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MODELING AND DESIGN
OF
DIGITAL SUPPLY CHAIN

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MODELING AND DESIGN OF DIGITAL SUPPLY CHAIN

(DİJİTAL TEDARİK ZİNCİRİNİN MODELLENMESİ VE TASARIMI)

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LIST OF SYMBOLS

AD	Axiomatic Design
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ARAS	Additive Ratio Assessment
CM	Cognitive Map
CR	Consistency Ratio
COPRAS	Complex Proportional Assessment
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DM	Decision Maker
DSC	Digital Supply Chain
DTZ	Dijital Tedarik Zinciri
GDM	Group Decision Making
HOQ	House of Quality
MCDM	Multi-Criteria Decision-Making
MOORA	Multi-Objective Optimization on the Basis of Ratio Analysis
N/A	Not Applicable
PFSs	Pythagorean Fuzzy Sets
PFCM	Pythagorean Fuzzy Cognitive Map
PFWA	Pythagorean Fuzzy Weighted Averaging
PF-QFD	Pythagorean Fuzzy Quality Function Deployment
PF-ARAS	Pythagorean Fuzzy Additive Ratio Assessment
PF-ANP	Pythagorean Fuzzy Analytic Hierarchy Process
QFD	Quality Function Deployment
RI	Random Index
SCM	Supply Chain Management
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje

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ABSTRACT

In today's industrial competitive environment, supply chains need to become digital in order to do business in the global market. However, the traditional supply chains are limited by their digital abilities. Digital Supply Chain (DSC) is emerged as a new concept to identify or solve existing problems in supply chains. DSC can be defined as an intelligent best-fit technological system that is based on the capability of cooperation and communication to support and synchronize interaction between organizations by making services more accessible with an effective outcome.

The extensive literature research on DSC area revealed that studies focusing on digitalization within supply chains are very limited and generally these studies are focusing to a single problem encountered in supply chain management. Integrated studies handling multiple problems are nonexistent to the best of our knowledge. This thesis aims to fill this absence by focusing on strategic issues that directly affect DSCs for building an effective management structure with integrated approaches.

Thus, the proposed thesis study consists of four main stages: Modelling a digitalization structure for supply chains with the Axiomatic Design approach; Analyzing the success and risk factors of DSC structure with the Cognitive Map approach; Planning technologic infrastructure of DSC with the Quality Function Deployment approach; and Evaluating technology partner(s) for DSC using the Multi-Criteria Decision-Making techniques. The analytical dimension of the proposed integrated structure is treated with the Pythagorean Fuzzy Set approach.

The first stage of the thesis provides us with a digital transformation framework. This framework can be used as a means to locate the inadequate areas of supply chains for transformation into truly DSC entities. By precisely locating the success and risk factors for DSC, this provides insight regarding the digitalization challenges in supply chain management. Prioritizing the most suitable DSC components helps entities successfully plan the technologic infrastructure in transforming into true DSC. Finally, the selection of the best technology partner can be used as a reference to guide modeling and design initiatives in DSCs.

The proposed approaches are applied on real case studies through the evaluations of industrial experts. The obtained results are discussed and the final remarks are made to construct an effective DSC structure.

ÖZET

Bugünün endüstriyel rekabet ortamında, küresel pazarda iş yapabilmek tedarik zincirlerinin dijital olmasını gerektirir. Ancak, klasik anlamdaki tedarik zincirlerinin sahip oldukları dijital yetenekler sınırlıdır. Dijital Tedarik Zinciri (DTZ) tedarik zincirlerindeki mevcut problemleri tanımlamak veya çözmek için son dönemlerde ortaya çıkmış yeni bir kavramdır. Hizmetlerin daha etkili yöntemler kullanılarak daha erişilebilir olmasını sağlayan, organizasyonlar arasındaki etkileşimi senkronize ederken iletişim olanaklarını mükemmelleştiren akıllı ve elverişli teknolojik sistemler DTZ olarak tanımlanır.

DTZ konusu ile ilgili yapılan detaylı yazın taramasında tedarik zincirinde dijitalleşmeye odaklanan çalışmaların sınırlı sayıda olduğunu ve bu çalışmaların genellikle tedarik zinciri yönetiminde karşılaşılan tek bir soruna odaklandığını ortaya koymuştur. DTZ ile ilgili birden fazla sorunu ele alan bütünleşik çalışmalar, bildiğimiz kadarıyla, mevcut değildir. Bu tez çalışmasında, etkin bir DTZ yönetim yapısı oluşturmak için DTZ'yi doğrudan etkileyen stratejik konulara odaklanılarak DTZ yapısı için entegre bir yaklaşım önerilmektedir.

Bu doğrultuda, önerilen tez çalışması dört ana aşamadan oluşmaktadır: Aksiyomlarla Tasarım yaklaşımı kullanılarak tedarik zinciri için bir dijitalleşme yapısını modellemek; Bilişsel Haritalama yaklaşımı ile DTZ yapısının başarı ve risk faktörlerini analiz etmek; Kalite Fonksiyon Açılımı yaklaşımı kullanılarak DTZ'nin teknolojik altyapısını planlamak; ve Çok Ölçütlü Karar Verme teknikleri ile DTZ için teknoloji ortaklarını belirlemek. Önerilen bu entegre yapının analitik boyutu Pisagor Bulanık Küme yaklaşımı ile birlikte ele alınmıştır.

Tezin ilk aşaması bize dijital dönüşüm için bir çerçeve sunmaktadır. Bu çerçeve, tam manasıyla DTZ yapılarına dönüşebilmek için tedarik zincirlerindeki yetersiz alanları bulmakta bir araç olarak kullanılır. DTZ'nin başarı ve risk faktörlerini tam anlamıyla tespit etmek, tedarik zinciri yönetiminde dijitalleşmedeki zorluklar hakkında doğru bilgilere erişilmesini sağlar. En uygun DTZ bileşenlerinin önceliklendirilmesi, kurumların gerçek manada DTZ'ye dönüşmesinde doğru teknolojik altyapıyı planlamasına yardımcı olmuştur. Son olarak, en iyi teknoloji ortağını seçmek, DTZ için modelleme ve tasarım girişimlerine yardımcı olmakta referans olarak kullanılmıştır.

Önerilen yaklaşımlar, endüstriyel uzmanların değerlendirmeleri alınarak gerçek vaka analizleri üzerinde uygulanmıştır. Elde edilen sonuçlar tartışılmış ve etkin bir DTZ yapısı için final çıkarımlar yapılmıştır.

1. INTRODUCTION

1.1. Digital Supply Chain (DSC)

The past several decades have shown the unequivocal demand and development in supply chain management (SCM), and rivalry among enterprises has come to center around SCM, with intensifying competition between businesses and rapid advances relating to novel technologies, the implementation of these technologies, logistics, and so on, in the world. Simultaneously, an increase in digital enablers has resulted in a gradual increase in ideas of digital evolution and technology implementation in the context of SCM around the global market.

Digitalization is involved in almost all aspects of any organization now. Supply Chains and Logistics are no exceptions. Nowadays, technological means such as Internet of Things, Cloud Computing, and Big Data have empowered many firms to transform the existing paper-based traditional processes or technology-supported hybrid processes into collaborative, agile and flexible digital processes (Büyüközkan & Göçer, 2018a). Industrial revolutions used to come one at a time and rather slowly. Today's disruptive new technologies and dramatic shifts in consumer behavior are coming in waves, and it can seem rather overwhelming. According to market forecasts (Penthin & Dillman, 2015), it is predicted that 76% of the world have now internet access and more than half of the population actively uses social media. It is estimated that more than 8.5 billion "Things" are on the internet today, up more than 30% from just one year ago. The internet of things will capture rivers of real time data across the entire supply chain from supply to distribution and logistics. Up to 40% of all computation will happen with the advanced analytics and big data tools in just the next couple of years with 43% of enterprises make use of it for now. Cloud and mobile powered platforms are available and actionable anytime, anyplace and they are predicted to store about 40% of all data by 2020. Industrial internet is enabling the manufacturing to become much smarter and more agile.

Paradigm shift, such as mass customization, is finally becoming a reality. Until now, managing omni-channel complexity profitably has largely being an issue for retailers. Now many consumer-oriented manufacturers have the opportunity to drive their brand directly when it comes to challenge on how to do so profitably. Augmented Reality means increase labor productivity and in transportation and logistics improvement invisibility along with emerging new service models including 3D printing and drones. All these advancements mean these days consumers can purchase anything, anytime, anywhere. They want their products customized to suit their lifestyles and personalized, so they say something about them. What's more, products that were once considered pedestrian to design and manufacture are now exploding in complexity as sensors and connected technology make the dumb things smart (Ganeriwalla et al., 2016). With these abounded possibilities, enterprises become more aware on how digitalization can add value to them. But, how to capitalize on this wealth of data is a significant inquiry.

Tomorrows leaders know that to capitalize on this wealth of data, their supply chains need to become digital, smart, and connected. However, the real question is how fast and efficiently the supply chain is adapting to the era of digitalization, hyper connection and personalized products available anywhere, anytime. The answer to this question is mostly they don't adapt fast enough. Then, it is time for supply chains to go digital. Traditional supply chains were fine for competing in the traditional world, where suppliers distributed raw materials to factories, factories provided finished products to distributers and retailers, then retailers ultimately sold these products to customers. Moreover, one size old linear supply chain is the thing of the past. Instead, we now create dynamic supply chains with optimized configurations for key segments having efficiency and margin along with value and differentiation to the consumers. Therefore, Digital Supply Chain (DSC) is about to usher in an era of hyper connected, ultra-efficient supply chains.

The term "digital supply chain" is a relatively new concept that was first introduced in the industrial world and getting its popularity in the academic area every passing month (Büyüközkan & Göçer, 2018a, 2018b). Now imagine a digital hub that senses the supply chain end to end and integrates it to the digital world so it is shelf connected, dynamically reporting customer signals, sensing the supply chain environment and the internet of things, etc. By sensing big data from the market and utilizing advanced analytics, the supply chain has the power to transform service delivery and generating greater profitability. Thus, existing supply chain structures cause inaccessible data, rigid organizational configurations and fragmented interactions with stakeholders while DSC provides digital managements of assets, flexibility, and process automation. With change, comes tremendous opportunities to transform and get ahead. Considering that the primary aim in any enterprise is to strengthen its core competences in the global market, modern-day supply chains should interact with their suppliers, distributers, retailers and consumers through DSC processes for their production, delivery and return operations of their goods or services. Creating a dynamic and connected seamless DSC is great for the digital age.

1.2. Definitions of DSC

There are multiple definitions exist in the industrial world for the DSC concept. The ones that are addressed in the industrial and academic literature are presented in this subsection with a chronological order. A formal definition is also presented at the end in order to reflect what DSC means in our view.

- Capgemini Consulting (Raab & Cryan, 2011) defines DSC as: “the capability of making widespread information available, superior collaboration and communications across digital platforms, resulting in enhanced reliability, agility and effectiveness.”

- Bhargava et al. (2013) define it as: “systems, such as software, hardware, communication networks, that support interactions between globally distributed organizations and orchestrates the activities of the partners in supply chains.”

- Accenture Consulting (Raj & Sharma, 2014) describes it as: “the potential to transform supply chains by making services more valuable, accessible and affordable.”

- Kinnet (2015) defines DSC as: “an intelligent, value driven network that leverages new approaches with technology and analytics to create new forms of revenue and business value.”

- Kearney consulting (Schmidt et al., 2015) defines DSC as “the best-fit technologies that support and synchronize supply chain processes and innovative planning and scheduling systems to quickly alleviate areas of pain, in a world where demand is volatile and risks are high.”

- The DSC Initiative (2015) describes as: “a customer centric platform that captures and maximizes the utilization of real-time information emerging from variety of sources.”

- Rouse (2016) define it as: “a supply chain whose foundation is built on Web-enabled capabilities.”

- Cecere (2016) defines as: “a process that uses new technologies to define processes to sense, respond and orchestrate bi-directionally from market to market, from the channel to supplier networks.”

As it could be observed, there are several types of definitions for DSC in the literature. But all the definitions have similar parts that unite them, thus in our view, DSC can be defined as follows (Büyüközkan & Göçer, 2018a): “An intelligent best-fit technological system that is based on the capability of massive data disposal and excellent cooperation and communication for digital hardware, software, and networks to support and synchronize interaction between organizations by making services more valuable, accessible and affordable with consistent, agile and effective outcome.”

1.3. Features of DSC

Supply chains evolve continuously and turn into something novel since today's digital savvy customer is in the driving seat. The old days of the traditional supply chains that only carry goods between rigid points are gone. Today, SCM requires an important amount of complex procedures all of which must be tracked and coordinated in real time. Hence, digital enablers empower supply chains to evolve into next generation by offering efficiency, flexibility and hyper connectivity. Due to digital enablers' disrupting property of the traditional supply chains, there exist some significant features associated with virtually every DSC. These features and their characteristics that DSC aims to achieve are displayed in Table 1.1.

Table 1.1: DSC Features

Features	**Characteristics**
Speed	This feature is central for stakeholders involved in DSC. Not just do enterprises wish to get the good as soon as they need, but also stakeholders within DSC desire to be able to move more goods in a shorter period of time. The ability of quick reaction to demand is one of the most significant pillars of DSC (Hanifan et al., 2014; Penthin & Dillman, 2015; Raj & Sharma, 2014).
Flexibility	This feature implies the need for operational agility with ease in adaption to changing circumstances. It gives an ability for DSC to define a way to react to problems within supply chains almost instantaneously by collecting data and modeling a solution (Hanifan et al., 2014; Schrauf & Berttram, 2016).
Global Connectivity	This feature establishes a way for building an effective global hub to supply goods or services locally, instead of carrying them across the globe for a single order (Hanifan et al., 2014; Schrauf & Berttram, 2016).

Features	Characteristics
Real-time inventory	This feature enables warehouse management more efficient and monitors stock levels continuously with the help of arrays of sensors or via other advanced technologies (Hanifan et al., 2014; Schrauf & Berttram, 2016).
Intelligent	This feature allows enhanced decision-making, automated execution and abets innovations in operations (Bechtold et al., 2014; Hanifan et al., 2014).
Transparency	This feature enables enterprises to act transparently, anticipate disruptions, and adjust instantaneously to changing circumstances (Schrauf & Berttram, 2016).
Cost-effective	This feature states the cost efficiency for enterprises by utilizing the enablers of DSC (Büyüközkan & Göçer, 2018a, 2018b).
Scalability	This feature brings an easier optimization and duplication of processes and simpler spotting of anomalies and errors (Bechtold et al., 2014; Hanifan et al., 2014).
Innovative	This feature of DSC dictates the new ways of incorporating the innovations into processes to remain competitive and ensure excellence in supply chain. (Cukier, 2015).
Proactive	This feature offers proactive solutions to anticipate issues prior to their occurrence, an effective analytics framework and operational intelligence to satisfy digitally enabled consumers (Büyüközkan & Göçer, 2018a, 2018b).
Eco-friendly	This feature dictates the necessity of DSC to extend eco-friendly process capabilities.

1.4. Components and Technologies of DSC

The prominent enterprises are trying to digitalize their supply chain operations. There are many important DSC trends that could be applied in SCM. From cloud computing and sensors to internet of things and big data, several enablers drive these trends. The following different DSC enablers are explored in this thesis as displayed in Table 1.2.

Table 1.2: DSC Enablers

Enablers	**Characteristics**
Big Data	This is an evolving term that describes large amounts of structured, semi-structured or raw data, which can potentially be processed for gaining insights from the embedded information (Jeske et al., 2013; Wang et al., 2016).
Advanced Analytics	This is the autonomous or semi-autonomous data or content analysis by means of complex techniques and tools (Heutger et al., 2016).
Robotics	This technology in Logistics is a branch of engineering that involves the conception, design, manufacture, and operation of R (Bonkenburg, 2016; Schmidt et al., 2015).
Sensor Technology	This is essential for robust detection and filling status, product quality, packaging quality, equipment status in a wide range of field conditions (Richter & Poenicke, 2013).
Internet of Things	This refers to the everyday objects that feature an IP address for internet connectivity allowing them to send and receive data, and so communication occurs between these objects and other network devices and systems (Macaulay et al., 2015).
Blockchain Technology	This is not only an electronic data interchange but also the backbone of DSCs. It offers clear benefits over conventional supply chain IT infrastructures and analytics capabilities (Korpela et al., 2017).

Enablers	Characteristics
Additive Manufacturing	This is also called 3D printing which corresponds to the additive manufacturing technique, where various processes are applied to manufacture 3-dimensional objects (Schmidt et al., 2015).
Wearable Technologies	This incorporates the dimension of exoskeletons that can be worn on the body as implants or accessories (Batty et al., 2017).
Virtual Reality	This builds fully rendered digital environments which mimic real-world setups. Features body and motion tracking capabilities (Batty et al., 2017).
Cloud Computing	This delivers a network of virtual services which are accessible for users anywhere in the world on a subscription basis for free, or at competitive prices (Raj & Sharma, 2014; Schmidt et al., 2015).
Unmanned Aerial Vehicle	This is also called a drone, stands for aircrafts that do not need pilots on board. They are either remote controlled or fly autonomously according to their flight algorithms or more complex dynamic automation systems (Heutger & Kuckelhaus, 2014).
Nanotechnology	This is the engineering of functional systems at the molecular scale (Schmidt et al., 2015).
Machine Learning	This is a field that gives machines the ability to learn without being explicitly programmed. Technological leaps in algorithms, computational power, and hardware facilitate the emergence of new machine learning applications in logistics. These applications provide huge opportunities for autonomous data-driven decision-making and process optimization in logistics (Heutger et al., 2016).
Augmented Reality	This extends the physical reality by adding layers of computer-generated virtual information, such as text, graphics, video, sound, haptic feedback, Global Positioning Systems (GPS) data, and even smell (Cirulis & Ginters, 2013; Glockner et al., 2014).
Self-Driving Vehicles	This is a vehicle that is capable of sensing its environment and navigating without human input (DHL Trend Research, 2014).

Enablers	Characteristics
Omni Channel	This is a multi-channel approach to sales by offering customers a smooth shopping experience irrespective of if the shopping takes place at a desktop computer, mobile device, telephone or physical stores (Kraemer, 2015).
Social Media	This induces visibility, improves communication, increases control, enables feedback, and reduces costs (Schlaepfer & Koch, 2015).
Digital Identifiers	This is pushing logistics processing towards a new level of granularity. It can securely identify single units, components and even individuals with unique, digital codes (Heutger et al., 2016).
Cognitive Computing	This addresses complex, ambiguous and uncertain problems and offers new solution pathways to them (Heutger et al., 2016).
Mobile Technologies	This promote the ability to access and integrate information almost any time and anywhere which will drive many end-to-end supply chain applications (Schlaepfer & Koch, 2015).
Control Tower	This is a central place that utilizes technological, organizational, and procedural systems to gather and apply supply chain data to guide short- and long-term decision-making according to strategic goals (Heutger et al., 2016).
Mixed Reality	This combines the AR, VR and IoT concepts for merging the virtual and real worlds and create new environments in which both digital and physical objects and their data can coexist and interact with each another (Batty et al., 2017).
Maker Movement	This is about the individual production of creative tools and technological gadgets as a response to automated, overly standard manufacturing (Batty et al., 2017).
Neurotech	This is the artificially interacting with the workings of the brain (Schmidt et al., 2015).

Enablers	Characteristics
Super-grid Logistics	This defines logistics service providers that primarily aim at orchestrating operations in global supply chain networks and integrating swarms of different production companies and logistics firms (Heutger et al., 2016).
Sharing Economy	This stands for economic activities in digital platforms where service providers grant users access to their temporarily underused assets, services, or skills (Heutger et al., 2016).
Solar Energy	This is the electromagnetic energy transmitted by the sun. it helps energy clients address critical challenges (Batty et al., 2017).
Tube Logistics	This is an underground freight pipeline system that is developed as an alternative solution to the growing road and rail traffic in cities (Heutger et al., 2016).
Grey Power Logistics	This offers logistics solutions for increasingly aging societies by developing new services to changing demographics and their needs (Heutger et al., 2016).
Crowdsourcing	This is an approach to harnessing the power of individuals to work to solve problems in a decentralized way (Batty et al., 2017).
Crowdfunding	This is the process of funding projects through small contributions from a large group of participants (Batty et al., 2017).
Biotech	This expands the physical limitations of biologic processes and explores new solutions for improving efficiency, health, and safety (Heutger et al., 2016).

1.5. Research Framework and Directions

Enterprises should consider how they could transform their traditional supply chains to cater to such well-equipped customers and should be prepared to serve the rising number of these types of customers. The review of academic literature and industrial reports revealed that some shortcomings of DSC literature should be underlined and new research directions should be discussed. Our extensive research on DSC revealed that studies focusing on digitalization within supply chains are generally limited to a single problem encountered in SCM. Integrated studies handling multiple problems are nonexistent to the best of our knowledge. The thesis aims to fill this absence by focusing on strategic issues that directly affect DSC for building an effective management structure with integrated approaches. Following statements summarizes the disposition of the proposed thesis.

- There exist some studies (especially industrial reports) that determine factors and/or approaches affecting DSC and its necessary conditions. Systematic approaches based on analytical methods to define DSC requirements are practically absent. This thesis proposes the use of axiomatic design (AD) approach to address this problem.

- Although DSC can provide many benefits for firms, its successful implementation is not easy. This study aims to determine the factors that will support better implementation of DSC structure and analyze them using cognitive map (CM) approach.

- Technologies to support DSC represent a recurring subject in literature. However, studies do not attempt to plan these technologies according to the requirements of various DSC factors. In this thesis, Quality Function Deployment (QFD) technique is applied to analytically prioritize technologic requirements in order to plan technologic infrastructure of DSC.

- Another important subject is to select most appropriate technology partner(s) for DSC implementations. The thesis also proposes a decision support system for partner selection by introducing an integrated MCDM approach, involving Analytic Network Process and Additive Ratio Assessment techniques. ANP technique is used to evaluate criteria weights and ARAS technique is used for the alternative assessment procedure.

- Many studies in the literature uses classical methods, such as crisp sets, fuzzy sets or intuitionistic fuzzy sets, since its similarity to human reasoning, to decide on an alternative among many. However, when compared to classical sets, Pythagorean Fuzzy Sets (PFSs) have more advantages in sense that they are more adequate and capable in identification of decision makers' judgments. For this purpose, the PFSs environment is utilized to evaluate DSC's strategic operational alignment with CM, QFD, ANP, and ARAS methodologies.

- Most of the decision-making problems require the participation of more than one Decision Maker (DM) in decision-making processes. Hence, many MCDM methods are also extended to a group decision making (GDM) environment. GDM is often preferred because of its advantages in minimizing bias and partiality. In the process of GDM, consensus measures are of utmost importance when looking for an agreeable solution by all experts despite their different opinions about the problem at hand.

The proposed thesis study consists of four main stages:

1) Modelling a digitalization structure for supply chains using AD theory.
2) Analyzing the success and risk factors of DSC structure with CM technique under PFSs GDM environment.
3) Planning technologic infrastructure of DSC with QFD technique under PFSs GDM environment.
4) Evaluating technology partner(s) for DSC with an integrated MCDM approach under PFSs GDM environment.

The detailed research scope is identified in Figure 1.1, which presents a recapitulative visual on the sub-problems, inputs of each research problem, the techniques employed to tackle the problem, and the output of that section. The thesis comprises eight chapters and the course in this thesis follows as summarized. Review of related publications on DSC are given in Chapter 2. Chapter 3 delivers the proposed research philosophy with an introduction to studied methods. Then in Chapter 4, the design and modeling of DSC structure is discussed with AD technique and a DSC transformation framework is developed. In Chapter 5, the implementation of DSC structure is discussed as the success and risk factors for DSC is presented. Then, technologic infrastructure planning is discussed in Chapter 6 and DSC partners are evaluated by MCDM techniques in Chapter 7. Finally, the last chapter ‘Chapter 8’ discusses the review of the aim, and the research questions. The contribution, limitations, and recommendations for future research is also presented in this chapter.

	Focus Area	**Input**	**Technique**	**Output**
Chapter 4	Modelling Digitalization Structure	DSC Design Domains	AD	DSC Transformation Framework
Chapter 5	Analyzing the Success and Risk Factors	DSC Concepts	PFCM	DSC Structure
Chapter 6	Planning Technologic Infrastructure	DSC Technologic Requirements	PF-QFD	DSC Technological Prioritization
Chapter 7	Evaluating Technologic Partner(s)	DSC Evaluation Criteria	PF-ANP and PF-ARAS	DSC Partner Selection Framework

Figure 1.1: Research Scope

2. LITERATURE REVIEW ON DSC

Literature review and a proposed framework for future research for DSC is done thoroughly in (Büyüközkan & Göçer, 2018a). A small section of it is highlighted here to give broader aspect. The review of DSC is done through a classification methodology, which presents how the literature is approached as a basis for the conceptual and theoretical framework. First, the classification method for the review is explained and then the method of the review is presented.

2.1. Method for the Review

Relevant publications are located with the help of a detailed online search with the objective to collect, organize, and synthesize existing DSC knowledge. Identified papers span several types of interrelated disciplines including marketing, management, operations management, management science, industrial engineering, and SCM. Due to the lack of precise key words defining the topic, substantial effort is put on to sort academic and industrial journals by reviewing their titles, abstracts and manuscripts in the traditional and electronic library systems. Usually, this step can be carried out by targeting prominent journals and conferences. This is not the case for DSC since this recent phenomenon has emerged only a few years ago and related publication channels are still scattered. It is more practical and appropriate to focus on online databases rather than reviewing library collections for a literature review on DSC. Therefore, the following major online databases were targeted for the past six years: Elsevier's Scopus, Thomson Reuter's Web of Science, IEEE Xplore, ProQuest (ABI/INFORM), and ScienceDirect (Elsevier). This search indicated that the concept of DSC is still in its early years of research and development among academics, while it is widely recognized and discussed among practitioners. To include industrial reports, Google search engine is also used for a wider reach-out.

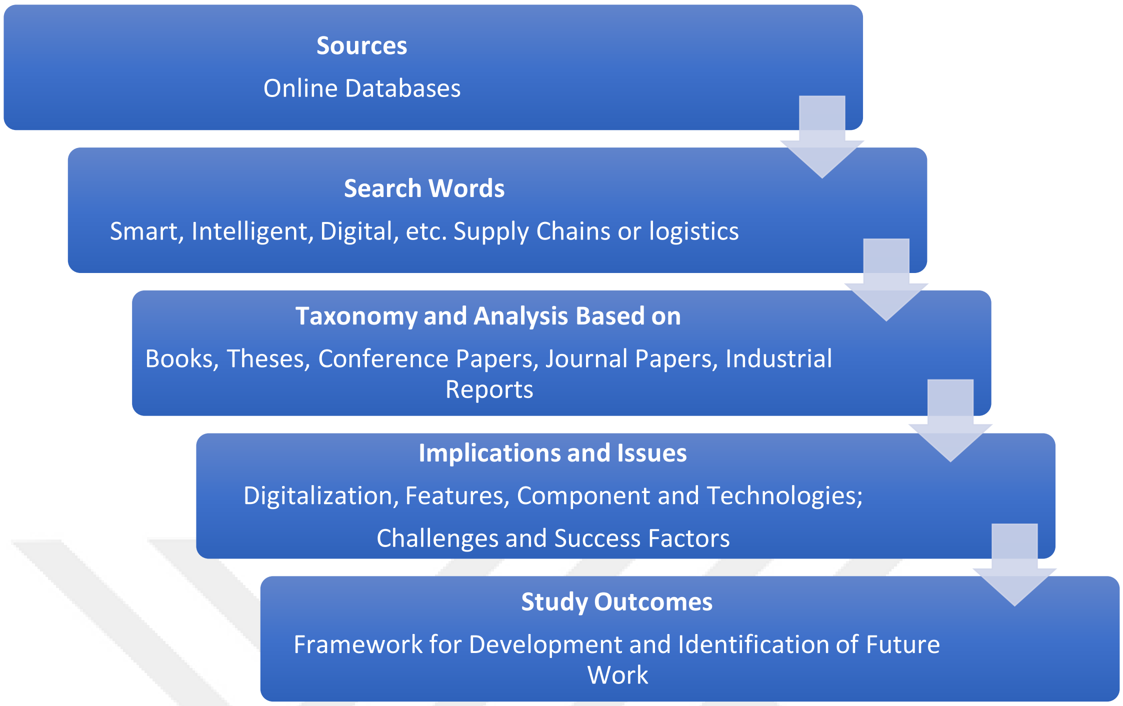


Figure 2.1: Review Methodology

In this study, we review and classify relevant studies to gain insight on DSC. The overall review methodology for DSC papers is graphically presented in Figure 2.1. Figure 2.2 illustrates the significant findings by presenting a detailed summary in terms of types of DSC publication and its enablers. The literature sources are investigated in scientific databases and regular search engines which include books, peer and non-peer reviewed papers, industrial reports and white papers. The keywords were not predetermined before the search but they have gradually emerged during the extensive reading process that took place while drafting this study. The nomenclature lists the non-exhaustive keywords which is completed with the mentioned keywords and terms. Accordingly, this research captures the trends in the DSC literature by examining published academic articles and industrial reports, including DSC technologies, in order ensure that these papers are sufficiently investigated based on the year of publication, subject, objective or method. Considering the nature of DCS, however, it is quite a challenge to confine studies into specific categories. Considering this fragmented structure, the search in major databases is supported with Google Scholar search engine queries to end up with a comprehensive bibliography of papers on DSC. The following section presents this comprehensive review.

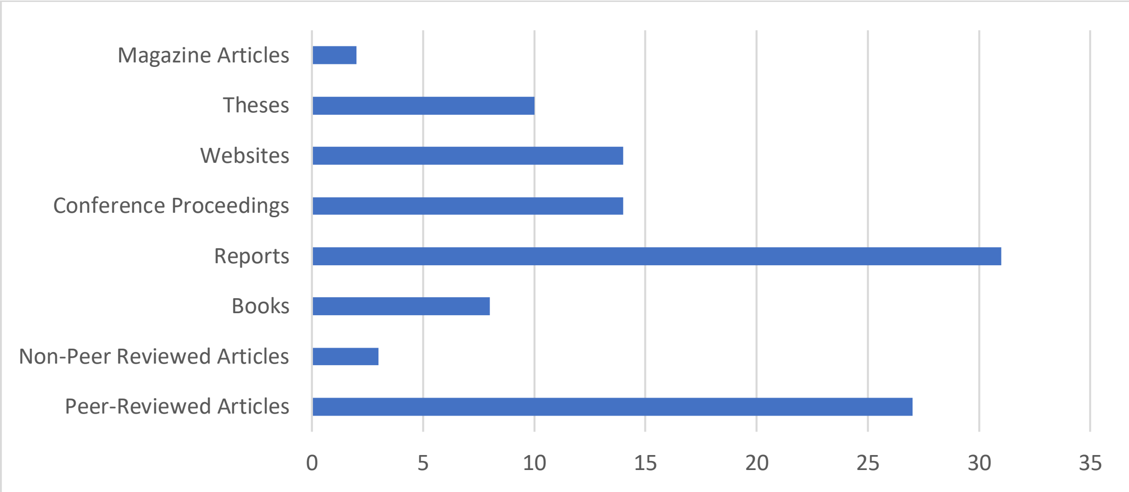


Figure 2.2: Types of Publication for DSC and its Enablers

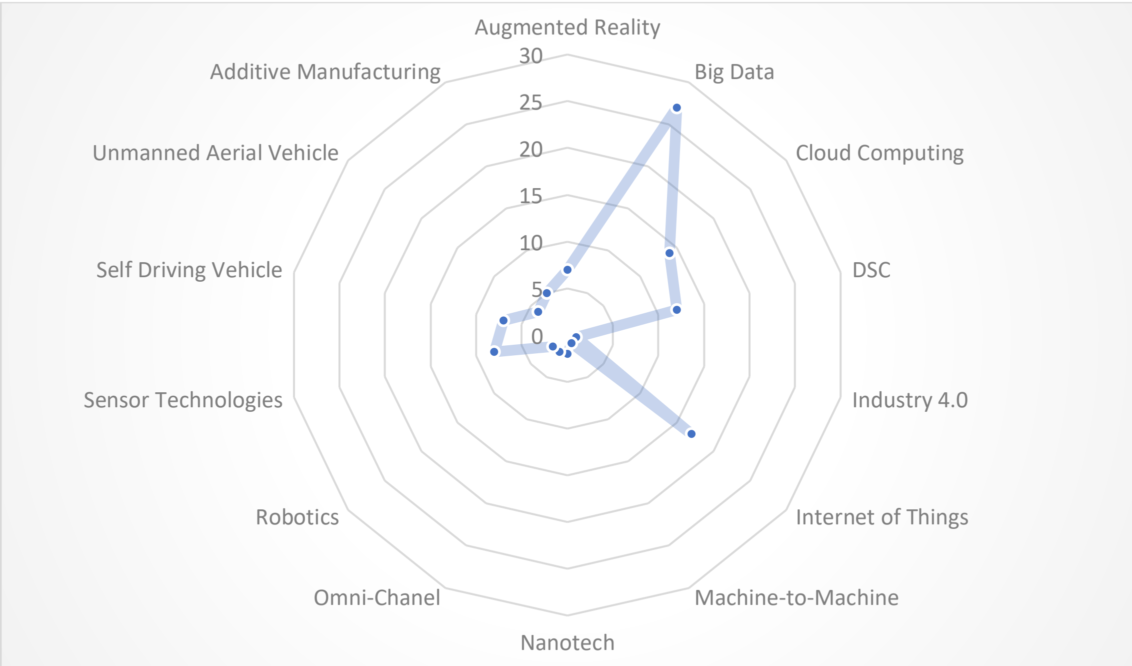


Figure 2.3: Various Subjects Covered in Selected Journals

2.2. Academic Literature Review on DSC

Digitalization has started to receive much attention from organizations all over the world as it creates superior benefits to a wide range of companies. Our review on DSC literature signifies a gap between the theory and practice in supply chains. Currently there is a limited number of studies regarding DSC. As far as we know, there are no academic studies that explicitly focus on the DSC concept. There however, exists supply chain focused articles which discuss DSC technologies in terms of their applications. The following analysis supports this statement. According to the factors on which DSC literature has been reviewed, the spider diagram in Figure 2.3 highlights that the focus of the study on DSC has primarily been on its enablers. Existing journal articles and conference papers related to DSC and its technologies that focus on supply chains are classified as follows:

Tiwari et al. (2018) investigate big data in supply chains between 2010 and 2016 and provides insights to industries. Farahani et al. (2017) provide 17 digital SCM cases for automotive supply chains using expert interviews to form the basis for the creation of the DSC. Hofmann & Rüsch (2017) shed light on the topic of Industry 4.0 in the context of logistics management. Merlino & Sproģe (2017) explore the main technological changes and the most advanced cases in supply chain. Majeed & Rupasinghe (2017) derive a conceptual framework to enhance inbound and outbound operations in ERP for fashion apparel and footwear industries. Nguyen et al. (2017) review the big data within supply chain context to responds where and how big data has been applied. Daya et al. (2017) explore the role of IoT and its impact on supply chain through an extensive literature review. Korpela et al. (2017) investigate the requirements and functionalities of DSC integration. Michel (2017) compiles the knowledge of technology executives, consultants and supply chain analysts in the area of DSC and industry 4.0. Scuotto et al. (2017) present the relationship among multiple buyers and suppliers in the context of DSC management. Vanderroost et al. (2017) provide an extensive overview of computer systems that are used in the logistics of a food package’s life cycle and that to a certain extent integrate novel technologies. Buyukozkan & Gocer (2017b) propose a novel MCDM approach to evaluate supplier selection process under DSC environment.

Buyukozkan & Gocer (2017a) approach the supplier selection problem in a DSC environment by the help of an extension of Multi-Objective Optimization by Ratio Analysis. Tenkorang & Helo (2016) discuss the big data issues, trends and perspectives in SCM. Gunasekaran et al. (2017) identify the influence of connectivity and information sharing resources under the mediation effect of top management commitment on big data and supply chains. Hazen (2016) presents a research by proposing an agenda based on a theory by reviewing the eight theories that can be used by researchers to examine and clarify the nature of big data analytics impact on supply chain sustainability. Kumar et al. (2016) examine the role of smart city in changing the nature and form of traditional supply chain using an integrative framework through a case study. Papadopoulos et al. (2017) present a framework in that the big data is used for sustainability in disaster relief activities in the aftermath of 2015 Nepal earthquake. Wu et al. (2016) focus on exploring the current status and remaining issues of smart SCM. Wu et al. (2017) present a methodology using the fuzzy and grey Delphi to identify a set of reliable attributes and transform big data to a manageable scale to consider their impacts. Zhao et al. (2017) offer multiple objective optimization methodology for a green SCM scheme that minimizes the inherent risk occurred by hazardous materials using big data analysis. Zhong et al. (2016) examine the representative big data applications and reviews the current technologies, as well as models and algorithms are reviewed. Wang et al. (2016) review the literature on big data business analytics in logistics and supply chains management and explores the applications of big data in supply chain strategy and operation. Cortés et al. (2015) offer revisions and proposal of IoT applications in SCM and reviews the applications of IoT in SCM. Chen (2015) designs the autonomous agent-based trace system using IoT architecture based on Fuzzy CM and fuzzy rule methods in products usage life cycles. Wamba & Akter (2015) provide big data analytics for SCM literature using studies related to the areas within SCOPUS. Gnimpieba et al. (2015) aim using IoT and CC technology for real time geo-positioning and tracing of goods and collaboration between involved players in a logistic process. Gospic & Bakmaz (2015) present comprehensive survey on Machine to Machine communications towards realization of smart logistics systems. Hofmann (2015) deals with big data potential on improving the various supply chain processes and aims elaborating big data characteristic with the greatest potential that mitigates the bullwhip effect. Isasi et al. (2015) aim to review the state-of the-art big data and business analytics applications in supply chains by means of bibliometric and systematic analysis. Mehmood & Graham (2015) use Markov models for the integration of big data with city transport sharing in health care. Schoenherr & Speier (2015) discuss the results of a large-scale survey on big data among SCM professionals and identifies major benefits and obstacles to predictive analytics. Mohr & Khan (2015) examines the areas of the supply chains which is most likely to be disrupted by additive manufacturing and identifies the key issues that must be addressed in a roadmap for future researches and practices. Tan et al. (2015) wish to address analytic techniques by testing and developing an infrastructure using the deduction graph techniques for companies to combine their capability sets with other companies. Tadejko (2015) describe some principles and characteristics of IoT, and briefly discusses the application of it in modern logistics. Some aspects of modern logistics related to the IoT technology is studied. Zhong et al. (2015) deal with a holistic big data methodology to excavate frequent trajectory from extensive RFID enabled shop floor logistics data with a number of innovations highlighted. Hazen et al. (2014) introduce the data quality problems in the context of supply chains management and proposes a methodology for monitoring and controlling data. Leveling et al. (2014) focus on big data solutions dealing with supply chains by representing a key discipline for managing the increased collaboration. Rozados & Tjahjono (2014) investigate which range from the fundamentals of big data, its taxonomy and the level of maturity of big data solutions. Wang & Liu (2014) introduce IoT technologies and then analyzes the functions and utilities of them on applications of agriculture resources. Bhargava et al. (2013) examine the challenges and approaches for secure collaboration among partners in DSCs. Cirulis & Ginters (2013) describe the basic elements of logistics and pays special attention to improvement possibilities in packaging, handling, storage and transportation phases. Ginters et al. (2013) present an augmented reality and RFID application for an outdoor environment combined logistic item visualization. Waller & Fawcett (2013) describe possible applications of predictive analytics and big data in practice and provides examples of research questions, as well as examples that stem from management theories. Sun (2012) presents an approach using applications of RFID technology for logistics on internet of things. Wagenaar (2012) analyses the benefits the internet of things has on supply chains through a literature study and looks how these benefits can increase revenue within supply chain.

2.3. Published Books on DSC

To the best of our knowledge, the DSC chapter in Managing Digital Enterprise book prepared by Xu (2014) is one of the earliest books which substantiates the concept of DSC. The book is mainly about rapid development of digitalization, dramatic advancements in digital technologies and its strategic importance in organizations. There is also a dedicated chapter about DSC that comprehensively presents DSC in terms of digital enterprises, issues and success factors of DSC, emerging trends and future directions. Skilton (2015) focuses on practical applications of new digital solutions and illustrates how companies can have a role in digital access and digital delivery while illustrating the DSC capability strategies. Sanders (2014) attempts to provide a systematic framework for companies to display the implementation of big data analytics across the supply chain on how to turn data into intelligence and thus succeed to competitive advantages.

Another book that elaborates on the field of DSC is Digital Enterprise Transformation prepared by Uhl and Gollenia (2014). The authors published its new edition in 2016 (Uhl & Gollenia, 2014). These original and new editions are dedicated to the combination of transformation ability and novel digital skills to be developed. Again, one of its chapters is dedicated to DSC management, explaining the key features of SCM and the SCOR model. It also introduces 18 cases of SCM to assess digital cases on the SCOR model to position strategic effort-benefits portfolio.

A recently published book on DSC entitled "E-Logistics: Managing Your Digital Supply Chains for Competitive Advantage" authored by Wang (2016) aims to capture the state-of-the-art developments in managing supply chains to gain competitive advantage. The book also investigates the emerging technological changes in e-logistics and considers what the future holds for this rapidly shifting and evolving field.

The latest book on DSC is authored by Editors Oswal and Kleinemeier (2017). This book presents an overview of digitalization, its impacts, drivers and objectives. It includes chapters on DSC management for the automotive supplier industry, digital business transformation and the effect of digital culture with its effect on supply chain organizations, etc. This book details the concept of DSC and its related technologies to enhance and improve SCM processes.

2.4. Industrial Reports on DSC

The analysis of industrial reports is provided in this subsection. There is a gradual increase in the number of sectoral reports about DSC as new technological improvements emerge. IBM (2009) predicted in its report that future supply chains would be smarter. They have identified the challenges and risks that supply chains will face and priorities that needed to be handled. As far as we know, one of the earliest reports about DSC is published by Capgemini Consulting (Raab & Cryan, 2011), which introduced a digital transformation approach to supply chains to describe the deficits and benefits of digitally transformed supply chains. Their framework consists of DSC execution and strategy stages that in essence defines DSC as an approach to access extensive information and achieve greater collaboration. Accenture (Raj & Sharma, 2014) is another consulting company that assessed the impact of digital technologies on SCM and offered new opportunities to unlock DSC's full potential. To enable DSC, they proposed the following four key attributes: Rapid, Scalable, Intelligent, and Connected. Another company, Supply Chain Insights, also published a report on DSC that sheds light on driving the DSC transformation in the industry (Cecere, 2014, 2016). Their report commences with a definition of digital organization and discusses the creation of a DSC strategy, then captures the highlights by conducting a questionnaire during the years 2013 and 2014. Their report aims to help supply chain managers to align their source, make and deliver strategies. ATKearney and WHU-Otto Beisheim School of Management united their forces to prepare a collaborative report about DSC (Schmidt et al., 2015). They dedicated their study to the future role of DSC in a global and connected world. Their analysis indicated that managers of leading European companies expect the digital transformation in next three years to be traditional (information technology integration) rather than novel technological advances. Monsanto farming company is among the pioneers investing in the DSC to bring new forms of revenue and business value to the farming market (Kinnet, 2015). They have presented several examples to share how DSC are connected to better product and customer experience. Their own improvements made them the 35th top supply chain company in 2015, a significant improvement from 100s, according to Gartner's ranking for the last 11 years.

Bearingpoint (Penthin & Dillman, 2015) consulting company presented a report on trends in DSC management and digitalization's impact on supply chain as it transforms every industry. Their approach consists of prepare, assess, analyze and roadmap & governance steps. The Digital Supply Chain Initiative (2015) gathered information from twenty-four top managers responsible for the world's largest supply chains. These executives forecast that the most significant transformation for organizations will occur over the next 5 years. This report provides a DSC implementation framework and roadmap to assist industry leaders, supply chains managers and any other specialists interested in leading-edge supply chains developments. These developments aim to transform supply chain organization by focusing on the customer, maximizing demand, decreasing supply chain costs and increasing organizations' revenues. The report's practical steps guide business managers to better comprehend game-changing technologies that affect all supply chain organizations and to gain overview of key differences between traditional and digital supply chains.

Bain & Company Consulting focused on the intangible benefits of a DSC (Guarraia et al., 2016). Accordingly, the latest digital transformation shaped intangible assets, things like intellectual property or customer relationship of a company, rather than its tangible assets. They offer solutions as applying various digital technologies across DSC to deliver powerful ways for organizations. Rakowski (2015) presented the latest technology trends in her article to emphasize that supply chains go digital. She suggests that the future of technology will drive a new wave of productivity by digitalization of key organization and financial processes and collaboration will increase and thus fuel innovation so that organization will be run simpler with blurred lines and smarter procurements. Cerasis (2015a, 2015b) also prepared reports on the future of supply chains to know how the technology is transforming different industries. EY (2016) prepared another report on DSC from the perspective of big data to notify companies to act as soon as possible to focus on big data to preserve their competitive edge. The Boston Consulting Group described the advantages of DSC in three key paths (Ganeriwalla et al., 2016). It suggests possible ways to address performance gaps, innovate business processes and disrupt supply chain strategies. These ways include applying digital technologies, such as advanced analytics to calculate the optimal inventory level and forecast future demand more accurately, rather than applying cumbersome conventional approaches.

The present and future state of digital transformation in supply chains is analyzed in the reports of GT Nexus and Capgemini Consulting (Dougados & Felgendreher, 2016; GTnexus, 2016). Their key findings from the survey with 337 leading executives from several global supply chain organizations suggest that 75% of executives deem DSC to be “important or very important”, 50% say DSC is “very important”, 33% of respondents are “dissatisfied” with the progress so far, while only 5% are “very satisfied”. They accept that key technology enablers are identified but have not been widely used. They also expect dramatic changes to occur within next five years.

DHL runs series of trend research on logistics about creating value (Bonkenburg, 2016; Bubner et al., 2016; DHL, 2015b; DHL Trend, 2013, 2014; Glockner et al., 2014; Heutger & Kuckelhaus, 2014; Jeske et al., 2013; Kraemer, 2015; Kuckelhaus & Yee, 2016; Macaulay et al., 2015; Richter & Poenicke, 2013). These reports on augmented reality, big data, unmanned aerial vehicle, low cost sensors, self-driving vehicle, internet of things, omni channel, additive manufacturing and robotics in Logistics inspire novel strategies and innovation in the logistics industry. Strategy& global team also prepared a series of reports on digitalization of supply chain organizations (Alvarez et al., 2016; Geissbauer, Weissbarth et al., 2016; Nowak et al., 2016; Schrauf & Berttram, 2016). However, there are not any companies that have yet succeeded in truly building DSC, and DSC applications remain limited. The experts predict that in the next five-to-ten-years many industries will be implementing DSC and tremendous changes to take place.

2.5. Advantages, Weaknesses and Limitations of DSC Literature

It is important to highlight that the identified 109 articles influenced the results of this study. In some circumstances, the paper under review will still be utilized to describe the results and to gain a better understanding of the topic. In this section, the advantages, weaknesses and limitations of the published methodologies are presented, which could correlate the papers in order to find future trends, identify knowledge gaps, synthesize past knowledge, identify important biases and to find common features among various studies. Listed in the rows, the subject indicates the literature's inclusive focus, objective clarifies the goal of the research paper; method identifies the methodology used in the paper while the contribution involves the goal of literature's contribution statement with its clear and concise focal points. These characteristics have been nominated based on authors' expertise in the field and the relevant studies. Books and industrial reports are synthesized to identify important biases by narrating their findings so that short, specific and precise knowledge gaps could be extracted from these statements.

When the relevant literature on DSC is consolidated and examined thoroughly, they exhibit certain advantages to the readers. These utilized advantages describe the roadmap for establishing the DSC framework in the following sections based on the overview of the content, scope, and findings of selected literature. On the other hand, academics and practitioners have defined DSC from diverse perspectives. It is easily comprehensible that so far, there is no unanimously adopted definition on the concept of DSC. These diverse definitions of DSC create a complexity for researchers to compile a general description that is acceptable by the majority. The key fundamental principles of existing DSC literature have significant limitations when establishing DSC framework. Based on the papers in this research category, following sections utilize and identify the key limitations and prospects in DSC, summarize prior research to identify knowledge gaps by providing advantages, weaknesses and limitations of individual methods and introduce a development framework as a roadmap for future research and practice.

3. THEORETICAL BACKGROUND

3.1. Overview of Pythagorean Fuzzy Sets (PFSs)

In 1965, Zadeh introduced the concept of the fuzzy set theory. Fuzzy sets extend the classical set theory by assigning a degree of membership to each element to allow gradual evaluation of elements' membership values in a set with the help of a membership function that generates a value between zero and one (Zadeh, 1965). However, fuzzy set only has a membership degree, which is unsuitable for managing several real decision-making problems. As a decision problem becomes more complicated, identifying a distinct candidate will be harder for decision makers (DMs). Three decades ago, Atanassov extended the fuzzy set theory into the Intuitionistic Fuzzy (IF) set theory by assigning degrees of membership, non-membership, and hesitancy to each element in the set (Atanassov, 1986). Yager recently extended IF sets to Pythagorean Fuzzy Sets (PFSs) theory, which defines elements with membership and non-membership degrees, the square sum of which is maximally 1 (Yager, 2014; Yager & Abbasov, 2013). The PFSs have been previously applied to many MCDM problems, as they can successfully represent the fuzzy character of things by incorporating their vagueness and uncertainty. PFSs are a novel way to handle vagueness by taking the membership grades as pairs into account (Yager & Abbasov, 2013).

A PFS P in X, where X be a fixed non-empty universe set, is denoted as:

$$P = \{\langle x, \mu_P(x), v_P(x)\rangle\}, \qquad (3.1.1)$$

The aforementioned Eq. is characterized by a membership degree $\mu_P: X \to [0,1]$ and a non-membership degree $v_P: X \to [0,1]$ of element x ∈ X to the set P, respectively. These values are considered with the following condition:

$$0 \leq \left(\mu_P(x)\right)^2 + \left(v_P(x)\right)^2 \leq 1 \quad \forall x \in \text{X}, \tag{3.1.2}$$

consequently, hesitancy degree $\pi_P(x)$ is presented as:

$$\pi_P(x) = \sqrt{1 - \left(\mu_P(x)\right)^2 + \left(v_P(x)\right)^2} \quad \forall x \in \text{X}, \tag{3.1.3}$$

Let $p_1 = \left(\mu_{P_1}(x), v_{P_1}(x)\right)$ and $p_2 = \left(\mu_{P_2}(x), v_{P_2}(x)\right)$ be two PFNs and $\lambda > 0$. Some basic operations are formulated by (Peng & Yang, 2015; Zhang & Xu, 2014) as the following:

$$p_1 \oplus p_2 = \left(\sqrt{\left(\mu_{P_1}(x)\right)^2 + \left(\mu_{P_2}(x)\right)^2 - \left(\mu_{P_1}(x)\right)^2 . \left(\mu_{P_2}(x)\right)^2}, v_{P_1}(x). v_{P_2}(x)\right), \tag{3.1.4}$$

$$p_1 \otimes p_2 = \left(\mu_{P_1}(x). \mu_{P_2}(x), \sqrt{\left(v_{P_1}(x)\right)^2 + \left(v_{P_2}(x)\right)^2 - \left(v_{P_1}(x)\right)^2 . \left(v_{P_2}(x)\right)^2}\right), \tag{3.1.5}$$

$$p_1 \ominus p_2 = \left(\sqrt{\frac{\left(\mu_{P_1}(x)\right)^2 - \left(\mu_{P_2}(x)\right)^2}{1 - \left(\mu_{P_2}(x)\right)^2}}, \frac{v_{P_1}(x)}{v_{P_2}(x)}\right), \tag{3.1.6}$$

$$if\ \mu_{P_1}(x) \geq \mu_{P_2}(x), v_{P_1}(x) \leq min\left\{v_{P_2}(x), \frac{v_{P_2}(x).\pi_{P_1}(x)}{\pi_{P_2}(x)}\right\},$$

$$\frac{p_1}{p_2} = \left(\frac{\mu_{P_1}(x)}{\mu_{P_2}(x)}, \sqrt{\frac{\left(v_{P_1}(x)\right)^2 - \left(v_{P_2}(x)\right)^2}{1 - \left(v_{P_2}(x)\right)^2}}\right), \tag{3.1.7}$$

$$if\ \mu_{P_1}(x) \leq \min\left\{\mu_{P_2}(x), \frac{\mu_{P_2}(x).\pi_{P_1}(x)}{\pi_{P_2}(x)}\right\}, v_{P_1}(x) \geq v_{P_2}(x),$$

$$\lambda p_1 = \left(\sqrt{1 - \left(1 - \left(\mu_{P_1}(x)\right)^2\right)^\lambda}, \left(v_{P_1}(x)\right)^\lambda\right), \tag{3.1.8}$$

$$p_1{}^{\lambda} = \left(\left(\mu_{P_1}(x)\right)^{\lambda}, \sqrt{1-\left(1-\left(v_{P_1}(x)\right)^2\right)^{\lambda}}\right), \tag{3.1.9}$$

$$p_1{}^{C} = \left(v_{P_1}(x), \mu_{P_1}(x)\right), \tag{3.1.10}$$

3.1.1. PFSs Aggregation Operators

In real life management and decision problems, it is a considerable challenge how to aggregate data and combine preferences. Management environments and decision problems themselves can sometimes be quite complex. Frequently, DMs are able to express their opinions to a certain degree of confidence, and sometimes they might hesitate on one or more evaluations, which is undesired for establishing adequate methods for finding solutions to decision problems. These hesitancy degrees can be successfully dealt with PFSs, where precise numerical values fail. Despite PFSs' advantage in this respect, acquiring fuzzy information without information loss remains a challenge. This makes aggregation of PFSs information an important topic in MCDM. Information (e.g. numerical values) can be mathematically fused into a single datum with the help of aggregation operators (Collier et al., 2014). Many PFSs information aggregation operators have recently been presented and analyzed. These operators are able to successfully fuse information. PFSs aggregation operators in Table 3.1 is designed to display some of the main operators used in the literature.

Table 3.1: PFSs Aggregation Operators and Their Characteristics

Aggregation Operator	Characteristics
Pythagorean fuzzy weighted averaging (PFWA)	PFWA operator based on the averaging mean focuses on the group opinion (Yager, 2014).

Aggregation Operator	Characteristics
Pythagorean fuzzy weighted geometric (PFWG)	PFWG operator based on the geometric mean puts more significance to the individual opinions (Yager, 2014).
Pythagorean fuzzy weighted averaging (PFOWA)	PFOWA operator weights only the ordered positions of the PFSs instead of weighting the PFSs themselves having more sensitivity to the group's influence (Yager, 2016).
Pythagorean fuzzy weighted ordered geometric (PFOWG)	PFOWG operator weights only the ordered positions of the PFSs instead of weighting the PFSs themselves having more sensitivity to the individual influence (Peng & Yang, 2016b).
Pythagorean fuzzy weighted power averaging (PFWPA)	PFWPA weights all the given PFSs values themselves, and the weighting vector depends on the input and permits the PFSs to be aggregated to reinforce and support each other giving more sensitivity to the group's influence (Peng & Yang, 2016b).
Pythagorean fuzzy weighted power geometric (PFWPG)	PFWPG weights all the given PFSs values themselves, and the weighting vector depends on the input and permits the PFSs to be aggregated to reinforce and support each other giving more sensitivity to the individual influence (Yager, 2016).
Pythagorean fuzzy hybrid averaging (PFHA)	The attributes take the form of PFSs and the weights of attribute take the form of real numbers giving more sensitivity to the group's influence (Yager, 2016).
Pythagorean fuzzy hybrid geometric (PFHG)	The attributes take the form of PFSs and the weights of attribute take the form of real numbers giving more sensitivity to the individual influence (Yager, 2016).

3.1.2. PFSs Literature Review

Following the literature review, some shortcomings of PFSs literature may be underlined and new research directions can be discussed. The number of studies on PFSs in literature is quite limited since it is a newly researched area. As a basis for the literature review on PFSs, the selection criteria of "Pythagorean Fuzzy Set" are explored as keywords, which resulted in 46 studies. Table 3.2 is designed to display the related categories of PFSs studies. It is constructed as to summarize the main concept of each paper to convey their essence to the readers. Thus, it is structured to four sections. The method illustrates which methodology is used in the paper, type of its application as Case study or Illustrative is presented next, papers are identified as GDM or not, and the Application Area are presented at the end to display the involvement of PFSs in each paper.

Table 3.2: PFSs Studies

Method	Type	GDM	Application Area	Author(s)
Critical Effect Analysis	Illustrative	N/A	Risk Assessment	(Karasan, Ilbahar, Cebi, & Kahraman, 2018)
Ranking Function	Illustrative	N/A	Investment Strategy	(Xian, Yin, Fu, & Yu, 2018)
Grey Rational Analysis	Illustrative	GDM	Method Proposal	(Khan & Abdullah, 2018)
Similarity Measure	Illustrative	GDM	Method Proposal	(Biswas & Sarkar, 2018)
Bonferroni Mean	Illustrative	N/A	Method Proposal	(D. Liang, Darko, & Xu, 2018)

Method	Type	GDM	Application Area	Author(s)
Muirhead Mean	Illustrative	GDM	Method Proposal	(J. Zhu & Li, 2018)
Linguistic Fuzzy	Illustrative	N/A	Method Proposal	(Garg, 2018)
Present Worth Analysis	Illustrative	GDM	Solar Energy Investment	(Çoban & Onar, 2018)
VIKOR	Illustrative	N/A	R&D Project Investment	(Chen, 2018)
AHP	Illustrative	N/A	Risk Assessment	(Ilbahar et al., 2018)
Scoring Methods	Illustrative	N/A	Method Proposal	(Kahraman et al., 2018a)
Present Worth Analysis	Illustrative	N/A	Investment Analysis	(Kahraman et al, 2018b)
Game Theory	Illustrative	N/A	Electricity Grid	(Baloglu & Demir, 2017)
Aggregation	Illustrative	GDM	Interval Valued	(Du et al., 2017)
Aggregation	Illustrative	N/A	Einstein t-norm and t-conorm	(Garg, 2017c)
Aggregation	Illustrative	GDM	Confidence Levels	(Garg, 2017b)
Accuracy Function	Illustrative	N/A	Interval Valued	(Garg, 2017a)
Conflict Analysis	Illustrative	N/A	Rough Sets Theory	(Lang et al., 2017)
TOPSIS	Illustrative	N/A	Interval Valued, Hesitant	(Liang & Xu, 2017)

Method	Type	GDM	Application Area	Author(s)
Aggregation	Illustrative	GDM	Bonferroni Mean	(Liang et al., 2017)
Aggregation	Illustrative	GDM	Linguistic Variables	(Liu et al., 2017)
Aggregation	Illustrative	N/A	In Chinese Language	(Liu et al., 2017)
Aggregation	Illustrative	N/A	Bonferroni Mean	(Liu et al., 2017)
Aggregation	Illustrative	N/A	Hesitant Hamacher Operations	(Lu et al., 2017)
Distance-Based	Illustrative	GDM	Internet Companies	(Mohagheghi et al., 2017)
Stochastic MCDM	Illustrative	N/A	Score Function	(Peng & Dai, 2017)
Similarity, Distance, Entropy	Illustrative	N/A	Information Measure	(Peng et al., 2017)
Mathematical Programming	Illustrative	GDM	Green Supplier	(Wan et al., 2017)
Aggregation	Illustrative	N/A	Hamacher operations	(Wu & Wei, 2017)
OWA aggregation	Illustrative	GDM	Supplier Selection	(Zeng, 2017)
Ranking Method	Illustrative	N/A	Smart Phones	(Zhang, 2017)
Aggregation	Illustrative	GDM	Bonferroni Mean	(Zhang et al., 2017)
Complex Fuzzy Logic	Illustrative	N/A	Fuzzy Intersection, Union and Lattice	(Dick et al., 2016)

Method	Type	GDM	Application Area	Author(s)
Correlation Coefficient	Illustrative	N/A	Medical Diagnosis	(Garg, 2016c)
Aggregation	Illustrative	GDM	Investment Decision	(Garg, 2016a)
Aggregation	Illustrative	N/A	Interval Valued	(Garg, 2016b)
Subtraction and Division Operations	Illustrative	N/A	Properties of PFSs values	(Gou et al., 2016)
Aggregation	Illustrative	N/A	In Chinese Language	(Liu et al., 2016)
Score Function	Illustrative	N/A	Domestic Airlines	(Ma & Xu, 2016)
Choquet Integral based MABAC	Illustrative	GDM	Average and Geometric Operator	(Peng & Yang, 2016b)
ELECTRE	Illustrative	GDM	Interval Valued	(Peng & Yang, 2016a)
Aggregation	Illustrative	N/A	Method Proposal	(Peng & Yuan, 2016)
TODIM	Case Study	N/A	Investment Bank	(Ren et al., 2016)
Properties	Illustrative	N/A	Ordered Weighted Geometric	(Yager, 2016)
QUALIFLEX	Case Study	N/A	Interval Valued	(Zhang, 2016)
Multi-granulation Rough Set	Illustrative	GDM	Merger and Acquisition	(Zhang et al., 2016)
Aggregation	Illustrative	GDM	Interval Valued	(Liang et al., 2015)

Method	Type	GDM	Application Area	Author(s)
Superiority and inferiority Ranking	Illustrative	GDM	Internet Stocks	(Peng & Yang, 2015)
Recommender System	Illustrative	N/A	Netflix Movie Recommendation	(Reformat & Yager, 2014)
PFSs Modeling	Illustrative	N/A	First Model Introduction	(Yager, 2014)
TOPSIS	Illustrative	N/A	Comparative Analysis	(Zhang & Xu, 2014)
PFSs Modeling	Illustrative	N/A	First Model Introduction	(Yager, 2013)
PFSs Modeling	Illustrative	N/A	First Model Introduction	(Yager & Abbasov, 2013)

On the PFSs side, papers mostly offer aggregation operators for PFSs in an illustrative numerical example. As it is obvious, CM, QFD, ANP and ARAS methods have not yet been integrated with PFSs. Thus, the originality of this thesis stems from offering a novel framework for DSC modeling and design by integrating CM, QFD, ANP and ARAS methods with PFSs values under GDM environment for the first time.

3.2. Overview of Axiomatic Design Methodology

AD has been first introduced by Suh (1990) and its application areas include quality system designs, software designs, general system designs, manufacturing system designs, ergonomics, e-commerce strategy designs, engineering system and office cell designs, etc. (Suh, 2001).

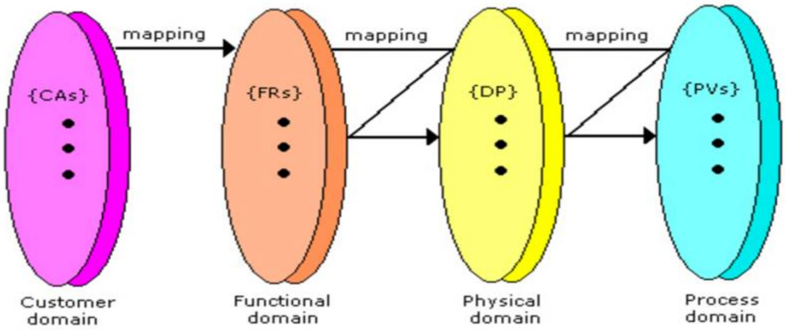


Figure 3.1: Fundamental Concept of AD (Acclaro, 2016)

AD approach is characterized by the four design domains which are called customer domain, functional domain, physical domain and process domain. Their characteristic vectors are represented as customer attributes (CAs), functional requirements (FRs), design parameters (DPs) and process variables (PVs), respectively. The transitions from left sides to right sides occur through mapping (Suh, 1995), as illustrated in Figure 3.1 and Figure 3.3. The connection between an FR and its related DP is represented by the dotted arrows in Figure 3.3.

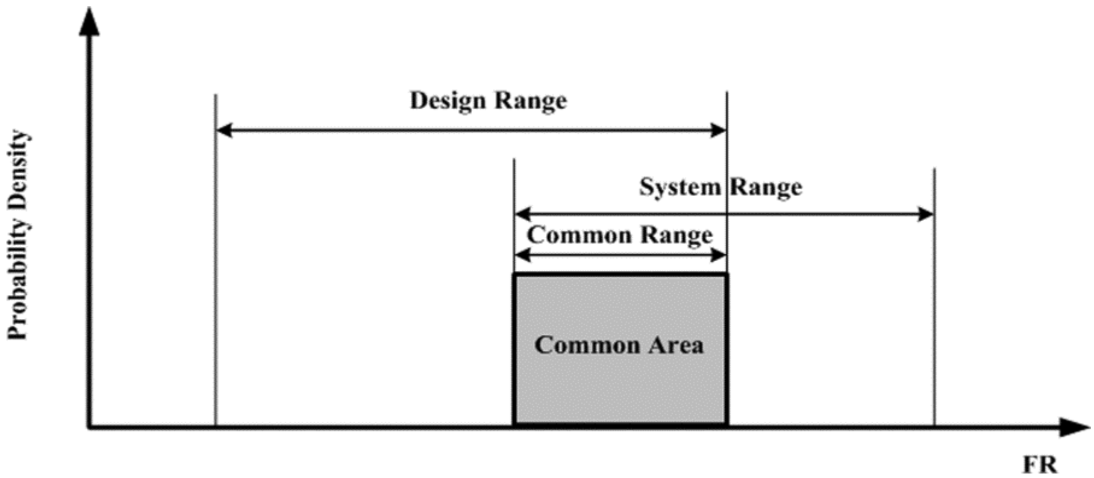


Figure 3.2: Design, System, Common Area and Probability Density Function of FRs (Kulak & Kahraman, 2005)

The defined axioms are identified through observation of the mutual features that are always present in good designs. The Independence Axiom is the first axiom which states continuous maintenance of the independence among the FRs. The Information Axiom is the second axiom. This axiom demands the best design to be the one with the minimum information content.

The Information Axiom should be among the designs that satisfy the first axiom. Here, information is specified in terms of the information content (I_{ij}) in a most basic form, where p_{ij} stands for the probability of success in satisfying the defined FRs with DPs. The I_{ij} regulates the design as the best design with the highest probability of success.

I_{ij} of a design with a probability of success p_{ij} is a uniform probability distribution function for a dedicated FR, which is expressed as:

$$I_{ij} = log_2(\frac{1}{p_{ij}}) \qquad (3.2.1)$$

Here, p_{ij} stands for the probability of fulfilling a dedicated FR. The expression "log_2" is the mathematical logarithm operator to the second base. For some FRs, the I_{ij} will be equal to the sum of all probabilities. The system will fail as I_{ij} goes to infinity. When all probabilities are equal to one, the I_{ij} will become zero. This means that infinite information will be needed when one or more probability values are zero (Chen et al., 2016). Figure 3.2 illustrates the design range, system ranges and their intersecting common area, which is a feasible solution. In this area, information content can be represented as the uniform probability distribution function. Then, the success probability becomes the following:

$$p_{ij} = \frac{Common\ Range}{System\ Range} \qquad (3.2.2)$$

This so-called Common Range is the intersection area of the triangles spanned by FR_i and alternatives A_i on criterion C_j. It is the only area where an FR will be met. The design range is the expected level set out by the Experts for the certain system or criteria.

The System Range designates the area of the triangle spanned by alternatives A_i on criterion C_j. The design range, system range, and common area are illustrated in Figure 3.2. In this setting, the I_{ij} is found as:

$$I_{ij} = log_2 \frac{System\ Design}{Common\ Area} \tag{3.2.3}$$

During the mapping process, where hierarchies are structured and decomposition of first level CAs, FRs, DPs, and PVs are done, the satisfaction of the first axiom is a must. Furthermore, during the decomposition process, zigzagging is needed between the design domains (Suh, 1995).

The second axiom can be utilized as an MCDM tool (Büyüközkan & Göçer, 2017; Kahraman & Çebi, 2009). For the design phase of this paper, however, it is not considered.

Design types can be categorized as coupled, decoupled and uncoupled. In ideal cases the number of FRs and DPs is equal (i=j). The values of the individual elements in design matrix [A] are uncovered by the change in a FR caused by a change in a DP.

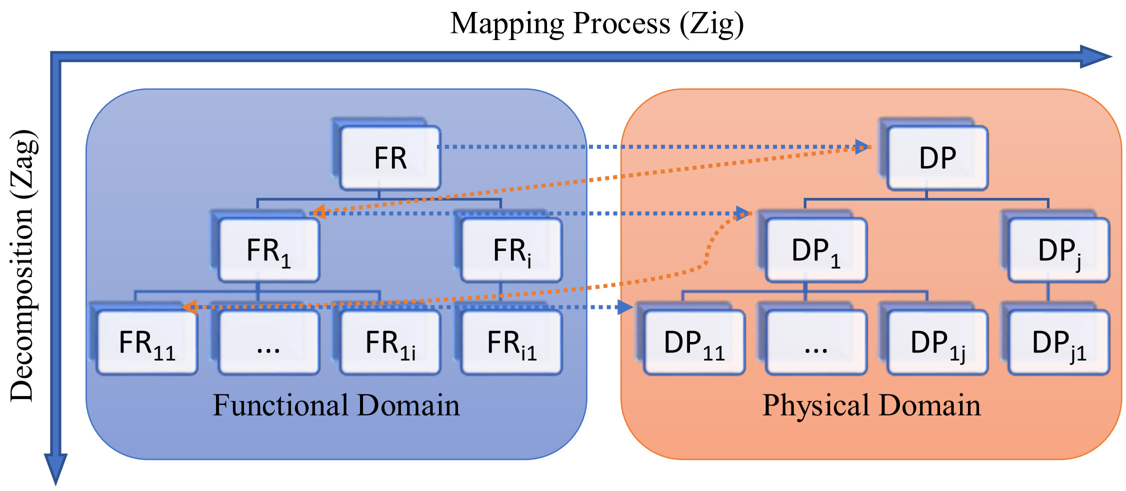


Figure 3.3: The FR and DP Hierarchies and the Zigzagging Process

The uncoupled design is represented in Figure 8. In the design matrix shown in Figure 8, it indicates that [A] are diagonal and each FR could be independently met by one DP. Nevertheless, such a setting is only achievable in ideal cases.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_i \end{Bmatrix} = \begin{Bmatrix} A_{11} & A_{12} & \cdots & A_{1j} \\ A_{21} & A_{22} & \cdots & A_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ A_{i1} & A_{11} & \cdots & A_{ij} \end{Bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_j \end{Bmatrix} \text{ where } A_{ij} = \frac{\partial FR_i}{\partial DP_j} \qquad (3.2.4)$$

Decoupled design is illustrated in Figure 3.4 by a triangular design matrix. Here, each FRs independence can be met if and only if the DP is determined in an appropriate sequence. The rest of the designs of [A], as represented in Figure 3.4, are called a coupled design, which should be avoided as much as possible, considering that such designs do not ensure that the first axiom be satisfied (Suh, 2001).

Basically, if the arrows are vertical, this symbolizes uncoupled design and if the arrows are diagonal in the model, it indicates a decoupled design. Every DP is linked to its related FR. But, if any DP linked to FR is also linked to a subsequent FR with a diagonal arrow, it refers to a precedence relationship among FRs (FR_i and FR_{i+1}); that is, execution of FR_{i+1} is conditioned by the first FR_i with its related DP. In AD application, it is common to witness decoupled designs. That is why AD includes diagonal arrows as well as vertical. The arrows imply the order of execution. They are also useful in developing and implementing the model.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{Bmatrix} X00 \\ 0X0 \\ 00X \end{Bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

Uncoupled design

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{Bmatrix} XXX \\ XX0 \\ X00 \end{Bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

Decoupled Design

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{Bmatrix} XXX \\ XXX \\ XXX \end{Bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

Coupled Design

Figure 3.4: Uncoupled, Decoupled, and Coupled Design Matrix Representations

3.2.1. AD Literature Review

In this section, the articles including AD approaches involving independence axiom have been analyzed. As a basis for the literature review, the papers were analyzed in a period of the last 12 years (2006-2018), and the selection criteria of "axiomatic design", keyword and origin language of English is applied to the search. Using the above-mentioned search criteria 72 papers could be identified. As it is presented in Table 3.3, the studies are structured into three main categories; Design Type, Application Area, and Application Type. Design Type expresses the main goal of the AD approach utilized. Thus, this section states Products design, Systems design, Software design, Manufacturing system design, and others. Application Area is formed to demonstrate the main goal of the applied AD approach. The last section of Table 3.3 is created to highlight the Application Type to state its base as if illustrative or case study in the researched paper.

Table 3.3: Literature Review of AD Studies

Design Type	Application Area	Application Type	Author(s)
Manufacturing	Computer Integrated Manufacturing	Illustrative	(Delaram & Fatahi Valilai, 2018)
Product	Product Development	Case Study	(Rizzuti & De Napoli, 2018)
Systems	Health Care	Illustrative	(Arcidiacono et al., 2017)
Manufacturing	Bolt-Driving Mechanism	Illustrative	(Cochran et al., 2017)
Systems	Transportation Electrification	Illustrative	(Farid, 2017a)
Products	Bird Feeders	Illustrative	(Farid, 2017b)

Design Type	Application Area	Application Type	Author(s)
Products	Spring Design	Illustrative	(Feyzioglu & Kar, 2017)
Systems	Automobile Diaphragm	Illustrative	(Göhler et al., 2017)
Systems	Automatic Washing Machine	Case Study	(He et al., 2017)
Systems	Insulin Injection Devise	Case Study	(Howard et al., 2017)
Product	Rehabilitation Equipment	Case Study	(Ko, 2017)
Systems	Refrigerator Door	Illustrative	(Mabrok et al., 2017)
Products	Prefabricated Housing	Illustrative	(Marchesi & Matt, 2017)
Manufacturing	Reconfigurable System	Illustrative	(Puik et al., 2017)
Manufacturing	Production System	Illustrative	(Schoonenberg & Farid, 2017)
Products	Fermentation Vessel	Case Study	(Voorthuysen et al., 2017)
Systems	Project based Learning	Illustrative	(Arcidiacono et al., 2016)
Products	Airplane Tail Design	Case Study	(Ashtiany & Alipour, 2016)
Systems	Shipbuilding Industry	Case Study	(Babur et al., 2016)
Systems	Rainwater Harvester	Case Study	(Betasolo & Smith, 2016)

Design Type	Application Area	Application Type	Author(s)
Manufacturing	Assembly Operation	Illustrative	(Fechter et al., 2016)
Products	Electro mechanical art	Illustrative	(Foley & Harðardóttir, 2016)
Products	Dimensional Tolerance	Case Study	(Fradinho et al., 2016)
Products	Grader Transfer Bin	Illustrative	(Gerhard & Foley, 2016)
Products	Photography Lighting	Illustrative	(Guls et al., 2016)
Products	Hydrostatic Spindle	Illustrative	(Jia et al., 2016)
Products	Rotor Bearing	Illustrative	(Jin et al., 2016)
Products	Hair Drier	Illustrative	(Kumar & Tandon, 2016)
Software	Habit Forming	Illustrative	(Liu & Li, 2016)
Products	Bicycle	Case Study	(Lu et al., 2016)
Products	Bicycle	Illustrative	(Modrak et al., 2016)
Software	CNC Machine	Illustrative	(Oliveira & Álvares, 2016)
Products	Hydraulic Press	Illustrative	(Qu et al., 2016)
Products	Active fastener design	Illustrative	(Peeters et al., 2016)

Design Type	**Application Area**	**Application Type**	**Author(s)**
Manufacturing	Bracket Additive	Case Study	(Salonitis, 2016)
Manufacturing	Modular Platform	Illustrative	(Schuh et al., 2016)
Products	Valve Design	Case Study	(Wang et al., 2016)
Systems	Emergency Response System	Case Study	(Yang & Yang, 2016)
Products	Circuit Breaker	Illustrative	(Zhu et al., 2016)
Products	Colonoscopy	Case Study	(Cao et al., 2015)
Manufacturing	Furniture Manufacturing	Case Study	(Gao et al., 2015)
Manufacturing	Assembly Systems	Case Study	(Holzner et al., 2015)
Software	Software Development	Illustrative	(Kandjani et al., 2015)
Manufacturing	Resilient Robot	Illustrative	(Zhang et al., 2015)
Organizations	Software Development	Case Study	(Arsenyan & Büyüközkan, 2014)
Systems	Reverse Logistic Network	Illustrative	(Cinar et al., 2014)
Products	Virtual Robot	Illustrative	(Taha et al., 2014)
Manufacturing	Remanufactured Lathe	Illustrative	(Du et al., 2013)

Design Type	**Application Area**	**Application Type**	**Author(s)**
Manufacturing	Supply Chain	Illustrative	(Kristianto & Zhu, 2013)
Systems	Microchannel	Illustrative	(Song & Zhang, 2013)
Products	In-Pipe Robot	Illustrative	(Qiao & Shang, 2013)
Products	Grinding Technology	Illustrative	(Linke & Dornfeld, 2012)
Systems	Six Sigma Methodology	Case Study	(Aksoy & Dinçmen, 2011)
Products	Rotating Lip	Illustrative	(Brown, 2011)
Manufacturing	Laser Cutting	Illustrative	(Duflou & Dewulf, 2011)
Theory	Complexity Measures	Illustrative	(Kandjani & Bernus, 2011)
Products	Hard Drive	Illustrative	(Ogot, 2011)
Manufacturing	Lean Design	Case Study	(Shirwaiker & Okudan, 2011)
Systems	Minimize Difficulties of QFD	Illustrative	(Carnevalli et al., 2010)
Products	Indicator Design	Illustrative	(Cebi & Kahraman, 2010a)
Products	Refrigerator Door	Illustrative	(Cebi & Kahraman, 2010b)
Products	Warehouse Trucks	Illustrative	(Janthong et al., 2010)

Design Type	Application Area	Application Type	Author(s)
Systems	Healthcare System	Illustrative	(Peck et al., 2010)
Systems	Hospital Emergency	Illustrative	(Peck & Kim, 2010)
Products	Endplate	Illustrative	(Yu et al., 2010)
Systems	Reactor	Illustrative	(Bang et al., 2009)
Products	Combustion Engine	Case Study	(Ferrer et al., 2009)
Products	Chocolate Wrapping	Illustrative	(Tang et al., 2009)
Manufacturing	Office Cells	Illustrative	(Durmuşoğlu et al., 2008)
Products	Product Lifecycle	Illustrative	(Gumus et al., 2008)
Products	Spacer Grid	Illustrative	(Shin et al., 2008)
Software	F16 Aircraft	Illustrative	(Togay et al., 2008)
Systems	Human-Machine Interaction	Illustrative	(Helander, 2007)
Systems	Emergency Cooling	Illustrative	(Heo & Lee, 2007)
Manufacturing	Unmanned Machine Shop	Illustrative	(Nakao et al., 2007)
Organizations	SC Strategy	Case Study	(Schnetzler et al., 2007)

Design Type	Application Area	Application Type	Author(s)
Manufacturing	Lean Production	Illustrative	(Houshmand & Jamshidnezhad, 2006)
Systems	Nuclear Reactor	Illustrative	(Thielman & Ge, 2006)

It can easily be observed that AD was applied over all the years as a tool for general aspects in all kinds of designs but it has been widely applied for products design in the researched paper over a period of the last twelve years. Readers could spot clearly that researched papers are mostly the illustrative studies rather than being a specific study about a real case. In recent years, AD was also used for systems, organizations and software designs. There is no study, however, embodies the digital transformation process of any organizations let alone supply chains. Therefore, as far as we know, the final goal of modeling a digitalization structure for supply chain with AD has not yet been done in the literature.

3.3. Overview of Cognitive Map Methodology

Cognitive mapping (CM) deals with mapping humans' mental activities during problem solving (Tolman, 1948). The topic is introduced in the 70s as a type of directed graphs used to capture and understand relationships of cause and effect in complex causal systems and to facilitate the understanding of the inter-connections within the elements of the concepts (Axelrod, 1976b). CM has two elements: concepts and causal belief. Concepts are the variables that represent the belief system of a person and the causal belief consists in the causal decencies between these variables (Axelrod, 1976a). Such variables can be continuous, ordinal or dichotomous. The elements of CM are shown in Figure 3.5 along with a simple representation of CM given in Figure 3.6.

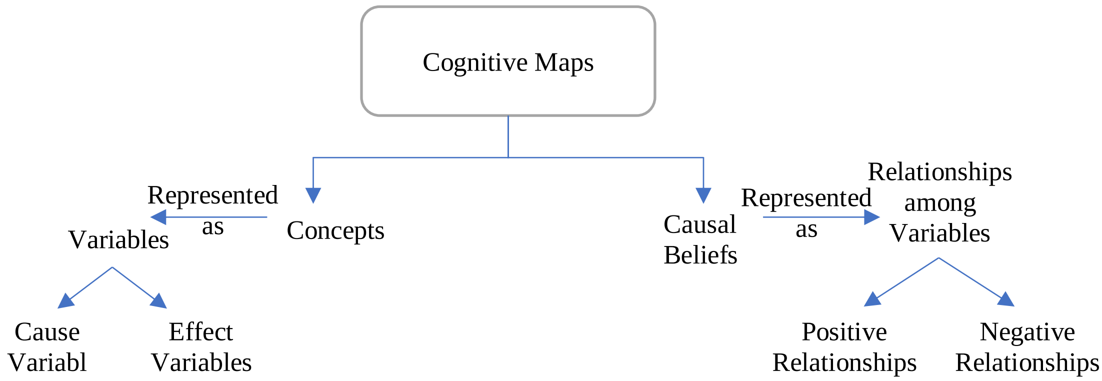


Figure 3.5: The Cognitive Map Elements (Büyüközkan & Vardaloğlu, 2012)

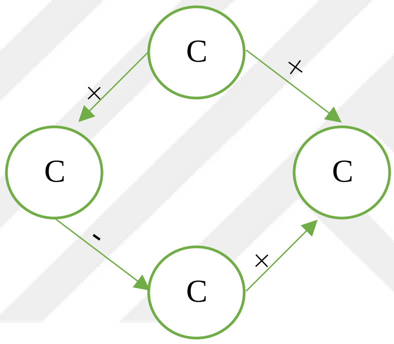


Figure 3.6: A Simple CM Representation

Fuzzy CM, an extension of traditional CM, is introduced in the 80s that includes the concepts to be represented in linguistic terms with a related fuzzy value rather than demanding them to be crisp (Kosko, 1986; Nápoles et al., 2016). The value of each concept is computed by applying (Eq.) (1), where $A_i^{(k+1)}$ is the value of concept i at iteration $k+1$, $A_i^{(k)}$ is the value of the interconnected concept j at iteration k, w_{ji} is the weighted arc and f is the threshold function. A simple representation of Fuzzy CM is shown in Figure 3.7.

$$A_i^{(k+1)} = f\left(A_i^k + \sum_{j=1}^{N} A_j^{(k)} w_{ji}\right) \qquad (3.3.1)$$

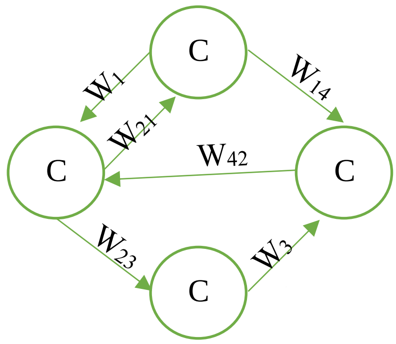


Figure 3.7: A Simple FCM Representation

IF CM is introduced in 2009 as an extension of CM and Fuzzy CM (E.I. Papageorgiou & Iakovidis, 2009). Since then, IF CM has been used in several studies (Dogu et al., 2018; Zhang et al., 2013; Iakovidis & Papageorgiou, 2011; Papageorgiou & Iakovidis, 2009,2013). The powerful feature of IF CM is its ability to cope with hesitations. IF CM also has the iteration-based system same as Fuzzy CM. An elementary version of IVIFCM is first mentioned in (Hajek & Prochazka, 2018) as an extension of IF CM.

PFCM is a novel study to be proposed by the authors in which generalization of Fuzzy CM is proposed in PF environment to cope with complex links among concepts for DSC structure.

3.3.1. CM Literature Review

Table 3.4 presents the publications on CM studies. As a basis for the literature review on CMs, the selection criteria of “Cognitive Map” and “Supply Chain Management” are explored as keywords, which resulted in 16 publications. It is designed to display the related categories of CM publications and is structured into five sections to summarize the main concept of each paper to convey their relevance. The application area is presented to display the involvement of supply chain in each paper. Its application environment is displayed in the next section. The integrated method illustrates which methodology is integrated with CM in the paper. The type of its application is presented fourth section. Following this, the publications are identified as GDM or not.

Table 3.4: Literature Review of CM Studies

Application Area	**Application**	**Integrated Method**	**Application Type**	**GDM**	**Author(s)**
Food Supply Chain	Type-I Fuzzy	Simulation	Illustrative	N/A	(Irani et al., 2018)
Leagile Supply Chain	Type-I Fuzzy	Delphi	Case Study	N/A	(Kalantari & Khoshalhan , 2018)
Supply Chain Risks	Crisp	AHP	Illustrative	N/A	(Mital et al. 2018)
Service Supply Chain	Type-I Fuzzy	Questionnaire	Illustrative	N/A	(Pandari & Azar, 2017)
Supply Chain Resilience	Type-I Fuzzy	AHP	Case Study	N/A	(López & Ishizaka, 2017)
Supply Chain Traceability	Type-I Fuzzy	Simulation	Case Study	N/A	(Chen, 2015)
Supply Chain Network	Type-I Fuzzy	Questionnaire	Illustrative	N/A	(Jamshidi et al., 2015)
SCM	Type-I Fuzzy	Questionnaire	Illustrative	N/A	(Vlahakis & Aposotlou, 2015)
Supply Chain Information	Type-I Fuzzy	Simulation	Illustrative	N/A	(Irani et al., 2014)
Supply Chain Risk	Type-I Fuzzy	TOPSIS	Illustrative	GDM	(Kar et al., 2014)
SCM	Type-I Fuzzy	Questionnaire	Case Study	N/A	(Kayikci & Stix, 2014)
Supply Chain Risk	Crisp	Bayesian Network	Case Study	N/A	(Qazi et al., 2014)

Application Area	Application	Integrated Method	Application Type	GDM	Author(s)
Supply Chain Collaboration	Type-I Fuzzy	Questionnaire	Illustrative	N/A	(Büyüközkan & Vardaloğlu, 2012)
Supply Chain Dependency	Type-I Fuzzy	Questionnaire	Illustrative	N/A	(Ferrari et al., 2011)
Supply Chain Resilience	Type-I Fuzzy	Questionnaire	Case Study	N/A	(Trucco & Ward, 2011)
Reverse Logistic	Type-I Fuzzy	Genetic Algorithm	Case Study	N/A	(Trappey et al., 2009)
Non-deterministic Supply Chain	Type-I Fuzzy	Genetic Algorithm	Illustrative	N/A	(Kim et al., 2008)

Following the literature review of CM, some shortcomings of DSC, PFSs, and CM literature can be underlined and new research directions can be discussed. As it is apparent, our study is the first of its kind given that there is no study that utilizes CM with PFSs. There also exists no study in the literature analyzing the structure of DSC. Thus, the originality of our thesis stems from offering a novel framework for analyzing the DSC structure by integrating the CM methodology with the PFSs values under the GDM environment for the first time.

3.4. Overview of Quality Function Deployment Methodology

QFD is first systematized in Japan at Mitsubishi, Japan (Akao, 1972) and is applied to match product characteristics with customer needs. Although QFD originally aimed to deliver a structured methodology for product development, it can also be used to systematically evolve system characteristics from a set of requirements (Kumar & Midha, 2001). Thus, QFD emerges today as a system design tool.

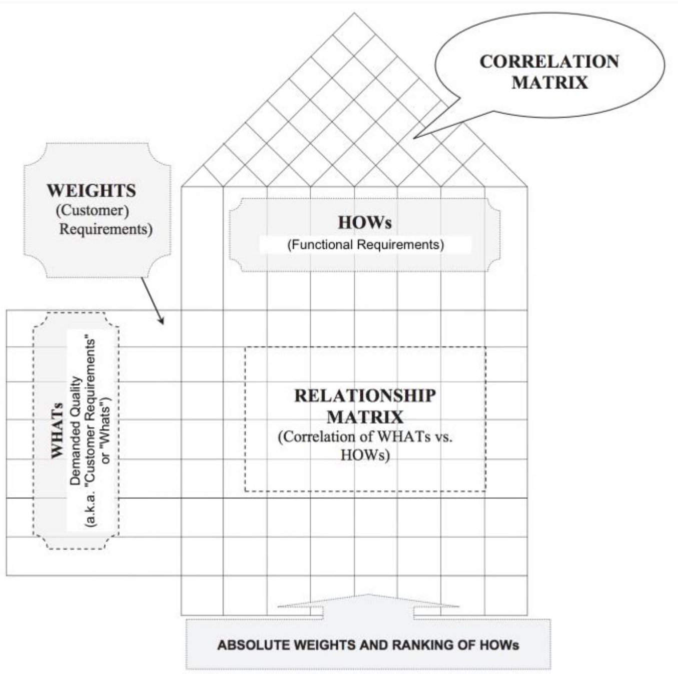


Figure 3.8: The Framework of QFD (Griffin & Hauser, 1993)

QFD transforms customer voice to engineering characteristics for a new or an existing product or service. House of quality is one of the main tools to facilitate this mapping. QFD has a point scale system to appraise the design prior to implementation (Wang & Chen, 2012). QFD can be regarded as a method for planning purposes, where it is utilized for translating customers' expectations into product planning, design, and manufacturing (Wang, 2017). QFD's first main function is to better understand what customers desire. Its second main function is to apply a structured algorithm to identify alternative ways of how to satisfy those expectations. QFD can thus be used to improve the coordination in a business unit and align resources with targets that correspond to customers' needs (Guinta & Praizler, 1993).

The steps involved in QFD are narrated next. The concept of House of Quality (HOQ) is closely linked to QFD. It is basically a matrix which establishes and maps out each process in implementing QFD. Figure 3.8 displays the framework of QFD. Key terms relevant to DSC are given next.

- Demanded Quality, also known as "Customer Requirements (CRs)" or "Whats" is the prime input in the HOQ. It is the main list of CRs, which is generally voiced with imprecise and vague terms. Each CR is documented as a What.

- Quality Characteristics, also known as "Functional Requirements (FR)" or "Hows" are the means of achieving the "Whats" once the CRs are generated. Therefore, FRs are the design characteristics that are meant to address the CRs. For each CR, a corresponding FR is identified.

- The relationship matrix is about how product characteristics affect the satisfaction of each CR. It relates Whats (CRs) to Hows (FRs), as illustrated in Figure 3.8.

- The correlation matrix is indicated at the top of the HOQ. This matrix shows the interdependencies among the Hows by playing a significant role in the decision of the number of FRs that directly affect ordering CRs and FRs.

- Absolute weights and ranking of the Hows include the results of the prioritization of design characteristics to meet the Whats. It characterizes the impact of each FR on the CRs. This is the final step before the ranking.

3.4.1. QFD Literature Review

This section provides a comprehensive review of QFD studies by examining all databases for a period of the last 30 years. The selected publications are categorized into specific groups to present a structured overview of ongoing research.

Since there are abundant amount of QFD studies in the literature, to narrow it down and to align it to our topic, the following research procedure is performed. The review of QFD evaluation has been conducted in order to identify QFD studies regarding supply chain studies. As a basis for the literature review on QFD, the selection criteria of "MCDM" +

"Supply chain" + "Quality Function Deployment", keywords and original language of English is applied to the search. Using the above-mentioned search criteria 24 articles were identified. Table 3.5 is designed to display the related categories of QFD studies summarizing the main concept of each paper. Out of the five sections provided, Application area presents the paper's involvement in supply chain areas. Application Type defines what types of fuzzy or crisp values the model utilizes. The integrated method besides QFD is illustrated in the third section. Similarly, Application defines the area of its applied, viz. it is a case study or Illustrative. Whether it uses GDM or not are presented at the final column.

Table 3.5: Literature Review of QFD Studies

Application Area	Application Type	Integrated Method	Application	GDM	Author(s)
Green Supply Chain	Trapezoidal Fuzzy	Stochastic MODM	Case Study	GDM	(Babbar & Amin, 2018)
Supply Chain Sustainability	Hesitant Fuzzy	-	Illustrative	GDM	(Osiro et al., 2018)
Green Supply Chain	Neutrosophic Set	TOPSIS	Case Study	N/A	(Van et al., 2018)
SCM	Type-I Fuzzy	TOPSIS	Case Study	GDM	(Yazdani et al., 2017a)
Green Supply Chain	Crisp	DEMATEL COPRAS	Case Study	N/A	(Yazdani et al., 2017b)
Supply Chain Sustainability	Crisp	ANP	Case Study	N/A	(Tavana et al., 2017)
Supply Chain Sustainability	Type-I Fuzzy	Questionnaire	Case Study	GDM	(Lin et al., 2017)

Application Area	Application Type	Integrated Method	Application	GDM	Author(s)
Lean agile Supply Chain	Type-I Fuzzy	AHP and TOPSIS	Case Study	N/A	(Haq & Boddu, 2017)
SCM in Supplier Selection	Type-I Fuzzy	Delphi Method	Illustrative	GDM	(Junior & Carpinetti, 2016)
Supply Chain Resilience	Crisp	Questionnaire	Case Study	N/A	(Lam & Bai, 2016)
Supply Chain Resilience	Type-I Fuzzy	AHP	Case Study	GDM	(Chowdhury & Quaddus, 2015)
Supply Chain Sustainability	Crisp	ANP	Case Study	GDM	(Lam, 2015)
Supply Chain Sustainability	Crisp	ANP	Case Study	GDM	(Lam & Lai, 2015)
Supply Chain Agility	Crisp	AHP	Illustrative	N/A	(Balaji et al., 2014)
SCM	Type-I Fuzzy	DEA	Case Study	GDM	(Karsak & Dursun, 2014)
Multimodal Supply Chain	Crisp	Questionnaire	Illustrative	N/A	(Wolfsmayr & Rauch, 2014)
Supply Chain Sustainability	Type-I Fuzzy	Questionnaire	Case Study	GDM	(Büyüközkan & Cịfçi, 2013)
SCM Strategies	Type-I Fuzzy	Multi-Objective	Case Study	N/A	(Ayağ et al. , 2013)
Supply Chain Flexibility	Crisp	Questionnaire	Illustrative	N/A	(Barad, 2012)
Logistics Outsourcing	Type-I Fuzzy	AHP	Case Study	N/A	(Ho et al., 2012)

Application Area	Application Type	Integrated Method	Application	GDM	Author(s)
Supply Chain Leanness	Type-I Fuzzy	AHP	Case Study	N/A	(Zarei et al., 2011)
Supply Chain Sustainability	Crisp	ANP	Case Study	N/A	(Büyüközkan & Berkol, 2011)
Supply Chain Agility	Type-I Fuzzy	Fuzzy Logic	Illustrative	N/A	(Bottani, 2009)
Supply Chain Efficiency	Type-I Fuzzy	Fuzzy Entropy	Illustrative	N/A	(Mirmahmutoğullari, 2007)
Logistic Service	Type-I Fuzzy	Fuzzy Logic	Case Study	N/A	(Bottani & Rizzi, 2006)
Supply Chain Reliability	Type-I Fuzzy	Fuzzy MCDM	Illustrative	N/A	(Sohn & Choi, 2001)

As far as we know, there is no QFD study applied so far in a PFSs environment for any subject. This study will be the first pioneering study that integrates PFSs values with QFD methodology. Following the literature review, some shortcomings of QFD literature will also be underlined and new research directions can be discussed. The review above shows that the QFD approach usually concentrates on implementing SCM in type-I fuzzy and they are mostly illustrative for non-GDM problems. Planning technological infrastructure of DSC with QFD under PFSs is a novel approach. Filling these gap, this study proposes a framework for planning technological infrastructure of DSC by integrating the QFD methodology with PFSs values under GDM environment for the first time.

3.5. Overview of Analytic Network Process

The Analytic Network Process (ANP) is developed by Thomas Saaty as an extension of the Analytic Hierarchy Process (AHP) in the late 1970’s (Saaty, 1977). ANP has become a dominant tool for dealing with MCDM problems over the years. It is proposed to overcome these problems with inter-dependence and feedback effects. An ANP model consists of the control hierarchies, clusters, elements, inter-relationships between elements, and inter-relationships between clusters. Figure 3.9 display a sample of hierarchical ANP model and Figure 3.10 presents its network structure. The ANP modeling process is better understood by dividing it into several steps.

Step 1: Pair-wise comparison and relative weight estimation. The local weights are constructed by the AHP. Saaty (1980) suggested a nine point pairwise comparison scale as shown in Table 3.6.

Step 2: Check Consistency Ratio (CR). CR is obtained with the use of a standard Random Index (RI), the value of which is taken from Saaty (1977) as presented in Table 3.7. CR is calculated by $CR = \frac{\lambda_{max} - n}{n-1}$ where n is the number of matrix elements and $\lambda_{max}$is the largest eigen value. If CR is less than or equal to the consistency threshold (0.10), then the consistency level is unacceptable. The judgment matrix shall be deemed as not consistent and DMs' opinions shall be collected once more.

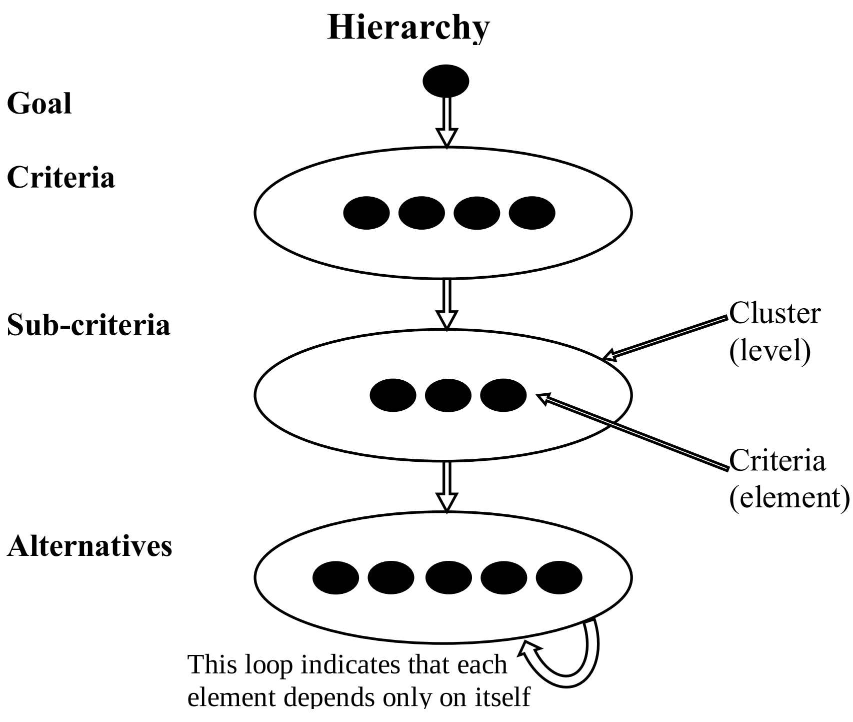


Figure 3.9: A Sample of ANP Hierarchy

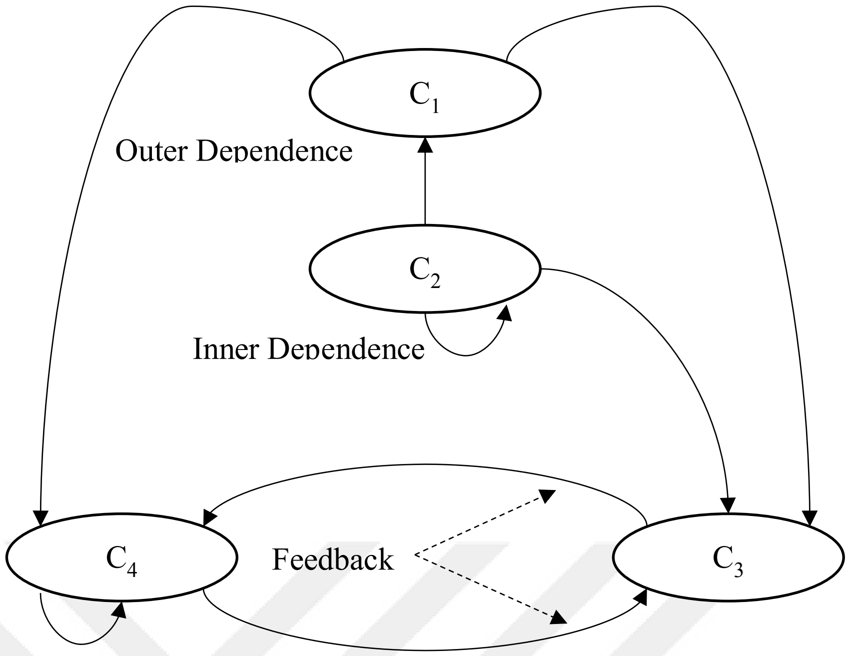


Figure 3.10: A Sample of ANP Network Structure

Table 3.6: Saaty's Scale for Pairwise Comparisons

Intensity of Importance	Definition	Explanation
1	Equal Importance	Activities contribute equally
3	Moderate Importance	Judgment slightly favor one activity over another
5	Strong Importance	Judgment strongly favor one activity over another
7	Very Strong or Demonstrated Importance	Judgment very strongly favor one activity over another
9	Extreme Importance	Judgment favor one activity over another with a highest possible order of affirmation
2,4,6,8	For compromise between the above values	Interpolate a compromise judgment numerically

Table 3.7: Random Indices

n	1-2	3	4	5	6	7	8	9	10	11	12
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54

Step 3: Formation of the initial super-matrix. The super-matrix is formulated according to the results of the local weights and the network structure. The general form of a super-matrix is represented in Table 3.8. C_N denotes the N^{th} cluster, X_{Nn} denotes the n^{th} element in N^{th} cluster, and W_{NN} is a block matrix consisting of priority weight vectors.

Step 4: Formation of the weighted super-matrix. The initial super-matrix consists of several eigen vectors each of which sums to one. The clusters in the initial super-matrix is weighted and transformed into a matrix in which each of its columns sums to one.

Table 3.8: A Sample of Super-Matrix

<table>
<tr><td colspan="2"></td><td>C_1</td><td>C_2</td><td>…</td><td>C_N</td></tr>
<tr><td colspan="2"></td><td>x_{11} x_{12} … x_{1n}</td><td>x_{21} x_{22} … x_{2n}</td><td></td><td>x_{N1} x_{N2} … x_{Nn}</td></tr>
<tr><td>C_1</td><td>x_{11}
x_{12}
…
x_{1n}</td><td>W_{11}</td><td>W_{11}</td><td>…</td><td>W_{1N}</td></tr>
<tr><td>…</td><td>…</td><td>…</td><td>… …</td><td>…</td><td>…</td></tr>
<tr><td>C_N</td><td>x_{N1}
x_{N2}
…
x_{Nn}</td><td>W_{N1}</td><td>W_{N2}</td><td>…</td><td>W_{NN}</td></tr>
</table>

Step 5: Calculation of global priority vectors. The weighted super-matrix is raised to limiting powers for obtaining the final results.

3.5.1. ANP Literature Review

The number of studies on SCM ANP is evolved over the years. The keywords of "Analytic Network Process" + "Supply Chain Management" are explored as a basis for the literature review on SCM ANP. This resulted in 37 studies and Table 3.9 is designed to display the related categories of ANP studies in the context of SCM area.

Table 3.9: Literature Review of ANP Studies

Application Area	Application	Integrated Method	Application Type	GDM	Author(s)
Supplier Selection	Type I Fuzzy	QFD	Case Study	N/A	(Apornak et al., 2018)
Supply Chain Resilience	Type I Fuzzy	VIKOR	Illustrative	GDM	(Parkouhi et al., 2017)
Supply Chain Sustainability	Crisp	QFD	Case Study	N/A	(Tavana et al., 2017)
Supply Chain Sustainability	Crisp	-	Illustrative	N/A	(Faisal et al., 2017)
Supplier Selection	Interval 2-tuple	ELECTRE	Case Study	N/A	(Wan et al., 2017)
Supply Chain Sustainability	Crisp	Goal Programming	Case Study	N/A	(Neumüller et al., 2016)
Green Supply Chains	Crisp	-	Case Study	N/A	(Chung et al., 2016)
Supplier Selection	Crisp	Dempster Shafer	Illustrative	N/A	(Zhang et al., 2016)
Supplier Selection	Crisp	Data Envelopment	Case Study	N/A	(Che & Chang, 2016)
Supply Chain Sustainability	Crisp	ELECTRE	Case study	N/A	(Girubha et al., 2016)

Application Area	Application	Integrated Method	Application Type	GDM	Author(s)
Green Supply Chain	Grey Relational	-	Case Study	N/A	(Hashemi et al., 2015)
Supplier Selection	Crisp	IF TOPSIS	Illustrative	GDM	(Rouyendegh, 2015)
Supplier Selection	Type I Fuzzy	-	Case Study	N/A	(Zhang et al., 2015)
Supply Chain Sustainability	Type I Fuzzy	-	Case Study	N/A	(Lin et al., 2015)
Supply Chain Risks	Type I Fuzzy	Factor Analysis	Case Study	N/A	(Sinrat & Atthirawon, 2015)
Agile Supply Chain	Crisp	DEMATEL and TOPSIS	Case Study	N/A	(Alimardani et al., 2014)
Green Supply Chain	Crisp	VIKOR	Illustrative	N/A	(Hsu et al., 2014)
Supplier Selection	Crisp	-	Illustrative	N/A	(Chen et al., 2014)
Green Supply Chain	Crisp	-	Case Study	N/A	(Paul & Jayant, 2014)
Supplier Selection	Type I Fuzzy	DEMATEL and VIKOR	Illustrative	N/A	(Hsu et al., 2014)
Supply Chain Sourcing	Type I Fuzzy	VIKOR	Case Study	GDM	(Rezaei et al., 2013)
Supply Chain Sourcing	Type I Fuzzy	Goal Programming	Case Study	N/A	(Huang & Hu, 2013)
Supply Chain Sustainability	Crisp	TOPSIS	Case Study	N/A	(Wu et al., 2013)
Supply Chain Efficiency	Crisp	-	Case Study	N/A	(Kivijarvi et al., 2012)

Application Area	**Application**	**Integrated Method**	**Application Type**	**GDM**	**Author(s)**
Green Supply Chain	Crisp	Linear Programming	Illustrative	N/A	(Lin et al., 2012)
Supply Chain Outsourcing	Crisp	-	Case Study	GDM	(Sadeghi et al., 2012)
Green Supply Chain	Crisp	Radial Basis Function	Illustrative	N/A	(Zhou et al., 2012)
Supply Chain Sustainability	Crisp	AHP	Illustrative	N/A	(Sarkis et al., 2012)
Supplier Selection	Type I Fuzzy	Linear Programming	Illustrative	N/A	(Lin, 2012)
Supplier Selection	Type I Fuzzy	-	Case Study	N/A	(Kang et al., 2012)
Supply Chain Sustainability	Type I Fuzzy	-	Case Study	GDM	(Büyüközkan & Çifçi, 2011)
Supply Chain Outsourcing	Type I Fuzzy	Questionnaire	Case Study	N/A	(Vinodh et al., 2011)
Supply Chain Sustainability	Crisp	-	Illustrative	N/A	(Dou & Sarkis, 2010)
Green Supply Chain	Crisp	Data Envelopment	Case Study	N/A	(Kuo et al., 2010)
Supplier Selection	Crisp	Linear Programming	Illustrative	N/A	(Lin, 2009)
SCM	Crisp	-	Case Study	N/A	(Kirytopoulos et al., 2008)
Supplier Selection	Crisp	-	Case Study	N/A	(Gencer & Gürpinar, 2007)
Supplier Selection	Crisp	-	Illustrative	N/A	(Chen & Lee, 2006)

On the PFSs side, ANP technique is not utilized under PFSs environment. Various MCDM techniques is used in combination with ANP. However, the originality of the proposed study stems from being first of its kind to offer a novel framework for DSC partner selection by integrating the ANP techniques with PFSs values under GDM setting for criteria evaluation.

3.6. Overview of Additive Ratio Assessment

The Additive Ratio Assessment (ARAS) method is proposed by Zavadskas and Turskis (2010). Similar to the other MCDM methods, the decision-making problem-solving process by the ARAS method starts with the decision matrix formation. The following steps are processed for ARAS method.

Step 1: Construct a decision-making matrix (x_{ij}) on alternatives (i) with respect to each criterion (j).

$$x_{ij} = \begin{bmatrix} x_{11} & \cdots & x_{m1} \\ \vdots & \ddots & \vdots \\ x_{1n} & \cdots & x_{mn} \end{bmatrix} \tag{3.6.1}$$

Where alternative $i = 1,2, \dots, m$, and criteria $j = 1,2, \dots, n$.

Step 2: Determine the optimal performance rating for each criterion.

$$x_{0j} = \begin{cases} \max\limits_{i} x_{ij}\,, j \in \Omega_{max}, \\ \min\limits_{i} x_{ij}\,, j \in \Omega_{min}, \end{cases} \tag{3.6.2}$$

Step 3: Calculate the normalized decision matrix.

$$r_{ij} = \begin{cases} \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}}, j \in \Omega_{max}, \\ \frac{1/x_{ij}}{\sum_{i=0}^{m} 1/x_{ij}}, j \in \Omega_{min}, \end{cases} \tag{3.6.3}$$

Step 4: Calculate the weighted normalized decision matrix (v_{ij}).

$$v_{ij} = w_{ij} r_{ij}, \tag{3.6.4}$$

Step 5: Calculate the overall performance rating (S_i) for each alternative, ($i = 1,2, \dots, m.$).

$$S_i = \sum_{j=1}^{n} v_{ij}, \tag{3.6.5}$$

Step 6: Calculate the degree of utility (Q_i) for each alternative, ($i = 1,2, \dots, m.$).

$$Q_i = \frac{S_i}{S_0}, \tag{3.6.6}$$

Step 7: Rank alternatives.

$$A^* = \left\{ A_i | \max_i Q_i \right\}, \tag{3.6.7}$$

Where A^* denotes the best alternative, $i = 1,2, \dots, m$.

3.6.1. ARAS Literature Review

ARAS is a discrete technique and has been successfully applied in several areas as the detailed review is given in Table 3.10. The keyword of "ARAS" is explored as a basis for the literature review on ARAS studies. This resulted in 27 studies. On the DSC side of the publications, there is no similar study that proposes partner selection assessments. On the PFSs side, no ARAS technique is utilized under PFSs environment for ranking. Various MCDM techniques are used in combination. However, the originality of the proposed study stems from being first of its kind to offer a novel framework for DSC partner selection by integrating the ARAS techniques with PFSs values under GDM setting for ranking alternatives.

Table 3.10: Literature Review of ARAS Studies

Application Area	Application	Integrated Method	Application Type	GDM	Author(s)
Supplier Selection	IF	AHP	Case Study	GDM	(Büyüközkan & Göçer, 2018b)
Personnel Selection	Grey Relational	SWARA	Case Study	N/A	(Dahooie et al., 2018)
Project Evaluation	Interval Type I Fuzzy	SWARA	Case Study	N/A	(Dahooie et al., 2018)
Mobile Banking	Type I Fuzzy	AHP	Case Study	N/A	(Ecer, 2017)
Energy Generation	Crisp	Monte Carlo simulation	Illustrative	N/A	(Baležentis et al., 2017)
Electricity Generation	Crisp	AHP and ARAS	Case Study	N/A	(Štreimikienė et al., 2016)
Green Supplier	Type I Fuzzy	AHP, Goal Programing	Illustrative	N/A	(Liao et al., 2016)
Material Selection	Crisp	-	Illustrative	N/A	(Soltes & Novakova, 2016)
Equipment Selection	Type I Fuzzy	AHP	Case Study	N/A	(Nguyen et al., 2016)
Performance Evaluation	Crisp	DEMATEL, ANP,TOPSIS	Case Study	N/A	(Varmazyar et al., 2016)
Partner Evaluation	Type I Fuzzy	TOPSIS, MOORA, COPRAS	Case Study	N/A	(Akhavan et al., 2015)
Building Assessment	Crisp	AHP	Case Study	N/A	(Medineckiene et al., 2015)
Port Assessment	Type I Fuzzy	AHP	Case Study	N/A	(Zavadskas et al., 2015)

Application Area	Application	Integrated Method	Application Type	GDM	Author(s)
Finance	Type I Fuzzy	AHP	Illustrative	N/A	(Ghadikolaei & Khalili, 2014)
Finance	Type I Fuzzy	AHP, VIKOR	Case Study	N/A	(Ghadikolaei et al., 2014)
Personal Selection	Type I Fuzzy	AHP	Case Study	GDM	(Keršulienė & Turskis, 2014)
Site Selection	Type I Fuzzy	-	Case Study	GDM	(Shariati et al., 2014)
Strategy Selection	Type I Fuzzy	ANP	Case Study	GDM	(Zamani et al., 2014)
Vendor Selection	Type I Fuzzy	-	Case Study	N/A	(Chatterjee & Bose, 2013)
Technology Selection	Crisp	AHP	Case Study	N/A	(Sliogeriene et al., 2013)
Personal Selection	Crisp	-	Illustrative	N/A	(Dadelo et al., 2012)
Architect Selection	Type I Fuzzy	SWARA	Case Study	N/A	(Keršulienė & Turskis, 2011)
Pile Columns	Crisp	-	Illustrative	N/A	(Sušinskas et al., 2011)
Location Selection	Type I Fuzzy	AHP	Case Study	N/A	(Turskis & Zavadskas, 2010a)
Supplier Selection	Grey Relational	-	Case Study	N/A	(Turskis & Zavadskas, 2010b)
Foundation Selection	Crisp	-	Case Study	N/A	(Zavadskas et al., 2010)
Climate Evaluation	Crisp	-	Case Study	N/A	(Zavadskas & Turskis, 2010)

4. MODELING DSC STRUCTURE

Nowadays enterprises seeking for digitalization and excellence in their supply chains move toward new methods and models that are able to support competitiveness in an aggressive and uncertain global market environment. Supply Chains has turned into strong assets that rely on coordination and large integration of its well-organized processes. In global competitive environment, Supply chain enterprises must struggle to be digital in order to exist on the market. However, they are mostly limited by their digital abilities. The thesis offers model that drives tools and methodologies in order to achieve supply chains’ strategic plans for DSC transformation. This transformation requires benchmarks and metrics as well as the definition of a set of design indicators. Literature offers many tools for defining system requirements of design, among these tools, Axiomatic Design (AD) stands out as the most appropriate tool to handle the complex nature of DSC while most effectively satisfying the required goals. Thus, a systematic modeling approach is presented in order to apply Suh’s axioms for evaluating and modeling the digital transformation into the DSC. AD theory is a consolidated designing process able to integrate well-known concepts of engineering designs, process management, and benchmarking into a functional framework. AD’s detailed and hierarchical approach makes it a unique tool to define preliminary requirements and design a systematic structure for DSC. Therefore, this thesis presents supply chain transformation to DSC process validated through the AD theory. That is, this thesis differentiates itself from extant literature by proposing a state-of-art modeling approach to construct digital transformation framework for the DSC.

4.1. Modeling DSC through AD

Initially, digital transformation in DSC and available responding design structures are found with a detailed literature analysis, supported with feedback collected from industrial specialists. Figure 4.1 displays the AD based digital transformation framework for supply chains as an outcome of this thesis on DSC design.

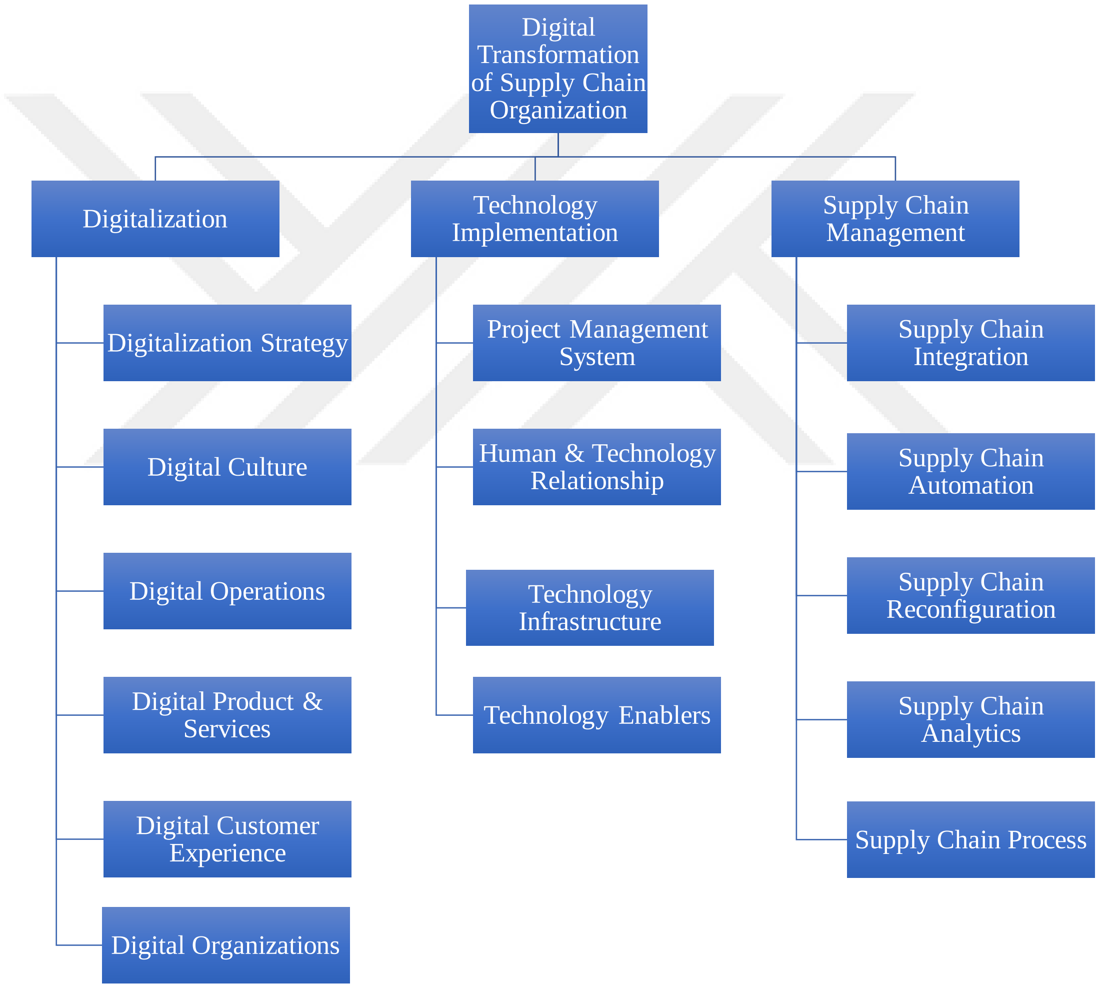


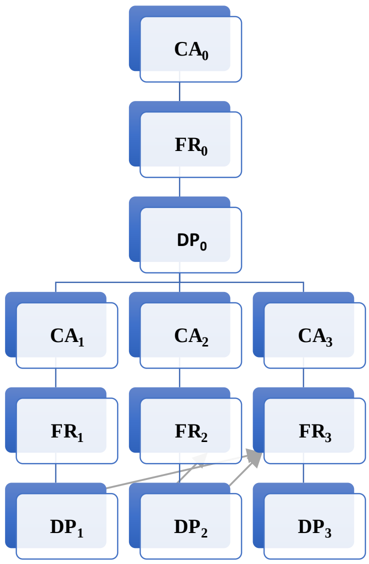
Figure 4.1: AD based Digital Transformation Framework for Supply Chains on Strategic Level

The proposed generic model investigating the digital transformation of supply chains consists of three stages, which is structured through AD technique. The model's stages refer to the three main domains of the DSC: customer, functional and physical domains, respectively from top to bottom. The DSC transformation goals are represented by the CAs variables. In other words, CAs are the customer needs which are delineated in the customer domain. CAs are transformed into FRs in the functional domain. FR variables are defined as the strategies required to be implemented to accomplish the DSC objectives. This FR, in essence, grasps the main aim in DSC effort, and answers to the "what". Any DSC endeavor is initiated to undertake to enhance the performance of a supply chain in the face of challenges for either the current or future. Accordingly, DPs are symbolized by the tools and methodologies used to apply FR strategies. To this end, ameliorating the performance metrics as the DP follows naturally, the "how". The proposed CA, FR and DP domain models with the mapping between goal, strategy, and methodology are described as shown in all Level decompositions.

Level 1 Decomposition

- **CA_0:** Digital Transformation for SC organization
  - **FR_0:** Define Digital Transformation Strategy
    - **DP_0:** DSC Framework

- **CA_1:** Effective Digitalization Process
  - **FR_1:** Define Effective Digitalization
    - **DP_1:** Digitalization Oriented Organization Initiative
- **CA_2:** Effective Technology Implementation Process
  - **FR_2:** Define Effective Implementation Strategy
    - **DP_2:** Analyzing Tools (PEST, SWOT, etc)
- **CA_3:** Effective SCM Process
  - **FR_3:** Define Effective SCM Strategy
    - **DP_3:** SC lifecycle Management



$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

The generic framework proposed in Appendix A.1 (Büyüközkan & Göçer, 2018a) for DSC presents a conceptual structure, offering a foundation for the digital transformation model at the strategic level. The total structured view is placed to Appendix A to give insight into whole design. At the initial level, customer need, the first CA represented as CA_0 is the Digital Transformation for supply chains and the first FR denoted as FR0 is determined as Defining Digital Transformation Strategy to yield improved performance of supply chains and first DP_0 to satisfy FR_0 is determined as building a DSC Framework. The arrow characterizes the mapping between FR domain and DP domain, while straight connector symbolizes the zigzagging. The presented matrices throughout the decomposition processes indicate the relationship among the strategy (FR) and the methodology (DP) with X indicating strong influence whereas 0 indicates weak influence. Then, other levels are presented to decompose the design further according to the structure explained as follows. This section introduces an AD methodology that any enterprises could use it to develop its digital vision and build newest organization model based on utilization of digital opportunities.

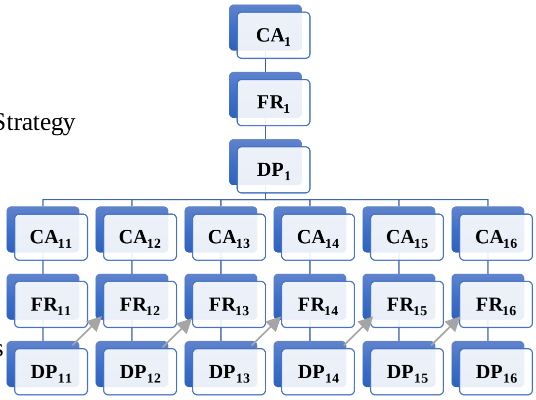
4.2. Digital Transformation of Supply Chains

The first level (Level 1) of DSC design defines the initial goal of digitalization, technology implementation strategy, and SCM framework (Büyüközkan & Göçer, 2018a). Level 1 could be expressed as the description of the problem. Consequently, the primary goal is the digitalization for supply chains, because the main objective of the proposed methodology is to come up with a useful guide for management of DSC enterprises. Subsequently, the decomposition of the three domains and their hierarchical structure is elaborated. The mappings through domains in the initial level are direct. As disclosed in the hierarchy of Level 1, it is decomposition displays a decoupled design. This is due to the fact that initiation of technology implementation activities primarily entails an effective digitalization process. That means the execution of the first DP has a direct effect on the application of the succeeding strategy. Likewise, a powerful SCM process is strictly linked to the implementation of all essential technologies and establishing the digital environment, illustrated here by the second DP.

4.2.1. Digitalization Process

Effective Digitalization process (CA_1) goal has been decomposed into six distinctive sub-goals, which indicate the different phases of the digitalization stage. In the digitalization decomposition phase, the development of the digitalization process is evaluated. Each defined strategy depends on the effective application of the corresponding methods. Once again, a decoupled design is detected in the digitalization phase of the decomposition, which is largely evoked by the steps that are taken one at a time in the digitalization methods. This brings a decoupled design matrix in which every DP affects its subsequent. Digital transformation processes often begin with a Digitalization Strategy (CA_{11}). Organizations must be concise about their digitalization strategy and concentrate on the digitalization abilities that they are going to build along the value chain. It is not only significant for organizations to survive the digitalization trend but also imperative to use digitalization enablers to their advantage (Strategy&, 2016). Digital culture (CA_{12}) of an organization is the second focus area for effective digitalization process. This process then spreads to two additional areas: Digital Operations (CA_{13}), and Digital Products & Services (CA_{14}). It resumes with the customers: How to get to know them better, improve service level and digitalize the Customer Experience (CA_{15}) (Corver & Elkhuizen, 2014), and it concludes with Digital Organizations (CA_{16}) in which the design decomposition is finalized for the digitalization process.

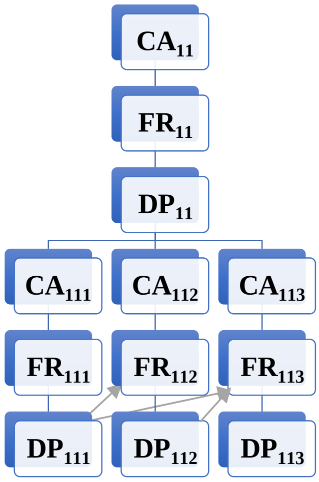
Level 2 Decomposition of Digitalization



- **CA_{11}:** Digitalization Strategy
  - **FR_{11}:** Set Effective Digitalization Strategy
    - **DP_{11}:** Digitalization Initiative for Corporate Strategy
- **CA_{12}:** Digital Culture
  - **FR_{12}:** Build Effective Digital Culture
    - **DP_{12}:** Culture Change for Digitalization
- **CA_{13}:** Digital Operations
  - **FR_{13}:** Manage Effective Digitalization Operations
    - **DP_{13}:** Digital Operations Management
- **CA_{14}:** Digital Product & Services
  - **FR_{14}:** Define Effective Digital Product & Services
    - **DP_{14}:** Digital Product & Service Management
- **CA_{15}:** Digital Customer Experience
  - **FR_{15}:** Evaluate Effective Digital Customer Experience
    - **DP_{15}:** Customer Relationship Management
- **CA_{16}:** Digital Organizations
  - **FR_{16}:** Define Effective Digital Organizations
    - **DP_{16}:** Organizations Management for Digitalization

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \\ FR_{15} \\ FR_{16} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 & 0 \\ 0 & 0 & X & X & 0 & 0 \\ 0 & 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \\ DP_{15} \\ DP_{16} \end{Bmatrix}$$

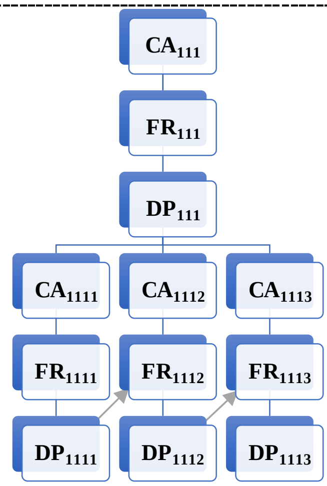
Level 3 Decomposition of Digitalization (Digitalization Strategy)



- **CA_{111}:** Digital Goal Setting
  - **FR_{111}:** Define the Strategic Goal for Digitalization
    - **DP_{111}:** Mission and Vision Statements
- **CA_{112}:** Digital Strategy Formulation
  - **FR_{112}:** Set Effective Digital Strategies
    - **DP_{112}:** Strategic Management
- **CA_{113}:** Digital Strategy Implementation
  - **FR_{113}:** Implement Effective Digitalization Strategy
    - **$DP_{113:}$** Action Plan & Monitoring Progress

$$\begin{Bmatrix} FR_{111} \\ FR_{112} \\ FR_{113} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{111} \\ DP_{112} \\ DP_{113} \end{Bmatrix}$$

Level 4 Decomposition of Digitalization (Digital Goal Setting)



- **CA_{1111}:** Goal Purpose
  - **FR_{1111}:** Set the Goals in Line with the Purpose
    - **DP_{1111}:** S.M.A.R.T. Goals
- **CA_{1112}:** Action Plan
  - **FR_{1112}:** Set an Effective Action Plan
    - **DP_{1112}:** Monitoring Tools (Software and DSS)
- **CA_{1113}:** Goal Implementation
  - **FR_{1113}:** Ensure Goal Implementation
    - **$DP_{1113:}$** Goal Setting Tools

      (Balanced Scorecard, Strategy Mapping, etc.)

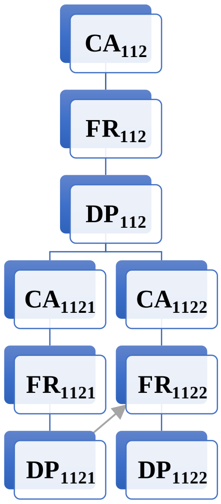
$$\begin{Bmatrix} FR_{1111} \\ FR_{1112} \\ FR_{1113} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{1111} \\ DP_{1112} \\ DP_{1113} \end{Bmatrix}$$

Level 4 Decomposition of Digitalization (Digital Strategy Formulation**)**

- **CA_{1121}:** Strategic Assessment for Digitalization
  - **FR_{1121}:** Define Effective Strategic Assessment
    - **DP_{1121}:** Strategic Planning Tools

      (SWOT, PEST, Benchmarking, Value Chain Analysis, etc.)
- **CA_{1122}:** Digital Strategy Choice
  - **FR_{1122}:** Set an Effective Strategy Choice
    - **DP_{1122}:** Strategy Formulation Tools

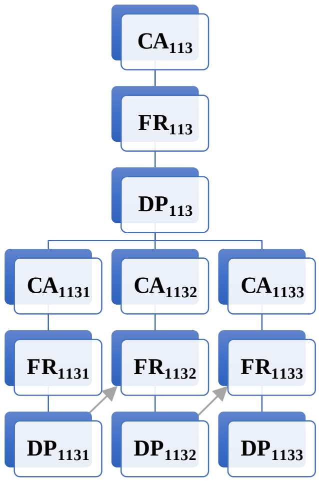
      (Simulation, Strategy Software, Analytic Tools, etc.)



$$\begin{Bmatrix} FR_{1121} \\ FR_{1122} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1121} \\ DP_{1122} \end{Bmatrix}$$

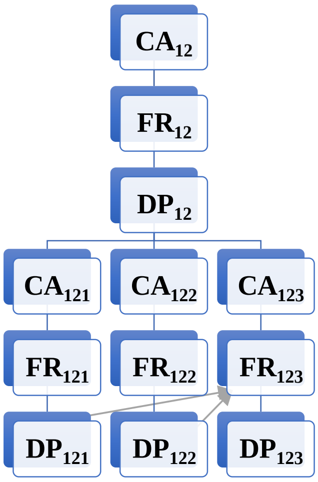
Level 4 Decomposition of Digitalization (Digital Strategy Implementation**)**

- **CA_{1131}:** Strategic Decision
  - **FR_{1131}:** Define an Effective Strategic Decision
    - **DP_{1131}:** Decision Making Tools
- **CA_{1132}:** Resource Allocation
  - **FR_{1132}:** Set Effective Resource Allocation
    - **DP_{1132}:** Resource Management Tools
- **CA_{1133}:** Control and Feedback
  - **FR_{1133}:** Define an Effective Control and Feedback Strategy
    - **DP_{1133}:** Digital Control and Feedback Tools



$$\begin{Bmatrix} FR_{1131} \\ FR_{1132} \\ FR_{1133} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{1131} \\ DP_{1132} \\ DP_{1133} \end{Bmatrix}$$

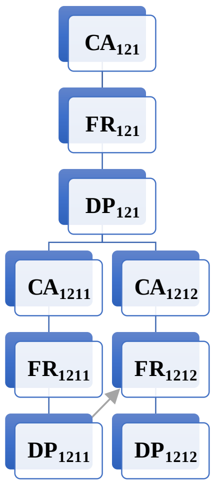
Level 3 Decomposition of Digitalization (Digital Culture)



- **CA_{121}:** Analyze the Current Culture
    - **FR_{121}:** Define Organization Culture Analyses
        - **DP_{121}:** Analyzing Tools (Digital Tools, Questionnaires, etc.)
- **CA_{122}:** Leadership
    - **FR_{122}:** Define Effective Leadership
        - **DP_{122}:** Senior Management Coaching and Mentoring
- **CA_{123}:** Transform Culture
    - **FR_{123}:** Develop Effective Digital Culture
        - **DP_{123}:** Motivation and Encouragement

$$\begin{Bmatrix} FR_{121} \\ FR_{122} \\ FR_{123} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{121} \\ DP_{122} \\ DP_{123} \end{Bmatrix}$$

Level 4 Decomposition of Digitalization (Analyze the Current Culture)

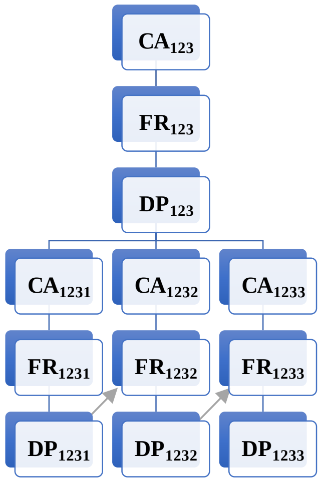


- **CA_{1211}:** Worker Attitude
    - **FR_{1211}:** Define Effective Worker Attitude Analysis
        - **DP_{1211}:** The Circumplex Model
- **CA_{1212}:** Adaptability
    - **FR_{1212}:** Define Effective Adaptability Analysis
        - **$DP_{1212:}$** Organizational Culture Assessment Methods

$$\begin{Bmatrix} FR_{1211} \\ FR_{1212} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1211} \\ DP_{1212} \end{Bmatrix}$$

Level 4 Decomposition of Digitalization (Transform Culture)

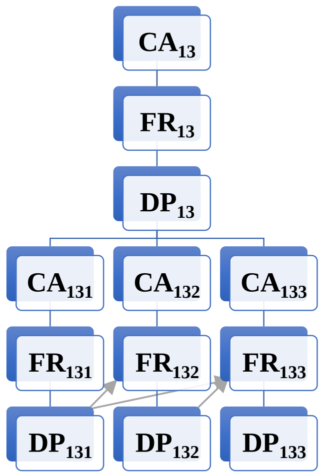
- **CA_{1231}:** Inspiration
  - **FR_{1231}:** Define Effective Inspiration Strategies
    - **DP_{1231}:** Motivational Activities to Change
- **CA_{1232}:** Information
  - **FR_{1232}:** Define Effective Information Strategies
    - **DP_{1232}:** Successful Encouragement
- **CA_{1233}:** Intimidation
  - **FR_{1233}:** Define Effective Intimidation Strategies
    - **DP_{1233}:** Incentives and Punishments



$$\begin{Bmatrix} FR_{1231} \\ FR_{1232} \\ FR_{1233} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_{1231} \\ DP_{1232} \\ DP_{1233} \end{Bmatrix}$$

Level 3 Decomposition of Digitalization (Digital Operations)

- **CA_{131}:** Operations Analysis
  - **FR_{131}:** Define Effective Analysis of Operations
    - **DP_{131}:** As-Is State
- **CA_{132}:** Operations Design
  - **FR_{132}:** Define Effective Design of Operations
    - **DP_{132}:** To-Be State
- **CA_{133}:** Operations Implementation
  - **FR_{133}:** Manage Effective Development of Operations
    - **DP_{133}:** Process Management

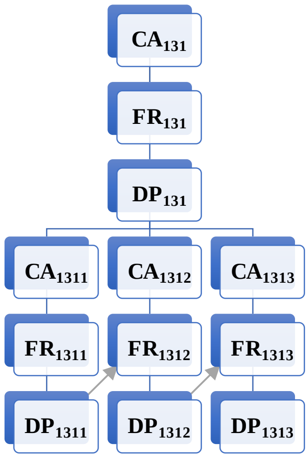


$$\begin{Bmatrix} FR_{131} \\ FR_{132} \\ FR_{133} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{131} \\ DP_{132} \\ DP_{133} \end{Bmatrix}$$

Level 4 Decomposition of Digitalization (Operations Analysis)

- **CA_{1311}:** Identify Analysis Procedure
  - **FR_{1311}:** Define Effective Analysis Procedure
    - **DP_{1311}:** Analysis Tools (Root Cause, Software, etc.)
- **CA_{1312}:** Create Analysis Strategy
  - **FR_{1312}:** Define Effective Analysis Strategy
    - **DP_{1312}:** DSS Tools (SWOT, What-if Analysis, etc.)
- **CA_{1313}:** Improve Current Operations
  - **FR_{1313}:** Define Effective Improvement Strategy
    - **DP_{1313}:** Process Analysis Tools

      (Process Mapping, cause/effect analysis, etc.)

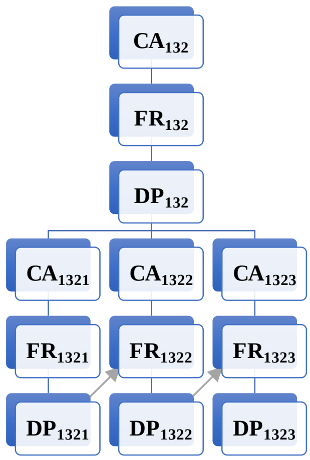


$$\begin{Bmatrix} FR_{1311} \\ FR_{1312} \\ FR_{1313} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{1311} \\ DP_{1312} \\ DP_{1313} \end{Bmatrix}$$

Level 4 Decomposition of Digitalization (Operations Design)

- **CA_{1321}:** Operational day-to-day Design
  - **FR_{1321}:** Define Effective Design of Operations
    - **DP_{1321}:** Digital Daily Operations Management Tools

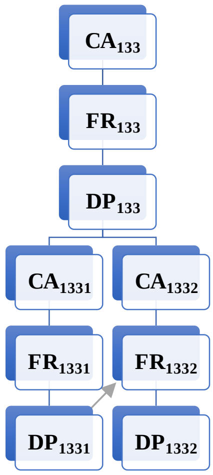
      (Microsoft Operations Manager, Software, etc.)
- **CA_{1322}:** Tactical Operations Management
  - **FR_{1322}:** Define Effective Tactical Operations Management
    - **DP_{1322}:** Digital Tactical Operations Management Tools
- **CA_{1323}:** Strategic Operations Management
  - **FR_{1323}:** Define Strategic Operations Management
    - **DP_{1323}:** Digital Strategic Operations Management Tools



$$\begin{Bmatrix} FR_{1321} \\ FR_{1322} \\ FR_{1323} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{1321} \\ DP_{1322} \\ DP_{1323} \end{Bmatrix}$$

Level 4 Decomposition of Digitalization (Operations Implementation**)**

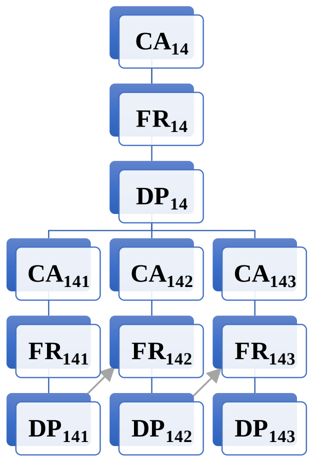
- **CA_{1331}:** Structure and System Implementation
  - **FR_{1331}:** Define Structure and System
    - **DP_{1331}:** Structure and System Implementation Tools (Pareto Analysis, Benchmarking, etc.)
- **CA_{1332}:** Monitor and Improve Implementation Operations
  - **FR_{1332}:** Define Monitoring and Improvement Systems
    - **DP_{1332}:** Monitoring and Improvement Tools **(**Balanced Scorecard, CC, DSC enablers, etc.)



$$\begin{Bmatrix} FR_{1331} \\ FR_{1332} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{1331} \\ DP_{1332} \end{Bmatrix}$$

Level 3 Decomposition of Digitalization (Digital Product & Services**)**

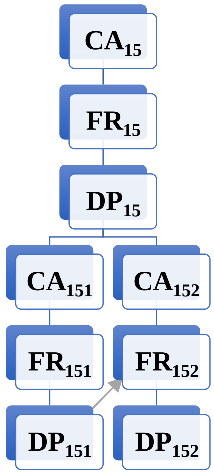
- **CA_{141}:** Customer Requirement Lifecycle
  - **FR_{141}:** Design for Entire Customer Lifecycle
    - **$DP_{141:}$** QFD or AD
- **$CA_{142:}$** Product & Service Ecosystem
  - **FR_{142}:** Develop Product & Service Ecosystem
    - **$DP_{142:}$** Product & Service Decision Support Systems
- **$CA_{143:}$** Customization & Personalization
  - **$FR_{143:}$** Effective Customization & Personalization
    - **$DP_{143:}$** Digital Aided Modularization Techniques



$$\begin{Bmatrix} FR_{141} \\ FR_{142} \\ FR_{143} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{141} \\ DP_{142} \\ DP_{143} \end{Bmatrix}$$

Level 3 Decomposition of Digitalization (Digital Costumer Experience)

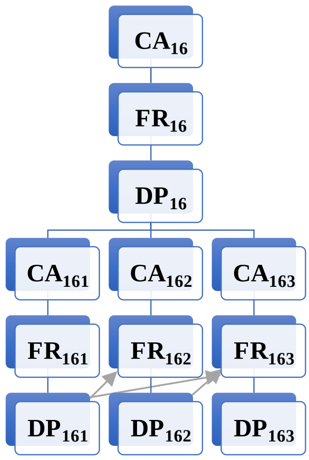
- **CA_{151}:** Customer Understanding
  - **FR_{151}:** Improve Customer Understanding
    - **$DP_{151:}$** Customer Touchpoints
- **$CA_{152:}$** Top Line Growth
  - **FR_{152}:** Enhance Top Line Growth
    - **$DP_{152:}$** Invest in Digital Initiatives and Skills



$$\begin{Bmatrix} FR_{151} \\ FR_{151} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{151} \\ DP_{152} \end{Bmatrix}$$

Level 3 Decomposition of Digitalization (Digital Organizations)

- **CA_{161}:** Analyze the Organizations Structure
  - **FR_{161}:** Define Organization Structure
    - **$DP_{161:}$** Analyzing Tools (Survey, OCP, ECO, etc.)
- **$CA_{162:}$** Decision Making and Structure
  - **FR_{162}:** Design Decision Making Processes and Structure
    - **$DP_{162:}$** Decision Support Systems
- **$CA_{163:}$** Work Processes and Systems
  - **$FR_{163:}$** Design Effective Work Processes and Systems
    - **$DP_{163:}$** Collaboration, Quality Improvement and Innovation, etc.



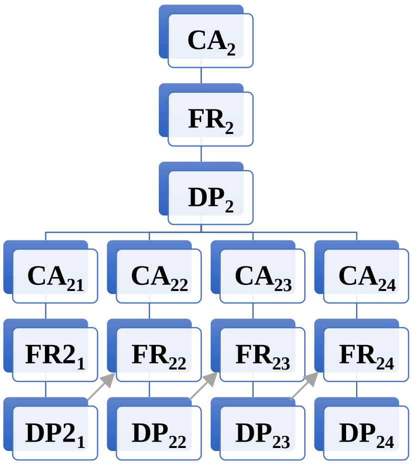
$$\begin{Bmatrix} FR_{161} \\ FR_{162} \\ FR_{163} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_{161} \\ DP_{162} \\ DP_{163} \end{Bmatrix}$$

4.2.2. Technology Implementation Process

An effective Technology Implementation (CA_2) goal differs from the effective Digitalization goal in the sense that it deals with the successful implementation achieved by the DSC efforts. Four sub-goals are defined for an effective Technology Implementation. These goals are assessed in order to leverage the technology enablers in the DSC and be fully aware of latest DSC solutions. This stage branches to Management Process (CA_{21}), Human and Technology Relationship (CA_{22}), Technology Infrastructure Formation (CA_{23}), and Utilization of Technology Enablers (CA_{24}). These goals are the building blocks of effective technology implementation process.

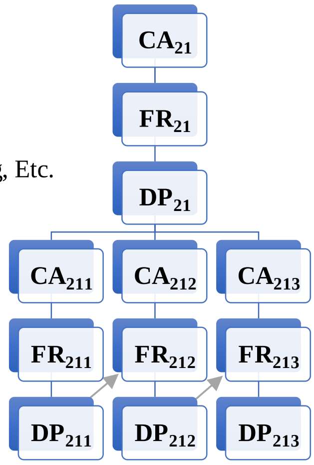
Level 2 Decomposition of Technology Implementation

- **CA_{21}:** Management Process
  - **FR_{21}**: Define Effective Project Management System
    - **DP_{21}**: Project Management System
- **CA_{22}:** Human & Technology Relationship
  - **FR_{22}**: Effective Human & Technology Relationship
    - **DP_{22}**: Human & Technology Management
- **CA_{23}**: Technology Infrastructure Formation
  - **FR_{23}:** Formation of Technology Infrastructure
    - **DP_{23}:** Technology Management
- **CA_{24}**: Utilization of Technology Enablers
  - **FR_{24}:** Apply Technology Enablers
    - **DP_{24}:** Technology Enablers



$$\begin{Bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & 0 \\ 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{Bmatrix}$$

Level 3 Decomposition of Technology Implementation (Management Process)

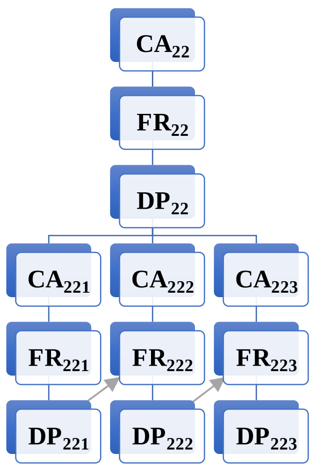


- **CA_{211}**: Initiate Process
  - **FR_{211}**: Initiate Technology Implementation Process
    - **DP_{211}**: Feasibility Study, Scheduling, Cost Control & Budgeting, Etc.
- **CA_{212}**: Implement Process
  - **FR_{212}**: Implement Technology Implementation Process
    - **DP_{212}:** Lean or Agile Project Management, etc.
- **CA_{213}**: Evaluate Process
  - **FR_{213}**: Evaluate Technology Implementation Process
    - **DP_{213}:** Project Management, Risk Management

$$\begin{Bmatrix} FR_{211} \\ FR_{212} \\ FR_{213} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{211} \\ DP_{212} \\ DP_{213} \end{Bmatrix}$$

Level 3 Decomposition of Technology Implementation

(Human & Technology Relationship)

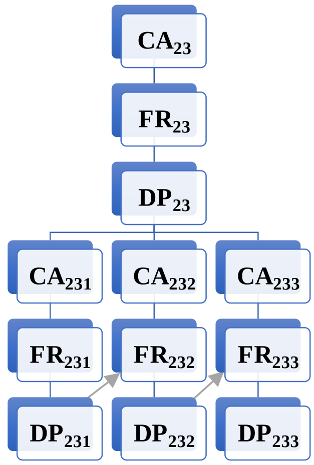


- **CA_{221}**: User Training
  - **FR_{221}**: Set Effective User Training
    - **DP_{221}:** Trainers and Training Guides
- **CA_{222}**: Human & Technology Interaction
  - **FR_{222}**: Utilize Frictionless workflow and Liquid Decisions
    - **DP_{222}**: Decision Support Systems, Digital Technologies, etc.
- **CA_{223}**: Human & Technology Collaboration
  - **FR_{223}**: Engender Human & Technology Collaboration
    - **DP_{223}**: Software

$$\begin{Bmatrix} FR_{221} \\ FR_{222} \\ FR_{223} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{221} \\ DP_{222} \\ DP_{223} \end{Bmatrix}$$

Level 3 Decomposition of Technology Implementation

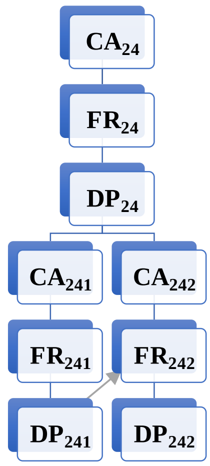
(Technology Infrastructure Formation)



- **CA_{231}**: Organization Infrastructure
  - **FR_{231}:** Formation of Organization Infrastructure
    - **DP_{231}:** CM Technique
- **CA_{233}**: Process Infrastructure
  - **FR_{232}:** Formation of Process Infrastructure
    - **DP_{232}:** Implement DevOps
- **CA_{233}**: Performance Infrastructure
  - **FR_{233}:** Formation of Performance Infrastructure
    - **DP_{233}**: QFD Technique

$$\begin{Bmatrix} FR_{231} \\ FR_{232} \\ FR_{233} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{231} \\ DP_{232} \\ DP_{233} \end{Bmatrix}$$

Level 3 Decomposition of Technology Implementation (Technology Enablers)



- **CA_{241}:** Process Enablers
  - **FR_{241}:** Define Process Enablers
    - **DP_{241}**: Technological Solutions (BD, CC, Robotics, etc.)
- **CA_{242}**: Product Enablers
  - **FR_{242}**: Define Product Enablers
    - **DP_{242}**: Technological Solutions (Sensors, IoT, etc.)

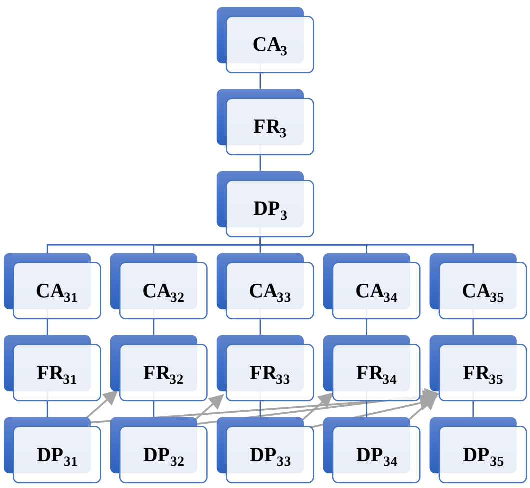
$$\begin{Bmatrix} FR_{241} \\ FR_{242} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{241} \\ DP_{242} \end{Bmatrix}$$

4.2.3. Supply Chain Management Process

The third consecutive goal of Digital Transformation of supply chain is the effective SCM process (CA_3). This goal is required to attain truly DSC using the AD methodology. CA_3 deals with the key objective of DSC transformation. These efforts will be supported by digitalization and technology implementation processes. Five sub-goals are determined and another decoupled design is obtained at this stage given that SCM design follows a sequence and each attribute depends on its predecessor. But, Supply Chain (SC) Process (FR_{35}) is also affected by DP_{31}, DP_{32}, DP_{33}, and DP_{34} since all of these DPs are dependent on defining the FR_{35}.

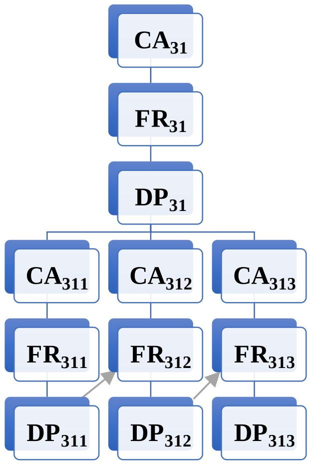
Level 2 Decomposition of SC Management

- **CA$_{31}$**: SC Integration
  - **FR$_{31}$:** Implement SC Integration
    - **DP$_{31}$**: Standardized Integration Approach
- **CA$_{32}$**: SC Automation
  - **FR$_{32}$:** Implement SC Automation
    - **DP$_{32}$:** Standardized Automation Approach
- **CA$_{33}$:** SC Reconfiguration
  - **FR$_{33}$:** Apply SC Reconfiguration
    - **DP$_{33}$:** Reconfiguration Infrastructure
- **CA$_{34}$:** SC Analytics
  - **FR$_{34}$**: Manage SC Analytics
    - **DP$_{34}$:** Analytic Management Methods
- **CA$_{35}$:** SC Process
  - **FR$_{35}$**: Define SC Process
    - **DP$_{35}$:** Process Management Infrastructure



$$\begin{Bmatrix} FR_{31} \\ FR_{32} \\ FR_{33} \\ FR_{34} \\ FR_{35} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ 0 & 0 & X & X & 0 \\ X & X & X & X & X \end{bmatrix} \begin{Bmatrix} DP_{31} \\ DP_{32} \\ DP_{33} \\ DP_{34} \\ DP_{35} \end{Bmatrix}$$

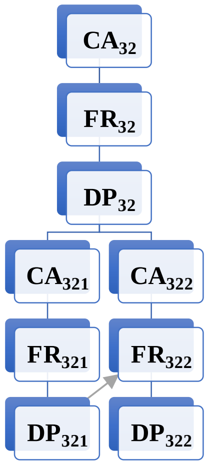
Level 3 Decomposition of SC Management (SC Integration)



- **CA_{311}:** Information Integration
  - **FR_{311}**: Define Effective Information Integration
    - **DP_{311}**: Digital Platforms
- **CA_{312}:** Coordination & Resource Sharing
  - **FR_{312}**: Define Effective Coordination and Resource Sharing
    - **DP_{312}**: Coordination and Resource Management
- **CA_{313}:** Organizational Relationship
  - **FR_{313}:** Define Organizational Relationship
    - **DP_{313}**: Organizational Relationship Linkage

$$\begin{Bmatrix} FR_{311} \\ FR_{312} \\ FR_{313} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{311} \\ DP_{312} \\ DP_{313} \end{Bmatrix}$$

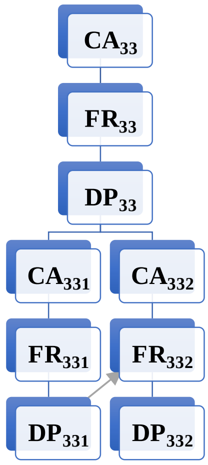
Level 3 Decomposition of SC Management (SC Automation)



- **CA_{321}:** Automation Requirements
  - **FR_{321}:** Define Automation Requirements
    - **DP_{321}:** Identify System Actors and Use Cases
- **CA_{322}:** Identification of Automation Technologies
  - **FR_{322}:** Define Effective Automation Technologies
    - **DP_{322}:** Use Automation Technologies

$$\begin{Bmatrix} FR_{321} \\ FR_{322} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{321} \\ DP_{322} \end{Bmatrix}$$

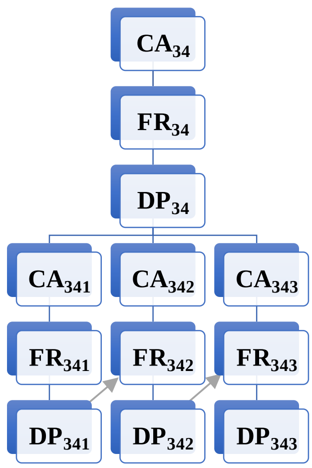
Level 3 Decomposition of SC Management (SC Reconfiguration)



- **CA_{331}:** SC Network Reconfiguration
  - **FR_{331}:** Form Effective Network Reconfiguration
    - **DP_{331}:** Value Management
- **CA_{332}:** Organizational Reconfiguration
  - **FR_{332}:** Form Effective Organizational Reconfiguration
    - **DP_{332}:** Structural Reconfiguration Tools (DSS, ISS, etc)

$$\begin{Bmatrix} FR_{331} \\ FR_{332} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_{331} \\ DP_{332} \end{Bmatrix}$$

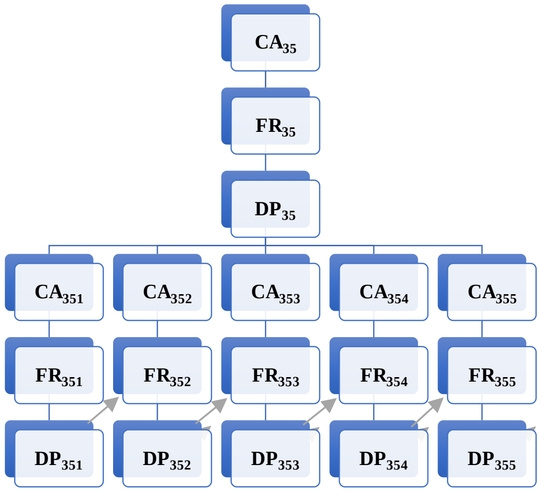
Level 3 Decomposition of SC Management (SC Analytics)



- **CA_{341}:** Data Collection
  - **FR_{341}:** Define Effective Data Collection Process
    - **DP_{341}:** Data Collection Methods (Survey, Interviews, etc.)
- **CA_{342}:** Data Analysis and Interpretation
  - **FR_{342}:** Implement Data Analysis and Interpretation
    - **DP_{342}:** Data Analytic Tools (BD, Statistics, Mathematical Modelling)
- **CA_{343}:** Decision Making
  - **FR_{343}:** Define Effective Decision Making
    - **DP_{343}:** Process Optimization & Cross Analytics (Optimization, Sensitivity, What-if Analysis, etc.)

$$\begin{Bmatrix} FR_{341} \\ FR_{342} \\ FR_{343} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{341} \\ DP_{342} \\ DP_{343} \end{Bmatrix}$$

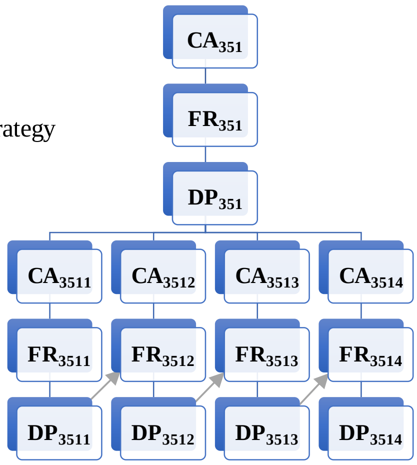
Level 3 Decomposition of SC Management (SC Process)



- **CA_{351}:** Plan
  - **FR_{351}:** Define Effective Planning
    - **DP_{351}:** Demand and Supply Planning
- **CA_{352}:** Source
  - **FR_{352}:** Improve Sourcing Performance
    - **DP_{352}:** Select Efficient Suppliers
- **CA_{353}:** Make
  - **FR_{353}:** Manage Manufacturing and Production
    - **DP_{353}:** Decide on Make Policy
- **CA_{354}:** Deliver
  - **FR_{354}:** Improve Delivery Performance
    - **DP_{354}:** Increase On-Time In Full, Decrease Backorders
- **CA_{355}:** Return
  - **FR_{355}:** Set Efficient Return Policy
    - **DP_{355}:** Effective Return Management Systems

$$\begin{Bmatrix} FR_{351} \\ FR_{352} \\ FR_{353} \\ FR_{354} \\ FR_{355} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{351} \\ DP_{352} \\ DP_{353} \\ DP_{354} \\ DP_{355} \end{Bmatrix}$$

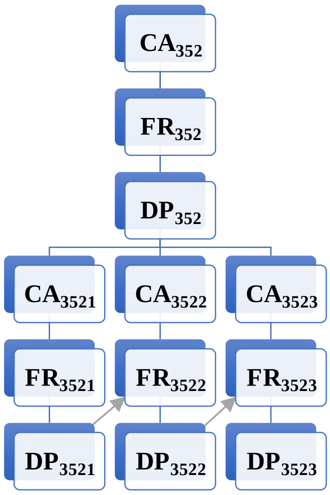
Level 4 Decomposition of SC Management (Plan)



- **CA_{3511}:** Aggregate and Prioritize Demand Requirements
  - **FR_{3511}:** Define Effective Aggregation and Prioritization Strategy
    - **DP_{3511}:** Demand Forecasting and Synchronizing
- **CA_{3512}:** Assess Supply Resources
  - **FR_{3512}:** Define Effective Assessment Strategy
    - **DP_{3512}:** non-biased outside party
- **CA_{3513}:** Inventory Planning
  - **FR_{3513}:** Define Effective Inventory Planning
    - **DP_{3513}:** Digital Inventory Planning Tools
- **CA_{3514}:** Plan Production Schedules
  - **FR_{3514}:** Define Effective Master Production Schedules
    - **DP_{3514}:** Rough-Cut Capacity Planning

$$\begin{Bmatrix} FR_{3511} \\ FR_{3512} \\ FR_{3513} \\ FR_{3514} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & 0 \\ 0 & 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{3511} \\ DP_{3512} \\ DP_{3513} \\ DP_{3514} \end{Bmatrix}$$

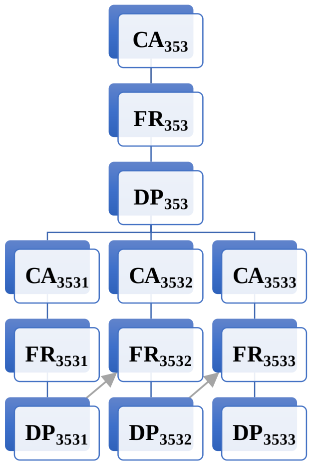
Level 4 Decomposition of SC Management (Source)



- **CA_{3521}:** Sourcing Plan
  - **FR_{3521}**: Create a Strategic Sourcing Plan
    - **DP_{3521}**: Strategic Sourcing Methodologies (Spend Analysis, Strategy Development, etc.)
- **CA_{3522}:** Source Quality
  - **FR_{3522}**: Define Effective Source Quality Monitoring
    - **DP_{3522}**: Source Quality Monitoring Tools
- **CA_{3523}:** Material Receiving
  - **FR_{3523}:** Define Effective Material Receiving Process
    - **DP_{3523}**: Material Receiving Process Tools

$$\begin{Bmatrix} FR_{3521} \\ FR_{3522} \\ FR_{3523} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{3521} \\ DP_{3522} \\ DP_{3523} \end{Bmatrix}$$

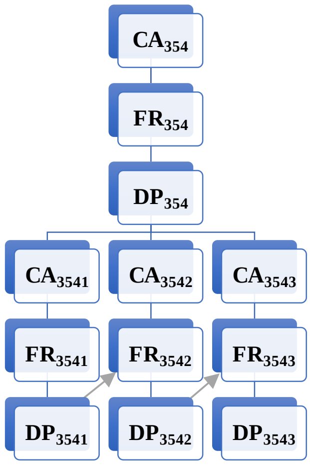
Level 4 Decomposition of SC Management (Make)



- **CA_{3531}:** Request and Receive Material
  - **FR_{3531}**: Define Effective Request and Receive Management
    - **DP_{3531}**: Request and Receive Management Tools
- **CA_{3532}:** Manufacture and Test Product
  - **FR_{3532}:** Define Effective Product Manufacturing and Testing Strategy
    - **DP_{3532}**: Manufacturing and Testing Tools
- **CA_{3533}:** Package, Hold, and/or Release Product
  - **FR_{3533}**: Define Effective Product Package, Hold, and/or Release Strategy
    - **DP_{3533}**: Product Package, Hold, and/or Release Tools

$$\begin{Bmatrix} FR_{3531} \\ FR_{3532} \\ FR_{3533} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{3531} \\ DP_{3532} \\ DP_{3533} \end{Bmatrix}$$

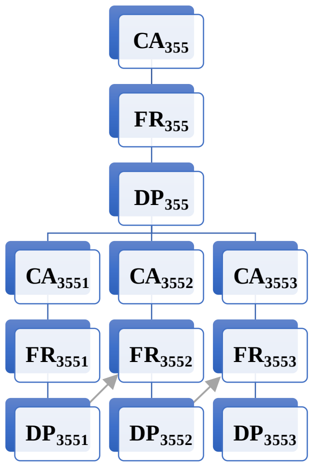
Level 4 Decomposition of SC Management (Deliver)



- **CA_{3541}:** Order Management Process
  - **FR_{3541}:** Effective Order Management Process
    - **DP_{3541}:** Order Management Software
- **CA_{3542}:** Customer Service Management Process
  - **FR_{3542}:** Effective Management of Customer Service
    - **DP_{3542}:** Digital Communication Tools
- **CA_{3543}:** Lifecycle Management Process
  - **FR_{3543}:** Effective Overall Management of Product Lifecycles
    - **DP_{3543}:** Digital Simulations

$$\begin{Bmatrix} FR_{3541} \\ FR_{3542} \\ FR_{3543} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{3541} \\ DP_{3542} \\ DP_{3543} \end{Bmatrix}$$

Level 4 Decomposition of SC Management (Return)



- **CA_{3551}:** Return Preparation
  - **FR_{3551}:** Effective Handling of Returns
    - **DP_{3551}:** Analyze Returns and Measure Performance
- **CA_{3552}:** Regulations
  - **FR_{3552}:** Set Effective Return Regulations
    - **DP_{3552}:** Decisive Regulations for DSC
- **CA_{3553}:** Customer Support and Follow-up
  - **FR_{3553}:** Efficient Post-Delivery Support Process
    - **DP_{3553}:** Use of Post-Delivery Support Process Tools

$$\begin{Bmatrix} FR_{3551} \\ FR_{3552} \\ FR_{3553} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{bmatrix} \begin{Bmatrix} DP_{3551} \\ DP_{3552} \\ DP_{3553} \end{Bmatrix}$$

4.3. Concluding Remarks on AD Modeling of DSC

The fundamental aim in this stage of the thesis is to fill the gap in the literature by offering a development framework for the digital transformation of supply chain enterprises. An AD decomposition consisting of CA, FR, and DP is introduced and the presented conceptual analysis is set in motion. The proposed decomposition method relates to a wide range of system designs in different supply chain environments. It is particularly useful for the supply chains that intend to transform digitally. It is clearly seen from the reviewed AD literature that there is no similar framework exist with an objective of digital transformation. Consequently, the resulting framework of this stage claims to be a quite beneficial for enterprises, wishing to adopt digital enablers but not having processes that are operable in an efficient DSC manner. Therefore, the defined framework should be adapted as a DSC transformation guideline. In addition, the proposed approach can be used to determine such an ideal procedure in application of the supply chain digital transformation to avoid inefficient decision processes and its unfulfillment of DSC objectives. Hence, the presented study and the proposed framework provide valuable insights to both practitioners and academicians in transformation of supply chains to truly DSC entity by applying the successful implementation AD-based design decomposition.

5. IMPLEMENTATION OF DSC STRUCTURE

Rapid advancement of digital evolution has become evident with its wide spread impact on almost all areas of life. As digitalization became a permanent part of everyday like activities, adopting to this change became a sine qua non of survival for both especially industries operating in highly competitive markets. For supply chains, digital evolution goes beyond using digital enablers. DSC necessitates the simultaneous and integrated evolution of digitalization, technology implementation and SCM. Although DSC is proven to be capable of providing various benefits for firms, its successful implementation is a challenging task. In order to sustain competency and to achieve continuous customer satisfaction, DSC must distinguish, manage, rank, and evaluate its DSC success and/or associated risk factors. These success and risk related factors and the components of DSC are interrelated directly or indirectly and present a complicated problem environment. Thus, the aim of this stage is to determine the factors that will aid in successful implementation of the DSC structure and to analyze these factors via the CM approach. Classic CMs and Fuzzy CMs have proven to be particularly useful in complex problem solving. An extension of IF sets, the PFSs, is considered to be even more capable of analyzing and modeling factors under ambiguity and vagueness. Hence, this research offers a systematic method for analyzing the success and/or risk factors of the DSC structure by utilizing the proposed PFSs CM (PFCM) approach for the first time in the literature. This stage proves that PFCM is particularly advantageous for decision-making where several numbers of controllable and uncontrollable decision factors are causally interrelated.

5.1. Success and Risk Factors of DSC Structure

The generic framework in AD stage proposed for DSC presents a theoretical structure, offering a foundation for the digital transformation model at a strategic level. Thus, the main decomposition of the DSC structure is originated from the three pillar of AD stage. This stage clearly confirms that the vital required digital evaluation objectives for supply chains often map to the areas of Digitalization, Technology Implementation and SCM, which are vital steps for organizational alignment. Hence, the factors of DSC structure are categorized into three groups as detailed in the following sections.

5.1.1. Digitalization Process

Several benefits can quickly accumulate for the enterprises that use the newest digital enablers. Cloud Computing, Big Data, and Internet of Things, for instance, bring major advantages to any enterprises that utilize them properly. Currently, there are a variety of different digital enablers at the disposal to generate simultaneously capability and efficiency. It is clear that most supply chains cannot use these enablers to their full potential mostly due to the lack of knowledge regarding the capabilities of these digital solutions or due to the complexity of analysis and sheer volume of data that make decision making a challenge (Corver & Elkhuizen, 2014). As a consequence, non-digital organizations cannot benefit from these opportunities. The following paragraph presents the success and/or risk factors determined through an extensive literature review and expert opinions for the improvement in the digitalization process to utilize these factors fully when constructing a DSC structure.

- Mindset Change (C_1) refers to the state that needed to be installed to be able to transform existing and established models. This is not only related to technologies or development, but to whole organization to go through a “mindset of change” (Büyüközkan & Göçer, 2018a; Tjahjono et al., 2017).

- New Talents Enhancement (C_2) displays that it is impossible to get everybody convinced and there are often also new skill sets required to transform products, services and organizations (Büyüközkan & Göçer, 2018a).

- Digitalization Know-How (C_3) can provide organizations with the tools needed to capture new digitalization opportunities (Büyüközkan & Göçer, 2018a).

- Executive Support & Participation (C_4) dispenses that executives always play more critical roles in digitalization process because of the magnitude of change, the degree of disruption, and the power of inertia (Büyüközkan & Göçer, 2018a; Raab & Cryan, 2011; Schlaepfer & Koch, 2015; Turhan et al., 2011).

- Conducting Feasibility Study (C_5) displays that it is always tough to check existing business models and revenue streams as long as they seem to work "somehow". It is even more difficult, if the change requires a modification of an established value chain. That's why feasibility study is needed ahead (Jeng, 2015).

- Risk Management (C_6) is the validated positive outcome of digitalization decisions. Any prioritization of functionality and features has to be driven by its digital value risk management (Baykasoğlu & Gölcük, 2015; Jeng, 2015).

- Digitalization Process Alignment (C_7) refers to digital innovations, and environmental dynamism in response to the challenge in nowadays world as contemporary organizations undergo tremendous changes in their strategic and operational models (Büyüközkan & Göçer, 2018a; Cerasis, 2015a; Heutger et al., 2016; Schlaepfer & Koch, 2015).

- Digitalization Structure Alignment (C_8) refers to the fact that digital transformation often includes something radical and disruptive that mostly cannot be realized based on implemented and established technology (Büyüközkan & Göçer, 2018a).

- Customer Integration (C_9) provides that the idea to put users of a product or service in the center of concept and development is not new at all. Customer integration to digitalization process transforms the customer experience in a way that requires a different approach (Büyüközkan & Göçer, 2018a; Cerasis, 2015a; Heutger et al., 2016; Schlaepfer & Koch, 2015).

- Identifying Digitalization Requirement (C_{10}) is the connector between mindset of change, cybersecurity, risk optimization and digitalization structure alignment and the enabler of a successful digital transformation (Büyüközkan & Göçer, 2018a).

- Employee & Partner Participation (C_{11}) refers to the promotion of new functions and skills development in customer integration to increase employee and partner participation in the digitalization process (Büyüközkan & Göçer, 2018a).

- Digital Asset Management (C_{12}) adds data to the commitment for digital asset management. Any new product idea, feature or potentially improvement of a product or service can be tested with users (Büyüközkan & Göçer, 2018a). Digital Assets are quite complex. They need descriptive metadata; especially non-text, most items are meant to be shared (Jeng, 2015).

- Cybersecurity (C_{13}) is the protection of the systems from the theft and damage to their systems, as well as from disruption or misdirection of the services provided (Büyüközkan & Göçer, 2018a; Tjahjono et al., 2017).

5.1.2. Technology Implementation Process

Technology Implementation process is different in a way from the Digitalization process that the context of successful implementation in DSC structure requires this process to be completed successfully. Technologies that support DSC remain a popular theme among researchers (Büyüközkan & Göçer, 2018a). Nevertheless, current literature does not consider how to plan these technologies regarding the requirements of multiple DSC factors. The following paragraph presents the factors constructed as success and/or risk Factors for successful Technology Implementation process improvement in constructing a truly DSC structure.

- Operations Improvement (C_{14}) demonstrates different ways in which technology can add value and be integrated into operations within the organizations (Baykasoğlu & Gölcük, 2015; Büyüközkan & Göçer, 2018a).

- Reliability (C_{15}) refers to the feature of being trustworthy or confidence of the performance in which the desired properties perform consistently well (Büyüközkan & Göçer, 2018a; Heutger et al., 2016; Schlaepfer & Koch, 2015).

- Financial Management (C_{16}) refers to the effective and efficient management of funds in such a manner as to accomplish the objectives of the organizations (Büyüközkan & Göçer, 2018a).

- Technology Strategy Planning (C_{17}) is the analysis of current technology needs, and the alignment of the content to those needs coupled with best practice recommendations (Büyüközkan & Göçer, 2018a; Yaman & Polat, 2009).

- Regulatory Compliance (C_{18}) assists organizations in adapting to a changing regulatory environment to help organizations anticipate or adapt to regulatory change and achieve a cost-effective balance between compliance and risk in response to enforcement (Broek & Veenstra, 2018).

- Effective Teamwork (C_{19}) is a vital aspect for the organizations' success by utilizing many benefits of teamwork, most notably, an increase in motivation (Jeng, 2015). Technology

- Market Dynamics (C_{20}) is a comprehensive assessment of the dynamics of the market, providing an essential outline of the manner in which the understanding of markets is evolving (Jeng, 2015).

- Connectivity (C_{21}) is the tools to allow connection across the organization, and thus leveraging the intellectual property and gaining insight from one another (Finklesein & Wong, 2012).

- Monitoring and Evaluation (C_{22}) provides the basis for performance improvement. Monitoring involves reporting, analyzing, and collecting information on activities in a way that supports technology implementation. Evaluation is a periodic practice that pursues providing credible information to guide DMs (Finklesein & Wong, 2012).

- Technology Transferability (C_{23}) refers not only to the concern about the transfer of knowledge or data but also to the technology recipient's capability to learn and absorb technology (Jeng, 2015).

- Technology Interdependency (C_{24}) refers to the degree in which different parts of the organizations' ability to exchange knowledge and data in order to perform their required activities (Jeng, 2015).

- Technical Requirements and Needs (C_{25}) describes the needs and provides data for the system to meet restrictions, adhere to regulations, and interoperate or integrate effectively with other systems (Broek & Veenstra, 2018).

- Technological Skills and Competence (C_{26}) refers to the dexterity, proficiency or facility that is acquired through training or experience and learned capacity to carry out predetermined results. Also, it is the cluster of related abilities, commitments, knowledge, and skills that enable organizations to act effectively in situations (Broek & Veenstra, 2018).

- Interoperability (C_{27}) denotes to the property that allows for the unrestricted sharing of resources between different systems (Büyüközkan & Göçer, 2018a; Heutger et al., 2016).

5.1.3. Supply Chain Process

Improving a supply chain process to achieve a bona fide DSC structure encompasses taking a number of complicated decisions at a time. These decisions are expected to enhance supply chain performance in line with DSC objectives. This requires a deep understanding of how detailed DSC factors can influence the performance of supply chain processes (Schmidt et al., 2015). Supply chain process improvement deals with the key requirements of the DSC structure. These factors are supported by digitalization and technology implementation processes to establish a fully functioning DSC structure. The following paragraph presents the factors depict the success and/or risk factors for supply chain process improvement while forming a DSC structure.

- Enhance Collaboration (C_{28}) displays the ability to leverage knowledge across the organizations with online, seamless, integrated and intuitive collaboration tools that enhance the ability to work together (Büyüközkan & Göçer, 2018a; Heutger et al., 2016).

- Information Sharing (C_{29}) is the vital aspect of coordination amongst parties which can increase efficiency by reducing redundant information and smoothing operations (Büyüközkan & Göçer, 2018b).

- Agility (C_{30}) refers to the concepts based on the ability to change the position efficiently and requires the integration of isolated movement skills (Batty et al., 2017; Büyüközkan & Göçer, 2018b; Heutger et al., 2016; Schlaepfer & Koch, 2015; Zhong et al., 2016).

- Flexibility (C_{31}) provides the ability that could detect and respond to the issues and opportunities in the short term. It could also adapt and execute new strategies and programs to support changes in overall company strategies or market place changes (Büyüközkan & Göçer, 2018b; Heutger et al., 2016; Schlaepfer & Koch, 2015).

- Value Chain Integration (C_{32}) refers to the processes in which organizations cooperatively manage, implement and plan services, data and the flow of goods from point of origin to point of consumption in a manner that optimizes the efficiency of the chain and increases the customer perceived value (Büyüközkan & Göçer, 2018a; Tjahjono et al., 2017).

- Real-Time Visibility (C_{33}) refers to the dynamic, secure and interactive visibility across the entire organization that will improve the management (Büyüközkan & Göçer, 2018a; Heutger et al., 2016; Schlaepfer & Koch, 2015; Zhong et al., 2016).

- Effective Cost Management (C_{34}) refers to the process of implementing effective strategies and providing the resources and process discipline needed to enable and ensure the highest level of productivity, reliability and quality at the lowest possible costs (Büyüközkan & Göçer, 2018a).

- Transparency (C_{35}) enables companies to act transparently and be better prepared to disruptions by anticipating, modeling the network, creating what-if scenarios and adjusting the chain instantaneously to changing conditions (Büyüközkan & Göçer, 2018b; Tjahjono et al., 2017).

- Responsiveness (C_{36}) demonstrates better information and sophisticated analytics which can help accelerate responses to competitors' moves, technology shifts, and changing demand and supply signals (Büyüközkan & Göçer, 2018a; Heutger et al., 2016; Schlaepfer & Koch, 2015).

- Anticipatory Supply Chain (C_{37}) refers to rich, data-intensive networks that not only perform efficiently and recover quickly from disruptions, but may also be able to spot and avert risks (Büyüközkan & Göçer, 2018a).

- Customer Satisfaction (C_{38}) demonstrates the measures how products or services supplied by organizations meet or surpass a customer's expectation (Büyüközkan & Göçer, 2018a).

- Supplier Relationship Improvement (C_{39}) refers to technologies, strategies, and practices that organizations use to analyze and manage all interactions to maximize the value with the goal of supplier relationship improvement (Büyüközkan & Vardaloğlu, 2012).

- Customer Relationship Improvement (C_{40}) refers to technologies, strategies, and practices that organizations use to analyze and manage data and customer interactions throughout the customer lifecycle aiming customer relationship improvement (Büyüközkan & Vardaloğlu, 2012).

- Resilience Management (C_{41}) assumes that the ability to manage resilience refers to being better positioned organizations than rivals to deal with and even gain competitive advantages from disruptions (Büyüközkan & Göçer, 2018a).

- Asset and Skills Management (C_{42}) refers to the maintenance and development of consequential assets and skills and the selection of competitive arenas and strategies in a manner that the assets and skills form supply chain process improvement (Büyüközkan & Göçer, 2018a).

- Effective SCM (C_{43}) refers to the improvement of product flow through accurate demand and sales forecasting and also improve inventory management to arrest the bullwhip effect and avoid underproduction (Büyüközkan & Göçer, 2018a; Tjahjono et al., 2017).

5.2. The Concept of Pythagorean Fuzzy Cognitive Map (PFCM)

The proposed PFCM model improves the CM approach by applying PF arithmetic operations. The results prove that the proposed methodology outperforms the existing CM approaches for the given application requirements. The following Equation (5.2.2) is proposed by the authors presents PFCM calculation process. The steps of PFCM approach is as follows:

Step 1: The concepts are defined by the DMs.

Step 2: The interactions between concepts are specified and their strengths are determined by the DMs in linguistic terms

Table 5.1: PFCM Linguistic Scale

Terms	**[$\mu_{\tilde{A}}(x)$,**	**$v_{\tilde{A}}(x)$]**
Extremely Low (EL)	[0.05,	0.90]
Very Low (VL)	[0.10,	0.80]
Low (L)	[0.20,	0.70]
Medium (M)	[0.50,	0.40]
High (H)	[0.70,	0.20]
Very High (VH)	[0.80,	0.10]
Extremely High (EH)	[0.90,	0.05]

Step 3: The individual opinions are fused by the PFWA aggregation operator.

$$PFWA(P_1, P_2, \dots, P_K)_{C_j} = \langle \sqrt{1 - \prod_{k=1}^{K} \left(1 - \left(\mu_{P_k}(x)\right)^2\right)^{\lambda_k}}, \prod_{k=1}^{K} v_{P_k}(x)^{\lambda_k} \rangle \qquad (5.2.1)$$

Here, $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_K)^T$ is the associated weight vector of PFWA aggregation operator, such that $\lambda_k \in [0,1]$ *and* $\sum_{k=1}^{K} \lambda_k = 1$. k is the index for the DMs $k = (1,2, \dots, \mathrm{K})$.

Step 4: By the PFCM Equation, each concept is calculated to get the final result.

$$A_i^{(k+1)} = f\left(Deff\left(\begin{array}{c} \{[\boldsymbol{\mu}_{\tilde{\boldsymbol{A}}}(\mathrm{c}), \boldsymbol{v}_{\tilde{\boldsymbol{A}}}(\mathrm{c})]\}_i{}^k \oplus, \\ \left(\underset{j=1, j\neq i}{\overset{N}{\oplus}} \left(\{[\boldsymbol{\mu}_{\tilde{\boldsymbol{A}}}(\mathrm{c}), \boldsymbol{v}_{\tilde{\boldsymbol{A}}}(\mathrm{c})]\}_j{}^k \otimes \{[\boldsymbol{\mu}_{\tilde{\boldsymbol{A}}}(\mathrm{w}), \boldsymbol{v}_{\tilde{\boldsymbol{A}}}(\mathrm{w})]\}_{ji} \right) \right) \end{array} \right) \right) \tag{5.2.2}$$

$$f(x) = \left(\frac{1}{1+e^{-tx}}\right) \tag{5.2.3}$$

$$Deff = \frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2} \tag{5.2.4}$$

$$negation(\tilde{A}) = \{\langle x, [v_{\tilde{A}}(\mathrm{x}), \mu_{\tilde{A}}(\mathrm{x})]\rangle \mid x \in X\} \tag{5.2.5}$$

Here, for negative influence, negation operator is applied. $\{[\mu_{\tilde{A}}(\mathrm{w}), v_{\tilde{A}}(\mathrm{w})]\}$ represent the membership and non-membership influence weights and $\{[\boldsymbol{\mu}_{\tilde{\boldsymbol{A}}}(\mathrm{c}), \boldsymbol{v}_{\tilde{\boldsymbol{A}}}(\mathrm{c})]\}$ represents the membership and non-membership values of concepts. Here, f is the sigmoid function of Deff, which de-fuzzifies PF values, in other words, resulting value is de-fuzzified before it is functioned by the sigmoid function.

5.3. Modeling DSC Structure With PFCM

The proposed approach models the success and risk factors of the DSC structure in three consecutive steps. The data obtained through the DM interviews is codified to create linguistic judgements using the PFSs logic. Finally, propagation is conducted to obtain the process improvement in and between the success and/or risk factors and the DSC structure using PFCMs. Ultimately, this last step pools the knowledge of DMs who have complete picture on the DSC structure. The factors obtained from the extant literature is evaluated by DMs to determine the significant ones for the DSC structure and for its three sub-system.

Figure 5.1, Figure 5.2 and Figure 5.3 present graphically the interactions among the concepts of sub-systems for Digitalization, Technology Implementation and Supply Chain, respectively. Figure 5.4 presents the structure of these all sub-systems together. The whole structure representation of CM modeling is added to Appendix B. Three DMs have defined a total of thirteen concepts for the Digitalization process improvement sub-system, fourteen concepts for the Technology Implementation process improvement sub-system, and sixteen concepts for the Supply Chain process improvement sub-system. Arrows from one concept to another represent the relationship among concepts. The “+” sign shows that the effecting concept is interacting with the effected concept positively whereas the “-” sign indicates that the effecting concept is interacting with the effected concept negatively. According to the proposed methodology, the opinions of the three DMs are fused together to describe the influence of concepts. DMs’ judgments are gathered in linguistic terms described by the PF values. The linguistic judgment defined by DMs for each concept is given in Appendix B. The priority weights of DMs are determined as 0.40, 0.35, and 0.25 for DM_1, DM_2 and DM_3, respectively. After defining the concepts, interactions between them and their strength; individual judgments are aggregated by PFWA operator.

MATLAB software has been decided to be used to code the system. The code is set to run freely until a hundred iterations. It stops if the convergence is achieved prior to hundred runs or stops at hundred runs whether it converges or not. The tolerance of convergence is taken as ten to the power of minus six (10^{-6}). Considering negative effect of the hesitancy degrees on the interrelations, the linguistic scale must be chosen carefully. Thus, PFCM linguistic scale is constructed as given in Table 5.1. Utilizing the initial values of the concepts as the initial state, the PF values with respect to ‘Medium’ are used for all concepts. The strengths of influence are displayed in Appendix B. The directions, positive and negative relations are displayed in Figure 5.1 through Figure 5.4. Simulation figure is shown in Figure 5.5. The PFCM are simulated in order to reach a steady state. The sigmoid function is used as activation functions. The PFCM experiment converged in twenty-one iterations and the concept value for ‘Effective Implementation of DSC Structure’ is calculated as 0.2144 as the highest value. The rest of the resulting values for the output concepts are given in Table 5.2. Besides, the sub-systems are also simulated individually to see the critical factors affecting them. Both the whole structure evaluations and individual sub-system simulations reveal that ‘Mindset Change and Customer Integration’, ‘Effective Teamwork and Technology Market Dynamics’, and ‘Customer Satisfaction and Value Chain Integration’ concepts are the critical factors for Digitalization Process, Technology Implementation Process and Supply Chain Process Improvements sub-systems, respectively.

Table 5.2: PFCM Results

Concept	Value	Concept	Value	Concept	Value
Digitalization Process	0.1922	Technology Implementation Process	0.1953	Supply Chain Process	0.2014
Mindset Change	0.1793	Operations Improvement	0.1529	Enhance Collaboration	0.1649
New Talents Enhancement	0.1915	Reliability	0.1864	Information Sharing	0.1813
Digitalization Know-How	0.1748	Financial Management	0.1936	Agility	0.1681
Executive Support & Participation	0.1807	Technology Strategy Planning	0.1621	Flexibility	0.1783
Conducting Feasibility Study	0.1768	Regulatory Compliance	0.1905	Value Chain Integration	0.2061
Risk Management	0.1800	Effective Teamwork	0.2032	Real-Time Visibility	0.1799

Concept	**Value**	**Concept**	**Value**	**Concept**	**Value**
Digitalization Process Alignment	0.1687	Technology Market Dynamics	0.1471	Effective Cost Management	0.2047
Digitalization Structure Alignment	0.1501	Connectivity	0.1503	Transparency	0.1813
Customer Integration	0.1892	Monitoring and Evaluation	0.1718	Responsiveness	0.1777
Identifying Digitalization Requirement	0.1805	Technology Transferability	0.1694	Anticipatory Supply Chain	0.1600
Employee & Partner Participation	0.1952	Technology Interdependency	0.1640	Customer Satisfaction	0.2056
Digital Asset Management	0.1723	Technical Requirements and Needs	0.1747	Supplier Relationship Improvement	0.1930
Cybersecurity	0.1939	Technological Skills and Competence	0.1655	Customer Relationship Improvement	0.1699
		Interoperability	0.1798	Resilience Management	0.1915
				Asset and Skills Management	0.1452
				Effective SCM	0.1679

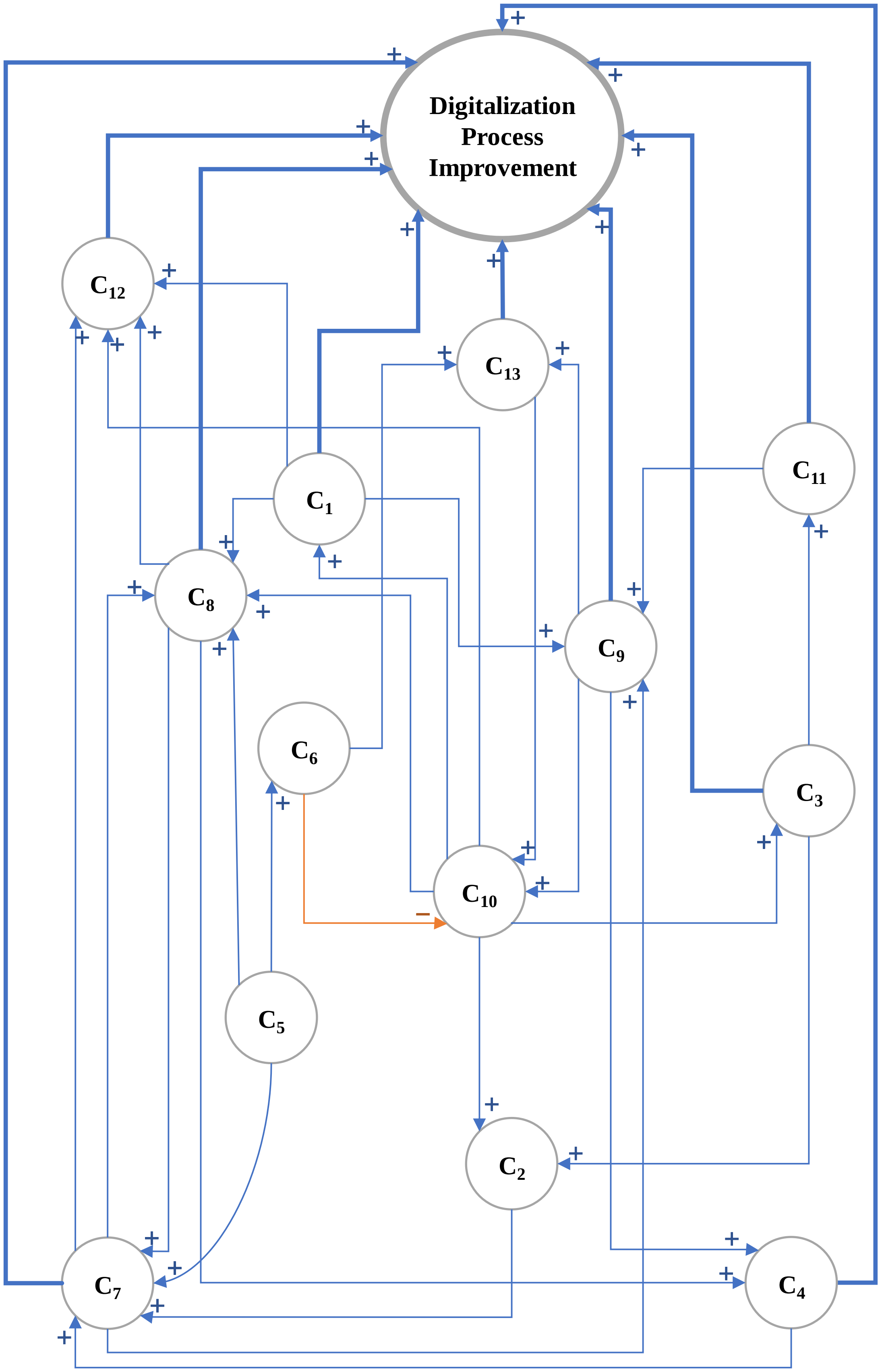


Figure 5.1: The CM of Digitalization Process

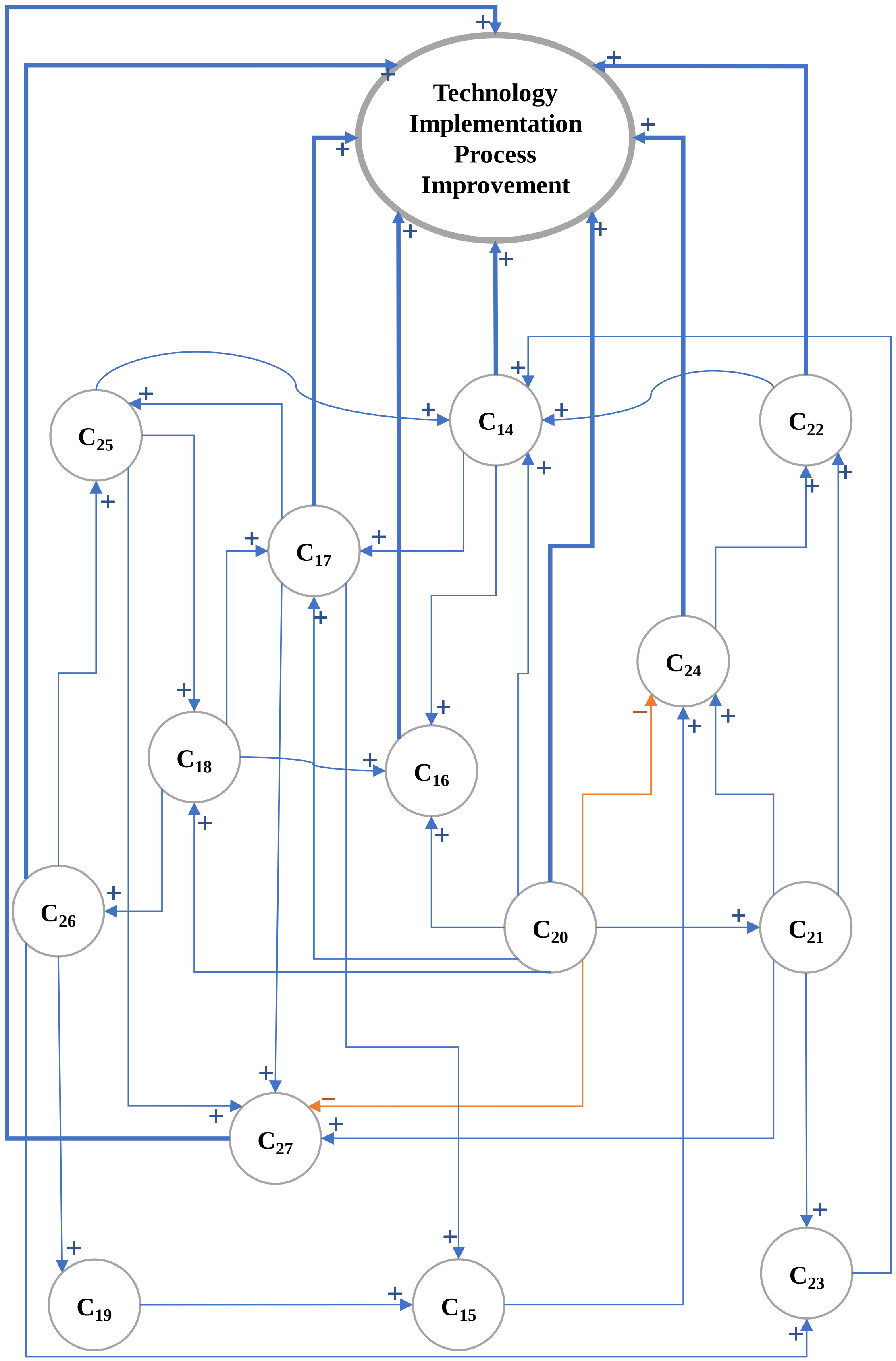


Figure 5.2: The CM of Technology Implementation Process

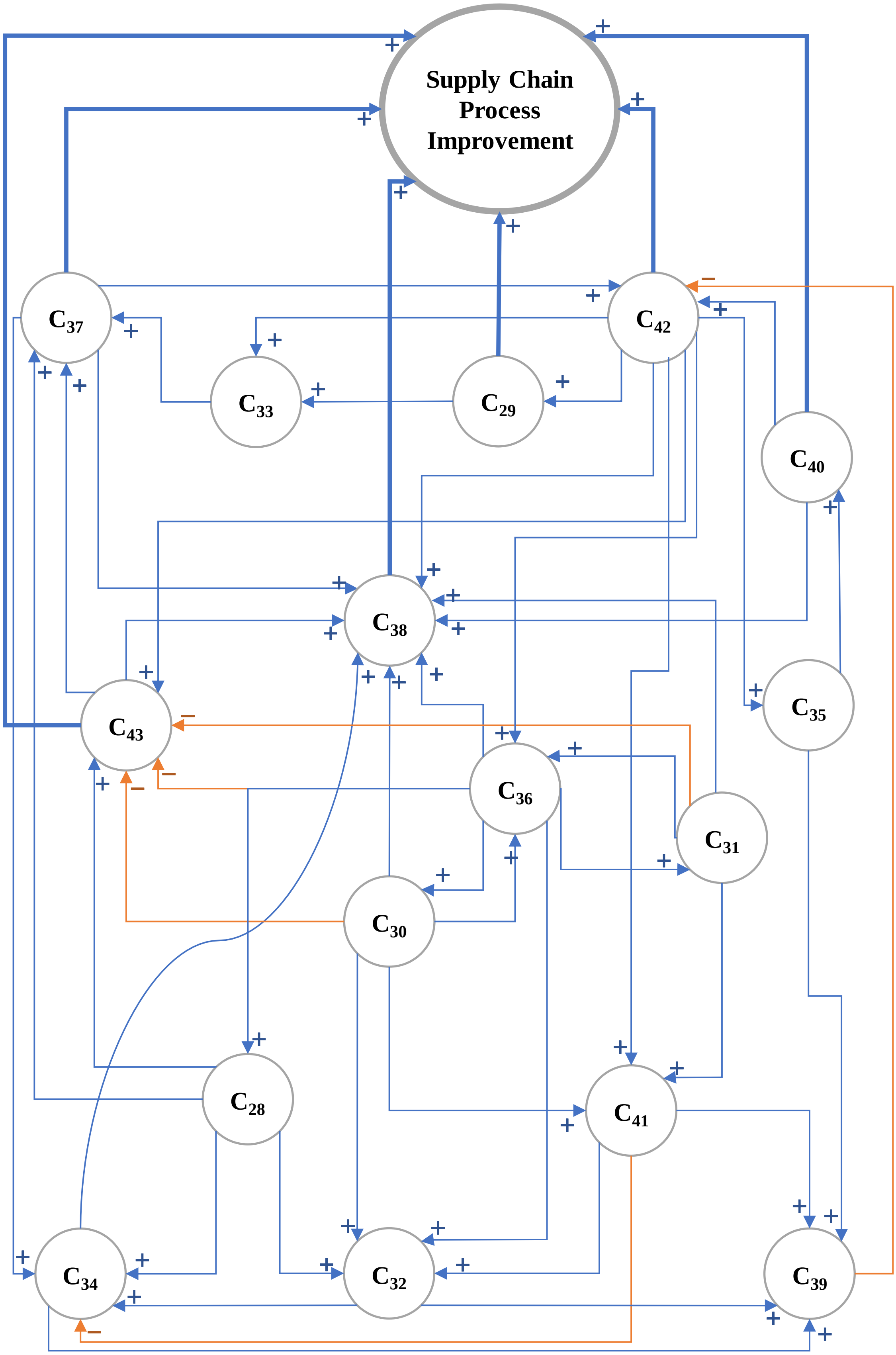


Figure 5.3: The CM of Supply Chain Process

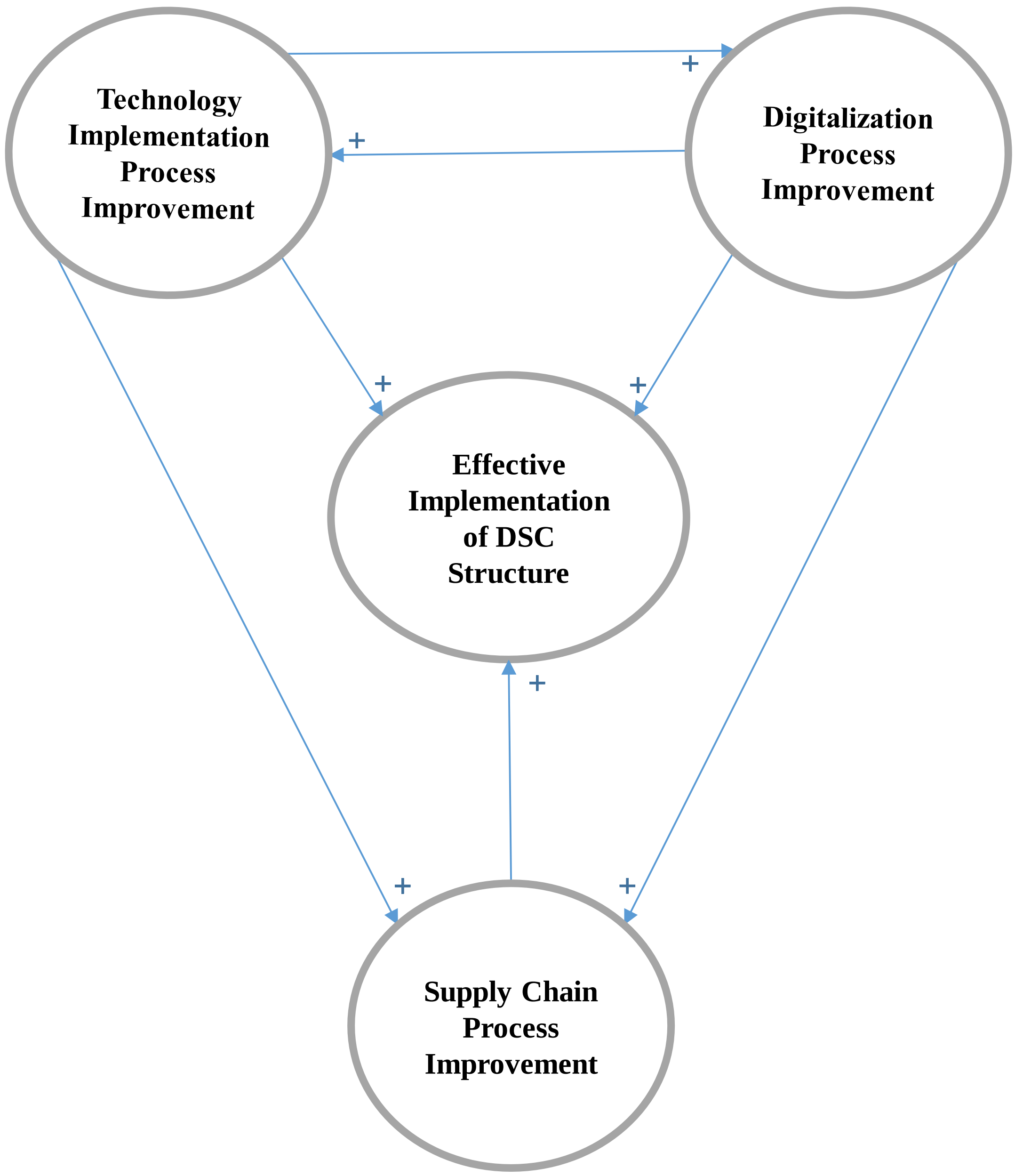


Figure 5.4: The CM of DSC Structure

Compared to the initial state values, the average hesitation of the PF values increases over time, corresponding to the emergence of uncertainty about the effective implementation of the DSC structure in the future. Although the resulting convergence is intensely related to the topology of PFCM, it is observed that the resulting outcome of concepts for DSC structure obtained by PFCM differs primarily in DSC structure analysis. This suggests that DSC factors are contemplated the most significant category of concepts in the PFCM model. Instead of traditional CM approaches, the PFCM model is based on a more general concept of PF sets, which provides a successful tool for dealing with robust ambiguity in the values of concepts and their causal relationships.

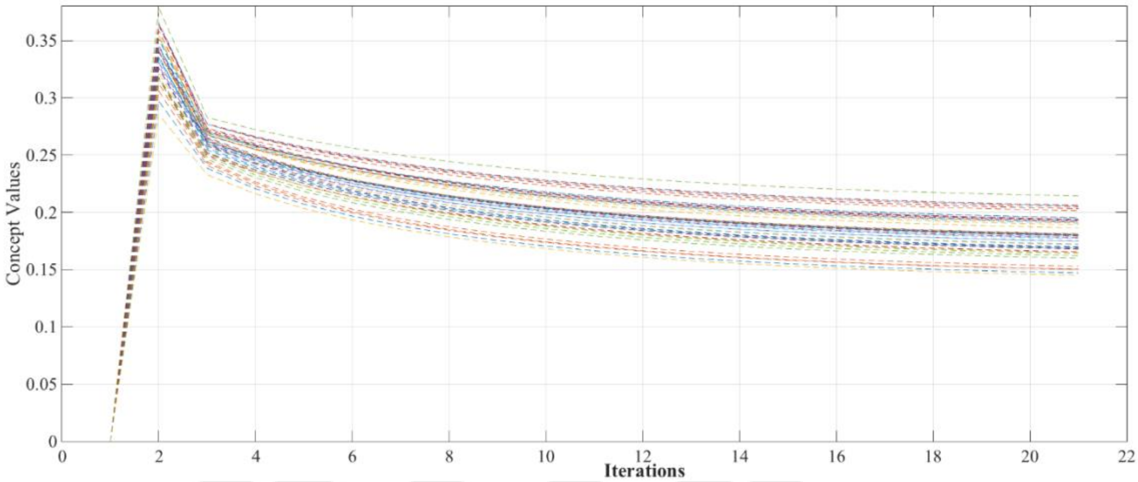


Figure 5.5: The Result of PFCM Simulation

5.4. What-If Scenario Analysis

After inserting the required data to MATLAB Software to simulate six what–if scenarios, the behavior of the proposed methodology could be analyzed under different circumstances. The success and/or risk factors constructed for the effective implementation of the DSC structure are investigated through the analysis of six scenarios. The selected six scenarios are provided to show the usefulness of the approach. First three scenarios deal with the behavior of the success and/or risk factors in which the nodes have the highest number of outgoing connections with the highest chance to influence the other factors. These three factors are ‘‘Identifying Digitalization Requirement’’, ‘‘Technology Market Dynamics’’, and ‘‘Asset and Skills Management’’. The following three scenarios are constructed to observe the effect of the influence of subfactors on the final outcome are selected as ‘‘Digitalization Process’’, ‘‘Technology Implementation Process’’, and ‘‘Supply Chain Process’’. In order to interpret the obtained results more effectively, the results for the scenario analysis are given in Table 5.3. The diagonal arrow represents the strength of the influence. When the concept under scenario analysis changes, the outcome is shown in the given row of the table as a symbol of the followings: upward diagonal arrow, downward diagonal arrow, or dash sign. Upward diagonal indicates that the factor in the given row of the table increases. Downward diagonal implies that the factor in the given row of the table decreases. Dash means the factor in the given row of the table shows no sign of change. The strength is explained by doubling the arrow. For instance, the double diagonal arrow is used to indicate that the relationship is strong. The slight escalation in the concepts “Identifying Digitalization Requirement”, ‘‘Asset and Skills Management’’, ‘‘Digitalization Process’’, and ‘‘Supply Chain Process’’ highly positively affects the most “Effective Implementation of the DSC structure”.

Table 5.3: Obtained Outcome for the What-if Scenario Analysis

Factors	**Scenarios**					
	1	**2**	**3**	**4**	**5**	**6**
Digitalization Process	↗↗	↗	↗↗	–	↗↗	↗
Mindset Change	↗↗	↘↘	↗	↗↗	↗↗	↗↗
New Talents Enhancement	↗↗	↗↗	↗↗	↗	↘↘	↗
Digitalization Know-How	↗↗	↘↘	↘↘	↗↗	–	↗↗
Executive Support & Participation	↗	↗	↗↗	↗	↗↗	↗↗
Conducting Feasibility Study	↗↗	↗↗	↗	↗↗	↗	↘
Risk Management	↗	↗↗	↗	↗↗	↗↗	↗↗
Digitalization Process Alignment	–	↗↗	↘↘	–	–	↗
Digitalization Structure Alignment	↗↗	↗↗	↗↗	↗	↗↗	–
Customer Integration	↗	↗↗	–	–	–	↗↗
Identifying Digitalization Requirement	–	↗	↘	↘	↗	↗↗
Employee & Partner Participation	↗↗	↘↘	↗	↗↗	↗↗	↗↗

Factors	Scenarios					
	1	**2**	**3**	**4**	**5**	**6**
Digital Asset Management	↗↗	↗↗	↗↗	↘	↗↗	↗↗
Cybersecurity	↗↗	↗↗	↗↗	↗↗	↗↗	↗↗
Technology Implementation Process	↗↗	–	↗↗	↗↗	–	↗↗
Operations Improvement	↗↗	↗↗	↗	↗↗	↗↗	↗↗
Reliability	↘↘	↗	↗↗	↗↗	↗	↗↗
Financial Management	↗↗	↘↘	↘	↗↗	↗↗	↗
Technology Strategy Planning	↗↗	↗↗	–	↗↗	↗	↗↗
Regulatory Compliance	↗	–	–	–	↗↗	↗↗
Effective Teamwork	↗↗	↗	↗↗	↗↗	↗↗	↗
Technology Market Dynamics	↗↗	–	↗↗	↗	↗↗	↗↗
Connectivity	↗↗	↗↗	↗↗	↗↗	↗↗	↗↗
Monitoring and Evaluation	↗	↗↗	↗↗	–	↗↗	↗↗
Technology Transferability	↗↗	↘↘	↗↗	↘	↗	↗↗
Technology Interdependency	↗↗	↗↗	↗	↗↗	↗	↗↗
Technical Requirements and Needs	↗	↗↗	↘↘	↘	↘↘	↗
Technological Skills and Competence	↗↗	–	–	–	–	↗↗
Interoperability	↗↗	↗	↗↗	↗↗	↗	↗↗
Supply Chain Process	↗↗	↗↗	↗↗	↗↗	↗↗	–
Enhance Collaboration	↗	↘↘	↗	–	↗↗	↗↗
Information Sharing	↗↗	–	–	–	–	↗↗
Agility	↗	↗	↘	–	↗↗	↗
Flexibility	↗↗	↘↘	↗	↗↗	↘	↘

Factors	**Scenarios**					
	1	**2**	**3**	**4**	**5**	**6**
Value Chain Integration	–	↗↗	↘↘	↗	↗↗	↗↗
Real-Time Visibility	↗	↗↗	↗	↗↗	↗↗	–
Effective Cost Management	↗↗	↗	↗↗	–	–	↗↗
Transparency	↗↗	–	–	↗	↘	↘
Responsiveness	↘	↘↘	–	–	–	↗
Anticipatory Supply Chain	↗↗	↗↗	–	↗↗	↗↗	↗↗
Customer Satisfaction	↗↗	–	–	↗↗	↗	↗↗
Supplier Relationship Improvement	↘↘	↗	–	–	–	–
Customer Relationship Improvement	↗	↗↗	↘	↗↗	–	↘↘
Resilience Management	↘↘	↘↘	↗↗	↗↗	↗↗	↗↗
Asset and Skills Management	↗	↘↘	–	↗↗	↗↗	↗↗
Effective SCM	↗↗	↗	↗↗	↗	↗↗	↗↗
Effective Implementation of DSC Structure	↗↗	↗	↗↗	↗↗	↗	↗↗

Exploiting PFCM linguistic scale, another set of what-if scenario analysis is performed by adding the input PFSs values representing the state of each node with the respective term. The value for each concept of the input case can be the respective value corresponding to the scale. Forty-Seven input configurations of Seven factors can be provided by the PFCM and results are evaluated. Specifically, let us consider the 'EL' input. Utilizing the initial values of the concepts as the initial state, the PF values [0.05, 0.90] with respect to 'Extremely Low' are used as input configurations. The rest of the PFSs linguistic scale terms are also simulated in a similar manner. The result of the simulation is graphically displayed in Figure 5.6 to reveal the behavior of converged concept values. This analysis discloses that as the non-membership degree for PFSs values decreases the resulting concept values tightens more. This analysis also concurs that ‘Mindset Change and Customer Integration’, ‘Effective Teamwork and Technology Market Dynamics’, and ‘Customer Satisfaction and Value Chain Integration’ concepts are the critical factors for Digitalization Process, Technology Implementation Process and Supply Chain Process Improvements sub-systems, respectively.

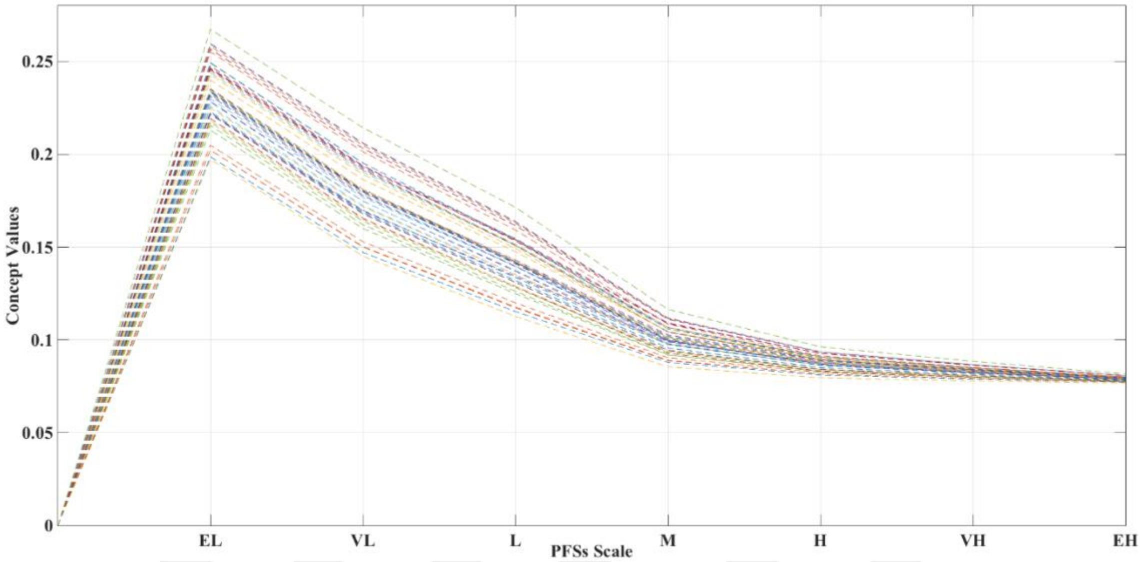


Figure 5.6: The Result of PFCM Simulation under Different PFSs Scales

5.5. Concluding Remarks on PFCM Implementation of DSC Structure

The proposed approach based on PFCM is a dynamic reasoning process which considers the built-in influence of success and/or risk factors on the DSC structure. In this stage, the PFCM approach is used to analyze the means of success and/or risk factors affecting digitalization, technology implementation and supply chain process comprehensively. With the introduction of PFSs into the proposed CM extension, the simulation results can more scientifically characterize the trends of success and/or risk factors on the DSC structure under different scenarios. Three supply chain professionals from various sectors are utilized as experts and served as the DMs of the problem at hand. So far, several extensions of CM have been developed for the more effective proposal of the CM approach. The PFCM approach introduces the membership and non-membership values of PFSs into the modeling approach, and in the application of DSC structure, the performance of the PFCM approach is successfully demonstrated. The analysis of the computational result clearly states that it performs significantly better than the other traditional CM approaches. The PFCM approach outlays superficially the basic operational functions of PFSs theory. The proposed novel extension is very effective for reasoning on the human cognitive process. The major contribution and the originality of the proposed study is deepening the knowledge of the cognitive image of the DSC, which provides insight regarding the digitalization challenges by introducing the PFCM technique for the first time. The proposed approach, therefore, bestows a feasible methodology to establish consequence propagation. The authors are committed to further developing the PFCM to meet DSC requirements. In the future, DSC success and/or risk factors can be elaborated and the research area can be widened to include other fuzzy environments into the comparison.

6. PLANING TECHNOLOGIC INFRASTRUCTURE FOR DSC

DSC is a new phenomenon that is able to deliver the latest tools and technologies to support global competitiveness in an aggressive and uncertain market environment. DSC can be a strong asset if its well-organized processes are coordinated and integrated appropriately of. Technologies supporting DSC are well studied in the literature. However, existing research falls short in including the requirements of DSC criteria for the planning of these technologies regarding.

Literature offers a large variety of tools for defining the system requirements for design. Among these, QFD stands out as the most appropriate tool to handle the complex nature of DSC to analytically prioritize technologic requirements in order to plan technologic infrastructure of DSC. Infrastructure development can be overwhelmingly vigorous and complex. Its intricacy can lead to uncertainty and vagueness, affecting the efficiency and effectiveness of design and planning procedures. The PFSs theory can be a useful tool to model ambiguous and imprecise information emerging in decision-making problems. This article contributes to the state of the art by proposing an evaluation model to develop technological infrastructure of DSC in a GDM setting. The objective of this study is to illustrate how QFD can improve DSC's strategic operational alignment by planning the technological infrastructure with the intention of digitalization.

6.1. The Proposed Pythagorean-QFD Methodology

The proposed novel approach incorporates linguistic terms expressed with PFSs values.

The steps of the QFD methodology under PFSs environment are as follow:

1. Gather a committee of DMs with $(DM_1, DM_2, \dots, DM_k, \dots, DM_K)$ K members who are composed of clienteles and analysts. Define the set of $i = 1, 2, \dots., m$ requirements CR = $(CR_1, CR_2, \dots, CR_m)$, which is established from the clients' perspectives, and the set of $j = 1, 2, \dots., n$ factors FR = $(FR_1, FR_2, \dots, FR_n)$, which is established form the analysts' perspective.

Suppose:

- $CR^k = \left(\widetilde{CR}_i{}^k\right)_{1xm} = \left(\mu_P(x)_i{}^k, v_P(x)_i{}^k\right)_{1xm}$is the linguistic decision making matrix of the weight of the CRs,
- whereas $FR^k = \left(\widetilde{FR}_j{}^k\right)_{1xn} = \left(\mu_P(x)_j{}^k, v_P(x)_j{}^k\right)_{1xn}$is the linguistic decision matrix of the FRs,
- $CF^k = \left(\widetilde{CF}_{ij}{}^k\right)_{mxn} = \left(\mu_P(x)_{ij}{}^k, v_P(x)_{ij}{}^k\right)_{mxn}$is the linguistic decision matrix of relationship between CR_i and FR_j.
- $FC^k = \left(\widetilde{FC}_{rs}{}^k\right)_{nxn} = \left(\mu_P(x)_{rs}{}^k, v_P(x)_{rs}{}^k\right)_{nxn}$ then represents the decision matrix of correlation between CR_r and FR_s.

2. Design the evaluation base (i.e. the linguistic scales) to assess the evaluative ratings as presented in Table 6.1.

3. Obtain the judgments of DMs and construct the QFD model. Experienced DMs with sufficient knowledge about the decision problem are asked to share their opinions on each factor as a linguistic term. Figure 6.1 illustrates the HOQ attributes for DM_k in this linguistic representation.

Table 6.1: PFSs Rating System as Linguistic Terms

Preference		$[\mu_P(x),$	$v_P(x)]$
Extremely High	**EH**	[0.95,	0.05]
Very Very High	**VVH**	[0.85,	0.15]
Very High	**VH**	[0.75,	0.25]
High	**H**	[0.65,	0.35]
Fair	**F**	[0.50,	0.50]
Low	**L**	[0.35,	0.65]
Very Low	**VL**	[0.25,	0.75]
Very Very Low	**VVL**	[0.15,	0.85]
Extremely Low	**EL**	[0.05,	0.95]

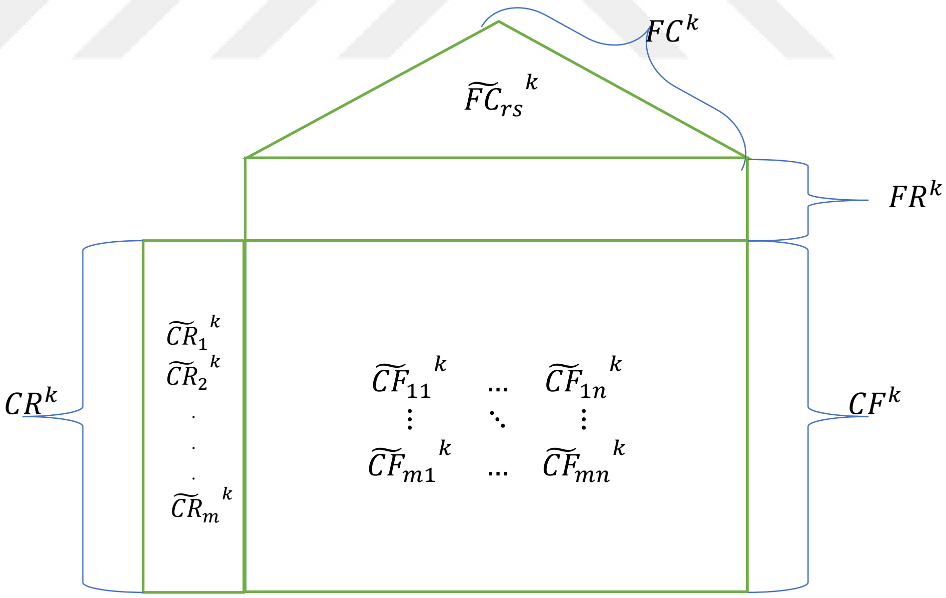


Figure 6.1: The HOQ Attributes for DM_k

4. Determine DMs' Weights

Let DM_k = $(\mu_{P_k}(x), v_{P_k}(x))$ be an PFS value to rate the k^th DM.

$$DM_k = \frac{\left[\mu_{P_k}(x)+\pi_{P_k}(x)\left[\frac{1-\pi_{P_k}(x)}{\mu_{P_k}(x)}\right]\right]}{\sum_{k=1}^{K}\left[\mu_{P_k}(x)+\pi_{P_k}(x)\left[\frac{1-\pi_{P_k}(x)}{\mu_{P_k}(x)}\right]\right]}, \text{ where } \sum_{k=1}^{K} DM_k = 1 \qquad (6.1.1)$$

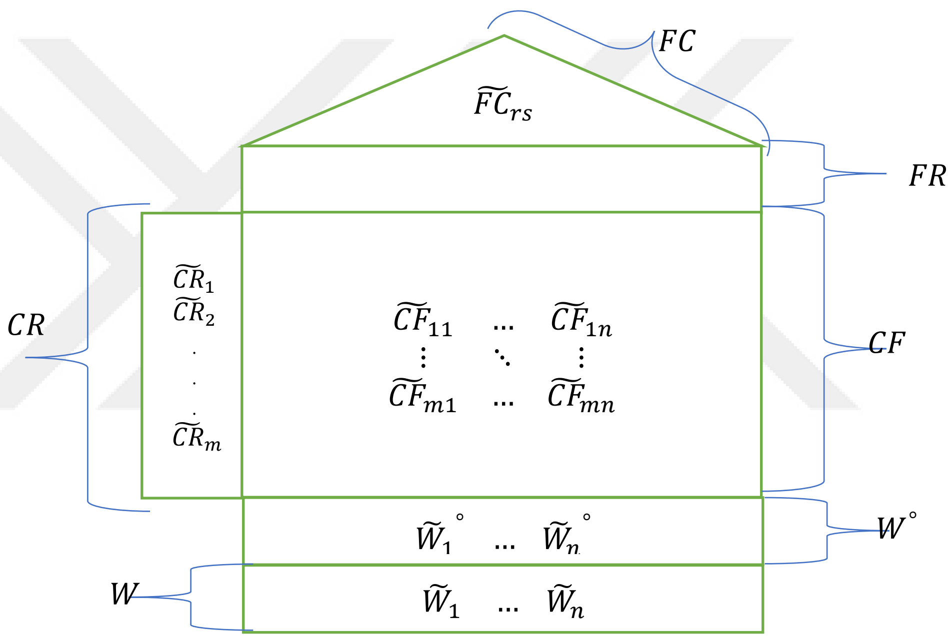


Figure 6.2: The Aggregated HOQ Attributes

5. Aggregate judgment matrix and construct aggregated QFD model. In GDM, all individual opinions need to be fused into group opinions. PFWA aggregation operator (Yager, 2014; Yager & Abbasov, 2013) is preferred here since it is widely used one in PFSs studies.

$$PFWA(P_1, P_2, \dots, P_Z) = \langle \sqrt{1-\prod_{z=1}^{Z}\left(1-\left(\mu_{P_z}(x)\right)^2\right)^{\lambda_z}}, \prod_{z=1}^{Z} v_{P_z}(x)^{\lambda_z} \rangle \qquad (6.1.2)$$

Here, $\lambda = (\lambda_1, \lambda_2, \dots, \lambda_Z)^T$ is the corresponding weight vector of the PFWA aggregation operator, where $\lambda_z \in [0,1]$ and $\sum_{z=1}^{Z} \lambda_z = 1$. Figure 6.2 illustrates the aggregated HOQ attributes in linguistic term representation.

5.1. Construct evaluative ratings matrix for CRs

Let $CR = (\widetilde{CR}_i)_{1xm}$ be the matrix of CR. Use PFWA aggregation operator in Equation (6.1.3), the aggregated results of the CR are derived as follows:

$$\widetilde{CR}_i = \widetilde{CR}_{i_1}{}^{\lambda_1} X\, \widetilde{CR}_{i_2}{}^{\lambda_2} X \dots X\, \widetilde{CR}_{i_Z}{}^{\lambda_z} = \langle \sqrt{1 - \prod_{z=1}^{Z} \left(1 - \left(\mu_{P_z}(x)\right)^2\right)^{\lambda_z}}, \prod_{z=1}^{Z} v_{P_z}(x)^{\lambda_z} \rangle \qquad (6.1.3)$$

5.2. Construct the collective relationship matrix between CRs and FRs

Let $CF = (\widetilde{CF}_{ij})_{mxn}$ be the relationship matrix between CR_i and FR_j. Similar to previous step, the aggregated results of the relationship between CR_i and FR_j are derived by:

$$\widetilde{CF}_{ij} = \widetilde{CF}_{ij_1}{}^{\lambda_1} X\, \widetilde{CF}_{ij_2}{}^{\lambda_2} X \dots X\, \widetilde{CF}_{ij_Z}{}^{\lambda_z} = \langle \sqrt{1 - \prod_{z=1}^{Z} \left(1 - \left(\mu_{P_z}(x)\right)^2\right)^{\lambda_z}}, \prod_{z=1}^{Z} v_{P_z}(x)^{\lambda_z} \rangle \qquad (6.1.4)$$

5.3. Construct the collective correlation matrix among FRs

Let $FC = (\widetilde{FC}_{rs})_{nxn}$ be the correlation matrix between CR_r and FR_s. The aggregated results are derived by:

$$\widetilde{FC}_{rs} = \widetilde{FC}_{rs_1}{}^{\lambda_1} X\, \widetilde{FC}_{rs_2}{}^{\lambda_2} X \dots X\, \widetilde{FC}_{rs_Z}{}^{\lambda_z} = \langle \sqrt{1 - \prod_{z=1}^{Z} \left(1 - \left(\mu_{P_z}(x)\right)^2\right)^{\lambda_z}}, \prod_{z=1}^{Z} v_{P_z}(x)^{\lambda_z} \rangle \qquad (6.1.5)$$

6. Construct the weights of FRs (W_j°). The importance of FRs determined by the relationship between CR and FR ($\widetilde{CF}_{ij}$) and the weight of CR ($\widetilde{CR}_i$), as follows:

$$W_j^{\circ} = \sum_{i=1}^{m}(\widetilde{CR}_i \ x \ \widetilde{CF}_{ij}) = \sum_{i=1}^{m}\left(\frac{\mu_{P_i}(x).\mu_{P_{ij}}(x),}{\sqrt{\left(v_{P_i}(x)\right)^2 + \left(v_{P_{ij}}(x)\right)^2 - \left(v_{P_i}(x)\right)^2.\left(v_{P_{ij}}(x)\right)^2}}\right) \quad (6.1.6)$$

7. Calculate the weights of FR by involving the correlation effects ($\widetilde{W}_j$). Once the importance values of FRs are determined, the effects of correlation from other FRs are considered. Accordingly, the importance of FR, the collective correlation among FR, as follows:

$$\widetilde{W}_j = \sum_{j=1}^{n}(W_j^{\circ} \ x \ \widetilde{FC}_{js}) = \sum_{j=1}^{n}\left(\frac{\mu_{P_j}(x).\mu_{P_{js}}(x),}{\sqrt{\left(v_{P_j}(x)\right)^2 + \left(v_{P_{js}}(x)\right)^2 - \left(v_{P_j}(x)\right)^2.\left(v_{P_{js}}(x)\right)^2}}\right) \quad (6.1.7)$$

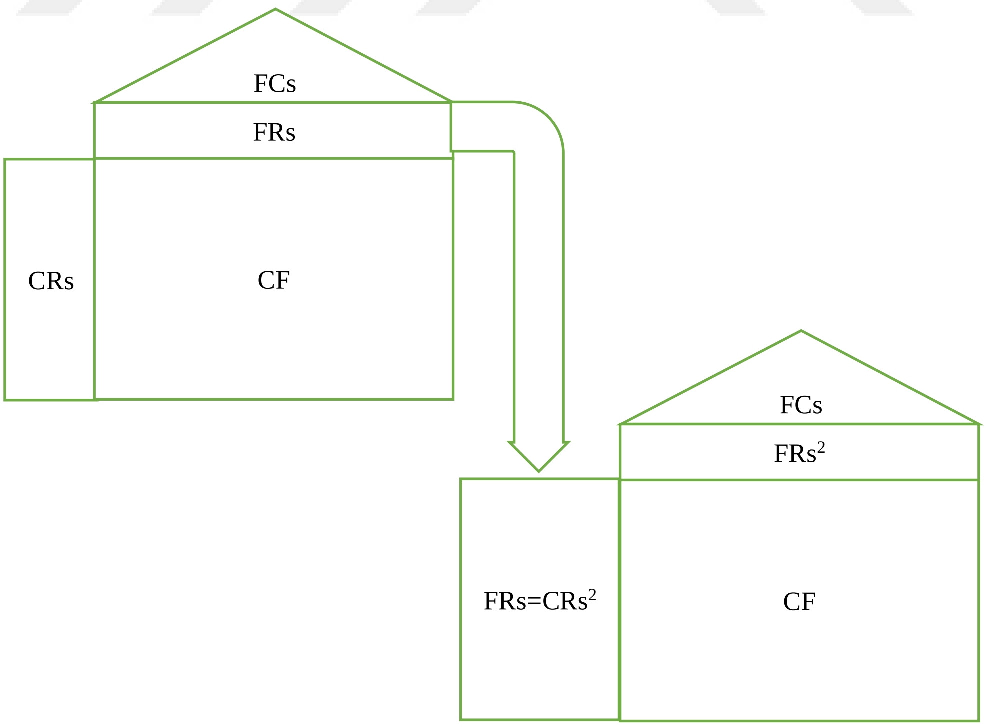


Figure 6.3: Representation of the Two-Stage QFD Process

- If QFD iteration continues

  $\widetilde{W}_j = \widetilde{CR}_i$,

  go to step 5.2
- else

The representation of the two-stage PF-QFD process is illustrated in Figure 6.3.

7.1. Defuzzification of PFSs (Kahraman, Oztaysi, et al., 2018) is applied as follows:

$$W_j{}^{Deff} = \text{Deff}(\widetilde{W}_j) = 1 - \frac{\sqrt{\mu_{P_j}(x)} - \left(v_{P_j}(x)\right)^2}{2} \quad (6.1.8)$$

- Normalize the defuzzified weights.

$$W_j = \frac{1 - W_j{}^{Deff}}{n - \sum_{j=1}^{n} W_j{}^{Deff}} \quad \text{where} \quad \sum_{j=1}^{n} W_j = 1 \quad (6.1.9)$$

6.2. QFD Modeling under PFSs on DSC

As part of digitalization, more and more supply chains will migrate their infrastructure to the DSC. Therefore, this section presents the case study conducted in the digital transformation of a supply chain to analytically prioritize technologic requirements in order to plan technologic infrastructure of DSC. The primary goal is the formation of digitalization infrastructure for supply chains, considering that the main objective is to come up with a useful guide for successful management of DSC. As digitalization progresses from a strategic decision to execution, it is quite common for supply chains to set the stake in the ground in terms of the main targets in DSC outcome. Therefore, every supply chain might have a slightly different set of digital transformation objectives with different concerns. In addition to rethinking and redesigning the entire supply chains structure, digital transformation for supply chains are related to digitalization, technology implementation, and SCM. These areas are vital for organizational alignment while the technological infrastructure for DSC still remains a must for successful implementation. Considering these, QFD is defined as establishing analytically prioritization for technologic requirements in order to plan technologic infrastructure of DSC.

Implementation of the QFD process involves putting together a "House of Quality". The first step in HOQ is the voice of customers. In order to prioritize spoken and unspoken CRs, four-real-experts from the industry have given their expertise on the construction of CRs as well as their linguistic judgments. In order to translate these CRs into technical requirements and specifications, the FRs' linguistic judgments depicted are provided by three-industry-analysts. Data are collected from interviewing with the DMs who have an extensive experience in Digitalization, SCM, and who are familiar to the implementation of digitalization in supply chain industry.

This section summarized the QFD process and the HOQ application as methods used for the design of new infrastructure. It should be noted that the QFD is an iterative process. The process begins from higher levels and goes down to technical characteristics as the requirements, where the second iteration begins. The method enables DMs to go a step further and support the rationale behind each set of design decisions. The results of the 1st and 2nd iterations are displayed below. Linguistic evaluations and acquired data are placed into Appendix C. The CR and significance of each customer need is presented in Table 6.2. The "Hows" are given in the subsequent Table 6.3.

6.2.1. The QFD Process – First Iteration

The steps described above detailed the PF-QFD method which can be applied for the evaluation of the key elements and requirements of DSC. Here, DMs define both the technological and infrastructure requirements of DSC according to their understanding of strategy and vision. This feedback is gathered from a focus group, as well as consultation activity reports. DMs transformation strategies for DSC include:

- -Reduction of Cost
- -Planning and Control
- -Global Supplier Market Integration
- -Upside/Downside Flexibility
- -Upside/Downside Efficiency
- -End-To-End Transparency
- -Perfect Order Fulfilment
- -Upside/Downside Adaptability

By utilizing these DSC transformation strategies, consensus is achieved among the DMs and 17 quality expectations, or CR (Whats), are determined. The new infrastructure needs to satisfy these requirements as given in Table 6.2. The requirements are grouped into different categories, including infrastructure for Organization and Process. This step reflects the strategy and vision of the DMs, as well as the needs of DSC. In the next stage, the DMs identified a set of 24 characteristics, or FR (Hows), based on which the technological infrastructure of DSC framework is planned with measurable and operational features. The DMs formulated and agreed upon the following FRs, as given in Table 6.3.

Table 6.2: Demanded Requirements and Their Characteristics for QFD

Organization		Process	
Row #	**Requirements or "Whats"**	**Row #**	**Requirements or "Whats"**
CR_1	Interoperability	**CR_{11}**	Effective Design and Development
CR_2	Collaboration	**CR_{12}**	Effective Marketing and Sales
CR_3	Reliability	**CR_{13}**	Effective Planning Process
CR_4	Innovation	**CR_{14}**	Effective Sourcing Process
CR_5	Flexibility	**CR_{15}**	Effective Make Process
CR_6	Efficiency	**CR_{16}**	Effective Delivery Process
CR_7	Visibility	**CR_{17}**	Effective Return Process
CR_8	Agility		
CR_9	Security		
CR_{10}	Privacy		

Table 6.3: Functional Requirements and Their Characteristics for QFD-First Iteration

Column #	Functional Requirements or "Hows"	Column #	Functional Requirements or "Hows"
FR_1	Digital Automation Tools	**FR_{13}**	Digital Customer-Centricity
FR_2	Digital Analytics Tools	**FR_{14}**	Digital Encryption Tools
FR_3	Digital Optimization Tools	**FR_{15}**	Digital Real-Time Integration Tools
FR_4	Digital Collaboration Tools	**FR_{16}**	Digital Disruptions Systems
FR_5	Digital Data-Driven Systems	**FR_{17}**	Digital Track-and-Trace Systems
FR_6	Digitally-Enhanced Decision Support Systems	**FR_{18}**	Digital Connectivity Platforms
FR_7	Digital Mobility Tools	**FR_{19}**	Digital Condition Monitoring Systems
FR_8	Digital Workplace	**FR_{20}**	Digital Reliability Systems
FR_9	Digital Culture Transformation	**FR_{21}**	Digitally-Enhanced Knowledge Sharing Systems
FR_{10}	Digital Reporting	**FR_{22}**	Digital Operations Tools
FR_{11}	Digital Risk Awareness Systems	**FR_{23}**	Digitally-Enhanced Human Resources
FR_{12}	Digital Communication Tools	**FR_{24}**	Digital Policies and Procedures

6.2.2. The QFD Process – Second Iteration

This section shows the results of the 2nd iteration of HOQ, for which the preceding characteristics are allocated to the requirements. The following iteration contains 32 requirements which are DSC enablers presented in literature review section 'Section 2'. This facilitates the DMs to come to a level in conceptualizing the design even further and thus ensuring strategy alignment, a common vision, and instituted targets. The DMs formulated and agreed upon the following FRs, as given in Table 6.4 for the second iteration.

Table 6.4: Functional Requirements and Their Characteristics for QFD-Second Iteration

Column #	Functional Requirements or "Hows"	Column #	Functional Requirements or "Hows"
FR_1^2	Big Data	FR_{17}^2	Social Media
FR_2^2	Advanced Analytics	FR_{18}^2	Digital Identifiers
FR_3^2	Robotics	FR_{19}^2	Cognitive Computing
FR_4^2	Sensor Technology	FR_{20}^2	Mobile Technologies
FR_5^2	Internet of Things	FR_{21}^2	Control Tower
FR_6^2	Blockchain Technology	FR_{22}^2	Mixed Reality
FR_7^2	Additive Manufacturing	FR_{23}^2	Maker Movement
FR_8^2	Wearable Technologies	FR_{24}^2	Neurotech
FR_9^2	Virtual Reality	FR_{25}^2	Super-grid Logistics
FR_{10}^2	Cloud Computing	FR_{26}^2	Sharing Economy
FR_{11}^2	Unmanned Aerial Vehicle	FR_{27}^2	Solar Energy
FR_{12}^2	Nanotechnology	FR_{28}^2	Tube Logistics
FR_{13}^2	Machine Learning	FR_{29}^2	Grey Power Logistics
FR_{14}^2	Augmented Reality	FR_{30}^2	Crowdsourcing
FR_{15}^2	Self-Driving Vehicles	FR_{31}^2	Crowdfunding
FR_{16}^2	Omni Channel	FR_{32}^2	Biotech

6.3. Obtained Results

Step 1: The DMs $(DM_1, DM_2, \dots, DM_7)$ include four clients denoted by DM_1, DM_2, DM_3, and DM_4, and three system analysts denoted by DM_5, DM_6 and DM_7. Eighteen CR_i $(i = 1, 2, \dots, 17)$ is established from the clients' perspectives. Twenty-four FR_j $(j = 1, 2, \dots, 24)$ is established form the analysts' perspective for the first iteration and Thirty-two ${FR_j}^2 (j = 1, 2, \dots, 32)$ is established for the second iteration.

Step 2: Nine-point PFSs linguistic scale is established. All DMs use the linguistic terms in Table 6.1 to express their preferences.

Step 3: The four clients provide their opinions regarding the weights of CRs. The three system analysts provide the linguistic ratings of the relationship between CRs and FRs and the linguistic ratings of the correlation between the FRs. The linguistic ratings are shown in Appendix C.

Step 4: The following calculations display the First DM's weighting process. Table 6.5 display the importance weights of the experts.

k = the first system analyst with a linguistic rating of 'EH' expertise on CRs of DSC' technology infrastructure.

$$DM_k = \frac{\left[0.95+0.31\left[\frac{1-0.31}{0.95}\right]\right]}{\left[0.95+0.31\left[\frac{1-0.31}{0.95}\right]\right]+\left[0.85+0.50\left[\frac{1-0.50}{0.85}\right]\right]+\left[0.85+0.50\left[\frac{1-0.50}{0.85}\right]\right]} = 0.3392\ ,$$

Table 6.5: Importance Weights of the Experts

	Clienteles				Analysts		
	DM_1	DM_2	DM_3	DM_4	DM_5	DM_6	DM_7
Linguistic Terms	EH	VVH	VH	H	EH	VVH	VVH
Weight	0.2686	0.2616	0.2439	0.2259	0.3392	0.3304	0.3304

Step 5: DMs' opinions are merged with the PFWA aggregation operator. After the PFSs transformation of the data, the collective weights of CRs, the collective relationships matrix between CRs and FRs, and the collective correlation matrix of FRs are shown in Appendix C. PFSs values are used for the remaining calculations, for practicality and visualization, collective weights of CRs are defuzzified and normalized defuzzified values are obtained, which are shown in Table 6.6. CR_4 and CR_{13} have the highest priorities in organization and process domains, respectively.

Table 6.6: Importance Weights of CRs

CRi	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
$\boldsymbol{W_{CR}}$	0.119	0.134	0.112	0.159	0.057	0.090	0.089	0.127	0.049	0.064
Rank	4	2	5	1	9	6	7	3	10	8
CRi	***11***	***12***	***13***	***14***	***15***	***16***	***17***			
$\boldsymbol{W_{CR}}$	0.157	0.192	0.218	0.077	0.132	0.115	0.110			
Rank	3	4	1	7	4	5	6			

Step 6. Utilizing the PFSs summation and multiplication operators, the importance of FRs (W_j°) are derived, which are shown in Appendix C.

Step 7. Considering the effects of correlation from other FRs, the importance weights of FRs ($\widetilde{W}_j$) are derived, as shown in Table 6.7. Even though the PFSs values are used for the remaining calculations, for practicality and visualization, the importance weights of FRs are de-fuzzified and normalized de-fuzzified values are obtained. As also depicted in the table, FR_2 has the highest priority in ranking.

Since QFD iteration does not stop at this stage, the resulting FRs weights are set as new CRs weights. Step 5.2 is executed then for the remaining calculations. The collective relationships matrix and the collective correlation matrix obtained in the second iteration. The importance of FRs^2 (W_j°) and the importance weights of FRs^2 ($\widetilde{W}_j$) along with the de-fuzzified and normalized second iteration values are also presented in Appendix C. As it can also be observed from the Table 6.8, FR_5^2 has the highest priority in ranking.

Table 6.7: Importance Weights of FRs for the First Iteration

FRj	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
W_j	0.051	0.052	0.049	0.046	0.047	0.05	0.044	0.045
Rank	2	1	4	8	7	3	11	9
FRj	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
W_j	0.048	0.045	0.039	0.039	0.047	0.042	0.038	0.042
Rank	5	10	18	17	6	13	19	14
FRj	***17***	***18***	***19***	***20***	**21**	**22**	**23**	**24**
W_j	0.044	0.039	0.036	0.033	0.028	0.039	0.032	0.027
Rank	12	15	20	21	23	16	22	24

Table 6.8: Importance Weights of FRs for the Second Iteration

FR_j^2	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
W_{FR}	0.035	0.034	0.034	0.034	0.035	0.034	0.034	0.033
Rank	2	7	4	5	1	9	8	11
FR_j^2	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
W_{FR}	0.028	0.034	0.031	0.032	0.033	0.034	0.032	0.031
Rank	28	3	17	15	13	6	14	18
FR_j^2	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***
W_{FR}	0.029	0.031	0.031	0.033	0.033	0.029	0.03	0.029
Rank	24	20	16	10	12	25	22	27
FR_j^2	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***
W_{FR}	0.031	0.03	0.029	0.031	0.026	0.027	0.028	0.027
Rank	19	23	26	21	32	31	29	30

6.4. Sensitivity Analysis

In order to see the effect of the voice of customers, a sensitivity analysis is conducted to see the change in the results and the priorities of technical requirements needed for DSC. Whereas all the other variables are fixed, the CRs, or “whats” are altered in the first iteration and 17 different scenarios are created. Starting from scenario one to scenario seventeen, the remaining sixteen CRs weights are fixed to ‘EL’ and respective scenario is assigned to ‘EH’ judgment. Ranking results are presented in Figure 6.4. As it can be observed, when there is an alteration in the voice of the customers, its effect on “hows” are measurable. Although ranking changes are quite enormous for the FRs which are ranked amongst the middle for the proposed methodologies results, alteration in the rankings of highest important and least important values are fairly minimal. For instance, highest given priority is FR_2 for the proposed methodology. FR_2 fluctuates only once to seventh place for the scenario 12, fourth place for the scenario 15, and third place to scenario 3. However, for the rest of the scenarios, it is consistent with either the first or the second place. This implies that the voice of customers has an effect on the result of the given priorities of enablers of DSC. However, since our proposed methodology also considers the individual judgment of FRs and the correlation among them in two iterations, fluctuations for the best and worst are minimal. A similar inference could be made for the result of the sensitivity analysis of the second iteration with the given Figure 6.5. Here, the effect of existing judgments of FRs and the correlation could be visible more intensely. The most important priority is given to Internet of Things (FR_5^2) and even with the alteration of the “whats” in the first iteration does not change it at all.

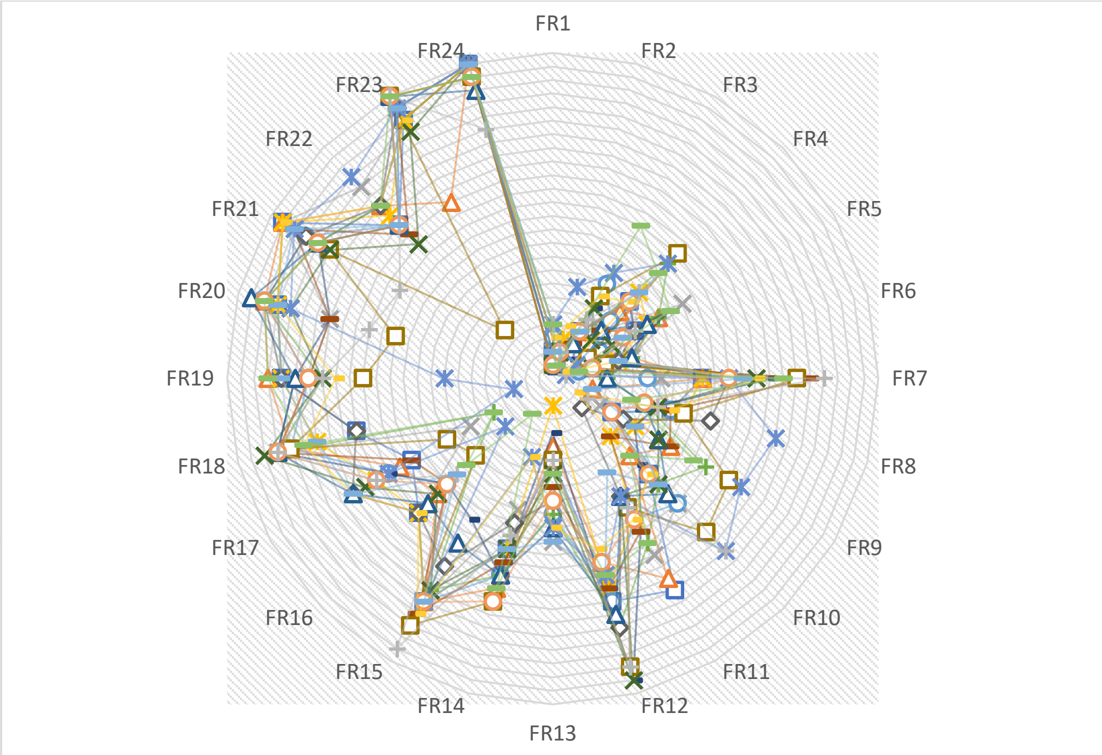


Figure 6.4: Changes in the Ranks of FRs with respect to CRs

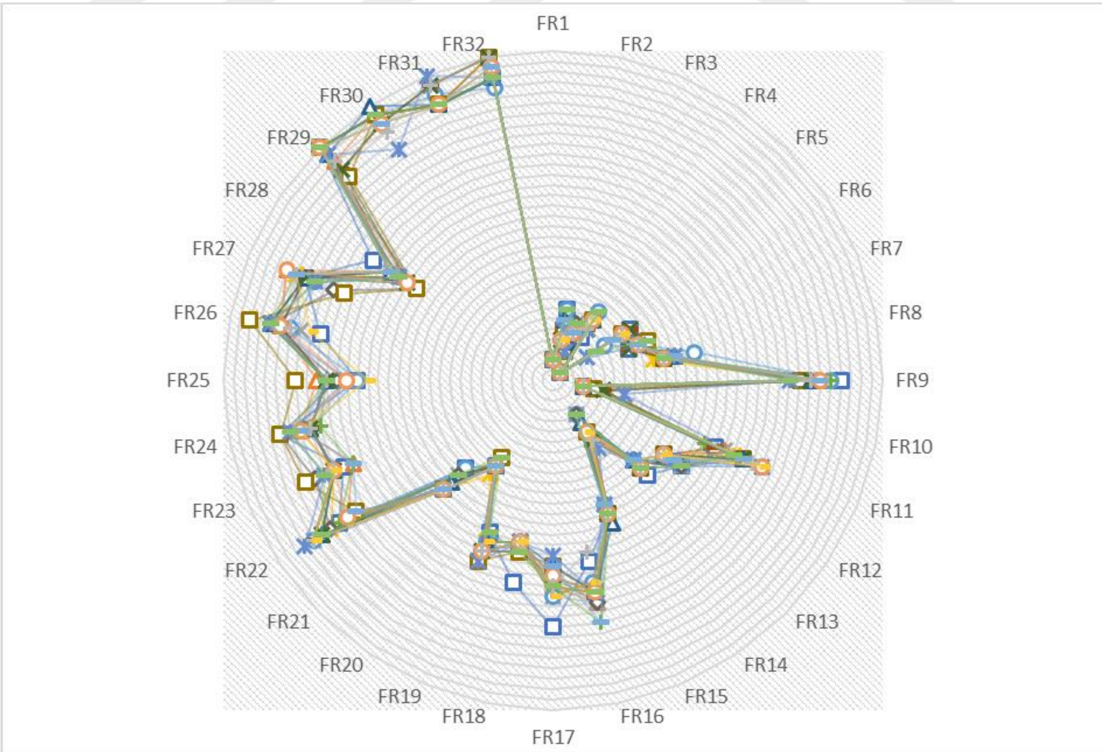


Figure 6.5: Changes in the Ranks of FRs with respect to CRs for the Second Iteration.

6.5. Concluding Remarks on PF-QFD Planning of DSC Infrastructure

Supply chains are exceptionally complex entities and none of the supply chains has yet succeeded in transforming into one that is truly digital. Most of the enablers required for this transformation are not yet broadly used in supply chains. However, the transformation has started and is expected to be completed over the next ten years with diverse businesses executing DSC at varying degrees. Supply chains that transform to DSC will gain first an unchallengeable competitiveness advantage in the race and will be able to set technical standards, or will at least gain influence over other businesses. In order to utilize this advantage and benefit from the revenue streams the DSC will open up supply chains today should plan the technological infrastructure of DSC. Among many different methodologies, QFD stands as the best choice to offer a framework since its distinctive properties to handle the complex nature of DSC to analytically prioritize technologic requirements in order to plan technologic infrastructure of DSC. As a whole, the major novelties and contributions of this paper are highlighted as: its offering of a novel original GDM technique integrating the QFD methodology under PFSs environment; the evaluative ratings are judged by real experts and expressed in PFSs in a GDM environment; This approach provides a greater flexibility and adequate determination of the GDM performance; by merging QFD methodology under PFS environment leads to an easier and efficient methodology and enables effective, logical, and sensible solution in decision-making process due to PFSs' substantial strength in describing the fuzzy and uncertain environment as an advantage over the crisp, fuzzy or IF; validation of the usefulness of the proposed method with its application on a case study with real experts from Turkey.

With regard to potential future research, this study can be further improved if the proposed methodology is applied to an existing supply chain. Furthermore, additional iterations would lead to more detailed and accurate results. This research has applied two iterations because of its novelty for the DMs and the DSC's maturity. In the future, the same method will be run with additional iterations until saturation is achieved. Since these findings are based on the case study, its generalization shall be sought after more applications in the future.

7. EVALUATION OF DSC PARTNERS

Serving under constantly changing market dynamics make linear and static supply chains to struggle to keep up with ever-changing technology trends. The properties of DSC, which get gradually popular in the industry, can unlock digital enablers and be a locomotive for growth, supports novel technology-driven approaches, enables quick responses, and creates innovative products and services for supply chains to cope with and stay competitive in this volatility. Partner Selection process from the digitalization perspective of SCM is a crucial task needs to be defined in DSC environment. In this stage, a very effective and efficient evaluation process is delivered to assess DSC partner alternatives but the partner selection problem is a complex procedure involving multiple criteria at once. Addressing this multi-criteria nature, a novel DSC partner evaluation approach is introduced in a GDM environment for an uncertain environment by employing MCDM tools. MCDM can assist in reaching a consensus judgment by collective participations of DMs to get objective decisions. In this study, a combined MCDM methodology is offered, in which ANP, to measure criteria weights, is integrated with ARAS, to measure the performance of DSC partners, under PFSs environment. Thus, the scientific value of this article stems from its ability to extant a state-of-art pioneer study that makes use of GDM based MCDM under a PFSs environment with combined PF-ANP and PF-ARAS approaches as a scientific novelty and developing a state-of-art evaluation model for a real-case application to improve DSC partner selection processes.

In order to conduce the PF-ANP methodology based on the above analyses, the hierarchy and the network structure should initially be constructed, and the dependences among the elements and the clusters should be identified. DMs individual priorities should be defined for GDM process. Then, the PFSs preference relations based on the pairwise comparisons between the elements in different clusters respect to the different criteria need to be constructed and PFSs preference relation on alternatives should be taken.

Afterwards, individual judgment need to be fused to and the local priority vectors from those PFSs preference relations need to be derived and then the initial super-matrix with these local priority vectors should be constructed. The initial super-matrix to the normalized super-matrix need further to be adjusted. Based on the final super-matrix, the limit priority from the normalized super-matrix can be calculated, and then they need to be limited by raising it to an arbitrarily large power. Finally, the final priorities can be calculated to be used in PF-ARAS ranking process.

7.1. The Integrated PF-ANP and PF-ARAS Methodology

Step 1 through Step 4 are the initialization stage of the methodology. From Step 5 to Step 9, it is specially designed for PF-ANP yet the other steps are designated for PF-ARAS approach. Figure 7.2 illustrates the flow chart of the proposed approach.

For the convenience of application, the step by step procedure of proposed methodology is developed as follows:

Step 1: Determine the overall goal, decision criteria, clusters as well as the elements and the available alternatives of the problem. Then, convene a group of DMs who have sufficient knowledge and expertise about the problem at hand. Dependences and feedbacks among the clusters and the elements are identified through DMs.

Let us denote:

- $D_k, \{D_1, D_2, \dots, D_K\}$ with $k = 1, 2, \dots, K$, as a set of DMs,
- The alternative set $A_i = \{A_1,\ A_2, \dots,\ A_m\}$, with $i = 1, 2, \dots, m$,
- The decision criteria set $C_c = \{C_1, C_2, \dots, C_C\}$, with $c = 1, 2, \dots, C$,
- The elements set $X_j = \{X_1, X_2, \dots, X_N\}$, with $j = 1, 2, \dots, N$,

- The Clusters set $C_g = \{C_1, C_2, \dots, C_G\}$, with $g = 1, 2, \dots, G$,.

- The priority vector set $w_j = \{w_1, w_2, \dots, w_n\}^T$ that defines the criteria weights, where $w_j \geq 0$, and $\sum_{j=1}^{n} w_j = 1$.

- The DMs' importance values λ_k for each for each D_k; $\sum_{k=1}^{K} \lambda_k = 1$.

Assume that the decision alternatives, the hierarchy with criteria, and the network which consists of clusters and elements are rated by the DMs in the form of PFSs values.

Table 7.1: Linguistic Variable for the Importance Assessment

Preference		**[$\mu_P(x)$,**	**$v_P(x)$]**
Extremely Unimportant	EU	[0.05,	0.95]
Very Unimportant	VU	[0.15,	0.85]
Unimportant	U	[0.25,	0.75]
Somewhat Unimportant	SU	[0.35,	0.65]
Medium Importance	MI	[0.50,	0.50]
Somewhat Important	SI	[0.65,	0.35]
Important	I	[0.75,	0.25]
Very Important	VI	[0.85,	0.15]
Extremely Important	EI	[0.95,	0.05]

Step 2: Determine the influence weights of DMs. The level of importance of each of the experts may not be the same, as their experience, knowledge and responsibilities may differ. These importance values of each of the DMs are also collected in terms of linguistic expressions. For this GDM process, a nine-interval scale for linguistic variables is used for estimating the weight of each DM, as given in Table 7.1. This new scale allows DMs to choose any linguistic evaluation between 'Extremely Unimportant' and 'Extremely Important'.

Let $D_k = \left(\mu_{P_k}(x), v_{P_k}(x), \pi_{P_k}(x)\right)$ be an PFS number to rate the k[th] DM.

DMs express the judgments on each other's qualification from the view point of the k[th] DM. For all DMs $\lambda^k(1 < k < K)$, DM_k express his/her opinion about other DMs in a linguistic term and this term is converted into PFSs values. There are numerous aggregation operators proposed. In this paper, we have utilized PFWA aggregation operator in our calculations since PFWA operator based on the averaging mean focuses on the group opinion, so it is not very sensitive to PFSs values and since it is the widely used one in PFSs literature. DMs' judgments are aggregated with the PFWA aggregation operator (Yager, 2014; Yager & Abbasov, 2013), then the level of influence of the k[th] DM on the decision is computed.

$$PFWA(P_1, P_2, \ldots, P_K)_{D_k} = \langle \sqrt{1 - \prod_{k=1}^{K}\left(1 - \left(\mu_{P_k}(x)\right)^2\right)^{\lambda'}}, \prod_{k=1}^{K} v_{P_k}(x)^{\lambda'} \rangle, \lambda' = \frac{1}{K-1} \tag{7.1.1}$$

$$\lambda_k = \frac{\frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}{\sum_{k=1}^{K} \frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}, \quad \text{where} \quad \sum_{k=1}^{K} \lambda_k = 1 \tag{7.1.2}$$

Step 3: Gather DMs' opinions on each factor. DMs share their judgments on each factor as a linguistic term defined in Table 7.1 and Table 7.2.

- Obtain the comparative judgments between the elements in different clusters regarding to each criterion. Then the PFSs preference relations can be acquired by the pairwise comparisons by the linguistic terms defined in Table 7.2.

- Get the opinions on alternatives for the preference relation by the linguistic terms defined in Table 7.1.

Table 7.2: Linguistic Variables for Criteria's Importance

Linguistic Variable		**PFSs Values**		**Reciprocal**	
		[$\mu_P(x)$,	**$v_P(x)$]**	**[$\mu_P(x)$,**	**$v_P(x)$]**
Equally Important	EI	[0.07,	0.30]	[0.30,	0.07]
Intermediate	IV	[0.18,	0.49]	[0.49,	0.18]
Moderately More Important	MI	[0.29,	0.60]	[0.60,	0.29]
Intermediate	IV2	[0.39,	0.65]	[0.65,	0.39]
Strongly More Important	SI	[0.50,	0.67]	[0.67,	0.50]
Intermediate	IV3	[0.61,	0.66]	[0.66,	0.61]
Very Strong Importance	VSI	[0.71,	0.61]	[0.61,	0.71]
Intermediate	IV4	[0.82,	0.52]	[0.52,	0.82]
Extremely More Important	EMI	[1.00,	0.00]	[0.00,	1.00]

Step 4: Combine individual PFSs values into group PFSs values. Once the hierarchy is created, the pairwise comparison matrix is set up. The pairwise comparison is based on a PFSs preference scale. Considering that linguistic terms are mathematically not operable, DMs' expressions shall be converted first into PFSs values after each DM are consulted on his or her opinion.

As the next action, each DM's assessment that was previously transformed into PFSs values is aggregated in the PFSs environment. PFWA aggregation operator is applied here. Under GDM, while fusing the pairwise comparison matrices the pairwise comparison matrices or individual opinions of each DM shall be aggregated into one group opinion so that a merged PFSs judgment matrix for criteria can be created.

$$PFWA(P_1, P_2, \dots, P_K)_{C_j} = P_1^{\lambda_1} \otimes P_2^{\lambda_2}, \dots, \otimes P_Z^{\lambda_K} = \langle \sqrt{1 - \prod_{k=1}^{K} \left(1 - \left(\mu_{P_k}(x)\right)^2\right)^{\lambda_k}}, \prod_{k=1}^{K} v_{P_k}(x)^{\lambda_k} \rangle \quad (7.1.3)$$

Here, $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_K)^T$ is the associated weight vector of PFWA aggregation operator, such that $\lambda_k \in [0,1]\ and\ \sum_{k=1}^{K} \lambda_k = 1$.

Step 5: Check the consistency of each PFSs preference relations. CR is obtained with the use of a standard RI, the value of which is taken from Saaty (Saaty, 1977).

$$\text{CR} = \frac{RI - \frac{\sum \boldsymbol{\pi_P}(x)_{ij}}{n}}{n-1} \tag{7.1.4}$$

In this formulation, n is the number of matrix elements and $\boldsymbol{\pi_P}(\boldsymbol{x})_{ij}$ is the value of hesitation. If CR is less than or equal to the consistency threshold (0.10), then the consistency level is unacceptable. Otherwise, the judgment matrix shall be deemed as not consistent and DMs' opinions shall be collected once more.

Step 6: Calculate the local priority vector from the GDM PFSs preference relations. Form the aggregated PFSs judgment matrix using PFWA aggregation operator, based on all expert opinions to find the PF-ANP criteria priorities.

Although PFSs values of ANP criteria weights are used for evaluation in PF-ARAS methodology, for practicality and visualization, Crisp ANP criteria weights are also given. The de-fuzzification of PFSs (Kahraman, Oztaysi, et al., 2018) is applied as follows:

$$W_j = \frac{\frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}{\sum_{j=1}^{n} \frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}}, \quad \text{where} \quad \sum_{j=1}^{n} W_j = 1 \tag{7.1.5}$$

Step 7: Construct the initial super-matrix with local priority vector. Form a super-matrix by entering local priority vectors of PF-ANP matrices into the appropriate columns for evaluation. A representation of PF-ANP super-matrix is displayed in Figure 7.1.

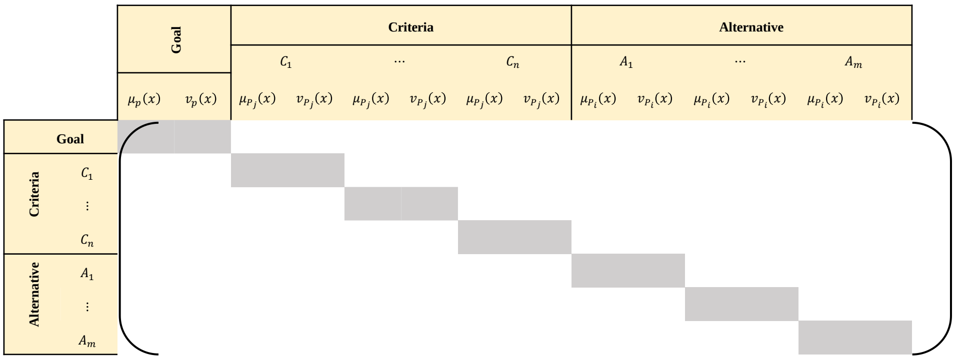


Figure 7.1: PF-ANP Super-Matrix

Step 8: Normalize the initial super-matrix.

$$\tilde{n}_{cr} = \left(\frac{\mu_{P_r}(x) - \min\limits_{c}\left(\mu_{P_{cr}}(x)\right)^2}{\sqrt{1-(\min\limits_{c}\left(\mu_{P_{cr}}(x)\right)^2+\min\limits_{c}\left(v_{P_{cr}}(x)\right)^2)}}, \frac{v_{P_r}(x) - \min\limits_{c}\left(v_{P_{cr}}(x)\right)^2}{\sqrt{1-(\min\limits_{c}\left(\mu_{P_{cr}}(x)\right)^2+\min\limits_{c}\left(v_{P_{cr}}(x)\right)^2)}} \right) \quad (7.1.6)$$

Where $\tilde{n} = \left(\mu_P(n), v_P(n)\right)$, c: index number of Column, r: index number of Row, r=c.

De-fuzzify the normalized super-matrix.

$$n_{cr} = \frac{\sqrt{\mu_{P_r}(n)} - \left(v_{P_r}(n)\right)^2}{2}, \quad (7.1.7)$$

Weighted super-matrix is constructed through normalizing the columns of de-fuzzified super-matrix.

$$L_{cr} = \frac{n_{cr}}{\sum n_c} \quad (7.1.8)$$

Step 9: Raise the weighted super-matrix to infinite powers until it is convergent. The limiting super-matrix is constructed by taking the weighted super-matrix to a significantly large power in order to have stable values.

Step 10: Calculate the global priority vector. The individual criteria level of influence vector is established with respect to each criterion. According to the limiting super-matrix, weights (w_j) of each criterion on the objective are shown in the ''Goal'' column to use in PF-ARAS steps later.

Step 11: Establish PFSs Decision Matrix ($\tilde{X}_{(k)}$) for Each DM and aggregated into GDM Matrix ($\tilde{X}_{(G)}$). The PFWA aggregation operator (Yager, 2014; Yager & Abbasov, 2013) is applied to fuse the individual judgments. Individual opinions of each DM shall be aggregated into one group opinion so that GDM alternative preference relation matrix ($\tilde{X}_{(G)}$) can be created.

$$PFWA(P_1, P_2, \ldots, P_K) = \langle \sqrt{1 - \prod_{k=1}^{K} \left(1 - \left(\mu_{P_k}(x)\right)^2\right)^{\lambda_k}}, \prod_{k=1}^{K} v_{P_k}(x)^{\lambda_k} \rangle \quad (7.1.9)$$

Here, $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_K)^T$ is the associated weight vector of PFWA aggregation operator, such that $\lambda_k \in [0,1]$ and $\sum_{k=1}^{K} \lambda_k = 1$.

$$\tilde{X}_{(G)} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{21} & & \tilde{x}_{i1} & \cdots & \tilde{x}_{m1} \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \tilde{x}_{12} & \cdots & \tilde{x}_{22} & & \tilde{x}_{i2} & \cdots & \tilde{x}_{m2} \\ & \vdots & & \ddots & & \vdots & \\ \tilde{x}_{1j} & \cdots & \tilde{x}_{2j} & & \tilde{x}_{ij} & \cdots & \tilde{x}_{mj} \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \tilde{x}_{1n} & \cdots & \tilde{x}_{2n} & & \tilde{x}_{in} & \cdots & \tilde{x}_{mn} \end{bmatrix}, where\ \tilde{x}_{ij} = \left(\mu_{P_{ij}}(x), v_{P_{ij}}(x)\right) \quad (7.1.10)$$

Step 12: Establish PFSs Optimal Decision Matrix. A typical optimal PFSs decision matrix containing m alternatives and n criteria, which is established by the linguistic terms with respect to each criterion on each alternative, in the form of $\tilde{X}_{(Opt)}$, as follows:

$$\tilde{X}_{(Opt)} = \begin{bmatrix} \tilde{x}_{01} & \cdots & \tilde{x}_{11} & & \tilde{x}_{i1} & \cdots & \tilde{x}_{m1} \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \tilde{x}_{02} & \cdots & \tilde{x}_{12} & & \tilde{x}_{i2} & \cdots & \tilde{x}_{m2} \\ & \vdots & & \ddots & & \vdots & \\ \tilde{x}_{0j} & \cdots & \tilde{x}_{1j} & & \tilde{x}_{ij} & \cdots & \tilde{x}_{mj} \\ \vdots & \ddots & \vdots & \cdots & \vdots & \ddots & \vdots \\ \tilde{x}_{0n} & \cdots & \tilde{x}_{1n} & & \tilde{x}_{in} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{7.1.11}$$

$where\ \tilde{x}_{0j} = \left(\mu_{P_{0j}}(x), v_{P_{0j}}(x)\right)$ denotes an PFSs value, which represents the performance value of the alternative i in terms of the criterion j, for $i = 0, 1, \ldots, m$ and $j = 1, \ldots, n$. $\tilde{x}_{0j}$ represents the optimal performance ratings of j^{th} criterion. The optimal performance values are constructed:

If it is a benefit criterion, then higher value is better,

$$\left(\mu_{P_{ij}}(\tilde{x}_{0j}) = \max_i \mu_{P_{ij}}(\tilde{x}_{ij}), v_{P_{ij}}(\tilde{x}_{0j}) = \min_i v_{P_{ij}}(\tilde{x}_{ij})\right) \tag{7.1.12}$$

If it is a cost criterion, then the lower value is better,

$$\left(\mu_{P_{ij}}(\tilde{x}_{0j}) = \min_i \mu_{P_{ij}}(\tilde{x}_{ij}), v_{P_{ij}}(\tilde{x}_{0j}) = \max_i v_{P_{ij}}(\tilde{x}_{ij})\right) \tag{7.1.13}$$

Step 13: Establish Normalized Preference Relation Matrix. Normalize the matrix, $\tilde{R} = [\tilde{r}_{ij}]_{mxn}$ with $\tilde{r}_{ij}$=$(\mu_P(r), v_P(r))$.

$$\tilde{r}_{ij} = \left(\frac{\mu_{P_j}(x) - \min_i \left(\mu_{P_{ij}}(x)\right)^2}{\sqrt{1 - (\min_i \left(\mu_{P_{ij}}(x)\right)^2 + \min_i \left(v_{P_{ij}}(x)\right)^2)}}, \frac{v_{P_j}(x) - \min_i \left(v_{P_{ij}}(x)\right)^2}{\sqrt{1 - (\min_i \left(\mu_{P_{ij}}(x)\right)^2 + \min_i \left(v_{P_{ij}}(x)\right)^2)}} \right) \tag{7.1.14}$$

Step 14: Establish Weighted Normalized Preference Relation Matrix. Construct the weighted normalized preference relation matrix ($\dot{\tilde{R}} = [\dot{\tilde{r}}_{ij}]_{mxn}$) through applying the PFSs scalar multiplication operator.

$$\dot{\tilde{R}} = w_j * \tilde{r}_{ij} \tag{7.1.15}$$

Step 15: Determine Optimality Function Values and Alternative Utility Degree. Optimality function value $\tilde{P}_i$ is constructed for all alternatives by applying the PFSs summation operator.

$$\tilde{P}_i = \sum_{j=1}^{n} \dot{\tilde{r}}_{ij} \tag{7.1.16}$$

By the comparison of variant, the alternative utility degree (Q_i) is determined by applying the PFSs division operator.

$$\tilde{Q}_i = \frac{\tilde{P}_i}{\tilde{P}_0} \tag{7.1.17}$$

Step 16: Rank Alternatives. The $\tilde{Q}_i$ values for $i = 0, 1, \ldots, m$ are de-fuzzified (Kahraman, Oztaysi, et al., 2018). The ranking of each alternative is made in an ascending order of de-fuzzified 'Q_i'. The i^{th} alternative with the biggest Q_i value is deemed as the best one, while the contrary is the worst one.

$$Q_i = \frac{\sqrt{\mu_{P_j}(x) - \left(v_{P_j}(x)\right)^2}}{2}, \tag{7.1.18}$$

The schematic diagram for the proposed methodology is presented in Figure 7.2.

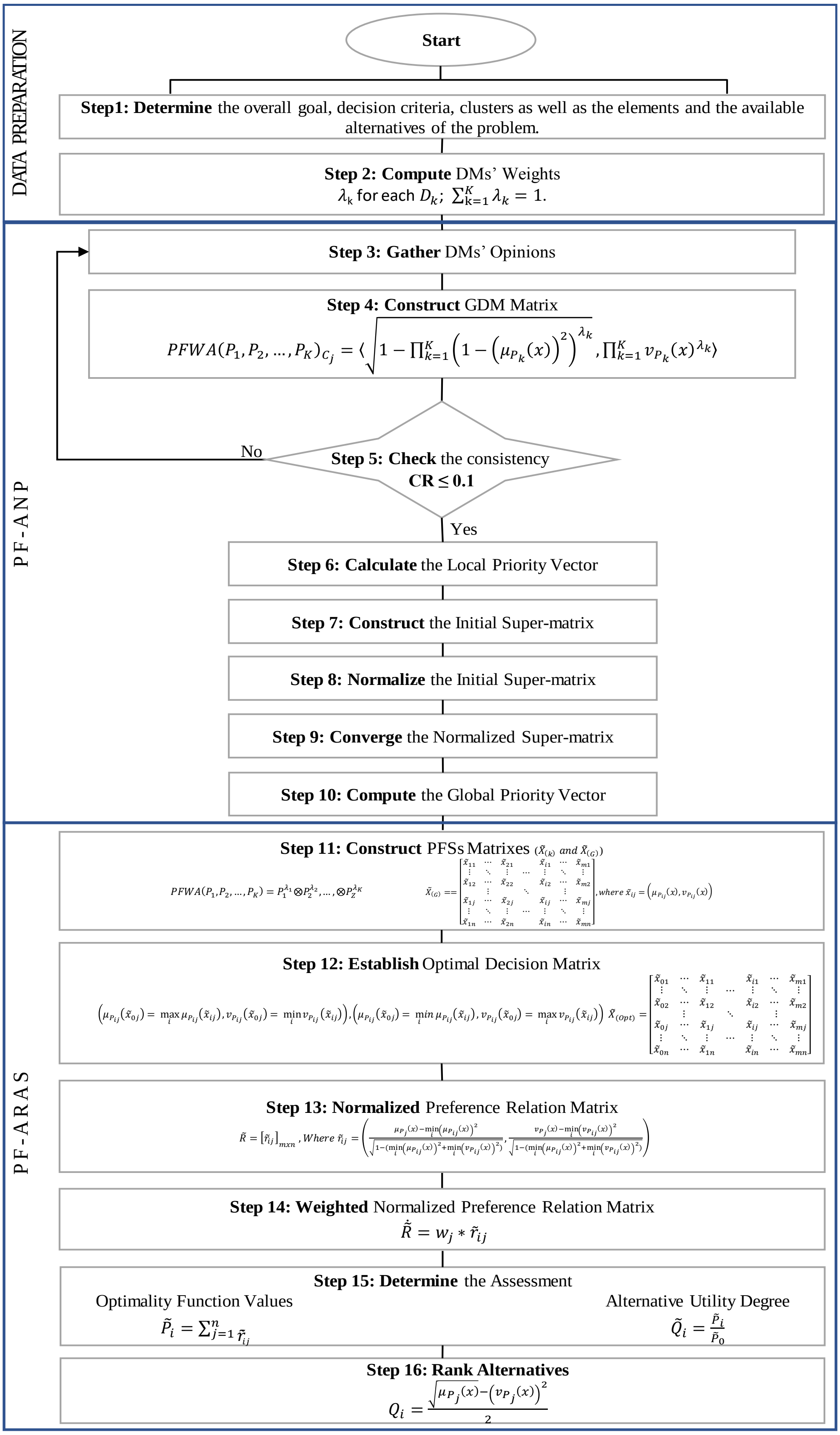


Figure 7.2: Schematic Diagram for Proposed Methodology

7.2. DSC Partner Selection Criteria

The goal in this sub-section is to determine the best available criteria for DSC partner selection through an extensive literature review and expert opinions. As far as we know, this is the first research to determine partner selection criteria in the context of DSC. Therefore, this section is an important part of this paper. The criteria are classified from the extant literature and through the extensive brainstorming of DMs, they are adapted to be used in the proposed methodology. Figure 7.3 presents the network structure of evaluation framework. Figure 7.4 presents the detailed evaluation model. The dimensions and criteria for DSC Partner Selection and their descriptions are summarized as follows:

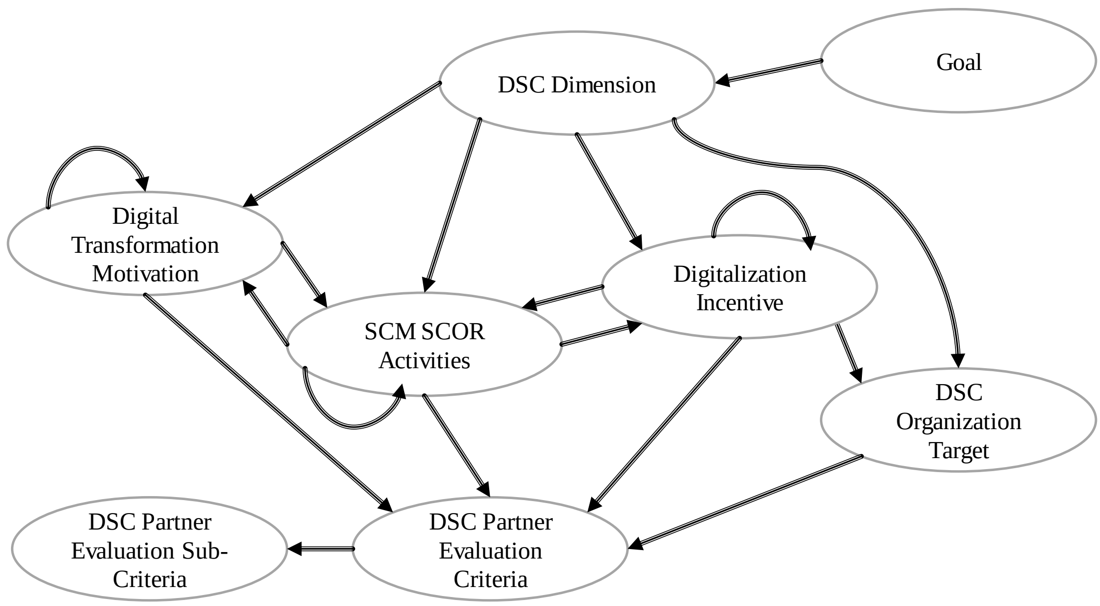


Figure 7.3: Network Structure of Evaluation Framework

Major Elements of DSC Dimension include: Digitalization Process, Technology Implementation Process, and Supply Chain Process. The primary goal is the formation of a DSC, considering that the main objective is to come up with a useful guide for successful management of DSC organization. As digitalization progresses from a strategic decision to execution, it is quite common for supply chains to set the stake in the ground in terms of the main targets in DSC outcome (Bradach, Tierney, & Stone, 2014).

Therefore, every supply chain might have a slightly different set of digital transformation objectives with different concerns. In addition to rethinking and redesigning the entire supply chains structure, digital transformation for supply chains are related to digitalization, technology implementation, and supply chain management. These areas are vital for organizational alignment while the technological infrastructure for DSC still remains a must for successful implementation (Büyüközkan & Göçer, 2018a, 2018b).

Major elements of Digital Transformation Motivation include: Reduction of Cost, Customer Pressure, Upside and Downside Efficiency, Upside and Downside Flexibility. These four motivations refer to the adoption of DSC that reflects vital transformation in the way of thinking and in the strategy of SCM. The digital transformation executives have been able to drive nonlinear growth in their profits, share of markets and productivity by transforming digitally. While these form a minority, most of the companies are still struggling to grasp the move in their ecosystem that digital enablers have brought in (Büyüközkan & Göçer, 2018a, 2018b).

Major elements of SCM SCOR Activities include the supply chain operations reference (SCOR) model which is co-developed by the “Supply Chain Council” with the assistance of seventy leading manufacturing companies of the world. These activities are management tools that is used to address, improve, and communicate SCM decisions within a company and with partners and clients (Counsil, 2004). These activities handle the five areas of the SCM: plan, source, make, deliver, and return. These activities loop along the supply chains.

Major elements of Digitalization Incentive include: Mindset Change, Employee Participation refers, Digitalization know-how, and Executive Support and Participation. Mindset Change refers to the state that needed to be installed to be able to transform existing and established models. This is not only related to technologies or development, but to whole organization to go through a “mindset of change” (Büyüközkan & Göçer, 2018a; Tjahjono et al., 2017; Yuen, Wang, Wong, & Zhou, 2017). Employee Participation refers to the promotion of new functions and skills development in customer integration to increase employee and partner participation in the digitalization process

(Büyüközkan & Göçer, 2018a). Digitalization know-how can provide organizations with the tools needed to capture new digitalization opportunities (Büyüközkan & Göçer, 2018a). Executive Support and Participation dispenses that executives always play more critical roles in digitalization process because of the magnitude of change, the degree of disruption, and the power of inertia (Büyüközkan & Göçer, 2018a; Raab & Griffin-Cryan, 2011; Schlaepfer & Koch, 2015; Turhan et al., 2011).

Major elements of DSC Organization Target include: interoperability, which is the ability of supply chains to transact with another supply chain by means of DSC (Heutger et al., 2016). Collaboration is the interaction supported by technologies between two or more parties that play a role in the supply chains (Heutger et al., 2016). Reliability is considered as the capacity to perform the promised service correctly and reliably (Govindan & Chaudhuri, 2016; Heutger et al., 2016; Schlaepfer & Koch, 2015). Innovation is the ability to assess the maturity in terms of innovation and digital adoption (Schlaepfer & Koch, 2015). Flexibility provides competitive advantage through flexible processes like technology sharing and cost saving (Heutger et al., 2016; Schlaepfer & Koch, 2015). DSC requires operational Efficiency to drive supply chain processes (Heutger et al., 2016; Schlaepfer & Koch, 2015). Visibility stands for the technology and processes to have end-to-end visibility through DSC (Heutger et al., 2016; Schlaepfer & Koch, 2015; Zhong et al., 2016). Agility represents how fast a DSC responds to the changes in customer preferences, environment, competitive forces etc. (Batty et al., 2017; Heutger et al., 2016; Schlaepfer & Koch, 2015; Zhong et al., 2016). Security stands for the tools DSC use to secure its assets, identity and technology in the online or physical world (Batty et al., 2017; Heutger et al., 2016; Schlaepfer & Koch, 2015; Zhong et al., 2016).

Major elements of Partner Evaluation Criteria include: Partner Service Competency is focused on a suitable partner selection that demonstrate the proven expertise in delivering quality solutions in specialized areas. Service competencies are designed to meet partners' needs and be recognizable to prospective ones (Guarraia et al., 2016; Kache & Seuring, 2017). Partner Alignment give priority to the willingness and ability to align with companies' needs and goals over time. Aligning the interest of partners with those of the focal company may require creating incentive mechanisms for increasing performance and developing trust (Bhattacharyya & Guiffrida, 2015; Johansson, Siverbo, & Camén, 2016). Total Cost is one of the most significant one assessing the total expense in all operations (Büyüközkan & Görener, 2015; Büyüközkan & Güleryüz, 2016; Büyüközkan, Güleryüz, & Karpak, 2017). The new generation technological enablers provide smart products that are equipped with defined algorithms and enough computing power. Digital Competency allows partners to utilize self-learning and autonomous decision-making approaches in a DSC with improved decision making, automated execution and innovations in operations (Attaran, 2017; Klewes, Popp, & Rost-Hein, 2017; Murawski & Bick, 2017). Technology Competency is especially important for any supply chain looking forward to transforming digitally. This transformation can be a key to shift out from the survival mode and move towards a growing successful company, with the help of suitable partner to support its technology infrastructure (Han, Wang, & Naim, 2017; Lee, Cho, & Kim, 2015; Oztaysi, 2014a).

Major elements of Partner Evaluation Sub-Criteria include: Responsiveness which refers to the digitalization in supply chains that needs to be sufficiently responsive to easily adapt to changing circumstances. This does not imply how things are delivered, but it is the way how it reacts to the problems within supply chain. Digital capabilities make it easier to configure and re-configure (Büyüközkan and Çifçi, 2012; Cecere, 2014; Dey et al., 2016; Lee et al., 2015; Raab and Cryan, 2011; Raj and Sharma, 2014). Education & Training Regular for DSC includes operations, technology, supply chain management processes under DSC environment (Büyüközkan & Görener, 2015; Büyüközkan & Güleryüz, 2016; Büyüközkan et al., 2017). Social and Environmental Responsibility for DSC allows easier share of awareness on social and environmental responsibility. Companies' consciousness on participation is an important criteria in partner selection (Alkhatib, Darlington, Yang, & Nguyen, 2015; Guarraia et al., 2016; Santos, Osiro, & Lima, 2017). Professional Support means supporting day-to-day operational services that is necessary to ensure service quality (Büyüközkan & Gocer, 2017; Lee et al., 2015; Oztaysi, 2014b). Financial Stability refers to the economic strength of a partner that is important for long-term relationships. Good finances is key for improving and adapting to new technologies, surviving and leading in the industry (Büyüközkan & Göçer, 2017; Lee et al., 2015; Shidpour, Da Cunha, & Bernard, 2016). Quality of Service can be measured in terms of empathy, ease of communication, and combination of services provided, such as: customer service, performance record, equipment and technology, courage, etc. (Büyüközkan, Kayakutlu, & Karakadılar, 2015; Lee et al., 2015; Santos et al., 2017; Shidpour et al., 2016; Jiuping Xu & Shen, 2014). Reputation means that DSC partners are expected to keep a good name among competitors. This is closely related with technical capabilities, as well as investing in long-term relationships, company culture and management's goodwill as a way to become a desirable organization for both clients and employees as a way to gain competitive advantage (Alkhatib et al., 2015; Büyüközkan, 2012; Büyüközkan, Arsenyan, & Ruan, 2012; Büyüközkan & Göçer, 2017; Lee et al., 2015; Jiuping Xu & Shen, 2014). Respect for the Privacy means that the regulatory environment, privacy concerns and ownership of data that are substantial challenges in establishing trust among stakeholders. Overcoming privacy issues is an essential selection criterion for partner selection (Büyüközkan & Göçer, 2017; Santos et al., 2017). Appraisal Cost is the cost to acquire quality control and regulatory requirements (Büyüközkan & Görener, 2015; Büyüközkan & Güleryüz, 2016; Büyüközkan et al., 2017). Investment Cost measures the first cost of investment for related technology (Büyüközkan & Görener, 2015; Büyüközkan & Güleryüz, 2016; Büyüközkan et al., 2017). Cost of Service is the cost of DSC technology to operate (Büyüközkan & Görener, 2015; Büyüközkan & Güleryüz, 2016; Büyüközkan et al., 2017). Follow-up Cost is found to affect the partner selection process by measuring the follow-ups of DSC technology infrastructure (Büyüközkan & Görener, 2015; Büyüközkan & Güleryüz, 2016; Büyüközkan et al., 2017). Digital Engagement is about the use of information and communications technologies to support, enhance or extend participation and engagement processes in DSC. These efforts can be accomplished by using digital tools and channels to find, listen to and mobilize companies around an issue and then taking proper actions (Attaran, 2017; Klewes et al., 2017; Murawski & Bick, 2017). Digital Innovation has the ability to assess the maturity in terms of innovation and digital adoption in selection process for DSC partner selection (Schlaepfer & Koch, 2015). Digital Collaboration refers to the capabilities that are harmonized within and beyond physical boundaries to increase collaboration between involved actors in the DSC. Deficient collaboration with external associates and insufficient input from internal functions is essential in selection processes (Alkhatib et al., 2015; Arsenyan, Büyüközkan, & Feyzioğlu, 2015; Dougados & Felgendreher, 2016; Lee et al., 2015; Pearson, Schatteman, Gjendem, Hanifan, & Kaltenbach, 2014). Digital Customization and personalization are the building blocks of digitally enhanced products and services. DSC partner can make it possible to deliver individual experiences to large numbers of groups (Klewes et al., 2017; Murawski & Bick, 2017; Zangiacomi, Fornasiero, Franchini, & Vinelli, 2017). Technologic Compatibility is about the technical compatibility of Partner to ensure their continued presence and profitability for long-term cooperation. This includes partners' accomplishments, references, delivery performance, legal compliance, etc. It seeks the tools and techniques that help partners to improve their approach to solve the problems the organizations face (Büyüközkan & Göçer, 2017; Dey et al., 2016). Global Connectivity is the ability to both source and sell all over the world (Heutger et al., 2016; Schlaepfer & Koch, 2015). Technology Capability involves more than the technologies needed for developing a product or providing a service that meets certain requirements. Technology capability in DSC partner selection refers to those activities, which enable companies to choose and use technologies to create competitive advantage (Alkhatib et al., 2015; Bai, Rezaei, & Sarkis, 2017; Büyüközkan & Çifçi, 2011, 2012; Büyüközkan & Güleryüz, 2016; Santos et al., 2017). Technology Integration means that partners need to apply their technological skills for learning and problem-solving in digital and non-digital supply chains. Management and use of digital tools in supply chains can address these efforts (Büyüközkan & Berkol, 2011; Dey et al., 2016; Lee et al., 2015).

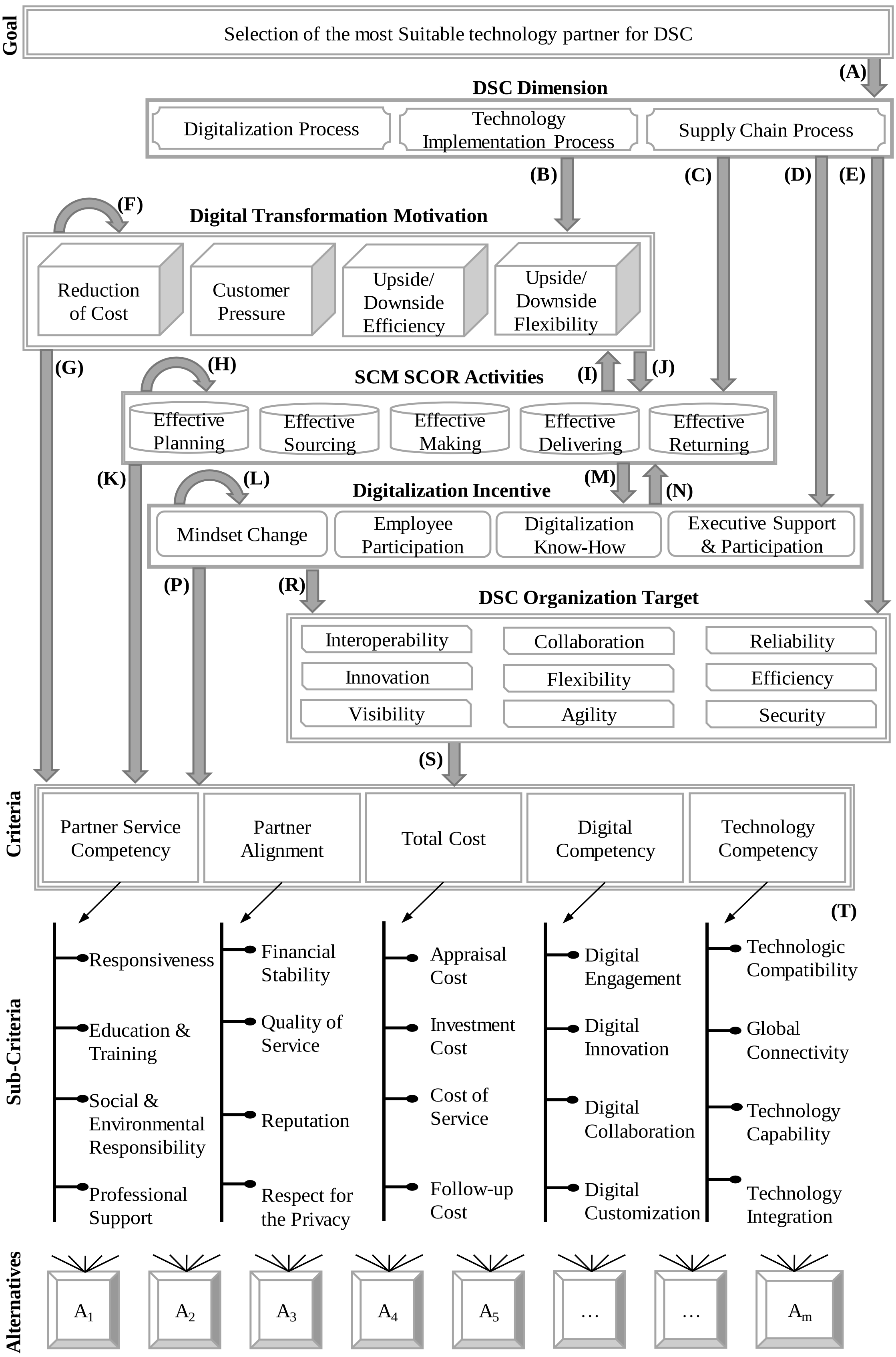


Figure 7.4: Detailed Evaluation Model

7.3. Obtained Results

Step 1: The overall goal is set to the selection of the most suitable technology partner for DSC. Five alternatives are evaluated by the Three DMs using the decision criteria, clusters as well as the elements. Figure 7.4 presents the detailed evaluation model.

Step 2: The individual priorities of each DM are determined through the procedures in Step 2 of the proposed methodology.

The importance values of DMs are expressed as:

D_1 judgment on 'D_2', and 'D_3' is 'VI', 'I', respectively,
D_2 judgment on 'D_1', and 'D_3' is 'EI', 'VI', respectively,
D_3 judgment on 'D_1', and 'D_2' is 'EI', 'VI', respectively.

The linguistic variables' conversion results as:

$D_1 = [0.95, 0.05]$, and $[0.95, 0.05]$,
$D_2 = [0.85, 0.15]$, and $[0.85, 0.15]$,
$D_3 = [0.75, 0.25]$, and $[0.85, 0.15]$.

DMs' judgments are aggregated with the PFWA aggregation operator. $PFWA(D_1, D_2, D_3)_{D_k} = D_1^{0.5} \otimes P_2^{0.5} \otimes P_3^{0.5}$. λ' $\left(\lambda' = \frac{1}{3-1}\right)$ is set to 0.5 to balance the unknown weights.

$PFWA(D_1)_{D_k} = [0.95, 0.05]$, $PFWA(D_2)_{D_k} = [0.85, 0.15]$, and $PFWA(D_3)_{D_k} = [0.81, 0.19]$.

The level of influence of the kth DM on the decision is computed. A sample of calculation for D_1 is presented below.

$$\lambda_1 = \frac{\frac{\sqrt{0.95}-(0.05)^2}{2}}{\left(\frac{\sqrt{0.95}-(0.05)^2}{2}\right)+\left(\frac{\sqrt{0.85}-(0.15)^2}{2}\right)+\left(\frac{\sqrt{0.81}-(0.19)^2}{2}\right)} = 0.356, \lambda_2 = 0.329, \lambda_3 = 0.315.$$

Step 3: DMs' opinions on SCM SCOR factor is presented in Table 7.3. Not all opinions are shown, the data is scaled to show the essence of the study, remaining sections are displayed in Appendix D. The other relations are established using the PF-ANP. Similar to AHP steps, for the elements in each level, pair-wise comparisons are conducted with respect to relative importance towards control criterion.

Table 7.3: Linguistic Evaluation Pairwise-Matrix of SCM SCOR with respect to Digitalization

		Plan	**Source**	**Make**	**Deliver**	**Return**
Plan	D_1	**EI**	1/MI	1/MI	MMI	1/IV4
	D_2		1/IV3	1/MI	SMI	1/VSI
	D_3		1/SI	1/IV4	SMI	1/MI
Source	D_1	MI	**EI**	SI	1/IV4	1/IV
	D_2	IV3		1/SI	1/MI	1/IV3
	D_3	SI		1/MI	1/IV4	1/IV
Make	D_1	MI	1/SI	**EI**	1/IV3	EVI
	D_2	MI	SI		1/VSI	EVI
	D_3	IV4	MI		1/MI	1/SI
Deliver	D_1	1/MMI	IV4	IV3	**EI**	1/MI
	D_2	1/SMI	MI	VSI		1/IV4
	D_3	1/SMI	IV4	MI		1/VSI
Return	D_1	IV4	IV	1/EVI	MI	**EI**
	D_2	VSI	IV3	1/EVI	IV4	
	D_3	MI	IV	SI	VSI	

Step 4: Individual PFSs values are fused into group PFSs values. The GDM values for the evaluation matrix of SCM SCOR is presented in Table 7.4.

Table 7.4: GDM Matrix of SCM SCOR with respect to Digitalization and Respective Local Weights

	$[\mu_P(x),$	$v_P(x)]$	W_j
Plan	[0.684,	0.319]	0.201
Source	[0.674,	0.281]	0.199
Make	[0.630,	0.315]	0.203
Deliver	[0.615,	0.205]	0.200
Return	[0.613,	0.214]	0.197

Step 5: The consistency of each PFSs preference relations is checked. CR is obtained with the use of a standard RI. All the pairwise comparison matrix is re-evaluated until they are consistent.

Step 6: The local priority vector is constructed from the GDM PFSs preference relations. The weights of SCM SCOR is displayed in Table 7.4.

Step 7: The initial super-matrix is constructed with the calculated local priority vectors. General sub-matrix notation for PF-ANP super-matrix is displayed in Figure 7.5. The PF-ANP initial super-matrix is constructed as displayed in Appendix D. Table 7.5 present the small sample of the initial super-matrix representation.

Step 8: The initial super-matrix is normalized. All values of normalized matrix are not disclosed. Table 7.6 and Table 7.7 present the small sample of the related super-matrix representation.

	Goal	DSCD	DTM	SCMA	DI	OT	PSEC	PSESC
	$\mu_P(x)$ $v_P(x)$	$\mu_P(x)$ $v_P(x)$	$\mu_P(x)$ $v_P(x)$	$\mu_P(x)$ $v_P(x)$	$\mu_P(x)$ $v_P(x)$	$\mu_P(x)$ $v_P(x)$	$\mu_P(x)$ $v_P(x)$	$\mu_P(x)$ $v_P(x)$
Goal	0	0	0	0	0	0	0	0
DSC Dimension (DSCD)	A	0	0	0	0	0	0	0
Digital Transformation Motivation (DTM)	0	B	F	I	0	0	0	0
SCM SCOR Activities (SCMA)	0	C	J	H	N	0	0	0
Digitalization Incentive (DI)	0	D	0	M	L	0	0	0
DSC Organization Target (OT)	0	E	0	0	R	0	0	0
PS Evaluation Criteria (PSEC)	0	0	G	K	P	S	Identity	0
PS Evaluation Sub-Criteria (PSESC)	0	0	0	0	0	0	T	Identity

Figure 7.5: General Sub-matrix Notation for PF-ANP Super-Matrix

Table 7.5: PF-ANP Initial Super-Matrix Representation

	Goal		***DSCD₁***		…	***PSESC₅₄***	
	$[\boldsymbol{\mu_P(x)},$	$\boldsymbol{v_P(x)}]$	$[\boldsymbol{\mu_P(x)},$	$\boldsymbol{v_P(x)}]$	…	$[\boldsymbol{\mu_P(x)},$	$\boldsymbol{v_P(x)}]$
Goal	[0.000,	1.000]	[0.000,	1.000]	…	[0.000,	1.000]
DSCD₁	[**0.434,**	**0.477**]	[0.000,	1.000]	…	[0.000,	1.000]
DSCD₂	[**0.504,**	**0.359**]	[0.000,	1.000]	…	[0.000,	1.000]
DSCD₃	[**0.494,**	**0.440**]	[0.000,	1.000]	…	[0.000,	1.000]
DTM₁	[0.000,	1.000]	[**0.075,**	**0.303**]	…	[0.000,	1.000]
DTM₂	[0.000,	1.000]	[**0.576,**	**0.700**]	…	[0.000,	1.000]
DTM₃	[0.000,	1.000]	[**0.578,**	**0.695**]	…	[0.000,	1.000]
DTM₄	[0.000,	1.000]	[**0.606,**	**0.656**]	…	[0.000,	1.000]
SCMA₁	[0.000,	1.000]	[**0.684,**	**0.318**]	…	[0.000,	1.000]
…	…	…	…	…	…	…	…
PSESC₅₄	[0.000,	1.000]	[0.000,	1.000]	…	**[1.000,**	**0.000]**

Table 7.6: PFSs-ANP Normalized Super-Matrix Representation

	Goal		***DSCD₁***		…	***PSESC₅₄***	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	…	$[\mu_P(x),$	$v_P(x)]$
Goal	[0.000,	1.000]	[0.000,	1.000]	…	[0.000,	1.000]
DSCD₁	[0.429,	0.472]	[0.000,	1.000]	…	[0.000,	1.000]
DSCD₂	[0.499,	0.353]	[0.000,	1.000]	…	[0.000,	1.000]
DSCD₃	[0.490,	0.435]	[0.000,	1.000]	…	[0.000,	1.000]
DTM₁	[0.000,	1.000]	[0.070,	0.296]	…	[0.000,	1.000]
DTM₂	[0.000,	1.000]	[0.575,	0.695]	…	[0.000,	1.000]
DTM₃	[0.000,	1.000]	[0.577,	0.690]	…	[0.000,	1.000]
DTM₄	[0.000,	1.000]	[0.605,	0.651]	…	[0.000,	1.000]
SCMA₁	[0.000,	1.000]	[0.684,	0.310]	…	[0.000,	1.000]
…	…	…	…	…	…	…	…
PSESC₅₄	[0.000,	1.000]	[0.000,	1.000]	…	**[1.000,**	**0.000]**

Table 7.7: De-fuzzified and Weighted Super-Matrix Representation

	De-fuzzified			
	Goal	***DSCD₁***	…	***PSESC₅₄***
Goal	0.000	0.000	…	0.000
DSCD₁	0.216	0.000	…	0.000
DSCD₂	0.290	0.000	…	0.000
DSCD₃	0.255	0.000	…	0.000
DTM₁	0.000	0.091	…	0.000
DTM₂	0.000	0.135	…	0.000
DTM₃	0.000	0.139	…	0.000
DTM₄	0.000	0.174	…	0.000
SCMA₃	0.000	0.347	…	0.000
…	…	…	…	…
PSESC₅₄	0.000	0.000	…	1

	Weighted		
Goal	***DSCD₁***	…	***PSESC₅₄***
0.000	0.000	…	0.000
0.283	0.000	…	0.000
0.382	0.000	…	0.000
0.335	0.000	…	0.000
0.000	0.017	…	0.000
0.000	0.025	…	0.000
0.000	0.026	…	0.000
0.000	0.033	…	0.000
0.000	0.065	…	0.000
…	…	…	…
0.000	0.000	…	1

Step 9: The normalized super-matrix is raised to infinite powers by applying matrix power operator of MATLAB programming until it is convergent. For the mentioned study, super-matrix is raised to the power of 30.

Step 10: The global priority vector is calculated. According to this convergent super-matrix, weights of the criteria on the objective of selecting the most suitable technology partner for DSC are shown in the ‘‘Goal’’. These values shown in goal column for the sub-criteria weights are to be used in PF-ARAS approach. The crisp values are also displayed to get an idea for the priorities of the evaluation criteria. Table 7.8 display the final criteria weights. Digital Innovation gets to be the most important while Follow-up Cost criterion gets to be the least important one, which is used in the calculation steps of PF-ARAS.

Table 7.8: The Global Criteria Weights

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}
W_j	0.048	0.041	0.055	0.044	0.040	0.046	0.043	0.058	0.047	0.066
RANK	11	17	8	14	18	13	15	5	12	2
	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}	C_{44}	C_{51}	C_{52}	C_{53}	C_{54}
W_j	0.052	0.025	0.056	0.069	0.054	0.057	0.042	0.033	0.059	0.065
RANK	10	20	7	1	9	6	16	19	4	3

Step 11: PFSs matrixes on alternatives are constructed with respect to each criterion. The values for the PFSs matrix of alternative A_1 is provided in Table 7.9. GDM Matrix is constructed by the PFWA aggregation operator. Table 7.10 display the aggregated matrix for A_1.

Step 12: Optimal Decision Matrix (A_0) with respect to each criterion is constructed through the procedure in Step 12 of the methodology. The Table 7.11 display the PFSs Optimal Decision Matrix.

Table 7.9: The Individual Preference Relation of PFSs Matrix for the Alternative A_1

		DM_1		DM_2		DM_3
	$\mu_{P_{ij}}(x)$	$v_{P_{ij}}(x)$	$\mu_{P_{ij}}(x)$	$v_{P_{ij}}(x)$	$\mu_{P_{ij}}(x)$	$v_{P_{ij}}(x)$
C_{11}	0.15	0.85	0.95	0.05	0.65	0.35
C_{12}	0.75	0.25	0.75	0.25	0.35	0.65
C_{13}	0.25	0.75	0.25	0.75	0.15	0.85
C_{14}	0.65	0.35	0.35	0.65	0.25	0.75
C_{21}	0.15	0.85	0.25	0.75	0.25	0.75
C_{22}	0.15	0.85	0.95	0.05	0.25	0.75
C_{23}	0.65	0.35	0.85	0.15	0.95	0.05
C_{24}	0.35	0.65	0.65	0.35	0.25	0.75
C_{31}	0.25	0.75	0.65	0.35	0.95	0.05
C_{32}	0.25	0.75	0.65	0.35	0.35	0.65
C_{33}	0.65	0.35	0.75	0.25	0.25	0.75
C_{34}	0.15	0.85	0.50	0.50	0.25	0.75
C_{41}	0.15	0.85	0.50	0.50	0.85	0.15
C_{42}	0.65	0.35	0.25	0.75	0.35	0.65
C_{43}	0.15	0.85	0.25	0.75	0.25	0.75
C_{44}	0.35	0.65	0.25	0.75	0.75	0.25
C_{51}	0.65	0.35	0.25	0.75	0.65	0.35
C_{52}	0.50	0.50	0.50	0.50	0.25	0.75
C_{53}	0.85	0.15	0.65	0.35	0.25	0.75
C_{54}	0.95	0.05	0.25	0.75	0.15	0.85

Table 7.10: The GDM Matrix for the Alternative A_1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}
$\mu_{P_j}(x)$	0.782	0.675	0.224	0.477	0.220	0.740	0.861	0.468	0.780	0.466
$v_{P_j}(x)$	0.253	0.338	0.780	0.546	0.784	0.322	0.143	0.555	0.249	0.558
	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}	C_{44}	C_{51}	C_{52}	C_{53}	C_{54}
$\mu_{P_j}(x)$	0.621	0.340	0.630	0.477	0.220	0.529	0.568	0.442	0.694	0.759
$v_{P_j}(x)$	0.398	0.686	0.413	0.547	0.784	0.504	0.450	0.568	0.329	0.298

Table 7.11: The Optimal Decision Matrix

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}
μ_{P_j}	0.894	0.876	0.897	0.917	0.786	0.748	0.861	0.871	0.467	0.466
v_{P_j}	0.116	0.126	0.112	0.085	0.242	0.304	0.143	0.133	0.568	0.558
	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}	C_{44}	C_{51}	C_{52}	C_{53}	C_{54}
μ_{P_j}	0.621	0.340	0.894	0.825	0.871	0.796	0.624	0.843	0.821	0.788
v_{P_j}	0.398	0.686	0.116	0.191	0.133	0.224	0.410	0.173	0.199	0.232

Table 7.12: The Normalized Matrix for the Alternative A_1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}
$\mu_{P_j}(r)$	0.761	0.649	0.182	0.445	0.178	0.717	0.842	0.435	0.758	0.433
$v_{P_j}(r)$	0.241	0.329	0.787	0.544	0.791	0.312	0.127	0.553	0.236	0.557
	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}	C_{44}	C_{51}	C_{52}	C_{53}	C_{54}
$\mu_{P_j}(r)$	0.594	0.303	0.603	0.444	0.178	0.498	0.538	0.408	0.669	0.736
$v_{P_j}(r)$	0.392	0.690	0.407	0.545	0.791	0.501	0.445	0.567	0.320	0.287

Table 7.13: The Weighted-Normalized Matrix for the Alternative A_1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}
$\mu_{P_j}(\dot{r})$	0.202	0.152	0.043	0.099	0.027	0.181	0.230	0.110	0.198	0.117
$v_{P_j}(\dot{r})$	0.934	0.954	0.987	0.973	0.995	0.948	0.913	0.966	0.935	0.962
	C_{33}	C_{34}	C_{41}	C_{42}	C_{43}	C_{44}	C_{51}	C_{52}	C_{53}	C_{54}
$\mu_{P_j}(\dot{r})$	0.150	0.062	0.158	0.122	0.042	0.126	0.122	0.074	0.185	0.224
$v_{P_j}(\dot{r})$	0.952	0.985	0.951	0.959	0.987	0.962	0.965	0.983	0.935	0.921

Table 7.14: The Ranking of Alternatives and Respective Indexes

	$\widetilde{P}_i$		$\widetilde{Q}_i$		Q_i	
A_i	$\mu_{P_j}(x)$	$v_{P_j}(x)$	$\mu_{P_j}(x)$	$v_{P_j}(x)$		**Rank**
A_0	0.735	0.217				
A_1	0.587	0.425	0.798	0.374	0.377	4
A_2	0.683	0.312	0.929	0.247	0.451	3
A_3	0.666	0.280	0.906	0.186	0.459	2
A_4	0.701	0.300	0.954	0.216	0.465	1
A_5	0.523	0.402	0.711	0.354	0.359	5

Step 13: Normalized preference relation matrix $\tilde{R} = [\tilde{r}_{ij}]_{mxn}$ is established. Table 7.12 display the normalized matrix for the alternative A_1 with respect to each criterion.

Step 14: Weighted-normalized preference relation matrix $\dot{\tilde{R}} = [\dot{\tilde{r}}_{ij}]_{mxn}$ is constructed using the criteria weights and normalized preference relation matrix. PFSs scalar multiplication operator is utilized to get the values of Weighted-Normalized matrix in Table 7.13 for alternative A_1 with respect to each criterion.

Step 15: Optimality Function Values and Alternative Utility Degree are determined through by the PFSs summation and division operators. Results are shown in Table 7.14.

Step 16: Alternatives are sorted by the Q_i values in an ascending order according to the conditions in Step 16 of the methodology. $\boldsymbol{A_4}$ is the chosen solution of the proposed method. The final ranking of alternatives is given in Table 7.14.

7.4. Discussions and Analyses

This research contributes to the development of a new approach for addressing judgments and consensus for GDM evaluation of partner selection and for the assessment of DSC partner in the supply chain industry. It provides a link between theory and practice in decision-making. Using the developed methodology, the best DSC partner can be selected. Second of all, this section has contributed to the discourse by demonstrating that PFSs' usability in different environments; that is, it gives better results when compared to other conventional theories.

Decision-making is a large part of every-day life. If a decision is taken by only one person, making that decision is relatively easy since an individual can make a quicker decision than a group can. Individual decision-making, however, could create a prejudice and bias when compared to a group's involvement. Many important decisions are made in GDM, and relatively recent literatures experimentally and theoretically demonstrate the systematic differences and excellency (Büyüközkan, Feyzioğlu, & Göçer, 2018; Büyüközkan & Göçer, 2017; F. Jin, Ni, Chen, & Li, 2016; Zeng, 2017). Hitherto, The ANP is a generalization of the AHP but many real-world decision-making problems cannot be constructed in a hierarchy due to the interaction and dependence of higher-level elements in a hierarchy on lower-level elements. ANP, however, has a specific property that gives an ability to consider inter dependencies among and between the levels of criteria and alternatives (Büyüközkan & Çifçi, 2012). ANP consists of at least one goal, criteria and clusters involving arrows between clusters or loops within clusters. The arrows and loops indicate the relationships among clusters or within clusters. This makes

ANP as a suitable technique to determine the criteria weights in decision-making problems. ARAS technique, on the other hand, has been recently proposed and heavily depends on the experience of DMs and the quality of their judgments. its advantages outweigh the disadvantages since it is a very effective and easy MCDM technique in which various decision-making problems are resolved, it is quite efficient to point out the best candidate among several alternative. It can effectively be extended into Fuzzy, IF, IVIF (Büyüközkan & Göçer, 2018a) and PFSs environments.

The extant review of literature suggests this is the first of its kind to integrate ANP and ARAS techniques under GDM with PFSs environment. The examined case study reveals that the proposed unique approach of PF-ANP and PF-ARAS integration gives better outcome compared to other methods. The criteria weights are evaluated under different objective world (Crisp Sets, Fuzzy Sets, IF Sets, PFSs) environments of ANP to see the effect of change in each criterion. The aim is to determine the variation between the criteria weights when the objective world is altered. Based on variation in criteria weights in Figure 7.6, the proposed methodology shows the flexibility and its capability of accepting various assumptions and conditions. The analysis reveals that there actually is some resemblance on the obtained weights among Crisp ANP-Fuzzy ANP and IF-ANP and PF-ANP. It is not a keen pattern but it is recognizable that IF Sets and PFSs divulges similar rankings in the criteria weights. Since a unified result had not been obtained in the combination of objective worlds, criteria weights were taken to check for any difference in ranking result. Thus, three MCDM methodologies existing in the literature are used as a comparison to validate the outcome of the proposed methodology. The Figure 7.7 elaborates how the proposed methodology performs better. The best alternative is same in three methodologies while it comes second in the PF-VIKOR and the worst alternative is the same in all. This analysis reveals that the proposed method is consistent and brings out the best alternative in a more flexible manner to confirm the credibility of the proposed approach.

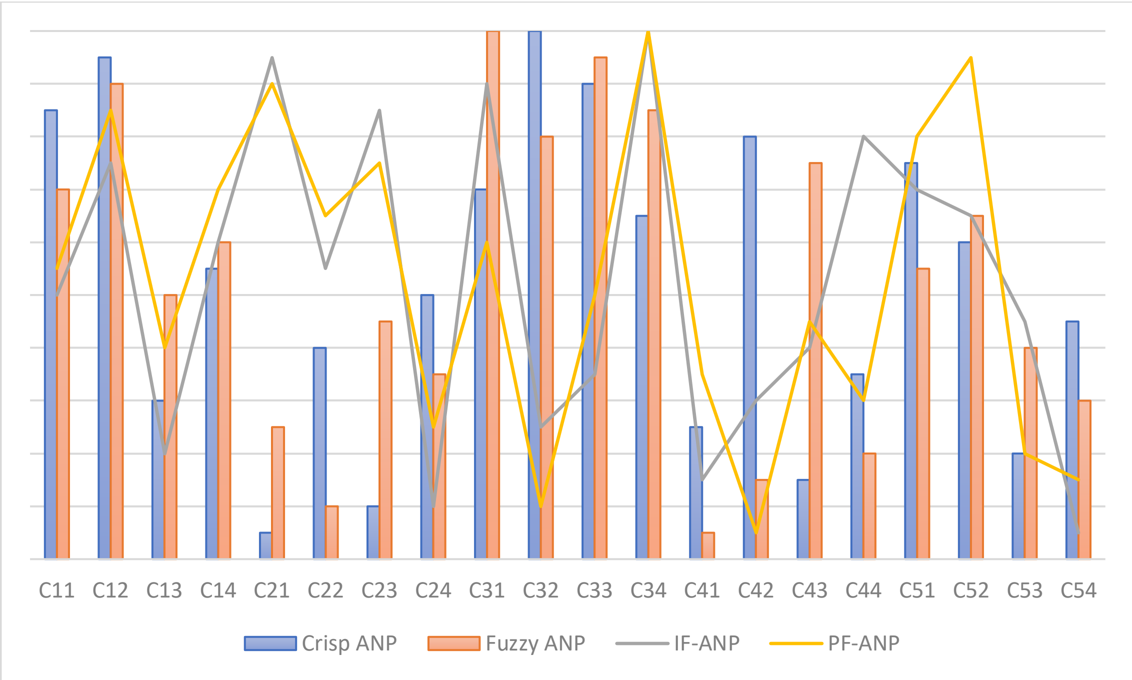


Figure 7.6: Criteria Sensitives under Different Objective World Environments

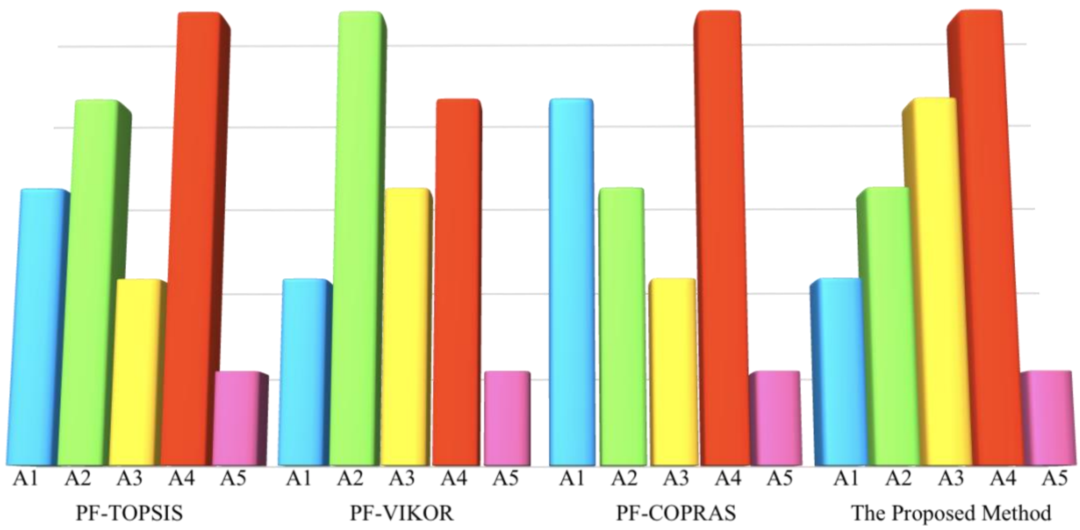


Figure 7.7: DSC PS Rankings for the Different MCDM Techniques

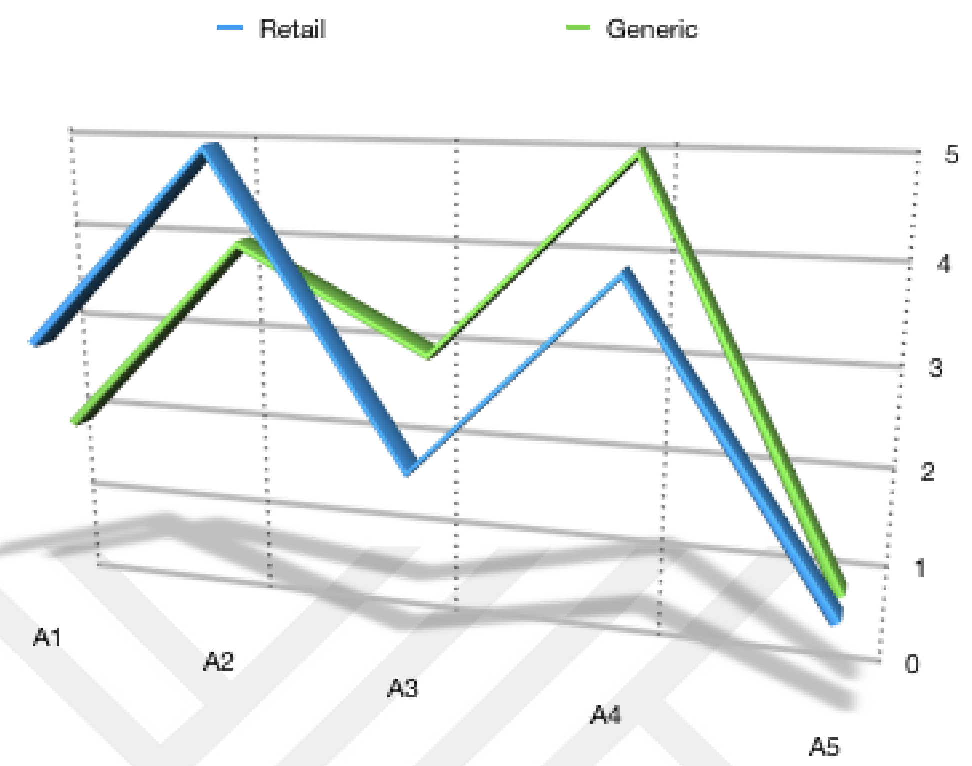


Figure 7.8: DSC PS Rankings for the Generic versus Retail Industry.

The cloud technologies, data analytics, mobile devices and internet, etc. will without a doubt transform all industries as well as retail industry. More devices than people will be connected to each other by 2020 (Büyüközkan & Göçer, 2018a). Therefore, it is essential for organizations to develop insights into how these changes will impact the business models supporting them. This is why retail industry should analyze advancing business models and plan how to integrate DSC into their existing operations. As it is obvious, the proposed analysis in the case study is compared to the retail industry. Therefore, in order to verify and validate the proposed methodology, this comparison is made through taking experts opinions in generic format and comparing it to retail industry results by the integrated PF-ANP and PF-ARAS methodology. Figure 7.8 display the comparison of the outcome for the generic and retail industry. The results show that although there are alterations in the rankings, it is foreseeable since different industries have different priorities to think about. The potential of the proposed methodology is clearly seen to bring out the best candidate into the light.

7.5. Concluding Remarks on DSC Partner Evaluation

In today's business environment, understanding of traditional rigid supply chains evolves into DSC. DSC partners can have ability to transform traditional chains into fully DSC in an easy and impeccable manner, that is DSC partner selection is an important step. When conventional crisp, fuzzy or IF sets are compared to PFSs, it is recognizable that PFSs provide greater opportunities in solving real case problems. As far as the authors aware of, ANP or ARAS techniques have not yet been integrated with PFSs and this research is a first of its kind to integrate these techniques under PFSs environment for GDM settings. DSC structure indicates the best partners that is imperative for enterprises. The methodology of DSC partner evaluation can now serve as a basis for the parties involved with DSC, as the enterprises must consider multiple criteria in decision-making. This study can also guide other supply chains to evaluate partners efficiently in their decision-making processes for digital transformation of being truly DSC organizations. The applicability of the proposed approach is demonstrated on a real DSC case with five partners. This research contributes to the state of study by providing a novel method for the first time and also by developing an evaluation methodology for a real case partner selection problem of a DSC. The functionality of methodology is tested and verified in PFSs environment. There are always several different paths possible for future research as a follow-up of this research. We make use of PFSs sets in this study. We could use of interval-valued PFSs and comparison of its results as a promising research topic. We could integrate other MCDM techniques with fuzzy, IF or PFSs to help explore method's effectiveness and also provide a novel scientific perspective.

8. CONCLUSIONS AND PERSPECTIVES

This final chapter presents the conclusions and perspectives from this thesis study. Limitations to the findings of this thesis and the influences to this study are presented. Future research possibilities are suggested based on the findings and limitations experienced in this research effort.

8.1. Conclusions on DSC

This thesis poses some questions, which stem from a need to better understand the role of digitalization in supply chains. This study conceptualizes and develops the dimensions of DSC practice (Digitalization Process, Technology Implementation Process, and Supply Chain Management Process) and designs the relationships between these DSC structure, competitive advantages, and organizational practice. A thorough review of prevalent DSC literature indicates that modeling and design of DSC is one of the main objectives of supply chain and logistics industry now. Thus, the purpose of this research is to provide an insight to the DSC through investigating existing literature in both academic and industrial world and, therefore, to identify the appropriate factors, to propose digitalization structure, to analyze the success and risk factors of this structure, and to plan technologic infrastructure, and also to evaluate technologic partner(s) of DSC.

Conventional MCDM methodologies are mainly rest on the use of crisp values. In real world problems, however, most of the multiple-choice problems occur in environments that are characterized by uncertain information that is mostly associated with some kind of vague, ambiguous and imprecision. Hence, the conventional MCDM methodologies do not provide adequate abilities to resolve such kind of problems and so extended into more encompassing environments (Büyüközkan & Göçer, 2018a). Fuzzy, IF, PFSs are some of the a few that are provided in the objective world. In order to fully grasp the objective world, an extension on fuzzy sets (Zadeh, 1965), IF sets (Atanassov, 1986), is defined in three aspects. Many researchers have widely studied the various aspects of the three, membership to support, non-membership to oppose, and hesitancy to neutral, respectively. Though IF sets able to express subjective opinions in a certain perspectives, recently Yager showed that there may be some cases in which the sum of membership and non-membership (supporters + opponents > 1) of the opinion of a DM is greater than one in the real world environment (Yager, 2014; Yager & Abbasov, 2013). For instance the case of student's qualification for a course, the teachers can indicate their membership to support as 0.7 and the non-membership to oppose as 0.4. It is clear that this is not allowed in IF sets since the sum is greater than one. Instead in PFSs theory, the sum of membership and non-membership can exceed one but the sum of squares cannot. This property gives much higher flexibility and ability to express the uncertain and vague information compared to IF sets. Thus, PFSs have better advantageous in imprecise and fuzzy modeling of objective world.

There are studies, mostly industrial reports to determine factors affecting DSC but the systematic approaches to define DSC requirements are practically absent. AD approach is the best way to address this problem. Thus, this thesis successfully models the digitalization structure for supply chains using AD theory. While DSC's ability to provide abundant benefits for enterprises, its implementation is a cumbersome process. This thesis aims to determine the factors that will support better implementation of DSC structure. Therefore, CM technique under PFSs GDM environment is successfully utilized to analyzing the success and risk factors of DSC structure. A recurring subject in literature on DSC is the technologies to support it. However, no study attempts to plan these technologies according to the requirements of DSC factors. In this thesis, QFD technique under PFSs GDM environment is successfully applied to analytically prioritize technologic requirements in order to plan technologic infrastructure of DSC. The other significant subject is to select a technology partner for DSC. An integrated MCDM approach under PFSs GDM environment for partner selection is successfully applied in this thesis. The above findings are few successful achievements of the many acquired throughout this thesis. These results have value to both the academic and industrial practice as they provide modeling and design of the widely held belief of the value of effective DSC.

8.2. Discussions on DSC

One of the most significant paradigm shift in the modern business management is that individual businesses no longer compete as solely autonomous entities, but rather as supply chains. In this emerging competitive market, digitalization has touched upon all aspects of enterprises, supply chains and logistics industry are no exception. Today, an emerging worldwide trend in SCM is a focus shift from the classical supply chain to DSC. And the way DSC, the broad concept that big data, cloud computing, self-driving vehicles, and internet of things, etc., will improve how the supply chains run, is top of mind for many scholars and industrial experts in SCM today.

Also discussed under similar terms like digitalization, smart factories, intelligent machines or Industry 4.0, DSC spans multiple technological enablers and includes its fair share of new introduced words to literature, but there is a strong evidence it's more than just a hype. According to annual survey of MHI's (Batty et al., 2017) for the next generation SCM, 80% of participants responded that the DSC will be the predominate model within the next five years, with just 16% saying it's already happening today. Similarly, a Capgemini survey (Dougados & Felgendreher, 2016) revealed that 50% of respondents believe "digital transformation" is "very important," yet only 5% is very satisfied with their progress to achieve it. Obviously, digitalization will change supply chains, but our understanding of how it will play out is a work in progress. Breaking down some of the enabling technologies should help SCM executives figure out how to embrace this new era.

8.3. Limitations and Further Research

This thesis is a state-of-the-art research within the given field of study on DSC. Therefore, it models and designs DSC, critically examines the digitalization of supply chains. As is the case with any research effort, this study is not without limitations. This thesis has also encountered a number of limitations. The following areas summarize these potential limitations:

- The methodological limitations of the study are related to the subjective focus of the analysis. For instance, the linguistic judgments are expressed by the expert relies on their past knowledge and experience and on their subjective assessments. Furthermore, the experts' assumptions and subjective evaluation have potentially an influence on the results, and this applies particularly to descriptive interpretations.

- The theoretical limitations of the study are related to the scope of the research. Although the goal is to cover all the steps in the process of DSC, the focus is limited to several factors. Therefore, there is a necessity for further analysis on the factors effecting the DSC.

- Another limitation is the fact that DSC context has a broad definition and like the DSC mentioned in this research it is not specified to a single industry. DSC might have different meanings for different industries.

Not forgetting the aforementioned limitations, the following future research trends on DSC are based on this elaborate study as well as the past working experience of authors. Further analysis of these suggestions can generate novel knowledge and robust theories in the area. Therefore, the following areas are proposed:

- As the literature has shown it is quite significant for executives to advance in building DSC enterprises. The severe consequences of disruptions can have a great negative influence on the performance of them. The pay offs of investing in DSC are not visible in the first place, though those who do build DSC have a big advantage in case of disruptions. In order to create a strategy to recover or to prevent disruptions effective utilization of DSC enablers is required.

- Enterprises from different industrial backgrounds have their own approach for DSC, depending on their specific purpose in using it. Current research on DSC is very broad. As mentioned in the former recommendation further research could be done on DSC with focus on specific types of industries. Therefore, key trends for future, necessitates a distinct roadmap for industry specific DSC modeling and design. The presented framework can, therefore, be further enhanced to inform both academics and practitioners by making sub-frameworks for each industry.

DSC is very far from deploying its full potential, and, as noted in this research, there are a number of areas that require immediate attention. In today's increasingly competitive global markets, enterprises that do not practice sound DSC may find themselves unable to compete with their competitors.

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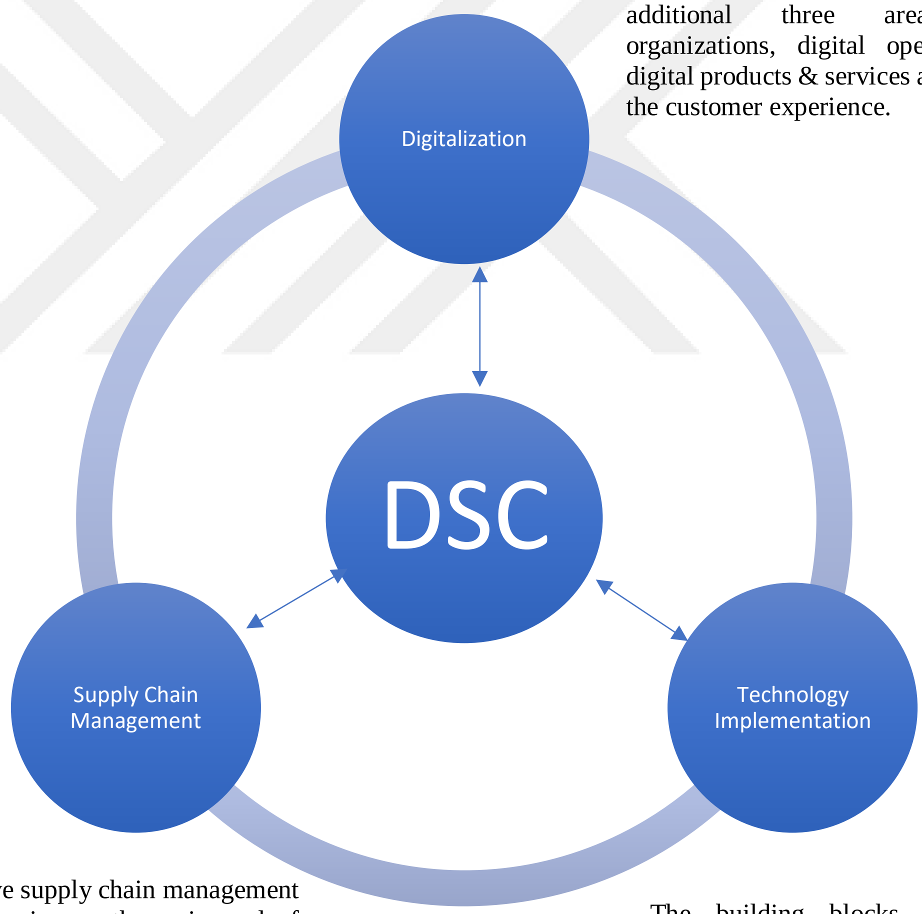
APPENDICES

Appendix A.

Digitalization often begins with a digitalization strategy and then extends to additional three areas: digital organizations, digital operations, and digital products & services and ends with the customer experience.



An effective supply chain management process focusing on the main goal of DSC transformation is enhanced with integration, analytics, automation, reconfiguration, and digital processes on plan, source, make, deliver, and return.

The building blocks of effective technology implementation process branches to technology enablers, project management, human and technology relationship, and formation of technology infrastructure.

Figure A.1: A Framework for the Development of DSC

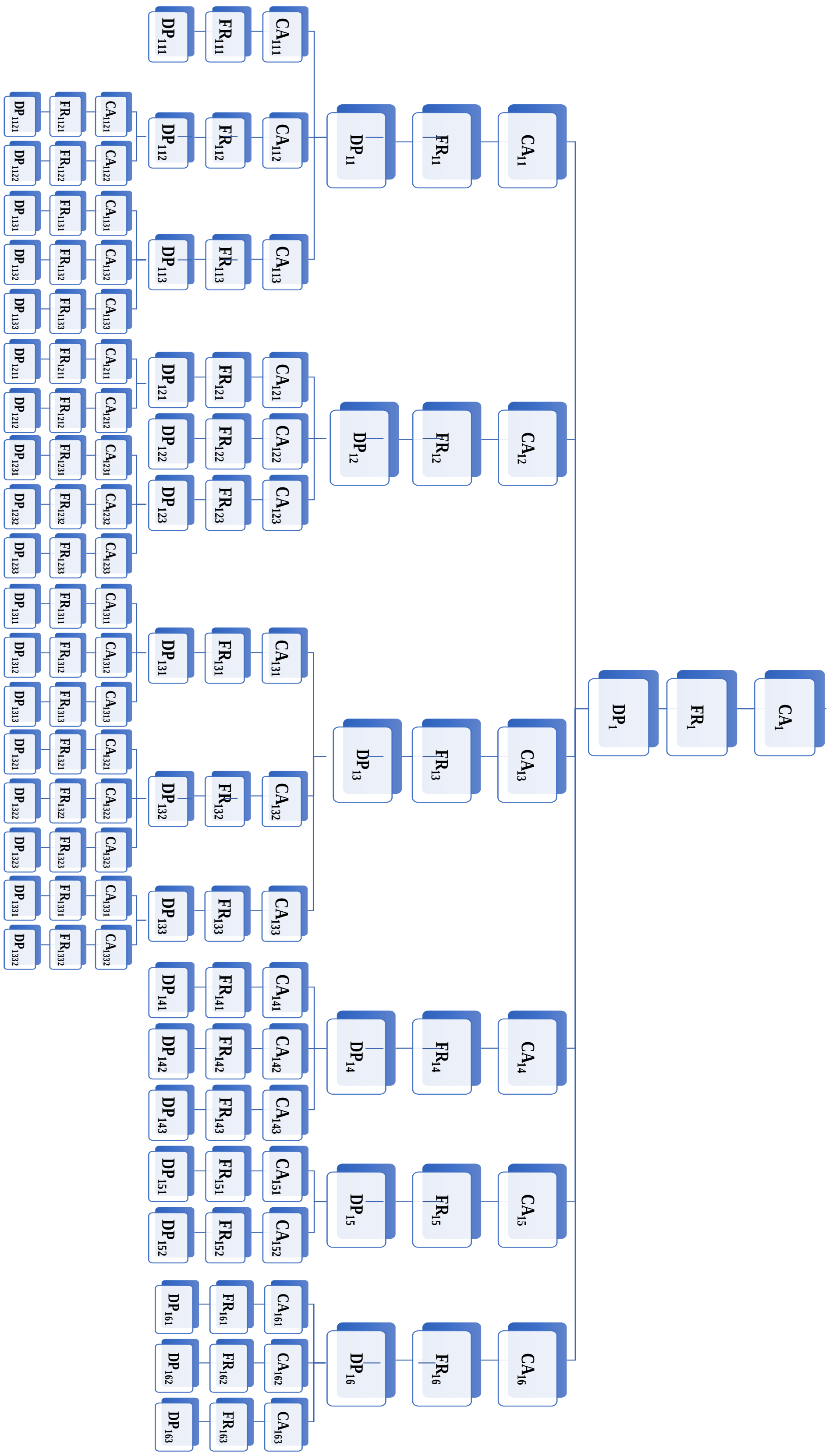


Figure A.2: AD Modeling of Digitalization Process for DSC

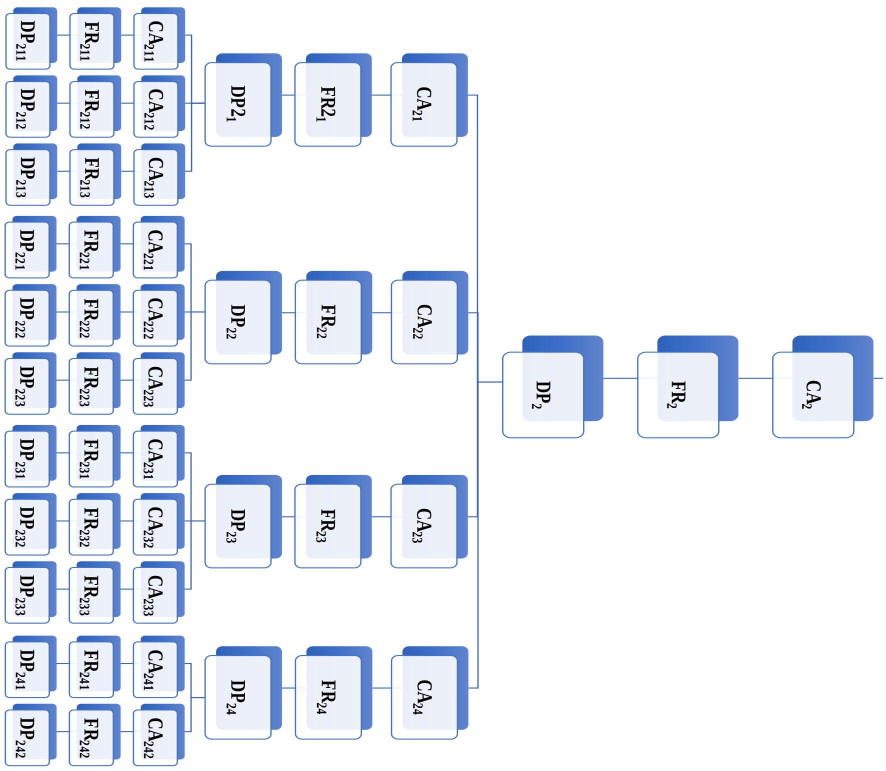


Figure A.3: AD Modeling of Technology Implementation Process for DSC

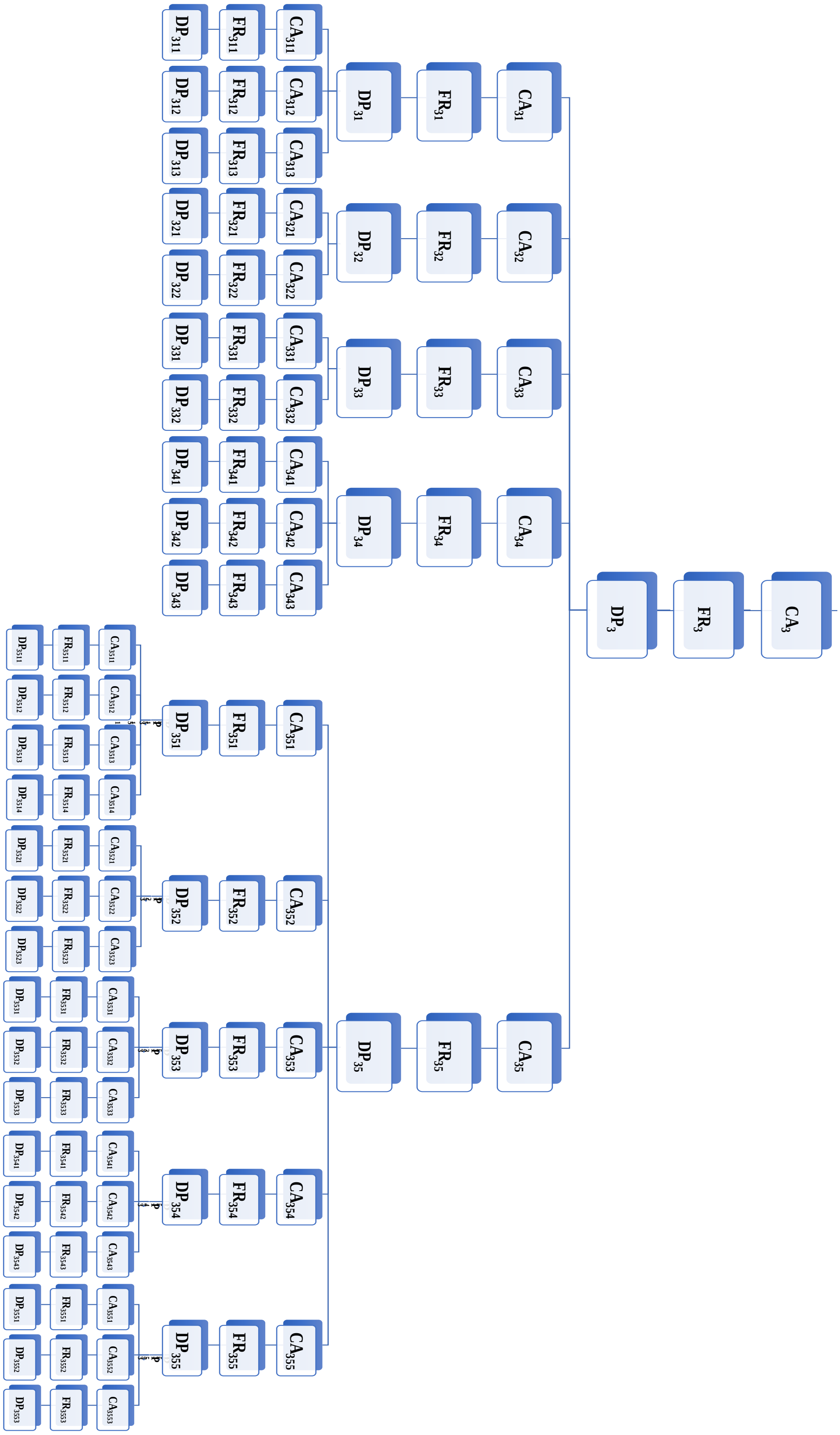


Figure A.4: AD Modeling of Supply Chain Management Process for DSC

Appendix B.

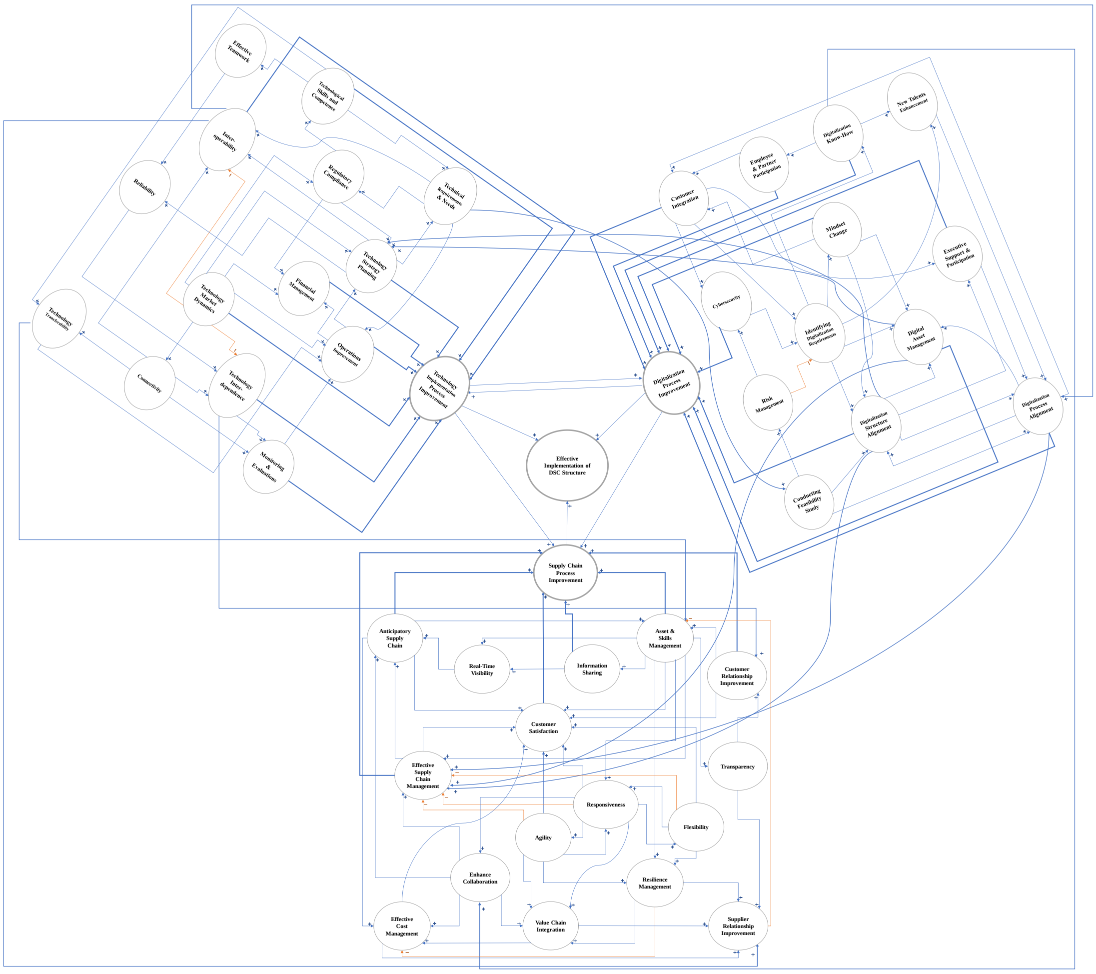


Figure B.1: The CM of Whole DSC Structure

Table B.1: Linguistic Judgments of Digitalization Process (DP)

DM	DP	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
1	VH	EL	EL	EL	EL	EL	EL	EL	M	L	EL	EL	L	EL
2	EH	EL	EL	EL	EL	EL	EL	EL	L	VH	EL	EL	VH	EL
3	VH	EL	EL	EL	EL	EL	EL	EL	VH	L	EL	EL	VH	EL
1	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	EL	L	EL	EL	EL	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EL	VL	EL	EL	EL	EL	EL	EL
1	VH	EL	M	EL	EL	EL	EL	EL	EL	EL	EL	M	EL	EL
2	VH	EL	VH	EL	EL	EL	EL	EL	EL	EL	EL	M	EL	EL
3	EH	EL	L	EL	EL	EL	EL	EL	EL	EL	EL	L	EL	EL
1	EH	EL	EL	L	EL	EL	EL	VH	EL	EL	EL	EL	EL	EL
2	M	EL	EL	L	EL	EL	EL	EH	EL	EL	EL	EL	EL	EL
3	VH	EL	EL	L	EL	EL	EL	EH	EL	EL	EL	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	M	VH	M	EL	EL	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	VH	VH	L	EL	EL	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EH	VH	L	EL	EL	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EL	EH
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EL	VH
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EL	VH
1	M	EL	EL	EL	EL	EL	EL	EL	EL	VH	EL	EL	VH	EL
2	M	EL	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	M	EL
3	VH	EL	EL	EL	EL	EL	EL	EL	EL	VL	EL	EL	M	EL
1	M	EL	EL	EL	M	EL	EL	VH	EL	EL	EL	EL	VH	EL
2	EH	EL	EL	EL	VH	EL	EL	EH	EL	EL	EL	EL	EH	EL
3	VH	EL	EL	EL	VH	EL	EL	VH	EL	EL	EL	EL	VH	EL
1	VH	EL	EL	EL	L	EL	EL	EL	EL	EL	VH	EL	EL	EL
2	M	EL	EL	EL	L	EL	EL	EL	EL	EL	EH	EL	EL	EL
3	M	EL	EL	EL	VL	EL	EL	EL	EL	EL	EH	EL	EL	EL

DM	DP	C_{1}	C_{2}	C_{3}	C_{4}	C_{5}	C_{6}	C_{7}	C_{8}	C_{9}	C_{10}	C_{11}	C_{12}	C_{13}
1	EL	L	EL	EL	EL	EL	EL	EL	VH	EL	EL	EL	VH	EL
2	EL	VL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	VH	EL
3	EL	L	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	VH	EL
1	VH	EL	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL
2	VH	EL	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL
3	EH	EL	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL
1	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	L	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
1	VH	EL	EL	EL	EL	EL	EL	EL	EL	EL	VH	EL	EL	EL
2	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EL	EL
3	VH	EL	EL	EL	EL	EL	EL	EL	EL	EL	VH	EL	EL	EL

Table B.2: Linguistic Judgments of Technology Implementation Process (TIP)

DM	TIP	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
1	EH	EL	EL	V	EH	EL	EL	EH	EL	EL	EL	EL	EL	EL	EL
2	V	EL	EL	EH	V	EL	EL	M	EL	EL	EL	EL	EL	EL	EL
3	V	EL	EL	V	M	EL	EL	V	EL	EL	EL	EL	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL	EL

DM	TIP	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
1	EH	EL	V	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EH
2	V	EL	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	V
3	V	EL	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	V
1	EL	EL	EL	V	V	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	EL	EL	EL	M	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	EL	EL	EL	L	L	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
1	EL	EL	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	EL	EL	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	EL	EL	V	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
1	EH	V	EL	V	EH	V	EL	EL	V	EL	EL	EL	EL	EL	V
2	V	EH	EL	EH	V	V	EL	EL	EH	EL	EL	EL	EL	EL	M
3	EH	V	EL	EH	EH	V	EL	EL	V	EL	EL	EL	EL	EL	V
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EH	EH	EL	EL	EH
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	M	V	EH	EL	EL	EH
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	V	EH	EL	EL	V
1	EL	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	EL	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	EL	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL

DM	TIP	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
1	EH	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EL	EL	EL	EL
2	V	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	EL	EL
3	M	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	EL	EL
1	EL	V	EL	EL	EL	EH	EL	EL	EL	EL	EL	EL	EL	EL	V
2	L	EH	EL	EL	EL	V	EL	EL	EL	EL	EL	EL	EL	EL	V
3	VL	EH	EL	EL	EL	V	EL	EL	EL	EL	EL	EL	EL	EL	EH
1	EH	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EH	EL	EL
2	V	EL	EL	EL	EL	EL	L	EL	EL	EL	EL	EL	M	EL	EL
3	EH	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	V	EL	EL
1	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL

Table B.3: Linguistic Judgments of Supply Chain Process (SCP)

DM	SCP	C_{27}	C_{28}	C_{29}	C_{30}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C_{38}	C_{39}	C_{40}	C_{41}	C_{42}
1	EL	EL	EL	EL	EL	V	EL	EH	EL	EL	EH	EL	EL	EL	EL	EL	V
2	EL	EL	EL	EL	EL	V	EL	M	EL	EL	V	EL	EL	EL	EL	EL	EH
3	EL	EL	EL	EL	EL	EH	EL	M	EL	EL	EH	EL	EL	EL	EL	EL	EH
1	EH	EL	EL	EL	EL	EL	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	V	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	EH	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL

DM	SCP	C_{27}	C_{28}	C_{29}	C_{30}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C_{38}	C_{39}	C_{40}	C_{41}	C_{42}
1	EL	EL	EL	EL	EL	V	EL	EL	EL	EH	EL	V	EL	EL	V	EL	V
2	EL	EL	EL	EL	EL	V	EL	EL	EL	V	EL	V	EL	EL	M	EL	EH
3	EL	EL	EL	EL	EL	M	EL	EL	EL	V	EL	EH	EL	EL	EH	EL	V
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	V	EL	EL	V	EL	V
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EH	EL	EL	M	EL	EH
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EH	EL	EL	EH	EL	V
1	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EL	VL	EL	EL	EL	EL	EL	EL	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL	EL	EL	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	L	L	EL	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	VL	VL	EL	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	L	EL	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	V	EL	EL	EL
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EH	EL	EL	EL
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	M	EL	EL	EL
1	EL	V	EL	EL	EL	V	EL	EL	EL	EL	EL	V	EL	EL	EL	EL	V
2	EL	M	EL	EL	EL	M	EL	EL	EL	EL	EL	EH	EL	EL	EL	EL	M
3	EL	M	EL	EL	EL	V	EL	EL	EL	EL	EL	EH	EL	EL	EL	EL	VL

DM	SCP	C_{27}	C_{28}	C_{29}	C_{30}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{37}	C_{38}	C_{39}	C_{40}	C_{41}	C_{42}
1	EH	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	EH	EL	EL	EL	EH	EL
2	M	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	V	EL	EL	EL	EH	EL
3	EH	EL	EL	EL	EL	EL	EL	M	EL	EL	EL	V	EL	EL	EL	EH	EL
1	V	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
2	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
3	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL
1	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL
2	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL
3	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EL
1	V	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	EH	EL
2	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	M	EL
3	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EL	V	EL	EL	EL	M	EL
1	EL	EL	EL	EL	EL	V	EL	V	EL	EL	EL	EL	V	EL	EL	EL	EL
2	EL	EL	EL	EL	EL	V	EL	EH	EL	EL	EL	EL	M	EL	EL	EL	EL
3	EL	EL	EL	EL	EL	V	EL	EH	EL	EL	EL	EL	M	EL	EL	EL	EL
1	EH	EL	V	EL	EL	EL	EH	EL	V	EH	EL	V	EL	EL	EH	EL	V
2	V	EL	EH	EL	EL	EL	V	EL	EH	V	EL	EH	EL	EL	V	EL	M
3	EH	EL	EH	EL	EL	EL	EH	EL	EH	M	EL	EH	EL	EL	V	EL	M
1	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	EH	EL	EL	EL	EL	EL
2	V	EL	EL	EL	EL	EL	EL	EL	EL	EL	M	V	EL	EL	EL	EL	EL
3	EH	EL	EL	EL	EL	EL	EL	EL	EL	EL	EH	V	EL	EL	EL	EL	EL

Appendix C.

Table C.1: The Linguistic Ratings of the CRs' Importance.

	Organization					**Process**			
	DM_1	**DM_2**	**DM_3**	**DM_4**		**DM_1**	**DM_2**	**DM_3**	**DM_4**
	VVH	EH	VVH	VH		VH	VVH	VH	H
CR_1	L	EH	VVH	H	**CR_{11}**	VH	VVH	H	L
CR_2	H	VVH	VH	F	**CR_{12}**	H	H	H	EH
CR_3	VH	H	VH	L	**CR_{13}**	H	VH	VVH	EH
CR_4	VVH	VH	H	EH	**CR_{14}**	F	F	H	VL
CR_5	L	H	H	VL	**CR_{15}**	VH	F	VH	L
CR_6	F	L	VH	H	**CR_{16}**	VVH	F	VH	VL
CR_7	H	F	H	L	**CR_{17}**	L	VH	VVH	L
CR_8	H	H	VVH	F					
CR_9	F	F	H	VL					
CR_{10}	H	F	VH	VL					

Table C.2: The Linguistic Ratings of the Relationships between the CRs and FRs for the First Iteration.

	FR_1	**FR_2**	**FR_3**	**FR_4**	**FR_5**	**…**	**FR_{24}**
	DM_5 | DM_6 | DM_7	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**		**DM_5 | DM_6 | DM_7**
CR_1	EL | VH | EH	F | EL | VVH	H | EL | VH	H | H | EL	F | EL | EL	…	VH | EL | EL
CR_2	F | VH | VH	VH | H | H	VH | EH | EH	H | F | F	F | VL | VL	…	EL | EL | EL
CR_3	H | F | VL	EL | F | VH	H | F | H	EL | EL | F	F | EL | EL	…	EL | VVH | EL
CR_4	H | EL | EL	VH | VH | VH	EL | H | VH	EL | EH | EH	EL | EL | EL	…	VH | EL | EL
CR_5	F | VH | VH	H | VL | H	VH | VVH | L	EL | EH | EL	EL | EL | EL	…	F | VH | EL
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
CR_{17}	VL | H | EL	VH | VVH | VH	EL | EH | EL	H | EL | H	EL | EL | EL	…	H | H | EL

Table C.3: The Linguistic Ratings of Correlation between FRs for the First Iteration

	FR_1	**FR_2**	**FR_3**	**FR_4**	**FR_5**	**…**	**FR_{24}**
	DM_5 | DM_6 | DM_7	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**		**DM_5 | DM_6 | DM_7**
FR_1	**EH | EH | EH**	H | VH | F	VH | L | F	EL | EL | F	EL | VH | H	…	VH | H | VL
FR_2		**EH | EH | EH|**	VH | VVH | H	VH | H | VVH	EL | F | L	…	EL | VH | EL
FR_3			**EH | EH | EH**	EL | VL | L	EL | VH | F	…	EL | F | VL
FR_4				**EH | EH | EH**	EL | L | EL	…	EL| L | EL
FR_5					**EH | EH | EH**	…	H | VH | H
. . .						. . .	. . .
FR_{24}							**EH | EH | EH**

Table C.4: The Linguistic Ratings of the Relationships between the CRs and FRs for the Second Iteration.

	FR_1^2	**FR_2^2**	**FR_3^2**	**FR_4^2**	**FR_5^2**	**…**	**FR_{32}^2**
	DM_5 | DM_6 | DM_7	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**		**DM_5 | DM_6 | DM_7**
CR_1^2	H | H | H	VH | H | VH	VH | F | H	VH | EL | VH	VH | F | VVH	…	F | EL | F
CR_2^2	H | VH | H	EL | EL | EL	F | F | EL	H | EL | F	EL | EL | EL	…	H | VH | L
CR_3^2	F | H | F	F | EL | F	L | H | H	H | H | H	EL | F | VL	…	F | EL | VL
CR_4^2	EH | VH | EL	EL | F | EL	VL | H | H	VH | F | F	EL | H | VVH	…	EL | EL | EL
CR_5^2	F | VH | F	H | EL | EL	EH | EL | F	H | EL | EL	EH | EH | VH	…	EL | L | EL
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
CR_{24}^2	H | EL | VVH	F | EL | EL	H | VL | EH	VH | H | H	VH | EL | EL	…	EL | EL | VL

Table C.5: The Linguistic Ratings of Correlation between FRs for the Second Iteration.

	FR_1^2	**FR_2^2**	**FR_3^2**	**FR_4^2**	**FR_5^2**	**…**	**FR_{24}^2**
	DM_5 | DM_6 | DM_7	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**	**DM_5 | DM_6 | DM_7**		**DM_5 | DM_6 | DM_7**
FR_1^2	**EH | EH | EH**	EL | H | F	H | F | L	F | VH | VL	EL | VL | L	…	F | H | EL
FR_2^2		**EH | EH | EH|**	F | EL | VH	L | VH | H	EL | L | EL	…	EL | L | EL
FR_3^2			**EH | EH | EH**	VH | H | F	EL | L | EL	…	EL | H | L
FR_4^2				**EH | EH | EH**	VH | VH | VL	…	EL | EL | F
FR_5^2					**EH | EH | EH**	…	VVH | VH | H
. . .						. . .	. . .
FR_{24}^2							**EH | EH | EH**

Appendix D.

Table D.1: PF-ANP Initial Super-Matrix

	Goal	
	$[\mu_P(x),$	$v_P(x)]$
DSCD₁	**0.435**	0.478
DSCD₂	**0.504**	0.360
DSCD₃	**0.495**	0.441

	DSCD₁		***DSCD₂***		***DSCD₃***	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$
DTM₁	0.075	0.303	0.755	0.563	0.751	0.565
DTM₂	0.576	0.700	0.075	0.303	0.502	0.688
DTM₃	0.578	0.695	0.714	0.454	0.075	0.303
DTM₄	0.606	0.656	0.511	0.479	0.610	0.711
SCMA₁	0.684	0.318	0.691	0.257	0.671	0.357
SCMA₂	0.674	0.281	0.733	0.203	0.608	0.368
SCMA₃	0.613	0.213	0.638	0.171	0.640	0.179
SCMA₄	0.630	0.315	0.578	0.363	0.637	0.262
SCMA₅	0.615	0.205	0.563	0.166	0.625	0.270
DI₁	0.728	0.386	0.791	0.344	0.689	0.404
DI₂	0.610	0.422	0.461	0.441	0.679	0.443
DI₃	0.678	0.389	0.728	0.405	0.678	0.387
DI₄	0.581	0.402	0.591	0.272	0.580	0.491
OT₁	0.816	0.520	0.816	0.520	0.711	0.610
OT₂	0.075	0.303	0.183	0.494	0.606	0.656
OT₃	0.656	0.606	0.289	0.595	0.494	0.183
OT₄	0.520	0.816	0.711	0.610	0.816	0.520
OT₅	0.656	0.606	0.075	0.303	0.075	0.303
OT₆	0.816	0.520	0.816	0.520	0.669	0.500
OT₇	0.711	0.610	0.075	0.303	0.289	0.595
OT₈	0.075	0.303	0.816	0.520	0.183	0.494
OT₉	0.610	0.711	0.494	0.183	0.075	0.303

	DTM₁		***DTM₂***		***DTM₃***		***DTM₄***	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$
DTM_1	0.656	0.606	0.791	0.344	0.689	0.404	0.678	0.420
DTM_2	0.716	0.511	0.461	0.441	0.679	0.443	0.656	0.381
DTM_3	0.711	0.610	0.728	0.405	0.678	0.387	0.608	0.373
DTM_4	0.075	0.303	0.591	0.272	0.580	0.491	0.569	0.507
$SCMA_1$	0.689	0.357	0.678	0.420	0.493	0.380	0.671	0.357
$SCMA_2$	0.660	0.306	0.656	0.381	0.582	0.278	0.608	0.368
$SCMA_3$	0.548	0.326	0.608	0.373	0.693	0.372	0.697	0.173
$SCMA_4$	0.674	0.326	0.569	0.507	0.659	0.316	0.745	0.282
$SCMA_5$	0.655	0.196	0.728	0.405	0.604	0.169	0.605	0.379
$PSEC_1$	0.618	0.372	0.675	0.223	0.718	0.210	0.684	0.175
$PSEC_2$	0.548	0.406	0.737	0.195	0.693	0.195	0.731	0.165
$PSEC_3$	0.589	0.288	0.551	0.298	0.664	0.213	0.594	0.148
$PSEC_4$	0.716	0.194	0.705	0.226	0.637	0.245	0.541	0.240
$PSEC_5$	0.671	0.261	0.716	0.192	0.721	0.179	0.649	0.235

	$SCMA_1$		***$SCMA_2$***		***$SCMA_3$***		***$SCMA_4$***		***$SCMA_5$***	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$
DTM_1	0.728	0.386	0.478	0.325	0.459	0.430	0.576	0.403	0.528	0.345
DTM_2	0.610	0.422	0.711	0.214	0.590	0.379	0.477	0.347	0.580	0.376
DTM_3	0.678	0.389	0.544	0.301	0.638	0.422	0.520	0.440	0.553	0.233
DTM_4	0.581	0.402	0.559	0.437	0.640	0.303	0.583	0.212	0.550	0.199
$SCMA_1$	0.627	0.365	0.689	0.357	0.634	0.394	0.764	0.344	0.689	0.357
$SCMA_2$	0.559	0.312	0.460	0.301	0.556	0.375	0.757	0.377	0.522	0.331
$SCMA_3$	0.682	0.278	0.651	0.328	0.679	0.394	0.667	0.280	0.634	0.325
$SCMA_4$	0.695	0.290	0.673	0.270	0.652	0.290	0.746	0.353	0.673	0.270
$SCMA_5$	0.621	0.231	0.655	0.196	0.683	0.345	0.614	0.403	0.690	0.250
DI_1	0.507	0.381	0.693	0.372	0.451	0.383	0.678	0.420	0.545	0.387
DI_2	0.614	0.301	0.639	0.358	0.615	0.285	0.587	0.426	0.613	0.356
DI_3	0.572	0.379	0.588	0.438	0.642	0.341	0.538	0.452	0.515	0.321
DI_4	0.595	0.308	0.655	0.338	0.623	0.445	0.625	0.383	0.576	0.242
$PSEC_1$	0.577	0.141	0.648	0.142	0.697	0.186	0.671	0.197	0.672	0.172

PSEC₂	0.434	0.255	0.672	0.211	0.712	0.166	0.594	0.090	0.665	0.149
PSEC₃	0.586	0.177	0.629	0.228	0.523	0.223	0.722	0.220	0.635	0.224
PSEC₄	0.737	0.195	0.573	0.247	0.664	0.242	0.666	0.232	0.636	0.240
PSEC₅	0.647	0.176	0.619	0.138	0.762	0.145	0.563	0.226	0.662	0.164

	DI₁		***DI₂***		***DI₃***		***DI₄***	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$
SCMA₁	0.700	0.365	0.636	0.385	0.611	0.408	0.675	0.373
SCMA₂	0.633	0.361	0.595	0.396	0.559	0.437	0.663	0.347
SCMA₃	0.662	0.331	0.703	0.296	0.794	0.321	0.667	0.280
SCMA₄	0.693	0.303	0.689	0.281	0.613	0.376	0.730	0.293
SCMA₅	0.665	0.328	0.672	0.306	0.697	0.302	0.642	0.362
DI₁	0.628	0.390	0.601	0.410	0.495	0.414	0.617	0.220
DI₂	0.616	0.351	0.568	0.302	0.682	0.396	0.513	0.183
DI₃	0.593	0.407	0.535	0.455	0.442	0.320	0.687	0.204
DI₄	0.635	0.385	0.567	0.223	0.613	0.327	0.476	0.241
OT₁	0.500	0.669	0.606	0.656	0.075	0.303	0.075	0.303
OT₂	0.711	0.610	0.075	0.303	0.610	0.711	0.650	0.394
OT₃	0.075	0.303	0.816	0.520	0.650	0.394	0.656	0.606
OT₄	0.669	0.500	0.650	0.394	0.606	0.656	0.595	0.289
OT₅	0.289	0.595	0.610	0.711	0.595	0.289	0.656	0.606
OT₆	0.711	0.610	0.816	0.520	0.711	0.610	0.289	0.595
OT₇	0.711	0.610	0.500	0.669	0.711	0.610	0.183	0.494
OT₈	0.075	0.303	0.075	0.303	0.075	0.303	0.075	0.303
OT₉	0.595	0.289	0.595	0.289	0.595	0.289	0.520	0.816
PSEC₁	0.636	0.131	0.697	0.186	0.671	0.197	0.661	0.159
PSEC₂	0.562	0.145	0.712	0.166	0.600	0.144	0.667	0.138
PSEC₃	0.622	0.168	0.551	0.198	0.719	0.166	0.578	0.117
PSEC₄	0.780	0.125	0.620	0.177	0.719	0.234	0.606	0.122
PSEC₅	0.658	0.111	0.644	0.152	0.563	0.226	0.689	0.140

	OT₁		***OT₂***		***OT₃***		***OT₄***		***OT₅***	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$
PSEC₁	0.660	0.315	0.707	0.154	0.627	0.143	0.717	0.268	0.587	0.364

PSEC₂	0.646	0.295	0.681	0.151	0.593	0.165	0.635	0.285	0.639	0.338
PSEC₃	0.617	0.195	0.541	0.183	0.583	0.189	0.590	0.182	0.622	0.177
PSEC₄	0.638	0.294	0.710	0.212	0.776	0.236	0.567	0.183	0.664	0.339
PSEC₅	0.612	0.204	0.498	0.146	0.686	0.209	0.605	0.209	0.618	0.179
	OT₆		***OT₇***		***OT₈***		***OT₉***			
PSEC₁	0.656	0.325	0.667	0.152	0.650	0.394	0.075	0.303		
PSEC₂	0.666	0.267	0.651	0.150	0.394	0.650	0.656	0.606		
PSEC₃	0.640	0.235	0.568	0.158	0.183	0.494	0.595	0.289		
PSEC₄	0.677	0.434	0.704	0.180	0.075	0.303	0.606	0.656		
PSEC₅	0.614	0.229	0.638	0.161	0.595	0.289	0.650	0.394		

	$PSEC_1$		$PSEC_2$		$PSEC_3$		$PSEC_4$		$PSEC_5$	
	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$	$[\mu_P(x),$	$v_P(x)]$
$PSESC_{11}$	0.805	0.044	0.075	0.303	0.816	0.520	0.656	0.606	0.289	0.595
$PSESC_{12}$	0.845	0.031	0.669	0.500	0.289	0.595	0.289	0.595	0.500	0.669
$PSESC_{13}$	0.827	0.042	0.595	0.289	0.595	0.289	0.183	0.494	0.394	0.650
$PSESC_{14}$	0.849	0.037	0.394	0.650	0.289	0.595	0.075	0.303	0.816	0.520
$PSESC_{21}$	0.827	0.026	0.520	0.816	0.075	0.303	0.520	0.816	0.075	0.303
$PSESC_{22}$	0.824	0.022	0.500	0.669	0.075	0.303	0.075	0.303	0.650	0.394
$PSESC_{23}$	0.810	0.034	0.075	0.303	0.610	0.711	0.669	0.500	0.394	0.650
$PSESC_{24}$	0.810	0.036	0.500	0.669	0.650	0.394	0.595	0.289	0.183	0.494
$PSESC_{31}$	0.823	0.025	0.650	0.394	0.606	0.656	0.394	0.650	0.075	0.303
$PSESC_{32}$	0.754	0.026	0.595	0.289	0.595	0.289	0.520	0.816	0.595	0.289
$PSESC_{33}$	0.723	0.037	0.289	0.595	0.711	0.610	0.500	0.669	0.816	0.520
$PSESC_{34}$	0.771	0.034	0.669	0.500	0.075	0.303	0.075	0.303	0.289	0.595
$PSESC_{41}$	0.743	0.038	0.075	0.303	0.669	0.500	0.500	0.669	0.595	0.289
$PSESC_{42}$	0.825	0.032	0.494	0.183	0.595	0.289	0.650	0.394	0.289	0.595
$PSESC_{43}$	0.818	0.038	0.289	0.595	0.669	0.500	0.595	0.289	0.075	0.303
$PSESC_{44}$	0.831	0.032	0.650	0.394	0.394	0.650	0.289	0.595	0.816	0.520
$PSESC_{51}$	0.789	0.043	0.394	0.650	0.500	0.669	0.669	0.500	0.289	0.595
$PSESC_{52}$	0.832	0.033	0.183	0.494	0.075	0.303	0.075	0.303	0.075	0.303
$PSESC_{53}$	0.846	0.030	0.075	0.303	0.494	0.183	0.494	0.183	0.610	0.711
$PSESC_{54}$	0.790	0.034	0.595	0.289	0.650	0.394	0.289	0.595	0.669	0.500

BIOGRAPHICAL SKETCH

Fethullah Göçer was born in Elbistan, Turkey on December 25, 1984. For his secondary education, he attended Elbistan İHL High school and graduated in 2001. He attended Süleyman Demirel University Technical Education faculty between 2002 and 2003. He started his undergraduate education in Industrial Engineering at University of Toronto, Canada in 2006 and transferred to Girne American University, Northern Cyprus in 2008. He received his degree in Bachelor of Science from Girne American University in 2010. Upon graduation, he went abroad for work experience. He has worked as a Site Engineer for a private company in Sierra Leone between 2010 and 2011. In 2012, he is placed to Kahramanmaraş Sütçü İmam University as a research assistant within OYP program of Turkish Council of Higher Education. He is appointed to Galatasaray University as a research assistant to complete his graduate education in Industrial Engineering area. He completed his Master of Science in 2014 and started his education in Doctor of Philosophy in the Graduate School of Science and Engineering. He is currently working as a research assistant in the Graduate School of Science and Engineering department at Galatasaray University. He has published several Science Citation Indexed papers and many proceeding papers in the field of Engineering. He has also published following two Science Citation Indexed papers emanated from this thesis during the preparation.

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