proven mathematical version) suggested for calculating standard uncertainty. Demonstrating the methodology's capability to calculate the uncertainty for supply networks with different probability density functions was another goal behind providing the numerical example. After showing the methodology's capabilities by applying it to two scenarios in the numerical example, the real-life executive capabilities of the methodology by applying it to three real supply networks were examined. In the first scenario, the executive capabilities of the methodology to a multi-product supply network engaged in providing two types of notebooks to two different markets were investigated. In the second scenario, these capabilities were applied to a supply network with multiple OEMs engaged in supplying Noramco's spray nozzles. In the last scenario, the methodology's executive capabilities were applied to a supply network with multiple critical paths engaged in supplying bulldozers. The next chapter will explain the capabilities of the methodology in the industry in detail

and provide relevant conclusions. It will also provide the research's limitations as well as suggestions for future research.

7 CHAPTER 7 – Conclusion and outlook

The last chapter of the thesis provides conclusions as well as suggestions for future research. The conclusion section of the chapter starts with a summary of the thesis and continues with the research's capabilities and innovations. Then, recommendations will be provided on the application of the research in the real world. Next, the limitations of the research are presented. Suggestions for future research will come at the end of this chapter.

7.1 Conclusion

This section states the final conclusions of the research. The first part provides the research's processes and obtained results in the previous chapters. The second part explains the capabilities and contributions of the proposed methodology. The last part discusses the methodology's practical applications and offers suggestions to improve its efficacy and application.

7.1.1 Summary of the research and results

This section provides a summary of the previous chapters. Chapter 1 started with an introduction and continued with the research motivations as well as a summary of the problem statement. It ended with the purpose and procedure of the thesis as well as the research structure.

Given the importance of supply networks and formation of problems related to them, the second chapter covered definitions for supply networks and the history of their formation, obstacles ahead of researchers when dealing with problems related to supply networks, and solutions on how to develop an efficient and effective supply network provided by the literature. This chapter divided the process of supply network formation into five stages based on the literature: decentralization of supplies, cost management, integration of functions, supply-chain management towards supply networks, and their data electronic management. The history of each stage was also provided. At the end, importance was attached to the QR and accuracy of supply networks.

Due to the importance of uncertainty in this research, chapter 3 dealt with uncertainty's definitions, sources and literature, introducing methodologies proposed in connection with it. A review on the literature of research on uncertainty revealed that a number of researchers had mistakenly used the term "error" instead of "uncertainty". Therefore, at the beginning, "error" and "uncertainty" were introduced and distinguished them from each other. Then, the uncertainty according to the literature was classified. Following that, the importance of uncertainty in supply networks and provided definitions of it had been highlighted. Identifying factors contributing to uncertainty is the first step in analyzing uncertainty sensitivity and control. Thus, fourteen factors contributing to uncertainty according to the literature were identified, and were put into the three groups of internal organization uncertainties, internal supply

network uncertainties and external supply network uncertainties. Supply network's suppliers and structure, on which the current research has focused, were assigned to the second group. Then, quantitative and qualitative models proposed for controlling, monitoring and analyzing different uncertainties in supply networks were introduced. The strengths and weaknesses of each model were examined at the end of this chapter.

Chapter 4 examined the research questions. In brief, each supplier in a network has its own delivery time uncertainty, and the delivery time uncertainty of the whole network was calculated through accumulating the uncertainties of its members. The method of calculating the network's uncertainty is directly related to the structure of the network. The method of conducting this calculation and the effectiveness of the network's structure on it was one of the main issues covered by this study. The effectiveness of each supplier on the network's final uncertainty and identification of suppliers with critical effects on the network's uncertainty were the other issues covered by the study.

Chapter 5 introduced a proposed methodology to solve the research question. In this chapter, the most probabilistic probability density functions required for delivery time were explained and it was tried to adapt their definitions to those of the supply network in the first section of this chapter, because the current methodology has employed probability density functions to introduce uncertainty quantitatively. Then, the basic supply networks were divided into six groups: linear networks, star networks, partial-relationship without loop networks, partial-relationship with loop networks, full-relationship without loop networks, and full-relationship with loop networks. Following that, all possible scenarios for the main supply networks with two, three and four nodes were examined and network preparation for conducting calculations was discussed. The basic networks with more than four nodes were not explained, because all the six possible scenarios were covered by four-node networks. In the next step, the main methods forming the proposed methodology, which had been taken from three different fields, including project management, calibration and simulation were introduced. Then it was explained, how these three methods could be adapted to the supply networks problems. Having introduced the adapted PERT, adapted GUM and Monte Carlo method algorithms and the calculation method for each of them, the hybrid methodology proposed by this dissertation was presented.

Chapter 6 was divided into two parts. The first part sought to establish the accuracy and efficiency of Monte Carlo method since it is a simulation algorithm contrary to GUM, which is a proven mathematical method with maximum accuracy. For this reason, a numerical example of a complex supply network was presented and assumed delivery times and probability density functions for it in two different scenarios in a bid to determine Monte Carlo method's efficiency and accuracy. In the first scenario, all probability density

functions were considered as normal since GUM is applicable only to networks with normal probability density functions. Then, the GUM and Monte Carlo methods were applied to this scenario and found out that the results were indicative of the efficiency and accuracy of Monte Carlo method. In the second scenario, the different probability density functions for each supplier were assumed, trying to evaluate the methodology's capability to solve such questions. The second part of this chapter included three real-life case studies taken from the literature. These case studies dealt with a supply network with two markets engaged in supplying two types of notebooks (which sought to show how the proposed methodology is applied to multiple-product networks), a supply network with different OEMs engaged in supplying Noramco's spray nozzles, and a bulldozer supply network. In the case study related to the bulldozer supply network, we encountered a network with two critical paths and examined how such questions are solved.

Chapter 7 has provided a summary of this dissertation, followed by a review on the research innovations. It then provides the researcher's suggestions for the research's real-life applications. Subsequently, the limitations are presented. Conclusions as well as suggestions for future research have been put at the end of the chapter.

7.1.2 Contribution of the research

Customer-oriented production and manufacturing flexibility are the most elementary principles for survival in today's competitive market (Subramanian, et al., 2014). Customers' demands and needs change frequently, making traditional supply networks with fixed structures uneconomical (Agus, 2011). Therefore, it is necessary to design a supply network for each type of ordered product in order to reduce production costs, increase quality and flexibility, and improve the ability to meet customers' different requests. Therefore, an OEM might have different supply networks in the short term. Today, managers have realized the importance of supply networks with dynamic structures and are trying to adapt the decision making strategies in traditional networks to dynamic one with high speed and accuracy. High speed and accuracy are the most important features of these kinds of strategies, which must be adapted to the dynamic networks, since supply networks are of short-term nature (Wilhelm, et al., 2013).

As stated, the importance of delivery time has been proved by literature. Furthermore, delivery time uncertainty could inflict irreparable damage on OEMs. Uncertainty in the supply networks with fixed structures has been examined by many scientists (Cardoso, et al., 2013; Peidro, et al., 2009; You & Grossmann, 2008). However, the current study has focused on delivery time uncertainty in dynamic supply networks. As mentioned at the beginning of this dissertation, the current research has sought to propose a methodology to analyze sensitivity and monitor delivery time uncertainty in structure-based

supply networks. In fact, this methodology is used to calculate the accumulated uncertainty of supply networks. The application of this methodology will be examined in section 7.2.

This research employs a supply network consisted of a number of suppliers and an OEM, which jointly proceeded toward the same goal. Each supplier has its own delivery time uncertainty, which is obtained through the random sampling of the supplier's previous delivery times. Also, the uncertainty behavior of each supplier is obtained based on probability density functions identified through the use of EasyFit software program. One of the innovations of this research is that it does not need to examine all internal events and details of each supplier in order to calculate its uncertainty. The author proposed that each supplier could be assumed as a black box whose previous outputs could show all internal events of that supplier. Such a holistic view towards issues related to the whole network could add to the simplicity and applicability of the process.

All probability density functions of the delivery times and standard uncertainties of each supplier were identified at this stage. Then, the PERT method, which had been taken from the project control field was applied. After that it was adapted to supply networks, to identify suppliers with the highest effect on the uncertainty of the whole network. In order to simplify the supply network, based on the relationship between its critical suppliers, the critical paths were determined. Later, the network had been ready for calculations. Two contributions are observed during this stage: (1) the methodology does not concentrate on suppliers whose uncertainty change does not affect the uncertainty of the whole network. It adds to the methodology's speed. (2) The methodology provides solutions to solve problems ahead of PERT in calculating expected delivery time for probability density functions apart from beta distribution functions. In the PERT method, all calculations are estimated based on beta distribution, reducing the accuracy of the answers as a result. The author of this research has employed the suggested PERT not only to adapt the calculations to delivery time of the supply networks, but also to take all possible distributions into account.

After the simplification process of the supply network, calculating the accumulated uncertainty of the network, which is the main part of the proposed methodology is needed. In this stage, to develop a mathematical method for calculating accumulated uncertainty through the use of JCGM 100:2008 standard guidelines and GUM, which were taken from the calibration field, were inspired. The new model was called "adapted GUM" since it was based on mathematical principles presented by GUM. The accuracy of GUM in conducting calculations, proven by calibration laboratories, was one of the main reasons for using its principles in our mathematical model. However, the adapted GUM also has setbacks in calculating uncertainty in spite of its

numerous strengths. The main drawback is that this method is accurate only when all parts of the system under calculation enjoy normal probability density functions. To calculate the uncertainty for elements, which are followed by other probability density functions, the probability density functions of these elements should be normalized by the central limit theorem (CLT). For this reason, in these cases, a tangible decline will be observed in the accuracy of the calculation's results. Another setback with the adapted GUM mathematic method is that the calculation process for networks with too many critical suppliers is difficult and time-consuming. Therefore, it was necessary to apply a method that could deal with these setbacks. For this reason, an adapted Monte Carlo method was employed in order to cover the adapted GUM's limitations due to the Monte Carlo method's capability to consider probability density functions for producing values. An adapted simulated method by a simulation program designed by Excel was prepared. The ability to consider all real-life probability density functions and the simplicity of relevant calculations even in the most complex supply networks were among the main features of this methodology. This stage offered three contributions: (1) offering a mathematical model based on GUM's principles, presented in the JCGM 100:2008 standard guidelines, and adapting it to calculate accumulated delivery time for supply networks, (2) simulation programming based on the Monte Carlo method's principles and adapting it to solve problems related to accumulated delivery time uncertainty in supply networks, and (3) offering a solution to accurately calculate delivery time uncertainty in the presence of all existing probability density functions.

Finally, the three adapted methods are integrated and harmonized to create a hybrid methodology, which is the main innovation of the research. All characteristics of the hybrid methodology, each of which could be regarded as a contribution, are mentioned below:

The proposed hybrid methodology is a network-based methodology which is sensitive to the network structure. In the methodology, delivery time uncertainty will change if the network structure undergoes changes. Thus, it is suitable for networks with dynamic structures.

Among the capabilities of this methodology is its macro approach, which accelerates calculations. The methodology considers each supplier as a black box shown as a node in the network. Based on the main theory of the methodology, the inputs and outputs of each "black box" fully reflect all events and slight uncertainties related to it and that it is only necessary to sample delivery times (output of the black box) to determine the uncertainty of the supplier. Besides, this methodology also has been designed to calculate internal delivery time uncertainty for every factory and supplier separately. For example, a network of the internal processes of each supplier could be created (e.g. each machine; workstation or department is considered a node and a black box), and

calculations are similar to those of supply networks could be applied to it in order to examine the final uncertainty of the supplier and assign the results as the input of the proposed methodology. Figure 7-1 illustrates the internal networks of a supplier who is a member of a supply network.

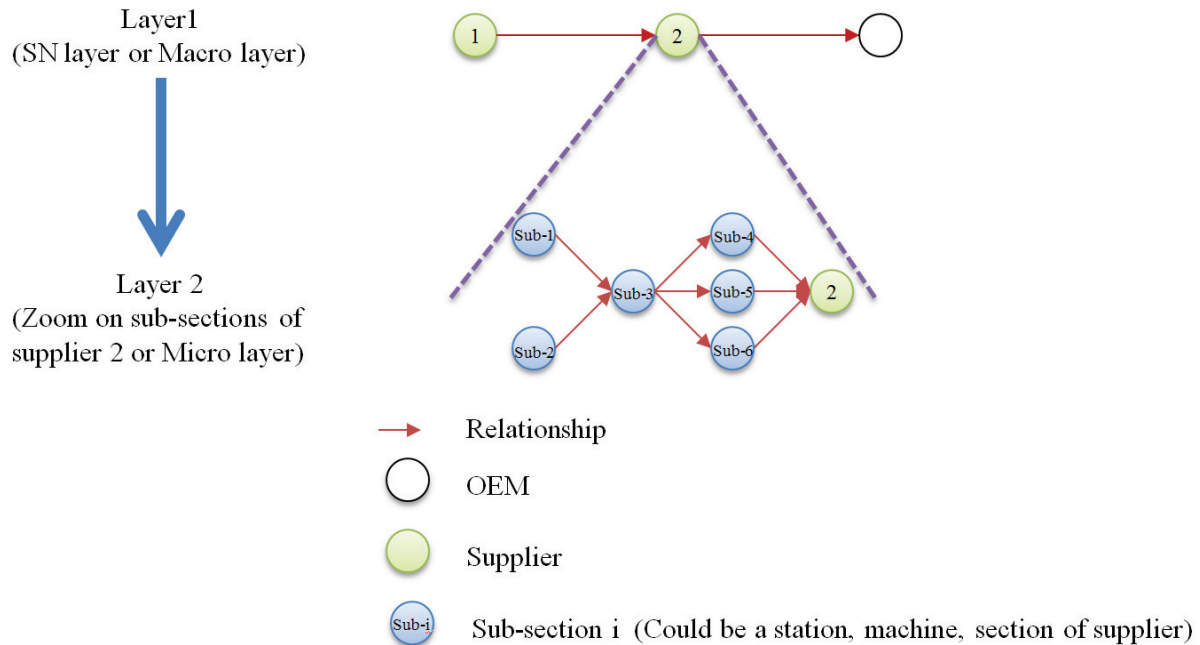


Figure 7- 1: An example of sub-sections network inside of a supplier in the supply network

The ability to employ all real-life statistical probability density functions is another capability of the hybrid methodology. In similar research carried out in the field of calibration, all uncertainty behaviors have been estimated as normal, which were significantly different from real behaviors in some cases. The hybrid methodology, however, is capable of considering at least 65 different probability density functions and finds the closest estimation in case of encountering complex networks. The methodology is associated with lower levels of error compared with previous methods. Thus, the accuracy of this model is higher than that of rival methodologies such as Markov, Bayesian and traditional GUM. As mentioned earlier, high speed and acceptable accuracy are among the features of methods required for dynamic supply networks.

In the hybrid methodology, it has been avoided to develop limiting hypotheses to bring the results closer to real-life results. Therefore, this methodology could also be applied to networks with loops. Given the characteristics of real-life production processes, sometimes it is essential to repeat the calculations for some orders in the supply network. Since the traditional PERT is not capable of considering loops, the strategy for dealing with such networks is added to the traditional PERT to produce the adapted PERT, thus adding the capability to repeat calculations for some orders. It aimed to adapt the hybrid methodology to the real life as much as possible.

Another important feature of the hybrid methodology is that it is capable of defining a sensitivity coefficient for each supplier of the supply network, determining the level of the significance of each supplier subsequently. Further adaption of the methodology to the real world has been the main goal behind fitting this capability into it. For example, a specific supplier of the network might be more important than other suppliers. Thus, the level of the importance of each supplier could be increased or decreased by changing its sensitivity coefficient. Less attention has been paid to this feature of the methodology in the numerical example and case studies presented in chapter 6, where all effective suppliers of the supply network have been assigned equal sensitivity coefficients.

The researcher has tried to present a simple applicable statistical method, avoiding suggesting complex mathematical formulas. It is believed that the applicability and usefulness of the methodology declines for users when the mathematical method is complicated. For this reason, the intention was to design a methodology which is understandable for both managers and users with elementary mathematical knowledge.

In the programming of the adapted Monte Carlo method, we are able to consider the nonlinear relationship functions. Therefore, it makes a possibility for our methodology to consider the nonlinear relationship function, something that is regarded as another innovation of this research.

Finally, the research has focused on delivery time uncertainty since it sought to propose a methodology for calculating delivery time uncertainty. However, the methodology could be modified to calculate demand uncertainty and also other measurable uncertainties. Furthermore, dynamics have been taken into consideration by all aspects of the methodology.

As mentioned in chapter 3, numerous methods have already been proposed for calculating uncertainty. The most important methods of this type which bear the highest similarity with the proposed hybrid methodology include Markov, Bayesian and traditional GUM methodologies. These three methods are considered as network-based models. Table 7-1 compares these three methods with each other and examines their application to dynamic supply networks.

Method	Markov	Bayesian	Traditional GUM	Recommended methodology
Characteristic				
Network base	●	●	●	●
Simplicity in calculation				●
Ability to consider non-normal probability density function and asymmetric				●
Ability to consider loop in the network				●
Ability to consider the sensitivity coefficient for members of the network			●	●
Ability to consider the non-linear relationship function	●	●		●

Table 7- 1: Comparing the hybrid methodology with most important methods

7.1.3 Suggestion for implementation

This section deals with the practical applications of the hybrid methodology as well as the researcher's suggestions with regard to the real-world implementation of it.

Proper design of a supply network could have a positive impact on its costs, response speed, delivery time, profitability and customer satisfaction, all of them affecting the flexibility, efficiency and performance of the network significantly (Agus, 2011). Since the proposed hybrid methodology is a network-based model which is highly sensitive to the network structure, it enables OEM managers and researchers engaged in network designing, to find the best possible structure in advance, thus increasing efficiency, performance and response rapidity and reducing uncertainty.

Trust between OEM and customer is one of the crucial factors contributing to success in supply networks and has a significant impact on customer satisfaction (Khalfan, et al., 2007). One of the practical applications of the proposed methodology is for those networks and OEM managers who want to determine the level of delivery time uncertainty for short-term dynamic networks as it enables these managers to measure uncertainty for their networks and prepare a timeframe with high speed and confidence to be delivered to their customers.

An examination of the models provided for supplier selection (Riedl, et al., 2013; Lienland, et al., 2013; Li & Zabinsky, 2011) reveals the importance of delivery time and delivery time uncertainty as two essential factors affecting the supplier selection process. The proposed hybrid method could serve as an assistance tool for supplier selection models thanks to its high accuracy and speed as well as its ability to identify critical suppliers. Therefore, managers could employ the capabilities of the methodology to identify suppliers with the worst performance in terms of delivery time uncertainty and replace them with other suppliers available as it will significantly improve the performance of the whole network.

At the end, it is noticeable that this model is able to monitor the rate of network uncertainty, and it is unable to decrease the uncertainty. These kinds of models are more applicable to match with other strategies to cope with uncertainty. This methodology is an initial tool for reducing strategies to apply them in the right place. Therefore, it increases the productivity of reducing uncertainty in the whole network. Consequently, one future research might be to find the most appropriate reducing strategy to this model. To make better understanding about the advantages and disadvantages of this methodology, Table 7-2 provides a comparison between the methods and models which have been proposed recently with the recommended methodology by this research.

Characteristic	Method	Sawhney, 2006	Taylor, 2006	Tracy & Knight, 2008	Hinalen, et al., 2009	Mulla, et al., 2010	Nepala, et al., 2012	Xu & Rong, 2012	Cardoso, et al., 2013	Recommended methodology
Type of model		QL	QL	QL	QN	QN	QL	QN	QN	QN
Network base		Yes	No	No	Yes	Yes	No	Yes	Yes	Yes
Source of uncertainty		Supply	Process	Process	Time	Demand	Demand	Demand	Demand	Time
Simplicity in implication		●	●	●	●	●	●	-	-	●
Ability to consider non-normal pdf and asymmetric		-	-	-	-	-	-	-	-	●
Ability to consider loop in the network		-	-	-	-	-	-	-	●	●
Ability to consider the sensitivity coefficient for members of the network		-	-	-	●	-	-	●	●	●
Ability to consider the non-linear relationship function		-	-	-	●	●	-	-	●	●
Ability to identify optimal locations for implementation		-	-	-	-	-	-	-	-	●
Provide the decreasing strategy		●	●	●	●	●	●	●	●	-

QN: Quantitative models

QL: Qualitative models

Table 7- 2: A comparison between recent models and recommended methodology

7.2 Limitations

This section deals with existing limitations. Lack of a computational formula to add up several independent variables with different probability density functions was one of the limitations we faced during the research. Therefore, the simulation process was proposed in order to deal with such problems. In this research, we made some assumptions based on which the methodology could be implemented. Determining the probability density functions of delivery times for factories through sampling the delivery times of previous projects was one of these hypotheses. Specifying the structure of the supply network was another assumption made during the research. Such data should be collected accurately as model inputs in order to increase the accuracy of the results.

Another limitation during this research was the difficulties associated with collecting data from factories to be used as the methodology's input data. If we intended to apply the methodology to a real-life supply network without referring to the relevant literature, we would have to collect samples of delivery times for each project or product handled by each supplier in the network. Since such information is considered confidential by suppliers, it was required to provide a numerical example and three real-life case studies in order to demonstrate the methodology's capability and performance. Also, assumed data or data provided by the literature were used in the numerical example and the case studies.

7.3 Future research and outlook

As mentioned in previous sections of this chapter, proposing a methodology to calculate the accumulated uncertainty for supply networks has been one of the main goals of the current research. The proposed methodology is sensitive to the network structure and is capable of monitoring and analyzing sensitivity due to its speed and accuracy. The researcher's suggestions regarding to future research will be mentioned in the following paragraphs.

As mentioned in chapter 3, there are three models for indicating uncertainty in a mathematical form, which include interval bound, fuzzy and probability density function. Today, the main competition is between fuzzy and probability density function model. In this research, the probability density function model is preferred to fuzzy model for two reasons: first, since the fuzzy model requires that many assumptions be made (e.g. membership number be assigned to each delivery time uncertainty value) to make the model applicable, the researcher decided that such assumptions will directly affect the final results and make them less realistic. The second reason is related to the way of identifying probability density functions. Uncertainty probability density function identification does not require additional assumptions since probability density functions are drawn based on the supplier's real behavior in the past and produce more realistic results. For future research, it is suggested to develop a methodology based on the principles of the fuzzy model and to compare its results to those of the current research presented in chapter 6.

Since the proposed hybrid methodology is capable of determining internal uncertainty for each supplier separately (see figure 7-1), the researcher suggests to implement the current methodology inside a supplier to calculate the accumulated internal uncertainty for that supplier especially through creating a sub-network of all activities affecting delivery time uncertainty.

Another subject for future research is adding parameters to the model to create a methodology capable of reducing and optimizing delivery time uncertainty for dynamic supply networks. The author also intends to modify the hybrid methodology in order to examine the accumulated demand uncertainty.

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9 Appendixes

9.1 Expected value of some common probability density functions

As mentioned in the chapter 5, traditional PERT used three parameters (Optimistic, pessimistic, and most likely time), to estimate the process time of an activity. It is noticeable that the PERT is estimated all of probability density functions to the Beta to calculate and find most likely activity time. To solve this problem, we suggest to consider the expected value of each probability density function in this method as most likely delivery time. Thus, by this contribution, we do not have any estimation in the PERT, and the result must be more accurate. Table 9-1 shows the optimistic, pessimistic, and expected value (as most likely) delivery time for some of the most common probability density functions.

Probability density function	Pessimistic	Optimistic	Standard uncertainty (ui)	Expected value (most likely)
Rectangular distribution $U(a, b)$	a	b	$u = \frac{(b - a)}{\sqrt{12}}$	$E(DT) = \frac{(a + b)}{2}$
Triangular distribution $T(a, b, c)$	a	b	$u = \sqrt{\frac{a^2 + b^2 + c^2 - ab - ac - bc}{18}}$	$E(DT) = \frac{(a + b + c)}{3}$
Normal distribution $N(\mu, u^2)$	$\mu + 3 \times u$	$\mu - 3 \times u$	u	$E(DT) = \mu$
Exponential distribution $EXP(\lambda)$	$\frac{\ln(1 - \beta)}{\lambda}$ β : Confidence coefficient	0	$u = \frac{1}{\lambda}$	$E(DT) = \frac{1}{\lambda}$
Gamma distribution $G(s, \theta)$	$s \times \theta + s \times \theta^2$	$s \times \theta - s \times \theta^2$ for optimistic numbers < 0 put 0	$u = \theta\sqrt{s}$	$E(DT) = s\theta$

Table 9-1: Calculation of the expected value of delivery time for most viewed probability density functions

These results and formulas are derived based on the study of the Montgomery book entitled “Applied statistics and probability for engineers” (Montgomery & Runger, 2010). To find out more probability density functions, please read this book.

9.2 The generalized extreme value distribution

“Extreme Value distributions arise as limiting distributions for maximum or minimum (extreme values) of a sample of independent and identically distributed random variables, as the sample size increases. Extreme Value theory (EVT) is the theory of modelling and measuring events which occur with very small probability. This implies its usefulness in risk modelling as risky events per definition happen with low probability. Thus, these distributions are important in statistics. These models, along with the Generalized Extreme Value distribution, are widely used in risk management, nance, insurance, economics, hydrology, material sciences, telecommunications, and many other industries dealing with extreme events.” (Alves & Neves, 2009).

Parameters

μ : Location parameter

u : Scale parameter ($u > 0$)

k : Shape parameter

Domain

$$1 + k \frac{(x - \mu)}{u} > 0 \text{ for } k \neq 0$$

$$x \in (-\infty, +\infty) \text{ for } k = 0$$

In this research delivery time is our variable and it could not be negative, then, if it became negative put it 0.

Function

$$f(DT) = \begin{cases} \frac{1}{u} e^{-(1+kz)^{-1/k}} \times (1 + kz)^{-1-1/k} & k \neq 0 \\ \frac{1}{u} e^{(-z - e^{-z})} & k = 0 \end{cases}$$

$$\text{where } z \equiv \frac{DT - \mu}{u}$$

Standard uncertainty and expected value

$$E(DT) = \mu - \frac{u}{\varepsilon} + \frac{u}{\varepsilon} \times g_1$$

$$u = \frac{u^2}{\varepsilon^2} (g_2 - g_1^2)$$

$$\text{Where } g_k = \Gamma(1 - k\varepsilon)$$

To calculate these parameters, we use EasyFit software and Excel formulas, which their functions are mentioned in Table 9-2:

Using generalized extreme value distributions in EasyFit

EasyFit supports the entire family of extreme value distributions, including the Gumbel, Fréchet, Weibull, and GEV models. Like most distributions in EasyFit, you can fit these models to your data or use them in Excel-based Monte Carlo simulations.

The Gumbel distribution is available in two forms: Gumbel Max (maximum extreme value) and Gumbel Min (minimum extreme value), enabling you to model left-skewed and right-skewed data: EasyFit software displays all graphs and properties of the Johnson SU distribution, presenting the results in an easy to read & understand manner. EasyFit calculates statistical moments (mean, variance etc.), quantiles, tail probabilities depending on the distribution parameters you specify (Mathwave, 2013).

- **Random numbers from the distribution**

You can easily generate random numbers from the distribution in a variety of ways:

- Directly from EasyFit
- In Excel sheets using the worksheet functions provided by EasyFitXL
- In your VBA applications using the EasyFitXL library

- **VBA and worksheet functions**

EasyFitXL provides a large number of functions which can be used in Excel VBA programs.

EasyFitXL makes a number of new high-performance worksheet functions available to Excel users. These functions can be applied in any worksheet on a computer with a licensed copy of EasyFit installed (Mathwave, 2013).

Description	VBA functions (EasyFit and Excel)	Worksheet Functions
Distribution Fitting	-	=DistFit("GenExtreme";Data)
Probability density function	GenExtremePdf(DT, k, u, m)	=GenExtremePdf(k; u; m) =DistPdf("GenExtreme(k; u; m)";DT)
Cumulative Distribution Function	GenExtremeCdf(DT, k, u, m)	=GenExtremeCdf(k; u; m) =DistCdf("GenExtreme(k; u; m)";DT)
Survival Function	GenExtremeSurv(DT, k, u, m)	=DistSurv("GenExtreme(k; u; m)";DT)
Hazard Function	GenExtremeHaz(DT, k, u, m)	=GenExtremeHaz(k; u; m) =DistHaz("GenExtreme(k; u; m)";DT)
Cumulative Hazard Function	GenExtremeCumHaz(DT, k, u, m)	=DistCumHaz("GenExtreme(k; u; m)";DT)
Inverse CDF (Quantile Function)	GenExtremeInv(P,k, u, m)	=GenExtremeInv(k; u; m) =DistInv("GenExtreme(k; u; m)";P)
Random Numbers	GenExtremeRand(k, u, m)	=GenExtremeRand(k; u; m) =DistRand("GenExtreme(k; u; m)")
Mode	GenExtremeMode(k, u, m)	=DistMode("GenExtreme(k; u; m)")
Mean	GenExtremeMean(k, u, m)	=GenExtremeMean(k; u; m) =DistMean("GenExtreme(k; u; m)")
Variance	GenExtremeVar(k, u, m)	=GenExtremeVar(k; u; m) =DistVar("GenExtreme(k; u; m)")
Standard Deviation	GenExtremeStdev(k, u, m)	=GenExtremeStdev(k; u; m) =DistStdev("GenExtreme(k; u; m)")
Skewness	GenExtremeSkew(k, u, m)	=DistSkew("GenExtreme(k; u; m)")
(Excess) Kurtosis	GenExtremeKurt(k, u, m)	=DistKurt("GenExtreme(k; u; m)")

Table 9-2: VBA and worksheet functions of generalized extreme value probability density function to use in EasyFit and Excel (Mathwave, 2013)

9.3 The Error probability density function

The Error distribution goes by variety of names: Exponential Power Distribution, Generalized Error Distribution (GED), Generalized Gaussian distribution (GGD), and Subbotin distribution. In this section regarding to the EasyFit tutorial and mathwave website some formulas and parameters of this probability density function are as follows (Mathwave, 2013):

- **Parameters**

k: Continuous shape parameter

u: Continuous scale parameter ($u > 0$)

m: Continuous location parameter

- **Domain**

$-\infty < x < +\infty$, but because in this research the variable is DT the negative interval bound of this probability density function is not accepted and the accepted results domain are: $0 < DT < +\infty$.

- **Function**

$$f(DT) = \frac{C_1}{u} \exp(-|C_0 \times z|^k)$$

$$where \begin{cases} C_0 = \sqrt{\frac{\Gamma(3/k)}{\Gamma(1/k)}} \\ C_1 = \frac{kC_0}{2\Gamma(1/k)} \end{cases} \text{ and } z \equiv \frac{DT - m}{u}$$

- **Standard uncertainty and expected value**

To calculate these parameters, we use EasyFit software and Excel formulas, which their functions are mentioned in Table 9-3:

- **Excel worksheet and VBA functions**

EasyFitXL enables you to use the following functions in your Excel sheets and VBA applications:

Description	VBA functions (EasyFit and Excel)	Worksheet Functions
Distribution Fitting	-	=DistFit("Error";Data)
Probability density function	ErrorPdf(DT,k,u,m)	=ErrorPdf(k;u;m) =DistPdf("Error(k;u;m)";DT)
Cumulative Distribution Function	ErrorCdf(DT, k, u, m)	=ErrorCdf(k;u;m) =DistCdf("Error(k;u;m)";DT)
Survival Function	ErrorSurv(DT, k, u, m)	=DistSurv("Error(k;u;m)";DT)
Hazard Function	ErrorHaz(DT, k, u, m)	=ErrorHaz(k;u;m) =DistHaz("Error(k;u;m)";DT)
Cumulative Hazard Function	ErrorCumHaz(DT, k, u, m)	=DistCumHaz("Error(k;u;m)";DT)
Inverse CDF (Quantile Function)	ErrorInv(P,k, u, m)	=ErrorInv(k;u;m) =DistInv("Error(k;u;m)";P)
Random Numbers	ErrorRand(k, u, m)	=ErrorRand(k;u;m) =DistRand("Error(k;u;m)")
Mode	ErrorMode(k, u, m)	=DistMode("Error(k;u;m)")
Mean and E(DT)	ErrorMean(k, u, m)	=ErrorMean(k;u;m) =DistMean("Error(k;u;m)")
variance	ErrorVar(k, u, m)	=ErrorVar(k;u;m) =DistVar("Error(k;u;m)")
Standard uncertainty	ErrorStdev(k, u, m)	=ErrorStdev(k;u;m) =DistStdev("Error(k;u;m)")
Skewness	ErrorSkew(k, u, m)	=DistSkew("Error(k;u;m)")
(Excess) Kurtosis	ErrorKurt(k, u, m)	=DistKurt("Error(k;u;m)")

Table 9-3: VBA and worksheet functions of Error probability density function to use in EasyFit and Excel (Mathwave, 2013)

9.4 Forward and backward calculations regarding to the adapted PERT algorithm

9.4.1 Calculations for exemplary complex supply network in section 6.1

The calculation method to fill the Table 6-3, to find the critical path for the exemplary complex supply network in section 6.1 are as follows:

1. After simplification, look at figure 6-3, and find those suppliers and nodes which have not any predecessor and choose them as beginner nodes. For this reason, in this figure, node 2 recognized as the beginner. Put $ES_2=0$.
2. Follow the forward pass calculation regarding the figure 6-3, in the Table 9-4:

Calculation of forward pass		
Node	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + E(DT_i)$
Supplier 2	$ES_2=0$	$Ef_2 = ES_2 + E(DT_2)=0+5=5$
Supplier 3	$ES_3 = \max(Ef_2)=5$	$Ef_3 = ES_3 + E(DT_3)=5+20=25$
Supplier 6	$ES_6 = \max(Ef_2, Ef_3)=25$	$Ef_6 = ES_6 + E(DT_6)=25+15=40$
Supplier 5	$ES_5 = \max(Ef_3)=25$	$Ef_5 = ES_5 + E(DT_5)=25+15=40$
Supplier 1	$ES_1 = \max(Ef_5)=40$	$Ef_1 = ES_1 + E(DT_1)=40+10=50$
Supplier 4	$ES_4 = \max(Ef_1)=50$	$Ef_4 = ES_4 + E(DT_4)=50+8=58$
Dummy supplier 5'	$ES_{5'} = \max(Ef_3, Ef_4, Ef_5)=58$	$Ef_{5'} = ES_{5'} + E(DT_{5'})=58+15=73$
Supplier 7	$ES_7 = \max(Ef_4)=58$	$Ef_7 = ES_7 + E(DT_7)=58+9=67$
OEM (8)	$ES_8 = \max(Ef_3, Ef_{5'}, Ef_6, Ef_7)=73$	-

Table 9-4: Forward pass calculation in detail for Table 6-3

3. Now, put $LS_8=ES_8=73$, and follow the backward pass calculation regarding the figure 6-3, in the Table 9-5 from OEM to beginner node:

Calculation of backward pass		
Node	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - E(DT_i)$
OEM (8)	-	$LS_8 = ES_8 = 73$
Supplier 7	$LF_7 = \min(LS_8) = 73$	$LS_7 = LF_7 - E(DT_7) = 73 - 9 = 64$
Dummy supplier 5'	$LF_{5'} = \min(LS_8) = 73$	$LS_{5'} = LF_{5'} - E(DT_{5'}) = 73 - 15 = 58$
Supplier 4	$LF_4 = \min(LS_{5'}, LS_7) = 58$	$LS_4 = LF_4 - E(DT_4) = 58 - 8 = 50$
Supplier 1	$LF_1 = \min(LS_4) = 50$	$LS_1 = LF_1 - E(DT_1) = 50 - 10 = 40$
Supplier 5	$LF_5 = \min(LS_1, LS_{5'}) = 40$	$LS_5 = LF_5 - E(DT_5) = 40 - 15 = 25$
Supplier 6	$LF_6 = \min(LS_8) = 73$	$LS_6 = LF_6 - E(DT_6) = 73 - 15 = 58$
Supplier 3	$LF_3 = \min(LS_5, LS_{5'}, LS_6) = 25$	$LS_3 = LF_3 - E(DT_3) = 25 - 20 = 5$
Supplier 2	$LF_2 = \min(LS_3, LS_6) = 5$	$LS_2 = LF_2 - E(DT_2) = 5 - 5 = \underline{0}$

Table 9- 5: Backward pass calculation in detail for Table 6-3

9.4.2 Calculations for notebook computer supply network case study in section 6.3.1

The calculation method to fill the Table 6-12, to find the critical path for the notebook computer supply network in section 6.3.1 are as follows:

1. After simplification, look at figure 6-10 (a) (because the structures of two figures (a) and (b) are the same, this is why we just show the calculation of the (a).), and find those suppliers and nodes which have not any predecessor and choose them as beginner nodes. The same before, in this figure, nodes 1, 2, 3, 4, 5, 6, 8, 9, and 12 recognized as the beginners, because there is no predecessor before them. Then, put $ES_1 = ES_2 = ES_3 = ES_4 = ES_5 = ES_6 = ES_8 = ES_9 = 0$.
2. Follow the forward pass calculation regarding the figure 6-10 (a), in the Table 9-4:

Calculation of forward pass		
Node	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + E(DT_i)$
Supplier 1	$ES_1=0$	$Ef_1 = ES_1 + E(DT_1)=0+40=40$
Supplier 2	$ES_2=0$	$Ef_2 = ES_2 + E(DT_2)=0+20=20$
Supplier 3	$ES_3=0$	$Ef_3 = ES_3 + E(DT_3)=0+20=20$
Supplier 4	$ES_4=0$	$Ef_4 = ES_4 + E(DT_4)=0+5=5$
Supplier 5	$ES_5=0$	$Ef_5 = ES_5 + E(DT_5)=0+60=60$
Supplier 6	$ES_6=0$	$Ef_6 = ES_6 + E(DT_6)=0+70=70$
Supplier 8	$ES_8=0$	$Ef_8 = ES_8 + E(DT_8)=0+60=60$
Supplier 9	$ES_9=0$	$Ef_9 = ES_9 + E(DT_9)=0+30=30$
Supplier 12	$ES_{12}=0$	$Ef_{12} = ES_{12} + E(DT_{12})=0+40=40$
Supplier 7	$ES_7 = \max (Ef_1, Ef_2, Ef_3, Ef_4)=40$	$Ef_7 = ES_7 + E(DT_7)=40+20=60$
Supplier 11	$ES_{11} = \max (Ef_5, Ef_6, Ef_7, Ef_8, Ef_9)= 70$	$Ef_{11} = ES_{11} + E(DT_{11})=70+5=75$
Supplier 14	$ES_{14} = \max (Ef_{11}, Ef_{12})= 75$	$Ef_{14} = ES_{14} + E(DT_{14})=75+1=76$
OEM (15)	$ES_{15} = \max (Ef_{14})= 76$	-

Table 9- 6: Forward pass calculation in detail for Table 6-7

- Now, put $LS_{15}=ES_{15}=76$, and follow the backward pass calculation regarding the figure 6-10 (a), in the Table 9-7, from OEM to beginner node:

Calculation of backward pass		
Node	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - E(DT_i)$
OEM (15)	-	$LS_{15} = ES_{15} = 76$
Supplier 14	$LF_{14} = \min(LS_{15}) = 76$	$LS_{14} = LF_{14} - E(DT_{14}) = 76 - 1 = 75$
Supplier 11	$LF_{11} = \min(LS_{14}) = 75$	$LS_{11} = LF_{11} - E(DT_{11}) = 75 - 5 = 70$
Supplier 7	$LF_7 = \min(LS_{11}) = 70$	$LS_7 = LF_7 - E(DT_7) = 70 - 20 = 50$
Supplier 12	$LF_{12} = \min(LS_{14}) = 75$	$LS_{12} = LF_{12} - E(DT_{12}) = 75 - 40 = 35$
Supplier 9	$LF_9 = \min(LS_{11}) = 70$	$LS_9 = LF_9 - E(DT_9) = 70 - 30 = 40$
Supplier 8	$LF_8 = \min(LS_{11}) = 70$	$LS_8 = LF_8 - E(DT_8) = 70 - 60 = 10$
Supplier 6	$LF_6 = \min(LS_{11}) = 70$	$LS_6 = LF_6 - E(DT_6) = 70 - 70 = \underline{0}$
Supplier 5	$LF_5 = \min(LS_{11}) = 70$	$LS_5 = LF_5 - E(DT_5) = 70 - 60 = 10$
Supplier 4	$LF_4 = \min(LS_7) = 50$	$LS_4 = LF_4 - E(DT_4) = 50 - 5 = 45$
Supplier 3	$LF_3 = \min(LS_7) = 50$	$LS_3 = LF_3 - E(DT_3) = 50 - 20 = 30$
Supplier 2	$LF_2 = \min(LS_7) = 50$	$LS_2 = LF_2 - E(DT_2) = 50 - 20 = 30$
Supplier 1	$LF_1 = \min(LS_7) = 50$	$LS_1 = LF_1 - E(DT_1) = 50 - 40 = 10$

Table 9- 7: Backward pass calculation in detail for Table 6-7

9.4.3 Calculations for Noramco's spray nozzles supply network case study in section 6.3.2

The same before, the calculation method to fill the Table 6-16, to find the critical path for the Noramco's spray nozzles supply network in section 6.3.2 are as follows:

1. After simplification, look at figure 6-14 (d) (because the structures of other figures are the same.), and find those suppliers and nodes which have not any predecessor and choose them as beginner nodes. The same as before, in this figure, nodes 1, 2, and 3, recognized as the beginners, because there is no predecessor before them. Then, put $ES_1 = ES_2 = ES_3 = 0$.
2. Follow the forward pass calculation regarding the figure 6-14 (d), in the Table 9-8:

Calculation of forward pass		
Node	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + E(DT_i)$
Supplier 1	$ES_1=0$	$Ef_1 = ES_1 + E(DT_1)=0+95=95$
Supplier 2	$ES_2=0$	$Ef_2 = ES_2 + E(DT_2)=0+65=65$
Supplier 3	$ES_3=0$	$Ef_3 = ES_3 + E(DT_3)=0+95=95$
Supplier 4	$ES_4 = \max (Ef_1)=95$	$Ef_4 = ES_4 + E(DT_4)=95+32=127$
Supplier 5	$ES_5 = \max (Ef_2)=65$	$Ef_5 = ES_5 + E(DT_5)=65+32=97$
Supplier 6	$ES_6 = \max (Ef_3)=95$	$Ef_6 = ES_6 + E(DT_6)=95+12=107$
Supplier 7	$ES_7 = \max (Ef_3)=95$	$Ef_7 = ES_7 + E(DT_7)=95+15=110$
Supplier 8	$ES_8 = \max (Ef_7)=110$	$Ef_8 = ES_8 + E(DT_8)=110+15=125$
Supplier 9	$ES_9 = \max (Ef_8)=125$	$Ef_9 = ES_9 + E(DT_9)=125+45=170$
Supplier 10	$ES_{10} = \max (Ef_4, Ef_5, Ef_6, Ef_9)=170$	$Ef_{10} = ES_{10} + E(DT_{10})=170+14=184$
Supplier 11	$ES_{11} = \max (Ef_{10})=184$	$Ef_{11} = ES_{11} + E(DT_{11})=184+6=190$
OEM (12)	$ES_{12} = \max (Ef_{11})= 190$	-

Table 9-8: Forward pass calculation in detail for Table 6-16

3. Now, put $LS_{12}=ES_{12}=190$, and follow the backward pass calculation regarding the figure 6-14 (d), in the Table 9-9, from OEM to beginner nodes:

Calculation of backward pass		
Node	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - E(DT_i)$
OEM (12)	-	$LS_{12}=ES_{12}=190$
Supplier 11	$LF_{11} = \min(LS_{12})=190$	$LS_{11} = LF_{11} - E(DT_{11})=190-6=184$
Supplier 10	$LF_{10} = \min(LS_{11})=184$	$LS_{10} = LF_{10} - E(DT_{10})=184-14=170$
Supplier 9	$LF_9 = \min(LS_{10})=170$	$LS_9 = LF_9 - E(DT_9)=170-45=125$
Supplier 8	$LF_8 = \min(LS_9)=125$	$LS_8 = LF_8 - E(DT_8)=125-15=110$
Supplier 7	$LF_7 = \min(LS_8)=110$	$LS_7 = LF_7 - E(DT_7)=110-15=95$
Supplier 6	$LF_6 = \min(LS_{10})=170$	$LS_6 = LF_6 - E(DT_6)=170-12=158$
Supplier 5	$LF_5 = \min(LS_{10})=170$	$LS_5 = LF_5 - E(DT_5)=170-32=138$
Supplier 4	$LF_4 = \min(LS_{10})=170$	$LS_4 = LF_4 - E(DT_4)=170-32=138$
Supplier 3	$LF_3 = \min(LS_6, LS_7)=95$	$LS_3 = LF_3 - E(DT_3)=95-95=0$
Supplier 2	$LF_2 = \min(LS_5)=138$	$LS_2 = LF_2 - E(DT_2)=138-65=73$
Supplier 1	$ES_1 = \max (Ef_4)= 170$	$LS_1 = LF_1 - E(DT_1)=170-95=43$

Table 9-9: Backward pass calculation in detail for Table 6-16

9.4.4 Calculations for Bulldozer supply network case study in section 6.3.3

The same before, the calculation method to fill the Table 6-20, to find the critical path for the Bulldozer supply network in section 6.3.3 are as follows:

1. Look at figure 6-17 and find those suppliers and nodes which have not any predecessor and choose them as beginner nodes. The same as before, in this figure, nodes 1, 2, 3, 4, 5, 6, 7, 8, 9, 12, 13, 17, 18, and 19 recognized as the beginners, because there is no predecessor before them. Then, put $ES_1 = ES_2 = ES_3 = ES_4 = ES_5 = ES_6 = ES_7 = ES_8 = ES_9 = ES_{12} = ES_{13} = ES_{17} = ES_{18} = ES_{19} = 0$.
2. Follow the forward pass calculation regarding the figure 6-17, in the Table 9-10:

Calculation of forward pass		
Node	$ES_i = \max(Ef_1, Ef_2, \dots, Ef_k)$	$Ef_i = ES_i + E(DT_i)$
Supplier 1	$ES_1=0$	$Ef_1 = ES_1 + E(DT_1)=19$
Supplier 2	$ES_2=0$	$Ef_2 = ES_2 + E(DT_2)=15$
Supplier 3	$ES_3=0$	$Ef_3 = ES_3 + E(DT_3)=8$
Supplier 4	$ES_4=0$	$Ef_4 = ES_4 + E(DT_4)=9$
Supplier 5	$ES_5=0$	$Ef_5 = ES_5 + E(DT_5)=9$
Supplier 6	$ES_6=0$	$Ef_6 = ES_6 + E(DT_6)=6$
Supplier 7	$ES_7=0$	$Ef_7 = ES_7 + E(DT_7)=9$
Supplier 8	$ES_8=0$	$Ef_8 = ES_8 + E(DT_8)=8$
Supplier 9	$ES_9=0$	$Ef_9 = ES_9 + E(DT_9)=24$
Supplier 10	$ES_{10} = \max(Ef_1, Ef_2) =19$	$Ef_{10} = ES_{10} + E(DT_{10})= 34$
Supplier 11	$ES_{11} = \max(Ef_3, Ef_4, Ef_5) =9$	$Ef_{11} = ES_{11} + E(DT_{11})= 15$
Supplier 12	$ES_{12}=0$	$Ef_{12} = ES_{12} + E(DT_{12})= 7$
Supplier 13	$ES_{13}=0$	$Ef_{13} = ES_{13} + E(DT_{13})= 12$
Supplier 14	$ES_{14} = \max(Ef_6, Ef_7, Ef_8) =9$	$Ef_{14} = ES_{14} + E(DT_{14})= 23$
Supplier 15	$ES_{15} = \max(Ef_9, Ef_{10}, Ef_{11}) =34$	$Ef_{15} = ES_{15} + E(DT_{15})= 44$
Supplier 16	$ES_{16} = \max(Ef_{12}, Ef_{13})= 12$	$Ef_{16} = ES_{16} + E(DT_{16})= 26$
Supplier 17	$ES_{17}=0$	$Ef_{17} = ES_{17} + E(DT_{17})= 11$
Supplier 18	$ES_{18}=0$	$Ef_{18} = ES_{18} + E(DT_{18})= 35$
Supplier 19	$ES_{19}=0$	$Ef_{19} = ES_{19} + E(DT_{19})= 10$
Supplier 20	$ES_{20} = \max(Ef_{14}, Ef_{15}, Ef_{16}) = 44$	$Ef_{20} = ES_{20} + E(DT_{20})= 52$
Supplier 21	$ES_{21} = \max(Ef_{17}, Ef_{18}) = 35$	$Ef_{21} = ES_{21} + E(DT_{21})= 52$
Supplier 22	$ES_{22} = \max(Ef_{19}, Ef_{20}, Ef_{21}) = 52$	$Ef_{22} = ES_{22} + E(DT_{22})= 59$
OEM (23)	$ES_{23} = \max(Ef_{22}) = 59$	-

Table 9-10: Forward pass calculation in detail for Table 6-20

- Now, put $LS_{23}=ES_{23}=59$, and follow the backward pass calculation regarding the figure 6-17, in the Table 9-11, from OEM to beginner nodes:

Calculation of backward pass		
Node	$LF_i = \min(LS_1, LS_2, \dots, LS_K)$	$LS_i = LF_i - E(DT_i)$
OEM (23)	-	$LS_{23} = ES_{23} = 59$
Supplier 22	$Lf_{22} = \min(LS_{23}) = 59$	$LS_{22} = Lf_{22} - E(DT_{22}) = 52$
Supplier 21	$Lf_{21} = \min(LS_{22}) = 52$	$LS_{21} = Lf_{21} - E(DT_{21}) = 35$
Supplier 20	$Lf_{20} = \min(LS_{22}) = 52$	$LS_{20} = Lf_{20} - E(DT_{20}) = 44$
Supplier 19	$Lf_{19} = \min(LS_{22}) = 52$	$LS_{19} = Lf_{19} - E(DT_{19}) = 42$
Supplier 18	$Lf_{18} = \min(LS_{21}) = 35$	$LS_{18} = Lf_{18} - E(DT_{18}) = \underline{0}$
Supplier 17	$Lf_{17} = \min(LS_{21}) = 35$	$LS_{17} = Lf_{17} - E(DT_{17}) = 14$
Supplier 16	$Lf_{16} = \min(LS_{20}) = 44$	$LS_{16} = Lf_{16} - E(DT_{16}) = 30$
Supplier 15	$Lf_{15} = \min(LS_{20}) = 44$	$LS_{15} = Lf_{15} - E(DT_{15}) = 34$
Supplier 14	$Lf_{14} = \min(LS_{20}) = 44$	$LS_{14} = Lf_{14} - E(DT_{14}) = 34$
Supplier 13	$Lf_{13} = \min(LS_{16}) = 30$	$LS_{13} = Lf_{13} - E(DT_{13}) = 18$
Supplier 12	$Lf_{12} = \min(LS_{16}) = 30$	$LS_{12} = Lf_{12} - E(DT_{12}) = 23$
Supplier 11	$Lf_{11} = \min(LS_{15}) = 34$	$LS_{11} = Lf_{11} - E(DT_{11}) = 28$
Supplier 10	$Lf_{10} = \min(LS_{15}) = 34$	$LS_{10} = Lf_{10} - E(DT_{10}) = 19$
Supplier 9	$Lf_9 = \min(LS_{15}) = 34$	$LS_9 = Lf_9 - E(DT_9) = 10$
Supplier 8	$Lf_8 = \min(LS_{14}) = 34$	$LS_8 = Lf_8 - E(DT_8) = 26$
Supplier 7	$Lf_7 = \min(LS_{14}) = 34$	$LS_7 = Lf_7 - E(DT_7) = 25$
Supplier 6	$Lf_6 = \min(LS_{14}) = 34$	$LS_6 = Lf_6 - E(DT_6) = 28$
Supplier 5	$Lf_5 = \min(LS_{11}) = 28$	$LS_5 = Lf_5 - E(DT_5) = 19$
Supplier 4	$Lf_4 = \min(LS_{11}) = 28$	$LS_4 = Lf_4 - E(DT_4) = 19$
Supplier 3	$Lf_3 = \min(LS_{11}) = 28$	$LS_3 = Lf_3 - E(DT_3) = 20$
Supplier 2	$Lf_2 = \min(LS_{10}) = 19$	$LS_2 = Lf_2 - E(DT_2) = 4$
Supplier 1	$Lf_1 = \min(LS_{10}) = 19$	$LS_1 = Lf_1 - E(DT_1) = \underline{0}$

Table 9-11: backward pass calculation in detail for Table 6-20

It is noticeable that the number of critical paths is equal to the number of findings (0) in the LS column. In this case, we have two (0) in the LS column, then the number of the critical path is two.

9.5 EasyFit and Monte Carlo method results

9.5.1 Obtained Monte Carlo method results for scenario 1, section 6.1.1

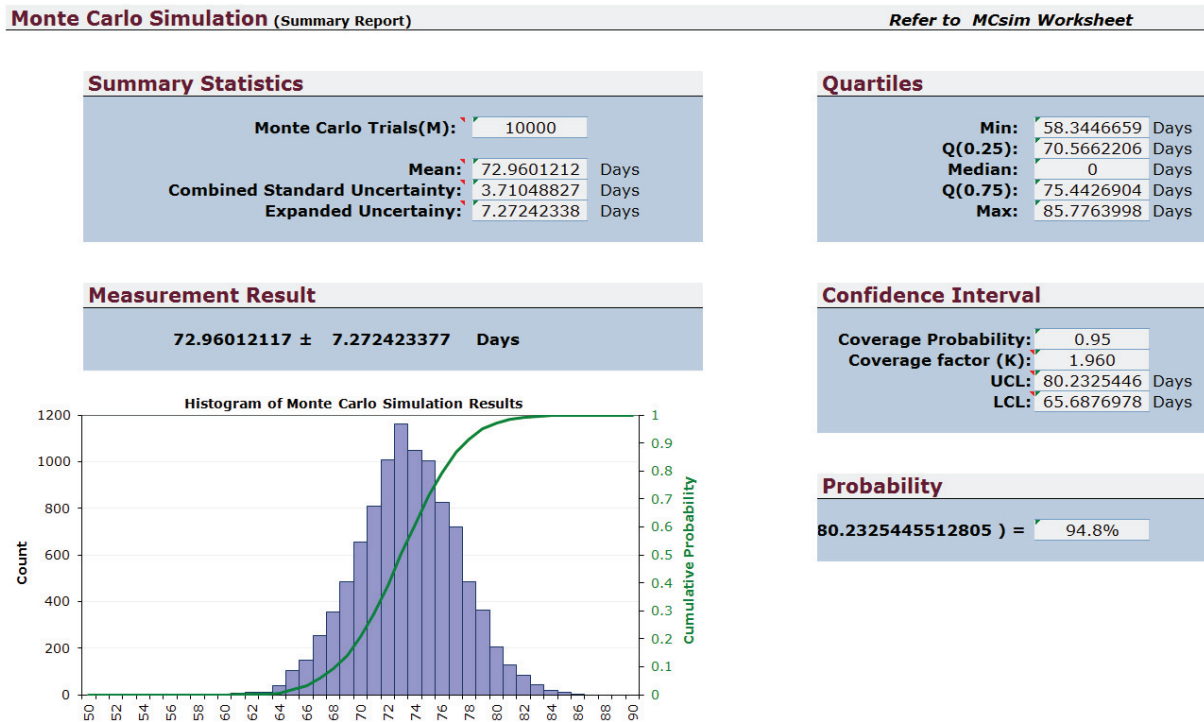


Figure 9-1: Obtained Monte Carlo method results for scenario 1, section 6.1.1

9.5.2 Obtained Monte Carlo method and EasyFit results for scenario 2, section 6.1.2

○ The Monte Carlo method results

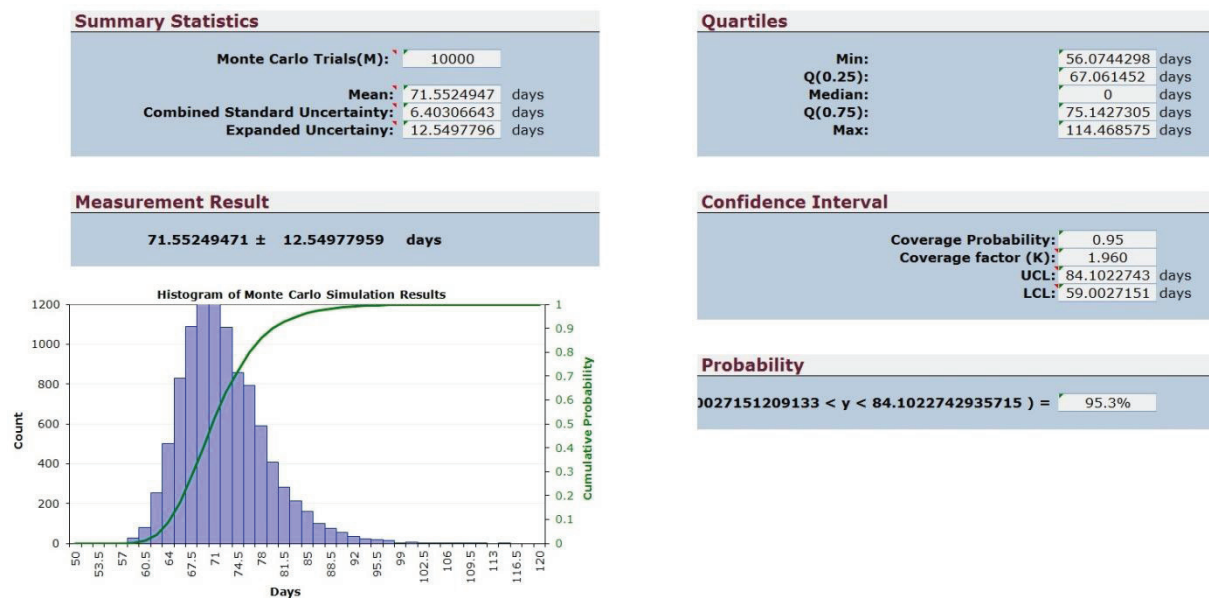


Figure 9-2: Obtained Monte Carlo method results for scenario 2, section 6.1.2

- **The EasyFit calculation regarding to the generated data by Monte Carlo method, in the scenario 2, section 6.1.2**

Goodness of Fit - Summary								#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared				Statistic	Rank	Statistic	Rank	Statistic	Rank
		Statistic	Rank	Statistic	Rank	Statistic	Rank								
1	Beta	0.01717	17	6.0288	17	50.726	17	33	Laplace	0.10471	42	138.48	38	1102.4	38
2	Burr	0.0197	19	5.0132	15	40.004	15	34	Levy	0.61346	60	4296.6	59	1.1736E+5	54
3	Burr (4P)	0.01083	2	1.2452	2	17.415	6	36	Log-Gamma	0.04292	22	37.485	21	240.94	22
4	Cauchy	0.09747	40	153.97	39	1517.2	40	37	Log-Logistic	0.04981	25	39.885	22	280.08	26
5	Chi-Squared	0.21139	47	767.42	45	4923.7	44	38	Log-Logistic (3P)	0.01311	10	2.5104	8	23.496	9
6	Chi-Squared (2P)	0.05785	33	98.272	36	245.35	23	39	Log-Pearson 3	0.01306	9	2.7387	9	17.408	5
7	Dagum	0.39732	54	3254.7	56	7001.5	45	40	Logistic	0.06455	37	75.861	32	524.16	33
8	Dagum (4P)	0.01221	6	2.3829	6	27.025	10	41	Lognormal	0.04558	23	42.276	23	265.21	24
9	Erlang	0.05166	29	58.269	27	395.75	29	42	Lognormal (3P)	0.01233	7	2.3903	7	22.145	8
10	Erlang (3P)	0.05051	27	47.308	25	129.77	20	43	Nakagami	0.05863	34	81.385	33	587.88	35
11	Error	0.08641	39	99.866	37	757.9	37	44	Normal	0.06377	35	85.421	34	565.95	34
12	Error Function	1	64	N/A		N/A		45	Pareto	0.35016	52	1818.1	49	11312.0	47
13	Exponential	0.55931	58	3472.2	57	74149.0	52	46	Pareto 2	0.61311	59	4113.8	58	75525.0	53
14	Exponential (2P)	0.3269	49	1591.7	47	9143.8	46	47	Pearson 5	0.03962	21	31.563	20	200.97	21
15	Fatigue Life	0.04595	24	42.768	24	267.28	25	48	Pearson 5 (3P)	0.01088	3	1.5706	3	15.484	3
16	Fatigue Life (3P)	0.01367	12	3.5091	10	29.667	12	49	Pearson 6	0.32746	50	2094.2	52	23933.0	50
17	Frechet	0.02954	20	24.661	19	124.56	19	50	Pearson 6 (4P)	0.01094	4	1.6031	4	16.055	4
18	Frechet (3P)	0.01489	14	5.0593	16	29.734	13	51	Pert	0.13627	46	449.31	43	2763.9	42
19	Gamma	0.05194	31	58.567	28	397.44	30	52	Phased Bi-Exponential	1.0	63	1.5857E+5	63	1.3058E+11	56
20	Gamma (3P)	0.01733	18	6.1884	18	53.979	18	53	Phased Bi-Weibull	0.53291	57	7424.5	60	N/A	
21	Gen. Extreme Value	0.00887	1	1.2086	1	8.6766	1	54	Power Function	0.34617	51	1854.3	50	N/A	
22	Gen. Gamma	0.05184	30	55.29	26	361.39	27	55	Rayleigh	0.41801	55	2425.5	54	34339.0	51
23	Gen. Gamma (4P)	0.01505	15	4.2447	13	37.674	14	56	Rayleigh (2P)	0.13579	45	305.23	40	1513.5	39
24	Gen. Logistic	0.01593	16	4.3715	14	42.801	16	57	Reciprocal	0.35833	53	1919.2	51	11407.0	48
25	Gen. Pareto	0.05236	32	1810.9	48	N/A		58	Rice	0.67896	61	85397.0	62	N/A	
26	Gumbel Max	0.01282	8	3.8596	12	21.112	7	59	Student's t	0.99984	62	73199.0	61	1.5348E+8	55
27	Gumbel Min	0.13328	44	603.67	44	N/A		60	Triangular	0.27623	48	1210.8	46	4374.3	43
28	Hypersecant	0.07629	38	88.435	35	636.77	36	61	Uniform	0.09812	41	2192.4	53	N/A	
29	Inv. Gaussian	0.06382	36	72.053	31	371.07	28	62	Wakeby	0.01401	13	425.49	42	N/A	
30	Inv. Gaussian (3P)	0.01358	11	3.747	11	29.157	11	63	Weibull	0.11642	43	365.34	41	1581.5	41
31	Johnson SU	0.01119	5	1.8695	5	12.309	2	64	Weibull (3P)	0.05002	26	66.022	29	469.33	31
32	Kumaraswamy	0.05129	28	68.113	30	481.36	32	65	Johnson SB	No fit					

Figure 9-3: The probability density function ranking (goodness of fit summary) by EasyFit, the generated data by Monte Carlo method, in the scenario 2, section 6.1.2

- The fitting results for each probability density function regarding to the EasyFit are as follows:

Fitting Results			#	Distribution	Parameters	#	Distribution	Parameters
1	Beta	$\alpha_1=8.0229$ $\alpha_2=8.3651E+6$ $a=53.889$ $b=1.8499E+7$	29	Inv. Gaussian	$\lambda=8955.4$ $\mu=71.639$	56	Rayleigh (2P)	$\sigma=12.217$ $\gamma=55.592$
2	Burr	$k=0.50016$ $\alpha=28.472$ $\beta=67.952$	30	Inv. Gaussian (3P)	$\lambda=319.85$ $\mu=23.411$ $\gamma=48.228$	57	Reciprocal	$a=55.596$ $b=108.41$
3	Burr (4P)	$k=1.5777$ $\alpha=4.0609$ $\beta=18.571$ $\gamma=54.763$	31	Johnson SU	$\gamma=-6.6314$ $\delta=3.1511$ $\lambda=4.5033$ $\xi=52.505$	58	Rice	$v=74.895$ $\sigma=0.43539$
4	Cauchy	$\sigma=3.5144$ $\mu=70.42$	32	Kumaraswamy	$\alpha_1=2.6121$ $\alpha_2=617.54$ $a=55.577$ $b=267.39$	59	Student's t	$v=2$
5	Chi-Squared	$v=71$	33	Laplace	$\lambda=0.22072$ $\mu=71.639$	60	Triangular	$m=66.528$ $a=55.586$ $b=108.41$
6	Chi-Squared (2P)	$v=18$ $\gamma=52.658$	34	Levy	$\sigma=71.102$	61	Uniform	$a=60.541$ $b=82.737$
7	Dagum	$k=304.3$ $\alpha=7.0425$ $\beta=33.366$	35	Levy (2P)	$\sigma=13.385$ $\gamma=55.481$	62	Wakeby	$\alpha=39.108$ $\beta=6.9093$ $\gamma=6.8173$ $\delta=0.10498$ $\xi=60.525$
8	Dagum (4P)	$k=0.74384$ $\alpha=5.2188$ $\beta=17.428$ $\gamma=54.733$	36	Log-Gamma	$\alpha=2423.7$ $\beta=0.00176$	63	Weibull	$\alpha=13.71$ $\beta=74.428$
9	Erlang	$m=125$ $\beta=0.57307$	37	Log-Logistic	$\alpha=20.66$ $\beta=71.362$	64	Weibull (3P)	$\alpha=2.6226$ $\beta=18.072$ $\gamma=55.574$
10	Erlang (3P)	$m=8$ $\beta=2.2588$ $\gamma=54.111$	38	Log-Logistic (3P)	$\alpha=5.7776$ $\beta=19.605$ $\gamma=51.123$	65	Johnson SB	No fit
11	Error	$k=1.1889$ $\sigma=6.4074$ $\mu=71.639$	39	Log-Pearson 3	$\alpha=9.4062$ $\beta=0.02827$ $\gamma=4.0019$			
12	Error Function	$h=0.11036$	40	Logistic	$\sigma=3.5326$ $\mu=71.639$			
13	Exponential	$\lambda=0.01396$	41	Lognormal	$\sigma=0.08668$ $\mu=4.2678$			
14	Exponential (2P)	$\lambda=0.06233$ $\gamma=55.596$	42	Lognormal (3P)	$\sigma=0.27403$ $\mu=3.0863$ $\gamma=48.902$			
15	Fatigue Life	$\alpha=0.08679$ $\beta=71.37$	43	Nakagami	$m=28.985$ $\Omega=5173.2$			
16	Fatigue Life (3P)	$\alpha=0.27008$ $\beta=22.439$ $\gamma=48.382$	44	Normal	$\sigma=6.4074$ $\mu=71.639$			
17	Frechet	$\alpha=14.711$ $\beta=68.618$	45	Pareto	$\alpha=4.0049$ $\beta=55.596$			
18	Frechet (3P)	$\alpha=1.9987E+8$ $\beta=1.0474E+9$ $\gamma=-1.0474E+9$	46	Pareto 2	$\alpha=142.91$ $\beta=8806.5$			
19	Gamma	$\alpha=125.01$ $\beta=0.57307$	47	Pearson 5	$\alpha=135.74$ $\beta=9651.1$			
20	Gamma (3P)	$\alpha=7.7596$ $\beta=2.2588$ $\gamma=54.111$	48	Pearson 5 (3P)	$\alpha=23.124$ $\beta=647.69$ $\gamma=42.361$			
21	Gen. Extreme Value	$k=-0.03533$ $\sigma=5.1907$ $\mu=68.818$	49	Pearson 6	$\alpha_1=6.0223$ $\alpha_2=2.4688E+9$ $\beta=3.1861E+10$			
22	Gen. Gamma	$k=1.0061$ $\alpha=128.72$ $\beta=0.57307$	50	Pearson 6 (4P)	$\alpha_1=99.874$ $\alpha_2=23.42$ $\beta=5.9796$ $\gamma=44.999$			
23	Gen. Gamma (4P)	$k=0.72109$ $\alpha=16.897$ $\beta=0.36433$ $\gamma=52.957$	51	Pert	$m=67.982$ $a=55.592$ $b=108.45$			
24	Gen. Logistic	$k=0.14742$ $\sigma=3.3627$ $\mu=70.802$	52	Phased Bi-Exponential	$\lambda_1=0.02892$ $\gamma_1=55$ $\lambda_2=0.37235$ $\gamma_2=15.048$			
25	Gen. Pareto	$k=-0.48608$ $\sigma=12.879$ $\mu=62.972$	53	Phased Bi-Weibull	$\alpha_1=1.2167$ $\beta_1=3861.6$ $\gamma_1=55$ $\alpha_2=3.9024$ $\beta_2=28.628$ $\gamma_2=3.1033$			
26	Gumbel Max	$\sigma=4.9958$ $\mu=68.755$	54	Power Function	$\alpha=0.75951$ $a=55.596$ $b=108.41$			
27	Gumbel Min	$\sigma=4.9958$ $\mu=74.522$	55	Rayleigh	$\sigma=57.159$			
28	Hypersecant	$\sigma=6.4074$ $\mu=71.639$						

Figure 9-4: The fitting results of EasyFit for each fitted probability density function

9.5.3 Obtained Monte Carlo method and EasyFit results for section 6.3.2

- The Monte Carlo method results

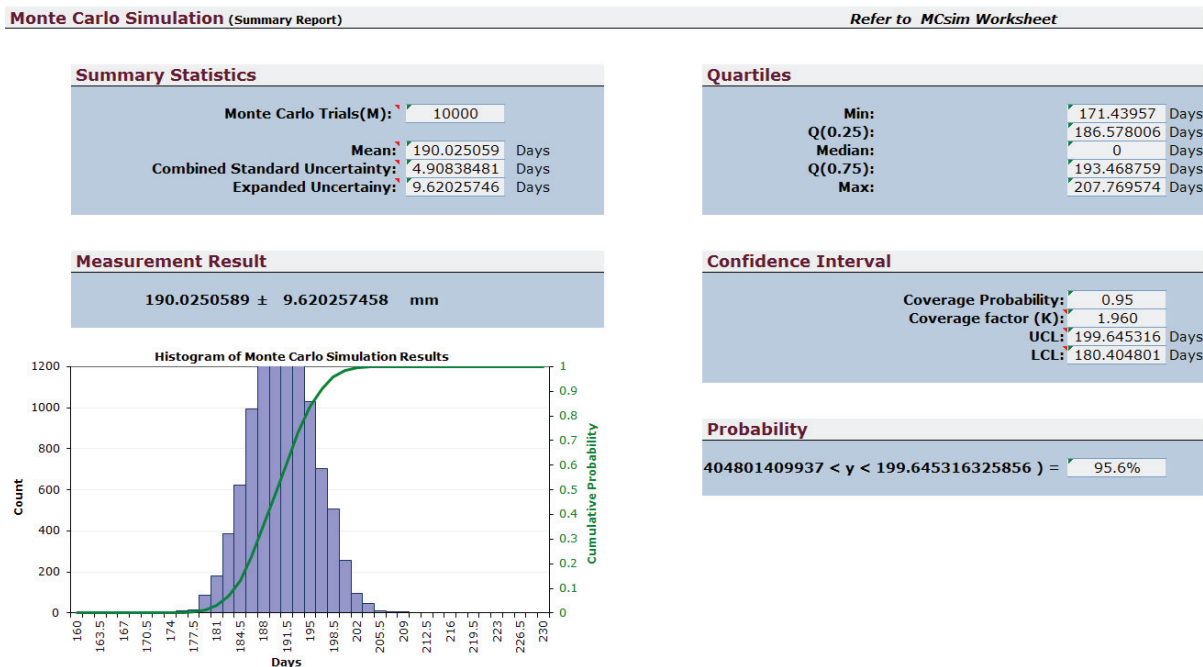


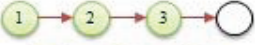
















Figure 9-5: Obtained Monte Carlo method results for section 6.3.2

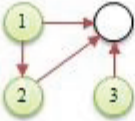
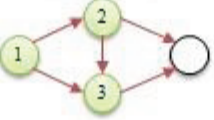




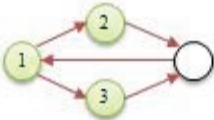





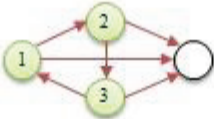
- **The EasyFit calculation regarding to the generated data by Monte Carlo method, in the section 6.3.2**

Goodness of Fit - Summary															
#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared									
		Statistic	Rank	Statistic	Rank	Statistic	Rank			Statistic	Rank	Statistic	Rank	Statistic	Rank
								33	Laplace	0.07061	38	126.73	33	911.98	33
1	Beta	0.01056	8	4.401	21	24.644	14	34	Levy	0.66454	57	5133.7	57	4.3050E+5	55
2	Burr	0.0208	26	11.134	25	97.767	25	35	Levy (2P)	0.55149	55	3724.7	55	37647.0	49
3	Burr (4P)	0.01654	22	3.9608	20	46.331	21	36	Log-Gamma	0.01464	17	1.9028	14	24.185	13
4	Cauchy	0.07734	42	143.78	36	2069.2	38	37	Log-Logistic	0.03144	31	21.647	29	141.8	28
5	Chi-Squared	0.30237	48	1985.0	50	18023.0	45	38	Log-Logistic (3P)	0.02131	27	11.805	26	98.524	26
6	Chi-Squared (2P)	0.09956	43	225.75	40	1087.5	37	39	Log-Pearson 3	0.00982	5	1.0842	3	16.889	4
7	Dagum	0.72023	59	12825.0	59	41602.0	50	40	Logistic	0.02928	30	24.029	30	154.62	29
8	Dagum (4P)	0.81166	60	13414.0	60	85003.0	51	41	Lognormal	0.01413	15	1.7322	11	23.479	12
9	Erlang	0.01524	19	1.8675	13	20.146	9	42	Lognormal (3P)	0.01601	21	2.347	17	28.566	16
10	Erlang (3P)	0.0186	23	3.679	19	35.974	20	43	Nakagami	0.01159	10	1.2294	5	16.403	2
11	Error	0.00553	1	0.2295	2	17.4	5	44	Normal	0.01018	6	1.1222	4	16.483	3
12	Error Function	1	63	N/A		N/A		45	Pareto	0.4125	53	2731.8	53	22815.0	47
13	Exponential	0.60303	56	4358.8	56	2.7974E+5	53	46	Pareto 2	0.6649	58	5243.4	58	2.8622E+5	54
14	Exponential (2P)	0.40454	52	2645.1	51	21056.0	46	47	Pareto 5	0.01541	20	2.205	15	29.03	17
15	Fatigue Life	0.01413	14	1.7279	10	23.479	11	48	Pearson 5 (3P)	0.02372	28	7.9964	23	59.369	22
16	Fatigue Life (3P)	0.01085	9	1.2438	7	18.196	7	49	Pearson 6	0.37564	51	2671.7	52	37108.0	48
17	Frechet	0.07513	41	166.84	37	938.75	36	50	Pearson 6 (4P)	0.01208	11	1.314	8	17.894	6
18	Frechet (3P)	0.05908	35	106.69	32	832.02	32	51	Pert	0.1057	44	366.75	41	2168.5	39
19	Gamma	0.0129	12	1.4248	9	21.125	10	52	Phased Bi-Exponential	1	62	N/A		N/A	
20	Gamma (3P)	0.0151	18	2.3499	18	32.351	19	53	Phased Bi-Weibull	0.06479	36	129.93	34	N/A	
21	Gen. Extreme Value	0.00571	2	12.399	27	N/A		54	Power Function	0.30659	50	1637.2	45	8979.2	43
22	Gen. Gamma	1	64	N/A		N/A		55	Rayleigh	0.49286	54	3532.8	54	1.3891E+5	52
23	Gen. Gamma (4P)	0.01456	16	2.2808	16	31.677	18	56	Rayleigh (2P)	0.26151	46	1304.2	44	6554.3	42
24	Gen. Logistic	0.02376	29	15.304	28	104.46	27	57	Reciprocal	0.30446	49	1640.5	46	11020.0	44
25	Gen. Pareto	0.05178	33	1768.5	49	N/A		58	Rice	0.26544	47	1700.6	48	3460.9	41
26	Gumbel Max	0.07224	39	177.11	38	927.67	35	59	Student's t	0.99998	61	1.0158E+5	61	3.8621E+9	56
27	Gumbel Min	0.07504	40	178.33	39	914.53	34	60	Triangular	0.14681	45	483.07	43	2715.1	40
28	Hypersecant	0.04464	32	54.773	31	362.8	30	61	Uniform	0.05601	34	1663.5	47	N/A	
29	Inv. Gaussian	0.00949	4	1.8533	12	27.107	15	62	Wakeby	0.01368	13	411.1	42	N/A	
30	Inv. Gaussian (3P)	0.01032	7	1.2303	6	20.052	8	63	Weibull	0.06838	37	130.92	35	730.95	31
31	Johnson SB	0.00593	3	0.21541	1	15.103	1	64	Weibull (3P)	0.01888	24	7.7738	22	72.595	23
32	Kumaraswamy	0.01979	25	8.4163	24	75.757	24	65	Johnson SU	No fit					

Figure 9-6: The probability density function ranking (goodness of fit summary) by EasyFit, for the generated data by Monte Carlo method, in the section 6.3.2

9.6 All possible basic types of network with 4 nodes

Row	Basic network type	One OEM property
1		Yes
2		No
3		No
4		No
5		Yes
6		Yes
7		Yes
8		Yes
9		Yes
10		Yes
11		Yes
12		No
13		No
14		Yes
15		Yes
16		Yes
17		Yes

Row	Basic network type	One OEM property
18		Yes
19		Yes
20		Yes
21		Yes
22		Yes
23		Yes
24		Yes
25		Yes
26		Yes
27		Yes
28		Yes
29		Yes
30		Yes





Row	Basic network type	One OEM property
31		Yes
32		Yes
33		Yes
34		Yes

Figure 9-7: All 34 possible basic types of network with four nodes