DESIGNING AND IMPLEMENTING A COLLABORATIVE STRUCTURE FOR PRODUCT DEVELOPMENT

(ÜRÜN GELİŞTİRME İÇİN İŞBİRLİKSEL BİR YAPININ TASARLANMASI VE UYGULAMAYA KONMASI)

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Jbid Ani ARSENYAN ÜŞENMEZ

TABLE OF CONTENTS

LIST OF SYMBOLS

AD	Axiomatic Design
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CA	Customer Attribute
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CMMI	Capability Maturity Model Integration
CORBA	Common Object Request Broker Architecture
CPD	Collaborative Product Development
CI	Consistency Index
CR	Consistency Ratio
CRM	Customer Relationship Management
CSD	Collaborative Software Development
DFSS	Design for Six Sigma
DP	Design Parameter
EC	Engineering Characteristics
ERP	Enterprise Resource Planning
FR	Functional Requirement
FRBS	Fuzzy Rule Based System
HoQ	House of Quality
HTML	HyperText Markup Language
IC	Information Content
IT	Information Technology
LIS	Library Information System
MADM	Multi Attribute Decision Making

MCDM	Multi-Criteria Decision Making
PD	Product Development
PERT	Program Evaluation and Review Technique
QFD	Quality Function Deployment
R&D	Research and Development
RFID	Radio Frequency Identification
RI	Random Index
SD	Software Development
SME	Small and Medium Enterprises
STEP	Standard for the Exchange of Product Model Data
SWOT	Strengths Weaknesses Opportunities Threats
TFN	Triangular Fuzzy Number
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRIZ	Theory of Inventive Problem Solving
UML	Unified Modelling Language
VRML	Virtual Reality Modeling Language
XML	Extensible Markup Language

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

In today's market, product development (PD) emerges as a business strategy to sustain competitive advantage and the complexity of the process compels firms to seek collaboration. However, collaborative PD (CPD) comes out as difficult to manage with its multi-cultural, multi-spatial, interdisciplinary teams. This study aims to propose a holistic structure to aid CPD practitioners throughout the process. An Axiomatic Design (AD) based three dimensional generic CPD structure is constructed initially and the structure is further decomposed within the collaborative software development (CSD) scheme. Then these three dimensions are investigated separately. Partner selection, the conditions of collaboration formation, and technology planning problems are handled with fuzzy multi-criteria decision making, game theory principles, and an integrated fuzzy approach, respectively. Applications of the proposed model are conducted within CSD processes. Four major outcomes are observed. The decomposition model helps managers to keep track of the CPD process. The partner selection model enables the decision makers to express their priorities and evaluate project targets separately. The bargaining model suggests that revenue sharing strongly depends on the knowledge stocks and mutual trust. The technology planning model provides an investment path regarding the project requirements.

The study presents guidelines for CPD in general, for CSD in specific, and is endorsed by case studies and applications in software industry. The AD based decomposition structure and the partner selection, collaboration formation, and technology planning models provide CPD practitioners with more control over the process, which results in improved CPD performance.

RESUME

Dans l'état actuel du marché mondial, le développement de produit (DP) se manifeste comme une stratégie des affaires pour créer un avantage compétitif. La complexité du processus oblige les sociétés à collaborer pour faciliter le DP. Toutefois, avec des équipes multiculturelles, multi spatiales et interdisciplinaires, le DP en collaboration (DPC) devient difficile à gérer. Cette étude propose une approche holistique pour le DPC. Une structure générique tridimensionnelle de DPC est construite par le Design Axiomatique (DA) et la décomposition est étendue dans le cadre du développement de logiciel en collaboration (DLC). Puis, les trois dimensions sont analysées séparément. Les problèmes de choix de partenaire, de négociation de la collaboration et de planification technologique sont traités à l'aide de la décision multicritère floue, de la théorie des jeux et une méthodologie floue intégrée. Les modèles proposés sont appliqués au sein du processus DLC et ils permettent aux décideurs à exprimer leurs priorités et les cibles du projet séparément pendant la sélection de partenaire, définit la quantité de partage des revenues, et fournit une voie d'investissement pour les besoins du projet.

La présente étude offre dans son ensemble des indications pour DPC en générale, pour DLC en spécifique, soutenue par des études de cas et par des applications dans l'industrie de logiciel. La structure de décomposition et les modèles de choix de partenaire, de formation de collaboration et de planification technologique donnent aux praticiens de DPC plus de control sur le processus et augmentent la performance de DPC.

ÖZET

Günümüzün rekabetçi pazarında; şirketler, rekabetçi avantajı elde tutabilmek için ürün geliştirme (ÜG) stratejisini benimsemişlerdir. ÜG'nin karmaşık yapısı ise, süreci hızlandırmak ve kolaylaştırmak amacıyla, işbirliği yapılmasını gerekli kılmaktadır. Fakat işbirliksel ÜG (İÜG), farklı kültür ve yerlerden gelen disiplinlerarası ekiplerin varlığıyla yönetilmesi güç bir süreçtir. Bu çalışmanın amacı, bütünsel bir İÜG yapısı ortaya koyarak uygulayıcılara yol gösterici olmaktır. Öncelikle Aksiyomlarla Tasarım (AT) tabanlı genel bir İÜG yapısı ortaya konmuştur ve bu üç boyutlu yapı işbirliksel yazılım geliştirme (İYG) çerçevesinde ayrıntılandırılmıştır. Ardından bu üç boyut ayrı ayrı ele alınmıştır: bulanık çok ölçütlü karar verme teknikleri ile ortak seçimi, oyun teorisi prensipleri ile işbirliği koşulları, bütünleşik bulanık bir yaklaşım ile teknoloji planlama problemleri incelenmiştir. Geliştirilen bu modeller İYG süreçlerinde uygulanmış ve sınanmıştır. Dört başlıca sonuç gözlemlenmiştir. Kavramsal model, İÜG süreci üzerindeki kontrolü arttırır. Ortak seçim modeli, karar vericilerin kişisel önceliklerini ve proje hedeflerini ayrı ayrı değerlendirebilmelerine imkan tanır. Pazarlık modeli, şirketlerin bilgi birikimlerinin ve karşılıklı güvenin gelir paylaşımı üzerinde etkili olduğunu öne sürer. Teknoloji planlama modeli ise proje gereksinimlerine göre bir yatırım önerileri geliştirir.

Bu çalışmada genelde İÜG, özelde İYG çalışmaları ele alınmıştır. Yazılım sektöründeki vaka analizi ve uygulamalar ile sınanan kavramsal modellerin, işbirliksel çalışmalarda bir kılavuz niteliği taşıması hedeflenmiştir. AT tabanlı yapı ve ortak seçimi, işbirliği oluşumu ve teknoloji planlama modelleri İÜG uygulayıcılarına süreç üzerinde daha fazla kontrol imkanı tanır ve İÜG performansının arttırılmasına yardımcı olur.

1 INTRODUCTION

The increasing pressure of global competitiveness compels enterprises to put more emphasis on product development (PD) and innovation. An effective PD process requires the integration of multiple competencies, coordination of interdisciplinary teams, and various knowledge inputs [**1**]. In this business environment, collaborative product development (CPD) emerges as a business strategy to share risk, reduce cost, improve quality, increase flexibility, and enhance competitiveness for the complex and challenging PD process [**2**,**3**].

CPD involves the coming together of different enterprises and the cooperation of cross functional teams for the development process. This involvement may occur at different stages of the value chain range, from consultation of suppliers within the product design process to the assignment of full responsibility during the production process [**2**,**4**]. Either way, CPD is a complicated process to manage.

Large corporations are already a major part of collaboration scheme with well-established cooperation with their suppliers, Research and Development (R&D) groups, universities, and even their customers. Companies such as IBM, Dell, and Glaxo set examples of successful CPD projects and collaboration know-how [**3**,**5**]. Small and Medium Enterprises (SMEs), on the other hand, are not as successful in the collaboration game as their big competitors. This lack of experience often results in CPD failures and therefore harms the collaborators' economy.

Poorly managed and miscoordinated CPD projects not only cause monetary loss but also result in time, resource, and knowledge waste. As industrial engineers, it is in the scope of our profession to prevent waste and achieve productivity by identifying main issues and developing guidelines. Accordingly, it is an apparent necessity to develop a generic structure for CPD that puts forward the rules to design and implement a collaborative process. In an economical state where 99% of all enterprises are SMEs worldwide and in Turkey [**6**,**7**], it is vital to institute some ground rules for SME managers in order to reduce risks and failures arising from CPD. This industrial need institutes the scope of this research, where we aim to develop a holistic approach to CPD at a managerial level.

For this purpose, first a systematic structure must be put forward for CPD, given that the effectiveness of the CPD depends on the system architecture [**4**]. A literature overview is conducted to examine the approaches presented by the CPD research. This analysis clearly suggests three main aspects: CPD dynamics, CPD partnerships, and CPD technologies. However, it is obvious that there is a lack of a systematic approach embracing these main aspects within a conceptual framework.

In addition, this study put special emphasis on the Turkish software industry, which consists mainly of SMEs. Given that it provides more than the half of the national employment and ranks as the fifth in R&D efforts [**8**], the dynamic and collaborative nature of this industry provides an exceptional area to develop and test the proposed approaches. Experts from the software industry are consulted throughout this study. Consequently, the presented work designs the CPD process from a general perspective and focuses on collaborative software development (CSD) for the implementation stage.

This study attempts to put forward a structure with the objective of *improving the performance of CPD (in general) and CSD (in specific)*. This main objective encloses four sub-problems, which summarize the points of performance improvement while initiating and conducting a CPD project:

- Need for general CPD guidelines
- Need to evaluate and select CPD partners
- Need to establish collaboration conditions
- Need to plan technological infrastructure for CPD

Figure 1.1 presents a recapitulative visual on the sub-problems, inputs of each research problem, the techniques employed to tackle the problem, and the output of the research.

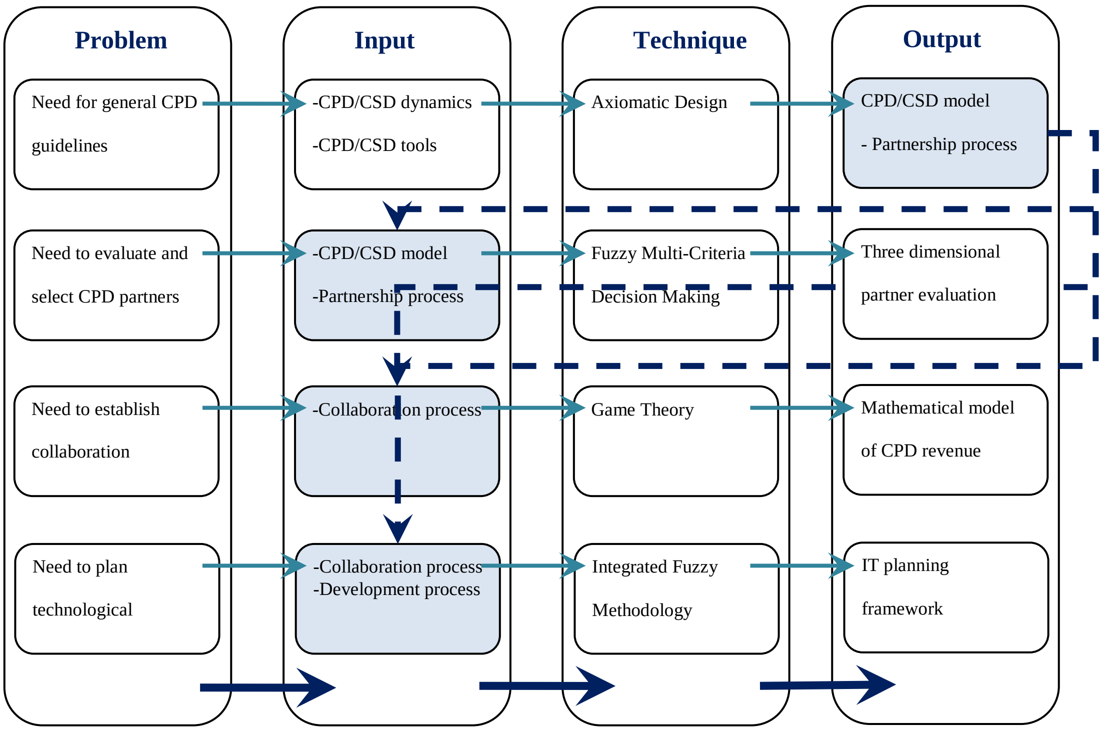


Figure 1.1 Research scope

Initially, a conceptual CPD model is developed. Given that a modelling framework with a top-down approach is required for this purpose, Axiomatic Design (AD) is employed to decompose and detail CPD into its constituents i.e., goals to achieve, strategies to follow for these goals, and methodologies to implement to fulfil these strategies. The AD based conceptual CPD model is expected to provide a map to of these constituents and highlight critical milestones. Two interviews are organized for the evaluation of the model, which is further detailed for the software development (SD) process following the experts' feedback. The performance of the conceptual model is evaluated within a case study in an SD process.

The three main dimensions presented in the conceptual model are then employed as an input for further research. These three dimensions are related to the three main aspects of CPD literature and are defined as the partnership process, the collaboration process, and the product development (PD) process.

A partner evaluation framework for CPD is proposed with a criteria set gathered from literature, and this set is improved by industrial feedback. The criteria set is three dimensional as the conceptual model: partner-focused criteria, collaboration-focused criteria, and development-focused criteria. Fuzzy multi-criteria decision making (MCDM) methodology, integrating Fuzzy Analytic Hierarchy Process (AHP) into Fuzzy AD, is proposed to evaluate and select partners. Fuzzy AHP provides a criteria weighting mechanism while Fuzzy AD assesses the partner performance in response to the requirements. Two case studies within a CSD project are conducted to observe the experts' approach to the importance of criteria and their perception of CSD partner evaluation.

Then the study focuses on the collaboration process, which employs the collaboration dimension of AD based structure as an input. A mathematical model is introduced to analyze negotiation conditions within the CPD. The model includes the four dimensions of the collaboration process: trust, coordination, co-learning, and co-innovation. These four dimensions, enhanced with other aspects such as knowledge investment, knowledge complementarity, coordination cost, etc. are reflected in the profit functions of the CPD partners. As game theoretical principles provide an appropriate basis for the analysis of this model, a game theoretical approach, namely Nash Bargaining, are applied to define the equilibrium, and different scenarios are analyzed in order to observe the behaviour of the model under diverse collaboration environments. Collaboration conditions are investigated for each partner pair, even though CPD may comprise more than two partners. Scenario analysis is conducted with the data of the CSD experiences of our industrial expert.

The final phase of this study focuses on the technological aspect of CPD. Before beginning the project, the planning of a collaborative and technological infrastructure is needed in order to manage and control the development process as the AD based model emphasizes the importance of Information Technologies (IT) within the collaboration network. The lack of a holistic managerial approach necessitates the identification of the technological requirements. CPD technologies literature is reviewed, and the experts are consulted in order to define these requirements, and then system features presented by researchers and commercial packages are investigated. Being a widely known planning methodology, House of Quality (HoQ) within the Quality Function Deployment (QFD) framework is employed to map the requirements versus the system features, and the methodology is enhanced with supporting techniques such as Fuzzy Sets Theory, AD, and Fuzzy Rule Based Systems (FRBS) in order to plan the investment path. The methodology is tested in a CSD case where a technology investment plan is proposed for the collaborative partners.

The four research areas seek to cover all the main aspects of CPD from a managerial perspective. The decomposition of the process into its major high points assures traceability and manageability of collaboration process by foreseeing risks and resolving conflicts before they arise. It is aimed to provide a roadmap for SME managers in their collaborative venture by offering general guidelines and defining general rules for the main steps of CPD. From an industrial engineering point of view, the analytic approach to the complex and problematic CPD benefits business as it seeks to minimize defects while improving the process.

As technology is yet to reach its saturation point, enterprises will keep on changing to adapt to new business processes compatible with rapid technological change. However, this rapidity precedes conceptual structures presenting guidelines on how to conduct the business process. This lack of standardization results in high failure rates and disables companies, especially SMEs, in the highly competitive market dominated by the major enterprises expert in the collaboration domain. It is therefore indispensable to design and implement a CPD structure from a managerial perspective for improved CPD performance. The following sections introduce CPD and its main concepts and present the four main problems covered in this research.

2 COLLABORATIVE PRODUCT DEVELOPMENT LITERATURE

The rapid growth of the global market drives organizations to invest further in NPD in order to maintain a competitive advantage [**9**]. Technological improvement combined with market experience provides sustainability as well as economic gain. PD involves competing goals of minimizing risk by acquiring sufficient market information while reducing costs and time to market, thus escalating the importance of the PD process design and implementation [**10**]. Therefore, PD holds a critical position in the business agenda [**11**].

However, the complex nature and uncertain environment which surround PD, lead organizations toward collaboration in order to share risks, reduce costs and time-to-market, improve quality, and benefit from complementary knowledge and competence throughout the PD process [**2**,**10**,**12**]. One third of the formal agreements worldwide are motivated by joint PD and the number increases to two thirds when eventual production and/or marketing of the products are also included [**12**]. The real source of sustainable competitive advantage develops with the ability to become involved and create value in innovation and improvement processes within inter-company collaborations [**13**].

PD collaborations can be defined as two or more partners joining complementary resource and experience with mutual aims, in order to design or develop a new or improved product. Recent literature highlights the importance of CPD and many researchers discuss its applications [**14**] under various concepts such as networks of companies, virtual organizations, customer-supplier collaboration, extended (manufacturing) enterprises, dynamic networks, strategic alliances, and joint ventures [**13**]. However, while improving the efficiency and effectiveness of PD demands effort, collaboration is a complex process to manage as well. Moreover, high CPD costs result from elevated failure rates. Therefore, CPD requires meticulous execution.

This study aims to examine CPD literature by reviewing studies dealing with various aspects and issues of collaboration in PD, and to identify the shortcomings of the literature and future research directions. It also aims to present a conceptual framework recapitulating the main issues affecting CPD on a strategic level.

The chapter is organized as follows: in the next section, PD and CPD are described. Furthermore, motivating factors, critical success factors, and limitations of CPD are explored. The following section reviews CPD studies in three categories (CPD dynamics, partner formation in CPD, and CPD infrastructure) and discusses the limitations of CPD literature as well as possible directions in CPD. Latter section of the chapter presents a conceptual framework for CPD, derived from the literature overview. The final section contains concluding remarks.

2.1 RESEARCH BACKGROUND

In a market where competitive pressures surround the industry, organizations face the demand for customized solutions, high quality products, short time-to-market, and lower costs. To ensure survival and continued prosperity, businesses must meet these challenges by providing a constant stream of new and improved products, processes, and services [**15**]. PD and innovation emerges consequently as a key process of competition and sustainability [**11**]. Innovation puts continual pressure on PD teams to produce a wider portfolio of new product opportunities and to manage the risks associated with advancing these portfolios from initial development to eventual launch [**9**]. Innovation concerns engineers, product designers, manufacturers, customers, and the technological infrastructure. In order to obtain the best performance from the process, efficient and effective management of the PD is vital. Also, literature suggests that speeding up the PD process is an important way to gain a competitive advantage in the market [**16**].

However, Yeh et al. [**17**] state that even though utilization of appropriate tools and techniques in the process of PD can assist firms in achieving better performance in launching new products, in practice many useful tools and techniques are not utilized effectively. In addition, the manufacturing environment is characterized by rapid change and heightened levels of competition that demand flexibility, increased delivery speed, and innovation [**18**]. Therefore, PD is becoming not only more important to organizations, but also more complex, often involving many different areas of skill and expertise as markets and technologies converge, product lifecycles shorten and technological change becomes increasingly rapid, leading to pressure to reduce PD periods [**2**]. As a consequence of this complex environment, only 14% of PD efforts turn out to be successful [**9**], and organizations seek ways to decrease PD times while simultaneously improving quality and reducing costs [**17**]. Inter-firm collaborations emerge in order to share PD risks and costs as well as shorten time-to-market and obtain additional benefits, such as reducing R&D costs, increasing market share, and exchanging expertise.

2.1.1 Collaboration in Product Development

CPD is "any activity where two (or more) partners contribute differential resources and know-how to agreed complementary aims in order to design and develop a new or improved product" [**19**]. By combining the strength and expertise of the best diverse and geographically dispersed PD teams, better mission scenarios, designs, and the corresponding products and technologies can be developed in less time [**2**]. In many industries, particularly those involving complex products and services, R&D is already conducted as a collaborative process [**13**,**20**].

Recent literature has widely addressed the belief that CPD and participation in a collaborative network of enterprises is commonly assumed to bring valuable benefits to the involved entities, including an increase in the "survival capability" in a context of market turbulence as well as the possibility of better achieving common goals [**21**]. However, despite its benefits, such as access to new skills, reduced time-to-market, innovation, expanding the market, and PD flexibility, CPD is a rather complicated and difficult issue.

CPD, in brief, can be defined as a collaborative process overlapping with the PD process [**22**]. Table 2.1 summarizes other definitions of CPD mentioned in literature underlining various aspects of the process. Another CPD definition can be developed following the various definitions in CPD literature:

CPD is a technology centred process including two or more partners with diverse competence, experience, culture, skill and location joining complementary resources to design/develop new/innovative/improved products in order to gain competitive advantage, innovate, explore new markets, share risks and costs and accelerate PD process.

Table 2.1 CPD definitions

- Cooperative relationship between firms aimed at innovation and the development of new products [**23**].
- Means by which problematic aspects of PD such as complexity, involving many different areas of skill and expertise as markets and technologies converge, shorter product lifecycles, increasingly rapid change of technology and pressure to reduce PD periods can be lessened [**2**].
- Application of team-collaboration practices to an organization's total PD efforts [**14**].
- Internet based computational architecture that supports the sharing and transferring of knowledge and information of the product life cycle among geographically distributed companies to aid taking right engineering decisions in a collaborative environment [**24**].
- Continued and parallel responsibility of different design disciplines and lifecycle functions for product and process specifications and their translation into a product that satisfies the customer but does not presuppose one single organization [**25**].
- Integrated framework that product companies can adopt to become competitive, innovative, and leaders in their sphere of influence [**26**].
- Cross-organizational linkage, which in addition to high levels of integration is characterized by high levels of transparency, mindfulness, and synergies in participants' interactions [**27**].
- Virtual process where one or more activities of the PD process are performed by different enterprises or the results of one or more activities of the PD process come from different enterprises [**28**].

On the other hand, there exist many stages where collaboration for PD may occur. Figure 2.1 describes CPD with potential overlap points and individual characteristics of each process. Collaboration may include only one phase of PD as well as the whole process from conceptual design to product launch.

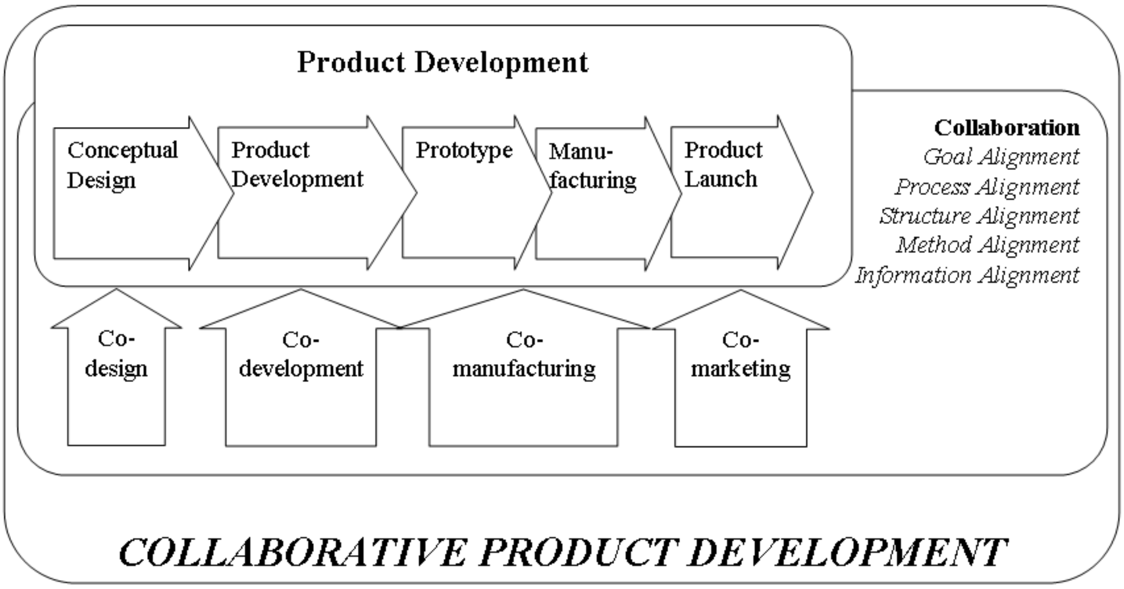


Figure 2.1 Collaboration in PD

2.1.2 Motivating Factors of Collaborative Product Development

The complex environment defining CPD generates uncertainty toward collaborative efforts. Consequently, studies highlight various motivations for potential collaborations in the PD process. These motivations form a guideline for organizations to help them decide whether or not to collaborate; and if the collaboration decision is made, they provide the possible outcomes of the process. Some studies such as Littler et al. [**2**] recite benefits of collaboration in PD, which are also considered as motivating factors. Table 2.2 recapitulates these motivations.

As seen in Table 2.2, the main motivation for CPD is improving PD performance. Another highlighted motivation is maintaining sustainability through CPD. Administrative initiative and willingness to adapt technological changes can be considered as proactive. However, although these motivations lead organizations into collaboration, due to its complex nature, the CPD process is hard to manage and often results in failure [**2**]. According to Marxt and Popovic [**22**], less than 50% of CPD efforts come out successful. This failure rate stimulates studies to investigate critical success factors for CPD reviewed in the next section.

Table 2.2 CPD motivations

CPD motivations	Sources
Sharing risks, reducing costs	Camarinha-Matos and Abreu [**21**], Farrukh et al. [**29**], Hou et al. [**30**], Littler et al. [**2**]
Technology, knowledge, experience	Burlat and Benali [**31**], Camarinha-Matos and Abreu [**21**], Farrukh et al. [**29**], Feller et al. [**20**], Littler et al. [**2**], Mazzola et al. [**32**], Mi and Shen [**33**]
Reducing time to market	Hou et al. [**34**], Littler et al. [**2**]
Market opportunities, competition	Burlat and Benali [**31**], Camarinha-Matos and Abreu [**21**], Littler et al. [**2**], Mazzola et al. [**32**]
Expending product family, innovation	Feller et al. [**20**], Littler et al. [**2**],
Administrative initiative, corporate culture	Littler et al. [**2**], Marxt and Popovic [**22**]

2.1.3 Critical Success Factors of Collaborative Product Development

Literature offers various factors for assuring, or at least improving, CPD success. Some success factors such as communication and trust are considered to be fundamentals of collaboration, while the existence of collaboration champion (leadership) and risk sharing are regarded as secondary issues. Some studies solely focus on one factor and investigate its dynamics, for example trust formation by Bstieler [**35**].

As seen in Table 2.3 which reviews these success factors emphasized in the literature, establishing trust between partners and assuring efficient communication are indeed the most highlighted success factors in CPD literature. Suitable partner selection and relationships between parties are often discussed as well. However, these factors do not guarantee success, given that the uncertain nature of CPD contains many risks, which are reviewed in the next section.

Table 2.3 Critical success factors of CPD

Success factors	Sources
Trust	Barnes et al. [**36**], Bstieler [**35**], Chin et al. [**37**], Fraser et al. [**38**], Hou et al. [**34**], Lam and Chin [**39**], Sako [**40**], Shah and Swaminathan [**41**],
Communication	Bstieler [**35**], Chin et al. [**37**], Fraser et al. [**37**], Lam and Chin [**39**], Littler et al. [**2**], Qiang et al [**42**], Sosa et al. [**43**]
Partner selection, preparation	Emden et al. [**27**], Fraser et al. [**37**], Glaister and Buckley [**44**], Littler et al. [**2**]
Product quality, attaining main goal	Hou et al. [**34**], Littler et al. [**2**], Marxt and Link [**45**], Shah and Swaminathan [**41**]
Commitment, interest, inter-team relationships	Barnes et al. [**36**], Chin et al. [**37**], Fraser et al. [**37**], Lam and Chin [**39**], Littler et al. [**2**], Marxt and Link [**45**], Shah and Swaminathan [**41**],
Fairness, reciprocity	Bstieler [**35**], Littler et al. [**2**], Shah and Swaminathan [**41**]
Flexibility	Barnes et al. [**36**], Hipkin and Naudé [**46**], Hou et al. [**34**]
Learning	Barnes et al. [**36**], Chin et al. [**37**], Marxt and Link [**45**]
Leadership	Barnes et al. [**36**], Chin et al. [**37**]
Experience	Hou et al. [**34**], Littler et al. [**2**]
Alignment	Emden et al. [**27**]
Information/risk sharing	Chin et al. [**37**]

2.1.4 Risks of Collaborative Product Development

Like any environment enclosing more than one party, collaboration is exposed to confrontation and limitations due to differences, which lead to some risks. Such risks not only affect CPD success but also influence negatively parties who would otherwise consider collaboration for PD. For example, leakage of information and opportunity costs may arise as much stronger factors than CPD motivations.

Table 2.4 Risks of CPD

Main CPD risks	Sources
Leakage of a firm's skills, experience, and knowledge that may form the basis of its competitiveness	Knudsen [**47**], Littler et al. [**2**], Parker [**48**]
Additional financial and time costs incurred in managing the collaboration	Littler et al. [**2**], Parker [**48**]
Loss of direct control by an organization over the PD process	Littler et al. [**2**], Parker [**48**]
Poor communication within and across organizational boundaries	Bardhan [**49**], Parker [**48**]
Documentation problems	Bardhan [**49**]
Opportunity cost	Littler et al. [**2**]
Trust issues	Parker [**48**]

Identifying these limitations may aid collaborators in taking initiative and preventing conflicts in the early stages of collaboration. Literature underlines several risks, essentials of which are summarized in Table 2.4.

Factors affecting CPD are usually determined by empirical evidence through case and field studies that generally lack a systematic approach. On the other hand, comprehensive studies are conducted for factors such as trust and communication, whereas other issues get often neglected.

2.2 LITERATURE OVERVIEW AND LIMITATIONS

The existing literature points out wide applications of CPD with various aspects. Approximately 150 papers were gathered during the literature survey. More than 80 of these papers were referred to in this overview. Others, while attacking issues of collaborations in the PD process, were eliminated, given that these were not essential studies or that similar issues were tackled in other studies.

During the review, many studies suggested that there were three major trends in CPD literature. The first category is labeled as "CPD dynamics" and includes studies handling trends and patterns [**50**], CPD success factors such as trust [**35**], collaborative competence [**51**], workplace flexibility [**52**]; processes including technical communication [**43**], innovation [**26**], acquisition and utilization of information [**53**], and conflict management [**39**]. These studies attempted to explain CPD dynamics and the methodologies were mostly case studies as well as hypothesis testing.

The second category appears definitely as partnership formation in CPD. Fraser et al. [**38**] highlighted choice of partner, win-win arrangements, open and frequent communication, and good personal relationships as CPD success factors. These success factors represented issues handled in the partnership process. As though collaboration and partnership may appear to be an item, partnership formation does not contain any problems generated with collaboration. Rather, this category tackles issues such as partner selection [**27**,**54**,**55**,**56**], partner selection criteria [**41**,**44**], collaboration with suppliers [**34**,**57**], and collaboration with customers [**58**].

On the other hand, R&D have been actively carried out to develop technologies and methodologies to support collaborative design and development systems [**59**]. Therefore, CPD infrastructure emerges as another category, including tools for risk management [**60**], collaborative decision making [**61**], control in manufacturing [**62**], integration systems [**24**,**63**,**64**,**65**], and reviews [**33**,**59**].

These three research areas are more thoroughly described in the next sections.

2.2.1 Collaborative Product Development Dynamics

The first group studies focus on factors affecting CPD process and problems and are outlines generally based on case studies and empirical evidence. Table 2.5 illustrates studies researching CPD dynamics. These dynamics include benefits, success factors, process management, information management, communication management, limitations, patterns, trends, competition, etc.

An essential CPD study was proposed by Littler et al. [**2**]. The study investigated factors affecting CPD within 100 UK firms with interviews and case studies. They determined benefits, risks, motivations, success definitions, and success factors of CPD. They also categorized the interviews as more experienced and less experienced. The "coopetition" notion and term (cooperation and competition) was introduced to literature by Chin et al. [**37**] where they defined critical criteria for strategic management of coopetition.

Lam and Chin [**39**], determined success factors in conflict management by AHP. Relationship management, PD process management, communication, and conflict management systems were the most important categories, respectively. Within the 13 criteria, the most important ones were communication management, trust, and commitment.

Table 2.5 CPD dynamics

Subject	**Authors**	**Method**	**Findings**
Knowledge contexts	Andersen and Munksgaard [**66**]	Empirical data, interviews	A framework is introduced for understanding how problem formulation, information search, and division of work in PD activities are shaped by mindsets vested in organizations.
Effort, revenue, and cost-sharing	Bhaskaran and Krishnan [**5**]	Mathematical modelling	Co-development approach should go beyond simple revenue sharing under which there exists an incentive for an innovating firm to under-invest in quality improvements.
Trust formation	Bstieler [**35**]	Hypothesis test, empirical data	The findings suggest that communication behaviour and fairness are positive contributors to trust. In contrast, conflicts during PD and perceived egoism of the partner appear to have a detrimental effect.
Collaborative effort	Cai and Kock [**67**]	Game theory, dynamic programming	Social punishments (including loss of reputation, shadow of future collaboration, ethical effects, and other social and psychological influences) should be large enough to enforce a full cooperation in symmetric discrete-strategy e-collaboration games.
Content and process learning	Chen and Li [**68**]	Hypothesis test, empirical data	Content learning in the technological field and process learning from functional comprehensiveness in alliances positively affect PD, but content learning in manufacturing and marketing has no impact on PD.
Knowledge management	Chen et al. [**69**]	ANP	ANP model with sensitivity analysis is constructed to prioritize the relative importance of multiple criteria and the preferences of new product mixes by generalizing experts' opinions.
Coopetition	Chin et al. [**37**]	Interview, AHP	Prioritizing critical success factors can help companies understand their relative importance and devise improvement plans that can maximize limited resources in dealing with several or all factors simultaneously.
CPD in R&D	Davis et al. [**14**]	Interview, survey	Collaboration within government R&D organizations can be negatively impacted by the instabilities in the budget process and by certain regulations that may hamper the expeditiousness of implementing these collaborative activities.
Integrating CPD	Deck and Strom [**70**]	Case study	Co-development model with three levels: a strategy for development chain design, process and governance structures that define how the partners will work together, and IT that effectively supports collaborative development.
Main and sub-supplier collaboration	Fagerstrom and Jackson [**71**]	Systems theory, interview	The main supplier needs to benefit directly from integration with sub-suppliers. It is important to know which roles are most suitable for the sub-suppliers during different stages in the PD and to clearly describe the level of involvement with the main supplier.
Assessing practice in CPD	Farrukh et al. [**29**]	Case study	Proposed tools assist in identifying risk, required contingency plans and areas for improvement of skills or transfer of good practice.
Inter-partner process learning	Feller et al. [**20**]	Business process simulation, case study	The study introduces the use of business process simulation as a tool for process innovation in collaborative R&D and provides a list of process improvements.
Collaborative maturity	Fraser et al. [**38**]	Interview, case study	Collaborative Maturity Grid is presented as a tool to describe key process areas of four levels of maturity.

Subject	Authors	Method	Findings
Trends and patterns in CPD	Hagedoorn [**50**]	Empirical data	Companies from the developed economies participate in 99% of the R&D partnerships, and 93% of these partnerships are made among companies from North America, Europe, Japan, and South Korea.
Inter firm relationships	Knudsen [**47**]	Hypothesis test	Relationships with customers are used most frequently at both early and late stages of the PD process, with a contradictory finding that at the same time customer relationships have a negative impact on innovative success.
Informal collaboration	Kreiner and Shultz [**72**]	Case study	The patterns of collaboration appear to be anarchistic and random, but these traits are domesticated by community norms. Also, despite its strategic importance, networking appears to be totally out of managerial purview and control.
Conflict management	Lam and Chin [**39**]	Interview, AHP	Relationship management is the most critical factor category, followed by NPD process management, communication, and conflict handling system. Communication management is the most critical factor.
Factors affecting CPD	Littler et al. [**2**]	Survey	Effective PD collaboration management is concerned with balancing diverse and sometimes contradictory influences.
Workplace flexibility and innovation	Martinez-Sanchez et al. [**52**]	Survey, hierarchical regression	High-cooperation firms may compensate the negative impact of external flexibility and perform better than low-cooperation firms in the flexibility influence on innovation context.
CPD design	Mazzola et al. [**32**]	Fuzzy MCDM, case study	Two kinds of approaches are observed in the literature and industry: one is more related to market transactions, specifically the west car-company style, the other is more relational based, as in the Japanese car-company style.
Novelty of product innovation	Nieto and Santamaria [**73**]	Survey	The role of different collaboration networks on product innovation is studied and the results show that technological collaboration networks lead to a higher degree of novelty.
Process complexity and its impacts on PD	[**12**]	Case study	PD challenges relating to coordinating inputs and involvement, assigning responsibilities, controlling and monitoring progress, and overall project governance are amplified when the process spans across a number of organizational boundaries.
Information exchange	Perks [**74**]	Case study	Complementarity of resource inputs and outputs and the state of competitiveness can influence the approach toward integrating marketing information in the collaborative NPD process.
Acquisition and utilization of information	Rindfleisch and Moorman [**53**]	Structural equation modelling, field study	Participants of horizontal alliances possess both higher levels of knowledge redundancy and lower levels of relational embeddedness compared with vertical alliances.
Collaboration in R&D	Saez et al. [**75**]	Case study	Among external sources of ideas for innovation customers are most valued, and research centres are the last on the list, despite the fact that when it comes to co-development research centres are most likely to be chosen.

Subject	Authors	Method	Findings
Collaborative product innovation	Sharma [**26**]	Maturity model	Collaboration, PD, and Innovation topics are studied separately and an IT framework is presented which integrates collaborative processes.
Computer supported collaborative design	Shen et al. [**76**]	Review	The paper presents a review of the R&D literature on CSCD (Computer supported collaborative design), from the pre-CSCD technologies of the 1980s to current state-of-the-art CSCD, as well as research challenges and opportunities.
Collaborative competence	Sivadas and Dwyer [**51**]	Structural equation modelling, empirical data	Cooperative competency (a combination of trust, communication, and collaboration) has a significant impact on the NPD success.
Technical communication	Sosa et al. [**43**]	Hypothesis test, empirical data	Relative location of interacting team members influences both communication frequency and media choice.
Organizational planning in CPD	Zhang et al. [**77**]	Simulation, agent-based modelling	An agent-based integrated simulation model is proposed to explicitly represent human behaviour, organizational interactions, and tasks networks in order to improve organization performance predictability and shorten process duration of a CPD project.

Emden et al. [**27**] studied partner selection with a process approach. According to this, technological alignment triggered the partner evaluation process and it was followed by strategic and relational alignment. After the three-phased process, partners with maximum potential to create value were selected. Hipkin and Naudé [**46**] focused on building effective partnerships and stated that for a high-technology alliance to be successful a flexible strategic framework should respond to end user requirements and build close linkages between key players, strengthen creativity, promote partner expertise, and nurture the changing relationships between partners.

Glaister and Buckley [**44**] categorized partner selection criteria as task-related and partner-related. The most important task-related criteria are, relatively, knowledge of local markets, access to distribution channels, linkage with major clients, and knowledge of local culture. The most important partner-related criteria are trust between management and relatedness of partners' business and reputation. Shah and Swaminathan [**41**] also studied factors affecting partner selection. However, instead of using conventional criteria such as trust, commitment, etc., they proposed an approach based on alliance project type. They utilized "process manageability" and "outcome interpretability" as evaluation criteria.

Perks [**74**] studied marketing information exchange and stated that inter-firm resource balance and competitiveness affected integration of marketing information into CPD. The nature of resources contributed affected determining integrative methods, and competitiveness required informal networks to develop trust. Rindfleisch and Moorman [**53**] explored acquisition and utilization of information, and they discovered that horizontal alliances, unlike vertical ones, contained less embeddedness and more knowledge redundancy. They found that while redundancy diminished acquisition and enhanced utilization of information, embeddedness enhanced both.

2.2.2 Partnership Formation

A second group of CPD studies focusing on partnership process during collaborations handles problems such as partner selection, relations between collaborative partners, partner evaluation, and partner selection criteria. Essential studies in this group are reviewed in Table 2.6. Partnership formation is considered as a separate group since partnering during collaborations presents a strategic importance.

Hacklin et al. [**55**] developed DS4iP (Decision Support System (DSS) for Strategic Innovation Partner Selection), which allowed the decision-makers to evaluate or even benchmark potential partner firms autonomously and with instant feedback. They offered a multi-perspective and interactive overview of potential partners, and they categorized criteria as strategic, cultural, and structural. Another DSS was proposed by Yoshimura et al. [**56**] with a different approach. Evaluation of partners was based on the technologies required for developing the new product and they were classified into two groups: technologies already developed and technologies that must be developed.

Table 2.6 Partnership formation in CPD

Subject	Authors	Method	Findings
Customer partnering	Campbell and Cooper [**58**]	Survey	Customer partnering may have long-term advantage from a strategic perspective and learning perspective.
Supplier performance	Le Dain et al. [**78**]		A framework is introduced to measure the supplier's performance in the context of NPD projects by identifying four main areas of performance expected by the customer in collaborative setting and by evaluating suppliers' development efforts throughout the NPD project with appropriate criteria for each stage of the project.
Customer performance	Le Dain et al. [**79**]	Action research approach	Co-design partners selected among customers are evaluated through three performance areas combined with three involvement stages. The proposed tool aims to evaluate the supplier involvement in the design process, given that benefit from CPD depends highly on the contribution of both parties.
Partner selection	Emden et al. [**27**]	Case study, narrative analysis	The study proposes three alignment approaches for partnership formation. It was found that partners with long-term orientations are selected over others because long-term orientation gives the partner the ability to overcome obstacles, to resolve conflicts, and to continue under uncertainty.
Partner selection in SME's	Fischer et al. [**54**]	Ant colony optimization, AHP	The most capable competence cell from a pool of potential competence cells is chosen where the selected competence cells fulfil the tasks of a value chain particularly well.
Partner selection criteria	Glaister and Buckley [**44**]	Hypothesis test, empirical data	Key task-related criteria are access to knowledge of local market, access to distribution channels, access to links with major buyers, and access to knowledge of local culture, whereas key partner-related selection criteria are trust between top management teams, and relatedness of partner's business and reputation.
Partner selection	Hacklin et al. [**55**]	Empirical data, SD	Being designed for usage within a coaching framework, the DS4iP tool provides a multi-perspective and interactive overview of potential venture partners to the decision-makers.
Effective partnership	Hipkin and Naudé [**46**]	Case study	For a successful high-technology alliance, a flexible strategic framework should respond to end user requirements and build close linkages between key players, strengthen creativity, promote partner expertise, and nurture the changing relationships between partners.
Supplier selection	Hou et al. [**34**]	AHP, case study	The characteristics and requirements of the supplier involvement during the process of collaborative development are analyzed and four indices are determined: satisfaction, flexibility, risk, and confidence.

Subject	Authors	Method	Findings
Internal coordination capability	Luo et al. [**3**]	Statistical tools	The effect of the interaction between internal and coordination capabilities of the partner firms on CPD performance is investigated. It is demonstrated that internal coordination capability acts as a moderator on CPD performance.
Partner selection criteria	Shah and Swaminathan [**41**]	Hypothesis test, experimental data	Critical criteria for assessing alliance partner attractiveness and selection vary depending on the differential levels of process manageability and outcome interpretability inherent in a strategic alliance.
Supplier involvement	van Echtelt et al. [**80**]	Case study	The study proposes to distinguish between the strategic management area, which provides long term strategic direction, and operational management area which supports project teams adopting supplier involvement.
Coordinating customers and proactive suppliers	von Corswant and Tunälv [**57**]	Case study, interview	Nine critical factors for the outcome of supplier involvement are identified within five case studies. The results indicate that suppliers' internal organization and their co-operation with other manufacturers and suppliers are of crucial importance.
Partner selection	Yoshimura et al. [**56**]	Modelling, case study	The DSS was shown to be effective in selecting the optimal collaboration partner from a group of candidates, so that production of a new product could be achieved with a minimum cost, both financial and in terms of effort and expended resources.

2.2.3 Collaborative Product Development Infrastructure

As emphasized before, CPD is a technology oriented process, hence the CPD infrastructure category. The existing literature contains numerous studies investigating CPD tools, methodologies, and technologies, including technology review, development and implementation of new software, and defining technological requirements for CPD. Given the vast area of research in this category, essential studies are reviewed in Table 2.7

Li et al. [**28**] proposed a comprehensive review of mainstream lightweight representation schemes and visualization-based systems and discussed integration systems for CPD. They also highlighted inefficiency due to the limited bandwidth of the internet as well as the need for security and interoperability of data and information. Rodriguez and Al Ashaab [**24**] proposed a knowledge-based system architecture for CPD, integrating engineering applications and production information. The proposed approach presented a support tool for communicating and sharing knowledge. Also, technological requirements for CPD were identified in the study.

Table 2.7 CPD infrastructure

Subject	**Authors**	**Method**	**Findings**
Internet-based information sharing	Al-Ashaab et al. [**83**]	Java, Object-oriented database	SPEED system is introduced to facilitate the sharing of product information in order to capture product life cycle information and support the decision taken during the PD.
Knowledge management	Chen et al. [**84**]	UML	An UML-based enterprise system development procedure is introduced in order to enable engineering knowledge management in collaborative product design.
Organizational knowledge capture and re-use	Cheung et al. [**85**]	XML, ontological approach	A generic manufacturing data structure as a part of organizational knowledge framework is developed, and a web-centric PDM (Product data management) method is used to manage and coordinate captured knowledge.
Infrastructure for data sharing and work coordination	Domazet et al. [**86**]	CORBA, STEP, Java	Event-driven STEP Object Management Framework enables the sharing of common STEP-based product model data, manages collaborative and distributed workflows, and provides interfaces to OMG (Object Management Group) compliant PDM systems and workflow management systems.
CPD management system	Han and Do [**87**]	Object-oriented modelling, UML	An object-oriented conceptual model of a CPD Management system based on a top-down approach is presented.
CPD architecture	Hou et al. [**30**]	AD	A prototype of the Integrated Management System for Product Collaborative Development Chain is developed, providing a coordinated teamwork platform for the effective development and deployment of the distributed resources.
Design planning	Hung et al. [**1**]	QFD, mathematical modelling	A CPD framework is proposed in order to link customer requirements, generate design alternatives, and then evaluate and select these alternatives to determine the optimum solution, from both design aspects and manufacturing concerns.
Interoperability of Workflows	Jiang et al. [**88**]	Petri net, process view	Interoperability of cross-organizational workflows is important for CPD to facilitate the successful execution of the whole PD process across enterprises boundaries.
Process management of CPD	Jiang et al. [**89**]	Web services, process view	Web Services and process-view combined approach is developed to manage the dynamic and distributed process of CPD to enhance the workflow interoperability among heterogeneous workflow management systems of enterprises.
Workflow management system	Jiang et al. [**90**]	Web services, P2P architecture, Process view	A web-service oriented peer-to-peer architecture with process view approach is adopted to develop a distributed workflow management system, which assures quick construction of virtual enterprises and provides a scalable and flexible system for CPD process management.
Cross-organizational workflow management	Jiang et al. [**91**]	Process-view, timed colored Petri net	Previous works are improved to develop an improved model where the aspects of control flow and data flow are considered together.

Subject	Authors	Method	Findings
Risk management	Kayış et al. [**60**]	Knowledge elicitation techniques, Java	A risk management tool, IRMAS is developed as a web-based risk management tool to improve communication between collaborative partners.
e-Engineering	Kuk et al. [**92**]	Service-oriented architecture, Web services technologies	The proposed framework provides an integrated engineering environment to support collaboration and integrating personnel, design/modelling/simulation activities, and engineering resources in the PD process.
PDM requirements for CPD	Kumar and Midha [**93**]	QFD	The proposed expert system compares company's requirements with different functionalities of PDM systems and then technical specifications are compared to specific PDM system.
CPD technologies and methodologies	Li and Qiu [**59**]	Review	The review presents collaborative design methodologies and technologies in three aspects: visualization-based collaborative systems, co-design collaborative systems, and concurrent engineering-based collaborative systems.
Web based collaboration	Li and Su [**82**]	COBRA	The presented server centralized model suits the administrative tasks, while the point-to-point model is more efficient in other circumstances, such as CAD data exchange and program invocation.
Complex products	Li et al. [**64**]	UML	Proposed three-tiered reference model for Collaborative Development Support Environment for complicated products, which can integrate and coordinate the information, resources, activities and applications in CPD.
Visualization models	Li et al. [**28**]	Field study	3D streaming technique, which can allow effective and efficient dispatch and access of large-volume CAD data as a series of patched streams across the Internet, provides solution to overcome limited bandwidth of the Internet and Web.
Information systems	Li et al. [**94**]	Modeling	Loose coupling message communication architecture based on JMS and web services technology is developed to orchestrate the cross-organizational PD processes.
Real time design	Li et al. [**63**]	Modeling	Product models are allowed to be constructed and modified from various sites using different client CAD systems synchronously with proposed integration-based solution for a real-time online collaborative design platform.
Distributed product lifecycle management	Luh et al. [**4**]	Web technologies	A networked PLM platform is developed on multiple layers where the deployment follows organization view, data view, content view, and application view steps. The infrastructure is implemented according to the job specifications of distributed teams on these four layers.
Change propagation	Ma et al. [**95**]	Unified feature, dependency network	A change propagation algorithm is proposed to control the information consistency among multiple applications of product lifecycle stages.

Subject	**Authors**	**Method**	**Findings**
R&D review	Mi and Shen [**33**]	Literature survey	The literature is reviewed from system architectures, product modelling and visualization, process modelling and coordination, communication and collaboration, and implementation methodologies.
CPD in SME’s	Mi et al. [**25**]	Empirical study	The requirements of CPD in SME’s are discussed and an Internet-based collaborative platform is proposed to support collaborations among PD team members and secondary users.
e-Engineering	Molina et al. [**96**]	PHP, MySQL, Apache Web Server	A collaborative engineering environment is developed and different applications are implemented such as MAS, SMT Advisor, and SPEED+ to support specific engineering activities.
Conflict management in collaborative design	Ouertani [**97**]	UML	DEPNET methodology is extended in order to assess the impact of a selected solution on the product as well as on the design process organization.
Conflict management in collaborative design	Ouertani et al. [**98**]	UML	DEPNET methodology is developed to support conflict resolutions and is based on a process traceability system capturing and qualifying product data dependencies.
Web based design	Qiang et al. [**42**]	Java	The proposed system allows product designers to exchange and share product data, communicate with team members, modify geometry data on particular aspects of the design, and maintain operations consistency in all the distributed cooperative sites on a wide variety of platforms.
Conceptual design support system	Qiu and Li [**99**]	Neural network, genetic algorithm	An Internet-based conceptual design support system for injection moulding is developed, and the proposed system makes full use of component-based web technology with a flexible distributed architecture.
Risk assessment	Qiu et al. [**100**]	Sociometry	A theoretical framework is proposed to capture heterogeneous risk evaluations at intra- and inter-levels, represent and quantify subjective risk evaluations, and facilitate the negotiations through a risk-based coordination mechanism.
Risk assessment	Qiu et al. [**101**]	Sociometry	The application paper enhances the previous research. The application shows that the risk-based coordination model can provide a systematic process to perform the global negotiation.
Collaborative knowledge	Robin et al. [**102**]	IPPOP	Types of knowledge characterizing a collaborative design process are identified as the sharing of expertise.
Knowledge web	Rodriguez and Al-Ashaab [**24**]	CIMOSA, UML, case study	The approach provides the integration between the engineering applications and the manufacturing process knowledge.
Change management	Rouibah and Caskey [**103**]	Parameter-based approach	An Engineering Change Management approach is introduced based on the SIMNET research project in order to provide early insight to suppliers about the impact of proposed changes and facilitate information exchange, retrieval, sharing, and use.
Product conceptualization	Roy and Kodkani [**81**]	WWW, Java	A collaborative product conceptualization tool within WWW is developed, taking advantage of information already available on the web. This tool aids designers to represent concepts and search similar concepts.

Subject	Authors	Method	Findings
Change control workflow	Shiau and Wee [**104**]	Configuration management, distributed routing algorithm	A distributed change control workflow for design network is proposed for maintaining the consistency of design documents among joint development manufacturers in a design chain.
Integrated design system	Tseng et al. [**105**]	SQL, OBDC, PHP, HTML, IIS	The proposed web-based integrated system covers a marketing information system, a human resources management system, a supply-chain management system, communication media, an integrated product design studio, and user interface and databases.
Heterogeneous environment	Wang and Zhang [**65**]	High level architecture	The integration of High Level Architecture and Web services achieves better interoperability and reusability among heterogeneous simulation components in a distributed environment.
CPD framework for a centre-satellite system	Wang et al. [**106**]	Service-oriented architecture	A CPD framework is developed and based on the framework of a generic communication component and is designed for the interoperability among five modules under heterogeneous contexts.
Collaborative multidisciplinary decision making	Xiao et al. [**61**]	Game theory	Principles of game theory are applied to model the relationships between engineering teams to support decision making. Also, it is stated that design capabilities indices are required to maintain design freedom.
Bid preparation	Yan et al. [**107**]	General sorting, neural networks	The study integrates the bidding aspect and the design aspect of PD with a collaborative bidding and design system, and a concurrent cost-schedule estimation strategy is developed for commercial analysis of product concept.
Bidding-based product conceptualization and partner selection	Yan et al. [**108**]	AHP, general sorting, neural networks	Product conceptualization and partner selection system is developed integrating concept development, bidding decisions and supply chain formation.
Internet-based CPD chain	Yujun et al. [**109**]	XML, VRML, HTML, Java, .Net	Internet-based CPD chain paradigm is introduced to carry out PD activities simultaneously and collaboratively using a series of tools, including product management tools, workflow management tools, and project management tools.
Control in co-manufacturing	Zhang and Li [**62**]	Modelling	Collaborative Manufacturing Task Configuration Management System support collaboration and agility in collaborative manufacturing through setting the lifecycle of configuration items and the relationship and the rules of lifecycle's statuses.
Distributed knowledge	Zhen et al. [**110**]		Traditional knowledge query model is improved by personal knowledge repositories in order to support engineering teams in their search when the information needed cannot be properly described.

Wang and Zhang [**65**] handled the problems in heterogeneous environments and stated that HLA (High level architecture) and web technologies were powerful tools for modelling and simulation. They claimed that these two technologies, together, enhanced efficiency of distributed and heterogeneous environments. Li et al. [**63**] also attacked heterogeneous environments, and they offered an integration-based solution for developing a real-time collaborative design platform on heterogeneous CAD (computer aided design) systems. Product models could be constructed and modified from various sites, as opposed to the visualization-based approaches.

Roy and Kodkani [**81**] also highlighted the appropriateness of web technologies. They presented a PD and selection tool for distributed design teams based on world wide web. This tool also included a module for designers to search existing ideas on similar products, which computed ratings for individual drawings for a set of criteria. Qiang et al. [**42**] proposed a web-based collaborative design study, and they offered a design support system to connect heterogeneous platforms. They claimed that the method shortened transfer times, synchronized team operations, and guaranteed consistency of product models. Li and Su [**82**] also proposed a web-based environment with various features such as scalability, openness, heterogeneity, resource access, interoperability, reusability, and artificial intelligence. The system was efficient in administrative tasks, as well as in interactive situations such as partner communication and data exchange.

2.2.4 Limitations of the Literature and Future Directions

Even though the competitive nature of PD leads many businesses to collaborate, the existing literature fails in some aspects to respond to the issues rising from collaboration efforts. As CPD literature is still in a development state, numerous limitations in the studies may be observed. Following the review in this study, some shortcomings of CPD literature are emphasized and new research directions are discussed.

- Studies tackling collaboration within PD are generally focused on one problem in the process. Integrated studies handling CPD as a whole are nonexistent to the best of our knowledge, whereas a large number of issues or challenges emerge from the increased complexity in PD processes involving a collaborative network of players from different organizations [**12**].
- Studies determine factors affecting CPD and its necessary conditions mainly by case studies and empirical evidence, which can differ in each sector. Systematic

approaches based on analytical methods to define CPD requirements are practically absent.

- Many studies are conducted as case studies, and therefore results are obtained from different sectors (Biotechnology - Kreiner and Shultz [**72**]; telecommunication – Littler et al. [**2**]; aviation - Shah and Swaminathan [**41**] etc.), different company sizes (Major companies - Deck and Strom [**70**]; SMEs - Mi and Shen [**33**]; etc.), and for different type of products (Semiconductors – Chen and Li [**68**]; automotive - von Corswant and Tunälv [**57**] etc.). In consequence, different approaches and outcomes are observed for different types of sectors, company sizes, and products. A generic CPD model proposal suitable for every sector and product type may be valuable for CPD practitioners.

- R&D have been actively carried out to develop technologies and methodologies to support collaborative design and development systems [**59**]. Many tools are proposed for various purposes, including control, information and knowledge sharing, conflict management, product conceptualization and visualization, and integration. CPD infrastructure represents a recurring subject in the literature. Nevertheless, studies do not attempt to plan and implement these technologies according to the requirements of various CPD factors.

- To support CPD at a technological level, various solutions are suggested by many researchers and practitioners; given that various requirements and priorities for different cases are necessitated by CPD. CPD infrastructure literature is shaped by these requirements accordingly. For instance, Al-Ashaab et al. [**83**] proposed an internet-based information sharing approach while Kayış et al. [**60**] employed the web to develop a risk management tool improving communication. Li et al. [**63**] presented a collaborative design platform where different CAD clients could work synchronously, while the approach of Rodriguez and Al-Ashaab [**24**] provided the integration between the engineering applications. A generic solution cannot be offered to CPD practitioners given that each instance requires its own specific approach. The literature lacks a guide mapping the requirements of the right tools.

- Although win-win agreements are underlined as essential for CPD [**38**], few studies exist suggesting contract management or game theory as CPD enabling methodologies. Partnership formation process requires a more detailed approach.

- Studies are significantly focused on the collaboration process, although the main concern of CPD is realizing an effective design and the development and marketing of products and services, i.e., effective PD. However, PD is generally neglected in CPD dynamics studies. CPD efforts must be directed towards PD, and collaboration notions should be constructed around the PD process.

- Molina et al. [**96**] stated that the integrated environment for PD must enforce four dimensions of e-engineering: process, information, organization and technology. On the other hand, Sharma [**26**] separately studied three topics: Collaboration, Innovation, and PD. While different processes within CPD may be considered separately, these separate approaches should be later integrated into CPD in order to manage and control CPD efforts.

- Partner selection is another recurring subject in CPD literature, and these studies generally investigate only on one type of partner, supplier, or manufacturer. However, organizations handling CPD may need to form partnership with various companies [**111**]. In modern manufacturing, firms tend to overcome their traditional boundaries by creating cooperation links with partners or even competitors [**31**]. Although inter-organizational structures involve leveraging the assets and capabilities of the firms located at various points along the value (supply) chain [**12**], CPD partnership studies usually focus on the R&D phase of the process. The existing literature lacks a general evaluation of various potential partners such as manufacturers, customers, suppliers, competitors, R&D departments, marketing departments, and universities. On the other hand, partnership studies offer many different approaches for partner selection, which are justified empirically: alignment model [**27**], project-type approach [**41**], task-related and partner-related criteria sets [**44**], etc. A consistent and generic model built around the partnership process, incorporating diverse approaches is required.

- A lack of interest exists for studies focusing on long-term collaborations and case studies investigating unsuccessful CPD efforts. These types of studies can give insight to practitioners, emphasizing CPD errors and risks that may occur inside inter-firm networks.

- Organizational learning during collaboration is another undervalued topic, yet CPD efforts do not only result in new products and services, but also increase corporate experience and knowledge. The CPD impact on organizational structure including knowledge management, IT management, R&D efforts, etc should be considered as well.

Given that CPD is a research area in progress, these limitations of the literature may offer new dimensions of research in collaboration within the PD process. Considering current limitations of the literature, this study proposes to consider Collaboration, PD, and Partnership as three separate, but closely related, major processes in order to develop a framework highlighting key CPD issues and then incorporate these three processes in order to present a holistic structure for CPD. The main structure of the proposed model will be further explained in the next section.

2.3 A CONCEPTUAL FRAMEWORK PROPOSITION FOR COLLABORATIVE PRODUCT DEVELOPMENT

Even though CPD literature covers a wide range of topics as mentioned previously, no systematic and holistic approach exists. The absence of a general guideline for practitioners is the main problem in studies dealing with collaboration issues. Given that CPD is a strategic initiative rather than an operational level problem, collaborative efforts in PD require a conceptual structure for managers considering collaboration. Therefore, a CPD framework is proposed to roughly categorize the key issues derived from the review. Figure 2.2 presents the proposed CPD framework. Also, four propositions are introduced to summarize the findings of this study.

Proposition 1. *CPD is mainly constituted of three fields interacting with each other but enclosing different dynamics: partnership process, collaboration process, and PD process.*

The literature review suggests three major investigation areas: CPD dynamics, partnership formation, and CPD infrastructure. These areas are then merged into CPD, which implies that there exist three dimensions to CPD efforts: partnership process, collaboration process, and PD process. Collaboration process differs from partnership process in that it focuses on the profits acquired by CPD efforts, whereas partnership process deals with the evaluation of the partnership. On the other hand, the PD domain tackles the development itself, without considering the dynamics of collaboration in PD. A generic development process is presented in the conceptual framework, which can be adapted to the specific characteristics of different industries.

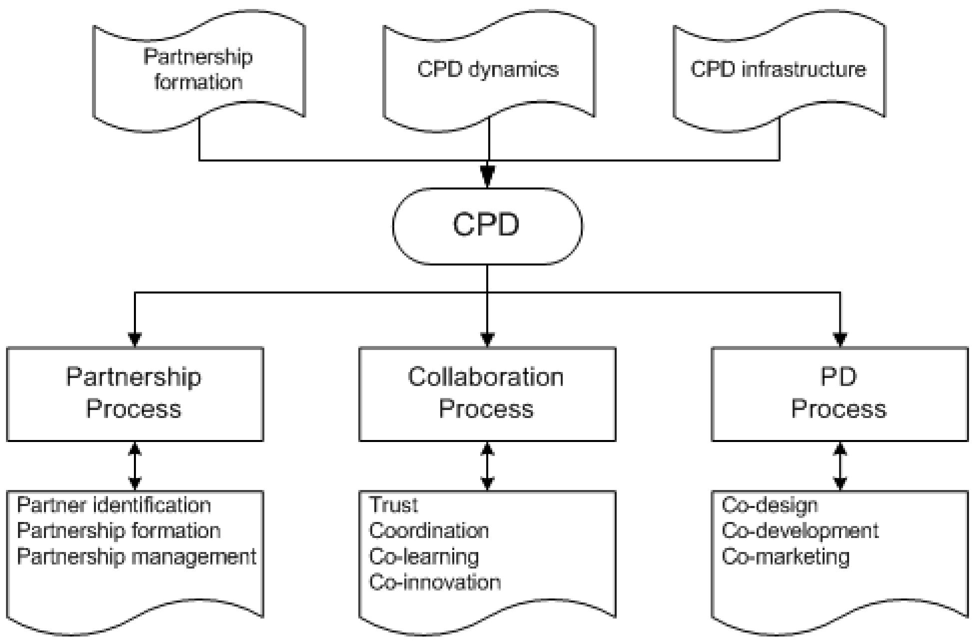


Figure 2.2 CPD framework

Proposition 2. *Partner identification, partnership formation, and partnership management are identified as the three main stages of the partnership process.*

First of all, the partnership process domain is derived from the partnership literature. Glaister and Buckley [**44**] emphasised the importance of recognizing a mutual partner need and of matching with the appropriate partner. These issues are tackled in the partner identification phase; where partner selection criteria as well as potential partners are identified. Partner selection criteria and success factors studies present an appropriate guideline for practitioners. However, partner selection goes beyond being able to astutely survey the list of potential partners to choose the one with the best skills and/or resources [**41**]. In consequence, formation of partnership is also stressed in partnership process domain, which is closely related with the negotiation and DSS for partner selection [**55**,**56**]. On the other hand, approximately 50% of all technology-based companies that have been involved in collaborative innovation projects perceive the ventures with their partner as a failure [**2**]. CPD success depends on how partners manage the governance of strategic objectives and expert knowledge [**46**]. In order to ensure the success of the partnership process, management of partnership is another major factor considered.

Proposition 3. *Four main factors, namely trust, coordination, learning, and innovation, are essential in the success of collaboration process.*

Another domain derived from the literature review is the collaboration itself. This domain includes key factors highlighted repeatedly by CPD dynamics studies, which are trust, coordination, learning, and innovation. Various scholars have identified trust between partners as a key factor that may help minimize uncertainties and reduce the threat of opportunism in strategic alliances [**41**]. Bstieler [**35**] stated that trust between partners becomes an essential element for a successful cooperation in PD. Therefore, trust is identified as the first key factor in the collaboration process. On the other hand, coordination, which can be defined as making different people work together for a goal, is naturally another key factor in collaboration. The multidisciplinary nature of CPD requires various activities to be coordinated effectively and efficiently [**33**]. CPD dynamics and collaborative infrastructure literature can be consulted for coordination issues.

On the other hand, Barnes et al. [**36**] identified learning one of the universal success factors, which are regarded as having an all-pervading influence across all elements and all stages of the life cycle of a collaborative project. Co-learning, whether corporate, individual or technical, is another goal to attain in an effective collaboration process in order to benefit from the synergy produced by collaboration. According to Marxt and Link [**45**], gaining knowledge, valuable insights and experience, or seeing new market opportunities can be the most important factor in assessing the success of collaboration.

Knowledge management in CPD literature can provide a guideline to assure learning in CPD projects.

According to Chapman and Corso [**13**], the increasing speed of innovation is one of the key drivers that lead companies to collaboration. Therefore, another key factor in the collaboration process domain is identified as co-innovation, innovation as a value-adding by-product of the collaboration process. Hacklin et al. [**55**] stated that the determinants of an efficient and rewarding implemented innovation cooperation could be put together through examining its success factors.

Proposition 4. *Design, development, and marketing are the three main stages of PD.*

The third domain of the framework is identified as the PD process. Design, development, and marketing of a new or improved product are the main stages, and the practitioners can consider these three stages as the main collaboration areas. CPD infrastructure literature offers many solutions for assuring integration of collaborating companies and real-time data transfer. Also, various control and management tools are introduced, and knowledge management systems are proposed. CPD practitioners may benefit from CPD infrastructure literature to review and select the most appropriate technologies for their PD process.

In conclusion, the presented framework can be employed as a strategic assessment tool by practitioners in order to measure CPD performance on a strategic level, and/or the framework can be further extended for specific sectors or product types.

2.4 SUMMARY

As PD becomes more and more complex, collaborating in PD attracts more attention from practitioners and researchers. Especially with the dynamic nature of the business model in the 21st century, CPD emerges as a novel way to be innovative while sharing risks and keeping the costs low. However, the literature is still developing in the CPD domain and lacks essential studies concerning some significant topics in CPD.

This chapter presented essential studies of CPD literature from 1993 to 2011 in three categories: CPD dynamics, partnership formation in CPD, and CPD infrastructure.

Methods or techniques applied in the study, the country and/or the sector, as well as the findings of the researches were examined. Factors affecting CPD, as stated in these studies, were also recapitulated. The shortcomings of the existing studies were analyzed and potential research areas were highlighted in order to represent possible directions in the subject. A new research direction in CPD was implied. A conceptual framework, which can guide practitioners through their collaborative efforts, derived from the literature overview was introduced to underline the main issues of CPD,.

Even though this overview does not comprise the entire collection of CPD literature, it provides a comprehensive review of the studies concerning inter-firm collaboration in PD in order to offer an overall view of the current state of the CPD literature and to provide a roadmap for future CPD studies.

3 MODELLING COLLABORATIVE PRODUCT DEVELOPMENT USING AXIOMATIC DESIGN PRINCIPLES

In order to maintain competitive advantage and sustainability in rapidly growing technological markets, firms seek to collaborate and form networks with other firms in order to improve the PD efforts. Collaborative networks bring valuable benefits to the involved parties such as an increase of survival capability in a context of market turbulence, but also the possibility to better achieve common goals[21]. More and more firms are engaging in collaborations in order to share risks, reduce costs and time-to-market, improve quality, and benefit from complementary knowledge and competence throughout PD process [2]. In consequence, CPD emerges as a new way of business to increase efficiency and effectiveness of PD.

Nevertheless, collaboration literature lacks of a systematic design of CPD from a strategic point of view, even though the subject is significantly explored in many studies. However, the development of a conceptual model is important for the design and analysis of processes, in order to propose guidelines to deal with the main problems related to a modelling domain [112]. Therefore, this chapter aims to design a collaborative structure by identifying CPD dynamics and developing a conceptual model through these dynamics.

Literature offers many system design tools such as QFD [113], AD [114], Design for X and TRIZ [115]. Among these methodologies, AD is an appropriate tool for the design of conceptual systems such as business plans and organizations [116]. AD technique considers the structure to be designed as a whole, instead of prioritizing the factors included in the system. Therefore, this study employs this technique in order to develop a CPD model, given that the use of AD in strategic formulation and business planning assures a strong relationship between the goals and strategies defined.

Given that CPD approach encompasses a wide area of industrial applications, the proposed structure remains highly generic. Therefore, software industry is selected as the application industry in order to detail the model and evaluate its applicability. Even though SD is an intrinsically collaborative process [117]; with the emerging importance of CPD, only recently collaborative nature of SD was recognized formally, and SD processes were formalized to improve both the product and process of SD [118].

CSD is gaining an increasingly competitive position with its dynamic and innovative structure, as the complex nature of SD makes collaboration indispensable, which presents an ideal environment to observe collaborative efforts in more detail with industrial insight.

The particular choice of SD is also motivated by the current position of Turkish software industry with its dynamic and innovative structure. SD experts' opinions and evaluations are considered throughout the model decomposition within the study. The conceptual model is then presented to two different SD experts, which is evaluated and verified through interviews. Subsequently, the model is employed in a case study as a guideline for managers.

The chapter is organized as follows. In the next section, CPD and CSD as well as their significance are described and state-of-the-art of the CPD/CSD models is presented. Third section reviews AD and presents its advantages compared to other design techniques. The proposed model is introduced in the fourth section. Fifth section presents the interviews conducted with software experts and their feedback, as well as a case study where the proposed model is applied. The chapter concludes with a few remarks.

3.1 BACKGROUND RESEARCH

While collaboration seizes the capacity to improve the efficiency and effectiveness of PD, it is also a complicated and challenging process to manage. Additionally, CPD activities have high failure rates in practice and, thus, they can be very costly. In order to take into account all these aspects, organizations should manage CPD activities thoroughly. This chapter attempts to design the CPD structure systematically, in order to offer a guideline for realizing collaboration in PD process.

As CPD includes a vast area of investigation as PD involves various processes, from development of physical entities to generating new ideas; an application industry was sought to detail and verify the proposed model. Software industry was selected given its collaborative and innovative nature. This section describes collaboration process within the software industry.

More than ever, organizations have been facing the challenge of improving the quality of their work processes as a strategy to remain alive and competitive. Many companies are struggling to reengineer, automate, and improve the way they perform their business [**119**]. SD has also been a challenging task for several decades [**120**] and the increasing complexity of SD, due to growing demands for different kinds of software as well as the ongoing globalization, requires more efficient SD processes [**121**].

SD is a combined process of research, development, modification, re-use, reengineering, maintenance and similar activities that result in software products. The development of large and complex software systems is considered to be a teamwork process that requires support for coordinating cooperative activities, maintaining project control and sharing information [**122**]. SD collaborations develop into a more structured activity, since mastering large SD projects becomes even more complex, not only because projects grow larger, but also because software teams are increasingly distributed across space and time due to globalization and internationalization [**122**]. Supporting efficient knowledge collaboration and transfer is, thus, essential for SD organizations to remain competitive [**123**]. While the software industry deals with the ever-increasing complexity of its products, collaboration among different people participating in the same development project is essential, and has already been considered as an everyday part of professional SD [**124**].

However, SD process and projects have a long and storied history of failure, where 82% of projects today run late, while errors cost 80% of the average project budget to fix. The growing complexity of software systems and the constant extension of new requirements entail the cooperation of multiple people such as analysts, developers, testers, and customers [**122**]. While the software engineering industry deals with the ever-increasing complexity of its products, collaboration among different people participating in the development project is essential and has already been considered as an everyday part of professional SD [**125**]. Collaboration helps SD teams to handle large software systems by knowledge sharing and communication. Communication and coordination are significantly hard to manage when a project is distributed over multiple geographic sites, sometimes spanning multiple countries or even continents [**126**]. Human-centric SD methods, such as Extreme Programming and other agile methods as well as internet-based multi-site cooperation tools that support remote CSD have been developed and implemented to deal with this complexity [**124**]. In software industry, collaboration occurs by developing software products or programming, testing, and operations [**127**], and CSD benefits its participants in time to market, reusability, robustness, extensibility, testability, and/or adaptability [**125**]. Nayak and Suesaowaluk [**128**] state that some of the most important differences between traditional SD and CSD are organizational culture, management, technical platform and development team, and socio-cultural issues. Kulmala et al. [**127**] maintain that the motivations for software industry alliances and networks are expected to differ from those of manufacturing industry because of the industry's high growth.

Table 3.1 Critical success factors in SD

Success factors	**Sources**
Communication	Bass et al. [**126**], Habib [**129**], Hyysalo et al. [**130**], Misra et al. [**131**], Setamanit and Raffo [**132**]
Understanding the customer	Misra et al. [**131**], Reel [**133**]
Project management	Bass et al. [**126**], Habib [**129**], Hyysalo et al. [**130**], Reel [**133**]
Team	Bass et al. [**126**], Habib [**129**], Hyysalo et al. [**130**], Misra et al. [**131**], Reel [**133**], Setamanit and Raffo [**132**],
Methodology and best practices	Hyysalo et al. [**130**]
Corporate culture	Habib [**129**], Misra et al. [**131**], Setamanit and Raffo [**132**]
Collaborative technology	Hyysalo et al. [**130**]

CSD encloses many challenges as it involves geographically distributed teams working within different units. Critical success factors for SD are recapitulated in Table 3.1 to supplement the critical success factors of CPD reviewed in Table 2.3.

As seen in Table 3.1, communication is cited as a very critical success factor for both CPD and CSD. This implies that formal and informal communication within each step of the collaboration is essential. On the other hand, factors such as team and understanding the customer are primarily software-specific; therefore, they are more emphasized in SD and CSD literature. Factors such as flexibility, learning, and information sharing are not underlined in CSD literature.

Araujo and Borges [**119**] state that improving awareness information about work processes and about the collaboration intrinsic may help SD teams to better accept the idea of defining, standardizing and continuously improving their work. Therefore, the proposed model depicts all processes included in SD in order to define methodically the requirements of CSD process, establishing the strategies to follow and methodologies to implement developing collaboratively new software.

3.1.1 Literature Review

CPD and CSD projects are usually evaluated within specific context and literature lacks of a generic modelling approach. However, a few study aims to capture a more holistic view of the collaborations. This section presents state-of-the-art of the collaboration framework.

An industry-specific model is presented by Chung and Lee [**134**] where they focus on injection mould design problems, given that it requires the collaboration of multidisciplinary divisions and companies working on separated sites. They develop a collaborative design framework for distributed environment where design information and evaluation results are shared through web. Another industry-specific model is introduced by Wang et al. [**135**]. They develop a CPD framework for centre satellite system, which can match the collaborative structure of key manufacturers and demonstrate the feature of central control during PD in the distributed environments.

A general approach example is provided by Hammond et al. [**136**]. They employ socio-technical theory to offer a framework within collaborative engineering design context. They examine design teams' patterns of interaction and their decision-making processes. However, the presented study fails to present a detailed model.

The model introduced by Choi et al. [**137**] is a detailed model, but it is design oriented. The Design Chain Collaboration Framework integrates three different views (design process reference model, service component reference model, and technology and standard reference model) and aims to appeal to business process managers. The model consists of business process, service component and technology & standard. The model proposed by Han and Do [**87**] is also design-oriented. They integrate product, process, project, participant, cost, and collaboration views to develop an object-oriented conceptual model in a CPD management system. Another design-oriented approach is provided by Jing and Lu [**138**], where they describe a co-construction process model for collaborative engineering design support. They aim to fill the gap between conceptual, logical, and analytical layers with a socio-technical framework.

A knowledge management oriented model is presented by Chen et al. [**84**]. They propose an integrated approach for collaborative product design, including a knowledge management-oriented engineering management work model, a distributed engineering knowledge management framework, and rules and methods for managing engineering knowledge. The system is developed using UML. Another knowledge-oriented study is presented by Bosch-Sijtsema et al. [**139**]. They analyze knowledge work in distributed collaboration teams and they develop a framework where they study the effects of five key factors (task, structure, processes, workplace, and organization context) on knowledge work performance and productivity.

Collaborative Product Commerce is investigated by Kim et al. [**140**], where they propose a framework for information sharing across enterprises. The focus is put on product metadata representation and application interoperability.

Ahram et al. [**141**] study the collaborative systems form social networking perspective and they propose a social networking approach to Systems Engineering in for the design and development of “smarter” products. The model is fairly detailed, but in the smart product context.

From the software engineering perspective, the focus is generally on collaboration support tools to improve the co-development process. Estublier and Garcia [**142**] develop a concurrent engineering system (the Celine system) that makes concurrent engineering processes explicit and controllable and which provides effective control over cost, quality and development time.

Two studies investigate software engineering collaboration support tools. Whitehead [**143**] proposes a roadmap for CSD by analyzing existing tools. Collaboration tools, environments, and infrastructure are investigated from model-based, process support, awareness, and collaboration infrastructure perspectives. Hildenbrand et al. [**121**] classify and analyze different approaches to CSD from three fields: Collaborative Requirements Engineering, Collaborative Design and Modelling Processes, and Collaboration in Implementation, Testing and Maintenance. They also investigate collaboration tool support. The study offers a comprehensive overview for CSD including academic literature, researches and commercial solutions. Integration frameworks and infrastructure are summarized by Li and Qiu [**59**], where they recapitulate state-of-the-art technologies and methodologies for CPD. They state that future trends include integration of various collaborative manners and systems, security and interoperability of collaborative systems, and advanced feature- and assembly-based methodologies in collaborative systems for efficient sharing of information and multiple domain applications. Recently, Jiang et al. [**91**] proposed a Web services and process view combined approach to manage the distributed CPD process. The approach claims to facilitate the workflow interoperability between heterogeneous Workflow Management Systems.

Although these studies each provide a roadmap or a guideline for CPD/CSD practitioners, it is evident that they lack the strategic perspective and the detailed analysis the presented study claims to provide.

3.1.2 Designing Systems using Axiomatic Design

AD is a systems design methodology enabling design thinking and defining problems in complex systems. AD is first introduced by Suh in 1990 with the goal to establish a scientific basis to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought process and tools [**144**]. AD provides a translation system between "what we want to achieve" and "how we want to achieve it", which are represented by the four domains of design: customer domain with characteristic vector of customer attributes (CAs), functional domain with characteristic vector of functional requirements (FRs), physical domain with characteristic vector of design parameters (DPs), and process domain with characteristic vector of process variables (PVs), as seen in Figure 3.1.

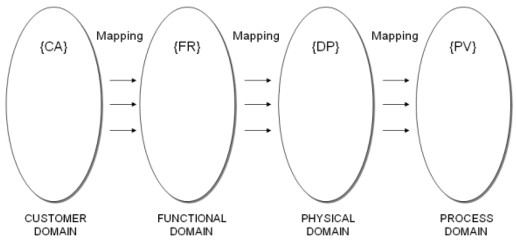


Figure 3.1 Four domains of design

The domain on the left represent "what"s and the domain on the right corresponds to "how"s. The transition between left to right occurs through mappings [**145**] as seen in Figure 3.2. The dotted arrows represent the connections between a FR and its related DP.

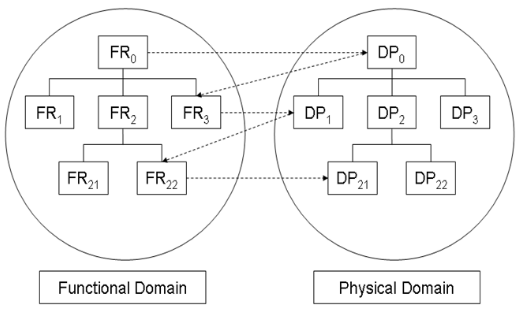


Figure 3.2 Mapping and zigzagging through domains

The most important concept of AD is the existence of two axioms [**144**]:

Axiom 1 - Independence axiom that demands to maintain the independence of the FRs

Axiom 2 - Information axiom that states that the design with the minimum information content is the best design.

During the mapping process, where first level CA, FR, DP and PV are decomposed into hierarchies, the independence axiom must be satisfied. Moreover, during decomposition, zigzagging between the design domains is required [**145**]. The independence axiom can be also defined as the case where DPs and FRs are related in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other FRs [**116**]. The information axiom, which is disregarded for the design phase of the study, can be used as a MCDM tool [**106**,**146**].

Zigzagging to decompose FRs and DPs and to create their hierarchies is an important part of AD [**147**]. Sub-levels of FRs and DPs are connected through zigzagging while maintaining the independence. The decomposition process is preceded layer by layer until the design reaches the final stage, creating a design that can be fully implemented [**144**].

The relation between FRs and DPs can be expressed as $\{FR\} = [A] * \{DP\}$. $\{FR\}$ and $\{DP\}$ represents the functional and physical vectors, respectively; whereas $[A]$ is the design matrix that displays the relation between each FR and DP. The independence of FRs is defined by the structure of the design matrix. To assure the independence, the design matrix should be either diagonal or triangular [**144**].

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

Uncoupled design | Decoupled design | Coupled design

Figure 3.3 Design types

There exist three types of design: coupled, decoupled, and uncoupled as seen in Figure 3.3. When $[A]$ is diagonal, the design is called an uncoupled design and each of the FRs can be satisfied independently by means of one DP. However, this represents an ideal design and it cannot always be achieved. Decoupled design is represented by a triangular design matrix, in which case the independence of FRs can be satisfied if and only if the DPs are determined in a proper sequence. Any other form of $[A]$ is called a coupled design and it should be avoided as the design cannot guarantee the independence axiom [**144**].

AD is generally applied to the design of physical entities and its applications include many areas such as software design [**159**], quality system design [**145**], general system design [**145**,**160**], manufacturing system design [**161**,**162**], ergonomics [**163**], and engineering systems [**164**,**165**]. Even though AD is widely employed in manufacturing areas, it is not frequently used for conceptual system design, and the few studies existing in this area are recapitulated in Table 3.2

The use of AD methodology for conceptual system design is a relatively recent topic and does not include a wide range of research topic. On the other hand, the literature does not propose much detailed work on the design of conceptual system and processes. Presented works generally go as far as to the second level decomposition even with case studies, which does not provide a deep hierarchical structure.

In this chapter, the proposed generic AD model for CPD, consisting of a two-level hierarchy presented in Arsenyan and Büyüközkan [**166**], is extended and the hierarchical structure becomes more detailed and specific, especially to the requirements of the software industry in the PD domain, which represents a contribution to the AD literature in the design of conceptual systems.

Table 3.2 AD applications to conceptual design

Authors	***Subject***	***Application***	***Study type***
Cochran *et al.* [**148**]	Production system segmentation	The presented segmentation procedure supports Lean Management practices following strategic, organizational, and technological design aspects.	Theory and case study
Cotoia and Johnson [**149**]	Business process redesign	The approach provides structure for analyzing process outcomes and the means used to achieve them, offering a framework in business process design.	Theory and application
Martin and Kar [**116**]	E-commerce strategies	A framework for the e-commerce applications in electronic retailing is proposed. The high level goals and strategies form the roots of the decomposition tree for the e-commerce strategy.	Theory
Yilmaz [**150**]	Urban transportation systems	A new model for urban public transportation systems to increase its efficiency is proposed, identifying the main factors contributing to design process of urban public transportation systems.	Theory and application
Schnetzler *et al.* [**151**]	Supply Chain Management	A method of supply chain design decomposition distinguishing objectives and means of Supply Chain Management is developed. Using a structured procedure, the Supply Chain Design Decomposition can be utilized to develop a supply chain strategy that is in alignment with corporate strategic goals and the context and the environment of the enterprise.	Theory and case study
Schnetzler and Schönsleben [**152**]	Supply Chain Management	A methodology for the alignment of all activities, which relate to Information Management in supply chains, is developed. Supply Chain Design Decomposition is developed that distinguishes objectives and means of SCM at different levels.	Theory and case study
Hou *et al.* [**30**]	Product Collaborative Development Chain	A modelling methodology and a web based framework to efficiently optimize and manage the information and resource of the Product Collaborative Development Chain (PCDC) are proposed.	Theory and prototype

Authors	*Subject*	*Application*	*Study type*
Yenisey [153]	E-commercial web-sites	A decomposition diagram for e-commercial web-sites is proposed, where FRs represent customer requirements and DPs represent web-site's physical design and processes developed.	Theory
Kabadurmuş and Durmuşoğlu [154]	Pull/Kanban production control systems	A road map is developed for the design of pull/kanban systems, denoting what kinds of kanbans are needed to be used in regard to design parameters.	Theory and application
Yang and Xiao [155]	Information systems	An innovative method of modelling complex information system combined with object-oriented method is proposed.	Theory and case study
Favaro [156]	Lean logistics	Lean logistics design decomposition is proposed, guiding the designer to achieve simultaneously the business fundamentals of quality, on time delivery, lead time, cost, and investment effectiveness.	Theory and case study
Aksoy and Dincmen [157]	Knowledge management	A new methodology, Knowledge Focused Six Sigma is presented, explaining the relations among critical success factors, the requirements from the Six Sigma infrastructure, the components of the Six Sigma infrastructure, and knowledge processes.	Theory
Taticchi *et al.* [158]	Business performance measurement and management	The framework ''Business System Design Decomposition'' is based on AD and AHP and it offers a holistic approach to performance measurement and management, identifying cause-effect relationships in business processes, measuring performance versus stakeholders, and offering interlinking between performance indicators.	Theory

3.2 MODELLING COLLABORATION THROUGH AXIOMATIC DESIGN

The work methodology followed is demonstrated in Figure 3.4. In the literature survey phase, first a thorough search on CPD literature and design techniques is conducted. Once AD is selected as the appropriate design methodology, AD applications are reviewed.

First, the generic AD based CPD model proposed by Arsenyan and Buyukozkan [**166**] is presented. Then, after selecting the software industry for the application, SD and CSD literature is reviewed. The generic model is detailed with assistance of expert reviews and feedback from software industry. These reviews and feedbacks assisted in finalizing the model. Expanded model includes more sub-levels, as well as factors descriptions in detail.

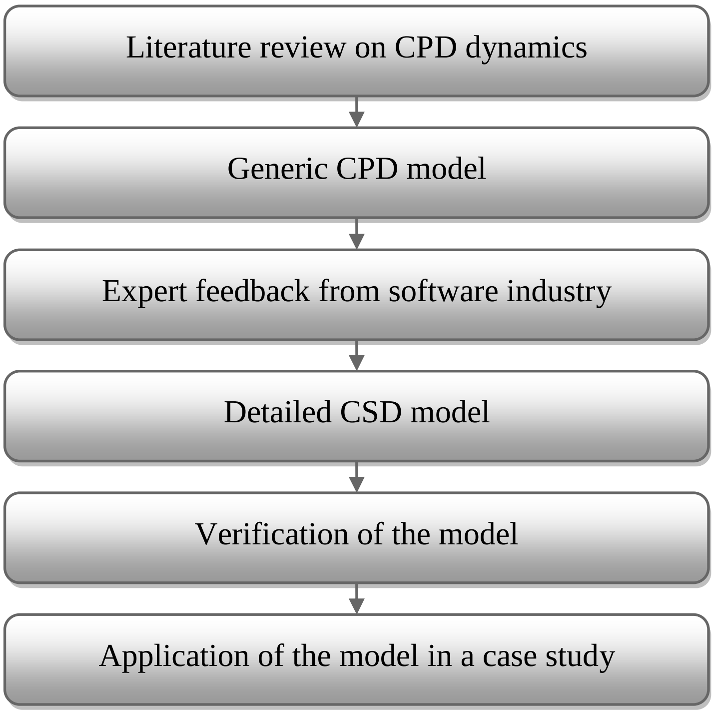


Figure 3.4 Modelling steps

3.2.1 Modelling Collaborative Product Development

The proposed *generic* model investigating CPD consists of three levels, based on the conceptual framework proposed by Büyüközkan and Arsenyan[**167**]. AD technique is employed to structure the framework.

The first level (Level 0) of the model describes the three main domains of the CPD: customer domain, functional domain, and physical domain. The variables defined as CAs represent the goals of the CPD efforts. FRs correspond to the strategies needed to be implemented to achieve these goals. Subsequently, the methodologies and tools used to implement these strategies are symbolized by DPs. Figure 3.5 displays the proposed three-level model with mappings between goals, strategies and methodologies. Arrows represent mappings between domains, while straight connectors symbolize the zigzagging.

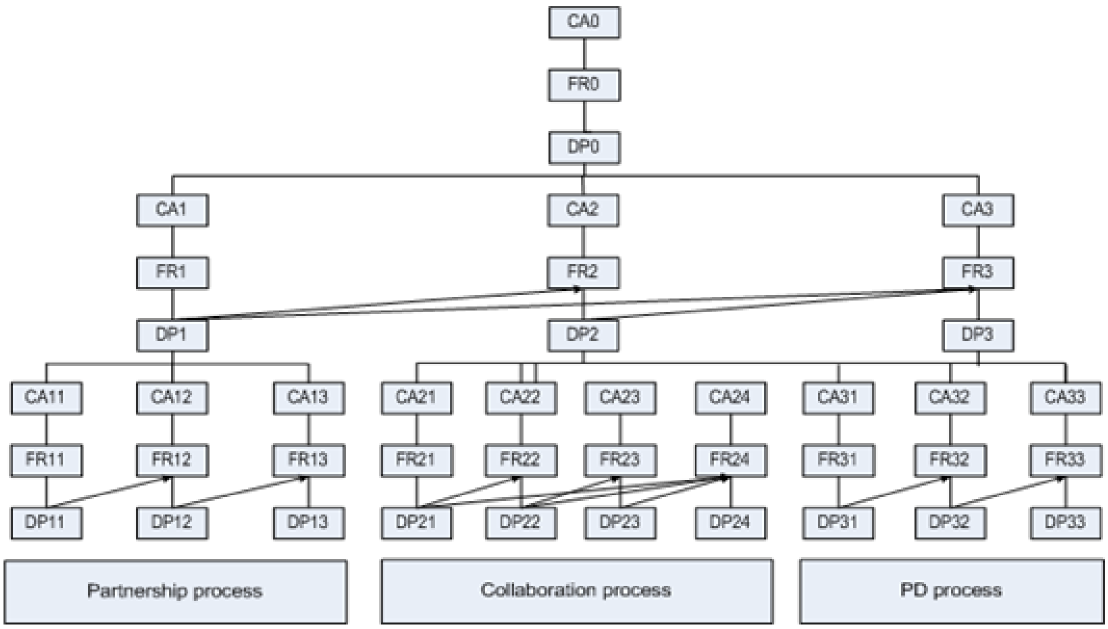


Figure 3.5 AD-based CPD model on strategic level

The matrices presented throughout the decompositions symbolize the relationships between the strategies and the methodologies. The matrices for the relationships between goals and strategies are not demonstrated given that each strategy corresponds to only its goal, and therefore, independence is naturally achieved.

3.2.1.1 Level 0: Description of the Problem

In this first level of CPD structure design, initial goal, strategy and framework are defined. This level can be defined as the description of the problem, given that it summarizes the problematic of the subject on hand [**166**]. Therefore, initial goal is set to be “Inter/intra-firm collaborations for PD” since the main objective of the model is to provide a guideline for successful PD collaborations. The related strategy is to define a collaboration strategy, accordingly. In order to have a successful collaboration, initial strategy must be to define a collaboration strategy to cover all possible collaboration areas. Consequently, CPD framework, including all methodologies and tools applied to CPD are included in DP_0 to satisfy the collaboration strategy. In this initial level, the mappings through domains are direct as seen in Figure 3.6.

- CA_0 = Inter/intra-firm collaborations for PD
- FR_0 = Define a collaboration strategy
- DP_0 = CPD framework

3.2.1.2 Level 1: Description of the Dimensions

First level goal is decomposed into three sub-goals. Effective PD is an essential goal of CPD efforts. Also, CPD includes concurrently both collaboration process and partnership process. Collaboration denotes all collaborative activities such as communication and interaction emerged during collaboration activities, whereas partnership process includes phases related to the evaluation and selection of the partners.

Figure 3.6 displays the goals, strategies and methodologies identified for the three domains of CPD. First, a corporate initiative is necessary to commence the partnership process. Then a collaborative infrastructure from a technological perspective should be established in order to implement the collaboration process. Subsequently, a Product

Lifecycle Management framework is needed in order to conduct the development process.

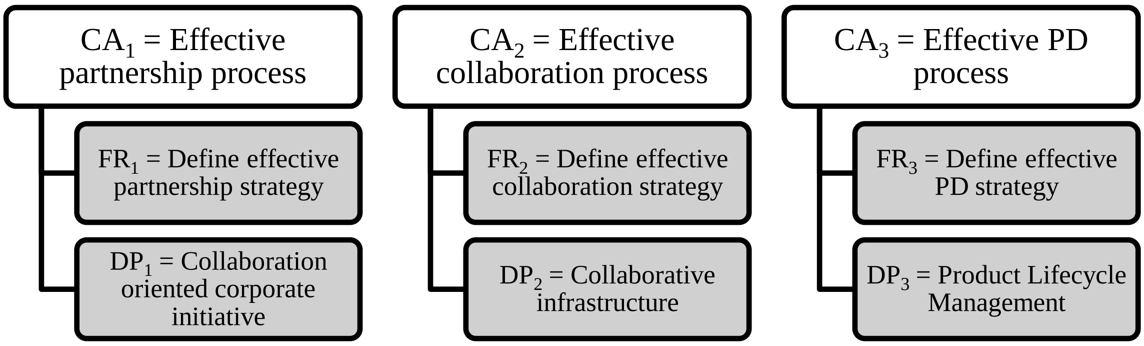


Figure 3.6 Level 1 decomposition

As seen in Figure 3.7, a decoupled design is obtained in the Level 1 decomposition. This is due to the fact that launching collaborative activities requires initially an effective partnership process. Therefore, the application of DP_1 directly affects the implementation of the next strategy. Similarly, effective PD process is closely related with the installation of all necessary collaborative technology and setting up the collaborative environment, which is represented by DP_2.

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

Figure 3.7 Level 1 design matrix

Level 1.1: Partnership Strategy

Effective partnership process is decomposed into three sub-goals and these sub-goals present the stages of the partnership process. In this decomposition, the development of the partnership is studied. Further analysis is presented in the section Modelling Collaborative Software Development. Once again, an uncoupled design is observed in this decomposition as seen in Table 3.3. This is essentially caused by the fact that strategies in partnership process are implemented progressively, each methodology at a time. This results in a triangular design matrix, where each DP affects its successors. Each strategy is dependent of the successful execution of the methodologies.

Level 1.2: Collaboration Strategy

Effective collaboration process differs from effective partnership process given that this goal focuses on the profits acquired by CPD efforts. Four sub-goals are determined for effective collaboration process. Differing from the partnership, collaboration process investigates the dynamics within the collaboration efforts once the partnership is formed, as introduced in the section Modelling Collaborative Software Development.

Level 1.2 decomposition results also in a triangular matrix. However, this structure does not represent a process. Instead, the importance of communication strategy is highlighted within the design matrix, as the main support for the collaboration process is the IT implemented. Therefore, each strategy is related with DP_{21}. On the other hand, remaining FRs are independent and executed separately.

Level 1.3: Product Development Strategy

Effective PD process focuses on the main goal of CPD, PD; however this process is enhanced with collaboration. Stages of PD are merged into three phases of design, production and marketing, and three sub-goals are determined as follows, based upon value-adding products.

- CA_{31} = Design of value adding products
- CA_{32} = Production of value adding products
- CA_{33} = Marketing of value adding products

In order to reach aforementioned sub-goals, three strategies are determined: effective co-design, effective co-manufacturing and effective co-marketing.

- FR_{31} = Apply effective Co-design
- FR_{32} = Apply effective Co-manufacturing
- FR_{33} = Apply effective Co-marketing

Computer aided design and manufacturing platforms (CAD/CAM) are indispensable tools for design and manufacturing and they support individual work in resolving the increased complexity in the engineering of new products and production facilities [**168**]. However, the tools to be employed for co-design and co-manufacturing must be on integrated platforms in order to support synchronization and collaboration of engineering teams. On the other hand, integrated customer relationship management (CRM) approach, as a methodology to employ for effective co-marketing, supports both inter-collaboration relations and acquiring customers for the new product [**169**]. Integrated CRM includes expanding the market with the client portfolio of all parties, accessing each partner's clientele and collectively acquiring new markets.

- DP_{31} = Integrated CAD platforms
- DP_{32} = Integrated CAM platforms
- DP_{33} = Integrated CRM

This domain represents a generic approach to PD, and it is important to emphasize that it requires an industry-specific approach to detail the requirements.

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

Figure 3.8 Level 1.3 Design matrix

Another decoupled design is obtained for Level 1.3 decomposition, as displayed in Figure 3.8, given that PD process follows a course and each step is dependent of its antecedent. Therefore, FR_{32} is also affected by the implementation of DP_{31}, and FR_{33} is also affected by DP_{31} and DP_{32}.

3.2.2 Modelling Collaborative Software Development

The generic AD structure proposed for CPD [**166**] presents a theoretical model, offering a foundation for the collaborative efforts at the strategic level. More detailed analysis of collaboration activities may be founded on the presented model depending on the industry, in which the development process is performed. However, industrial insight is required for the model to be applicable in real life, given that each industry possesses its own characteristics, and variations occurs in sub-level hierarchies of the model. Software industry can promote collaboration, given that it holds a dynamic and innovative structure, and thus, it is an appropriate sector. The theoretical model is further detailed by feedback of experts from software industry, and is adapted to SD. However, partnership and collaboration processes remain generic given that these are not industry-specific processes on strategic level.

SD process is often introduced by considering ‘why’, ‘what’ and ‘how’: ‘why’ is defined by whoever commissions the project, the architect’s primary concern in to specify ‘what’ must be done, and ‘how’ it is done is the software engineer’s province [**170**]. In this study; ‘why’, ‘what’ and ‘how’ are transformed into CAs, FRs and DPs, translating goals, strategies and methodologies. Level 0 decomposition is transformed as follows:

- CA_0 = Inter/intra-firm collaborations for SD
- FR_0 = Define a CSD strategy
- DP_0 = CSD framework

It is important to be aware of the three different types of goals (individual goal, collective goal, and project goal) to better understand a participative system [**171**]. In this study, these goals are translated as effective partnership process, effective collaboration process, and effective SD process, respectively, in the first level decomposition of the model. It is necessary to understand what the customer wants most in supportability and to align the capability of the organization to provide it [**172**]. Therefore, the starting point of the model is the customer domain, where the strategic goals of the CSD system are clearly defined. The decompositions for the three main domains and the hierarchical structure will be elaborated subsequently.

3.2.2.1 Effective Partnership Process

Effective partnership process is decomposed into three sub-goals and these sub-goals present the stages of the partnership process: identification of potential partners, formation of partnership, and management of partnership. Through Strategic Analysis of the External Environment, market research is conducted in order to identify potential partners, which itself consists of four sub-strategies:

- define the strategic goal of the partnership using the organization's mission and vision statements
- define required competencies for the goal using AD, the technique used in this study as well, as it represents an appropriate methodology to define functional requirements for a conceptual system
- find most suitable alternatives for partner applying SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, i.e. an external scan and an internal assessment, to the identified potential partners during market research
- evaluate alternatives according to competencies using Decision Analysis [**55**], [**56**]) A more detailed evaluation is conducted through Decision Analysis, following a general assessment offered by SWOT. Selection criteria such as trust, cultural alignment, reputation, competence, experience and other partner selection criteria are gathered in order to evaluate and select partners for CPD.

The next step goal is the formation of partnership with a strategy of negotiation and reaching an agreement through Game Theory, given that different cooperation and competition strategies emerge according to the level of competition and cooperation between the "players" [**37**]. While forming the partnership, first potential benefits and risks of the partnership are defined using Nominal Group Technique [**173**] as it prevents the domination of discussion by a single person, encourages the more passive group members to participate, and results in a set of prioritized solutions or recommendations [**174**].

Then Negotiation Management is employed to negotiate with potential partner(s). Contracts serve as a coordinating device, clarifying mutual expectations, enabling goal correspondence, and establishing a basis for shared common ground [**175**]. Therefore, Contract Management is an appropriate tool to make agreement with partner(s). Contracting phase deals with issues such as intellectual property rights, governance structure, and Service Level Agreement.

After reaching an agreement with partners, the goal is the management of the partnership while maintaining the partnership applying Partnership Management. Long-term commitment can maintain a partnership relationship with competitors, and can neutralize possible conflicts [**37**]. Firstly, Risk Management is used to define risks and take action. Then partnership performance is monitored and improved through Balanced Scorecard, which is a strategic planning and management system aligning business activities to the vision and strategy of the organization and monitoring organization performance against strategic goals [**176**]. Finally, Contract Management Maturity Model is applied to improve the contract as it presents an evolutionary roadmap an organization would pursue in improving its contract management process capability from an immature process to a continuously improved or optimized process [**177**].

Figure 3.9 displays the branch of partnership process whereas Table 3.3 presents the variables of the branch.

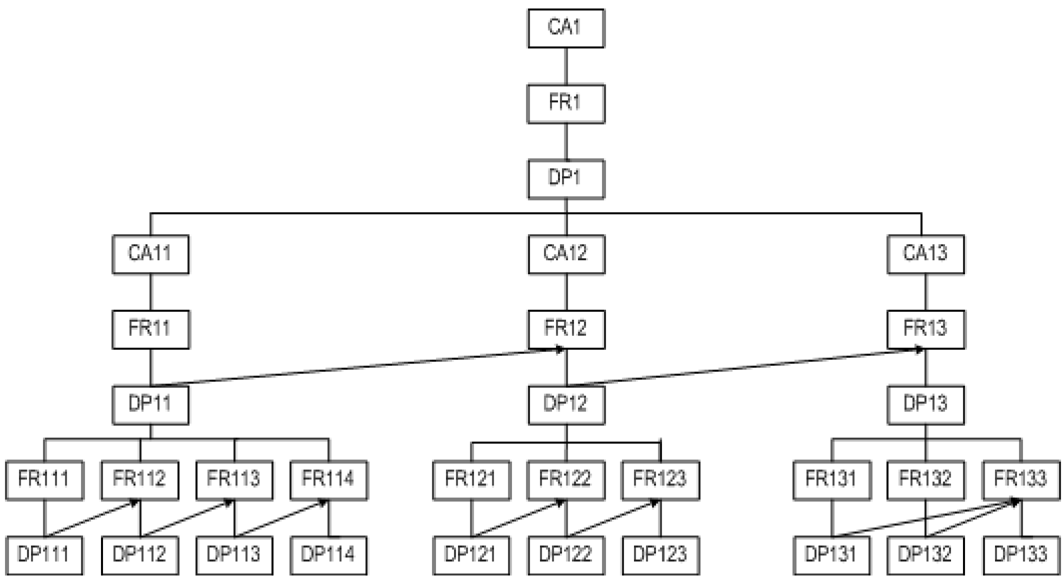


Figure 3.9 Partnership process

Table 3.3 Decomposition for effective partnership process

CA_{11} = Identification of potential partners FR_{11} = Do market research DP_{11} = Strategic Analysis of the External Environment CA_{12} = Formation of partnership FR_{12} = Negotiate and reach an agreement DP_{12} = Game Theory CA_{13}= Management of partnership FR_{13} = Maintain the partnership DP_{13} = Partnership management $\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} x & & \\ x & x & \\ & x & x \end{bmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix}$	FR_{111}= Define the strategic goal of the partnership DP_{111}= Mission and vision statement FR_{112}= Define required competencies for the goal DP_{112}= Axiomatic Design FR_{113}= Find most suitable alternatives DP_{113}= SWOT FR_{114}= Evaluate alternatives according to competencies DP_{114}= Decision Analysis $\begin{Bmatrix} FR_{111} \\ FR_{112} \\ FR_{113} \\ FR_{114} \end{Bmatrix} = \begin{bmatrix} x & & & \\ x & x & & \\ & x & x & \\ & & x & x \end{bmatrix} \begin{Bmatrix} DP_{111} \\ DP_{112} \\ DP_{113} \\ DP_{114} \end{Bmatrix}$
FR_{121}= Define potential benefits and risks of the partnership DP_{121}= Nominal group technique FR_{122}= Negotiate with potential partner(s) DP_{122}= Negotiation management FR_{123}= Make agreement with partner(s) DP_{123}= Contract management $\begin{Bmatrix} FR_{121} \\ FR_{122} \\ FR_{123} \end{Bmatrix} = \begin{bmatrix} x & & \\ x & x & \\ & x & x \end{bmatrix} \begin{Bmatrix} DP_{121} \\ DP_{122} \\ DP_{123} \end{Bmatrix}$	FR_{131}= Define risks and take action DP_{131}= Risk management FR_{132} = Monitor and improve partnership performance DP_{132}= Balanced scorecard FR_{132}= Improve the contract DP_{133}= Contract management maturity model $\begin{Bmatrix} FR_{131} \\ FR_{132} \\ FR_{133} \end{Bmatrix} = \begin{bmatrix} x & & \\ & x & \\ x & x & x \end{bmatrix} \begin{Bmatrix} DP_{131} \\ DP_{132} \\ DP_{133} \end{Bmatrix}$

3.2.2.2 Effective Collaboration Process

According to Chapman and Corso [**13**], stability and effectiveness of a network is strongly dependent on softer issues such as open communication, knowledge sharing, trust and common goals. Accordingly, four main goals are defined for the collaboration process: trust, coordination, co-learning and co-innovation. To reach trust between partners, a trust environment must be cultivated using Trust Management. Building open, trust-based relationships is the key to successful partnership development, and integrated information systems facilitate the flow of data and information between staff [**178**]. While focusing on trust, impartial collaborative environment is implemented to provide fairness and reciprocity to the employees. Team culture is engendered with team work and motivational training, as organisational culture is a key factor aiding the transfer of knowledge between firms [**179**]. Conflict Management is employed to resolve conflicts in three phases:

- define problems with Cognitive Mapping as it provides a visualization on the abstract issues
- discuss problems with Open Groups where organizational problems are discussed in an informal manner
- resolve problems with Quality Circles who are trained to identify, analyze and solve work-related problems, and present their solutions to management in order to improve the performance of the organization.

Understanding the role of trust in collaboration during inter-organizational process implementation can potentially increase the probability of achieving a successful B2B implementation that leads to a productive longer-term relationship [**180**]. Once trust has been firmly established, a bond will develop between staff in the partner organizations [**178**].

For coordination, Information and Communication Technologies provide basis to assure interoperability between collaborating firms. This goal is divided into two strategies: communication and management of the collaboration process. Collaborative software is implemented to communicate by defining communication channels with communication plan, which describes the communication goals, stakeholders and strategies, activities and timeframes. Communication is documented with communication records. Accessible record of all communication regarding development provides project independence from individual designers and programmers [**181**]. On the other hand, Collaborative Project Management is employed to manage the collaboration process while defining time constraints with PERT (Project Evaluation and Review Technique) and budget constraints through Earned Value Analysis, as well as assigning teams with Human Resources Management.

Improved learning at all these levels is partly the result of effective communication and information distribution systems, both within and between organisations [**179**]. Therefore, co-learning is another goal to attain by implementing a collaborative learning system through learning organization. Becoming a learning organization seems to be the most effective way of embedding processes and enabling partners to sustain continuous development without adding to everyone’s workload [**182**]. The sub-strategies to follow are

- document and share value adding data through collaborative databases
- secure data using data security system
- adopt best practices by documentation

The integration process can be facilitated by sharing information that results in more appropriate decision making [**178**]. To document and share value adding data, partners must benefit from inter-organizational data flow through data mining, and then transform value adding data into information using Knowledge Management Software. Identifying relevant knowledge inputs from various partner organizations involved in the partnership arrangement is something that needs to be viewed as a constant [**178**]. On the other hand, securing data consists of conserving data with back-up systems, conserving infrastructure by anti-virus programs, and defending the system by firewall. Finally, best practices are adopted by providing inter-organizational information flow using institutional communication, and by defining best practices using key performance indicators and metrics. A key goal for firms is to shift from an essentially static approach to learning, based on information acquisition, towards a greater emphasis on information interpretation and distribution [**179**].

The final goal to attain in collaboration process is co-innovation, which is crucial in maintaining competitive advantage in the market. Partnership arrangements represent a means through which senior managers can find ways to innovate and place innovation within the context of sustainable development [**178**].The strategy is to engender an innovative infrastructure by Innovation Management. Sub-strategies are investment in innovation by R&D department and to create innovative work environment using creativity techniques. It is important to create an organizational environment to support intrinsic motivations and appropriate reward schemes to foster a creativity culture [**183**]. Once a sustainable partnership arrangement has been established, it should be possible to promote innovative practices throughout the partnership arrangement, and to promote a more integrated R&D policy [**178**]. Creative work environment comprise two aspects: the organization must support institutional creativity using brain storming, a group creativity technique, designed to generate a large number of ideas, and support individual creativity by TRIZ as a technique to promote creative thinking.

Figure 3.10 displays the branch of collaboration process whereas Table 3.4 presents the variables of the branch.

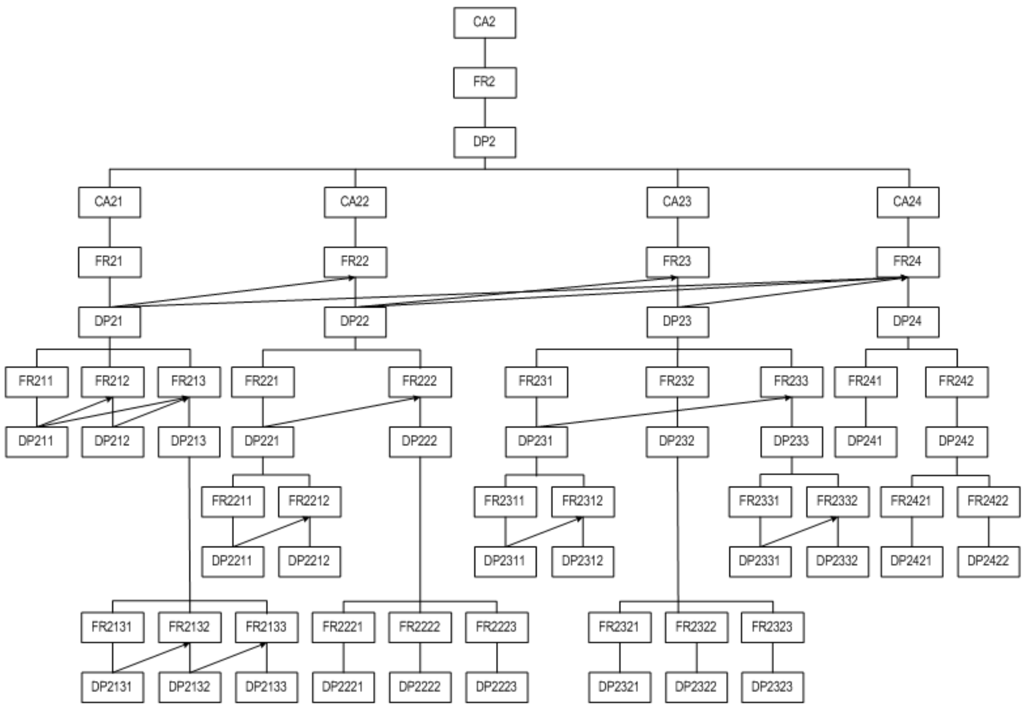


Figure 3.10 Collaboration process

Table 3.4 Decomposition for effective collaboration process

CA_{21}= Trust
FR_{21} = Cultivate trust environment
DP_{21} = Trust management
CA_{22} = Coordination
FR_{22} = Assure interoperability
DP_{22} = Information and Communication Technologies
CA_{23} = Co-learning
FR_{23} = Implement a collaborative learning system
DP_{23} = Learning organization
CA_{24} = Co-innovation
FR_{24} = Engender innovative infrastructure
DP_{24} = Innovation management

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

FR_{211} = Provide fairness and reciprocity to the employees
DP_{211}= Impartial collaborative environment
FR_{212} = Engender team culture
DP_{212} = Team work and motivational training
FR_{213} = Resolve conflicts
DP_{213} = Conflict management

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

FR_{2131} = Define problems
DP_{2131}= Cognitive mapping
FR_{2132} = Discuss problems
DP_{2132} = Open groups
FR_{2133} = Resolve problems
DP_{2133} = Quality Circles

$$\begin{Bmatrix} FR_{2131} \\ FR_{2132} \\ FR_{2133} \end{Bmatrix} = \begin{bmatrix} x & & \\ x & x & \\ & x & x \end{bmatrix} \begin{Bmatrix} DP_{2131} \\ DP_{2132} \\ DP_{2133} \end{Bmatrix}$$

FR_{221}= Communicate
DP_{221}= Collaborative software
FR_{222}= Manage the collaboration process
DP_{222}= Collaborative project management

$$\begin{Bmatrix} FR_{221} \\ FR_{222} \end{Bmatrix} = \begin{bmatrix} x & \\ x & x \end{bmatrix} \begin{Bmatrix} DP_{221} \\ DP_{222} \end{Bmatrix}$$

FR_{2211}= Define communication channels
DP_{2211}= Communication plan
FR_{2212}= Document communication
DP_{2212}= Communication records

$$\begin{Bmatrix} FR_{2211} \\ FR_{2212} \end{Bmatrix} = \begin{bmatrix} x & \\ x & x \end{bmatrix} \begin{Bmatrix} DP_{2211} \\ DP_{2212} \end{Bmatrix}$$

FR_{231} = Document and share value adding data
DP_{231} = Collaborative databases
FR_{232} = Secure data
DP_{232} = Data security system
FR_{233} = Adopt best practices
DP_{233} = Documentation

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

FR_{2311} = Benefit from inter-organizational data flow
DP_{2311} = Data mining
FR_{2312} = Transform value adding data into information
DP_{2312} = Knowledge management software

$$\begin{Bmatrix} FR_{2311} \\ FR_{2312} \end{Bmatrix} = \begin{bmatrix} x & \\ x & x \end{bmatrix} \begin{Bmatrix} DP_{2311} \\ DP_{2312} \end{Bmatrix}$$

FR_{2321} = Conserve data
DP_{2321} = Back-up systems
FR_{2322} = Conserve infrastructure
DP_{2322} = Anti-virus programs
FR_{2323} = Defend system
DP_{2323} = Firewall

$$\begin{Bmatrix} FR_{2321} \\ FR_{2322} \\ FR_{2323} \end{Bmatrix} = \begin{bmatrix} x & & \\ & x & \\ & & x \end{bmatrix} \begin{Bmatrix} DP_{2321} \\ DP_{2322} \\ DP_{2323} \end{Bmatrix}$$

FR_{2331} = Provide inter-organizational information flow
DP_{2331} = Institutional communication
FR_{2332} = Define best practices
DP_{2332} = Key performance indicators and metrics

$$\begin{Bmatrix} FR_{2331} \\ FR_{2332} \end{Bmatrix} = \begin{bmatrix} x & \\ x & x \end{bmatrix} \begin{Bmatrix} DP_{2331} \\ DP_{2332} \end{Bmatrix}$$

FR_{241} = Invest in innovation
DP_{241}= R&D department
FR_{242} = Create innovative work environment
DP_{242} = Creativity techniques

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

FR_{2421} = Support institutional creativity
DP_{2421}= Brain storming
FR_{2422} = Support individual creativity
DP_{2422} = TRIZ

$$\begin{Bmatrix} FR_{2421} \\ FR_{2422} \end{Bmatrix} = \begin{bmatrix} x & \\ & x \end{bmatrix} \begin{Bmatrix} DP_{2421} \\ DP_{2422} \end{Bmatrix}$$

FR_{2221} = Define time constraints
DP_{2221}= PERT
FR_{2222} = Define budget constraints
DP_{2222} = Earned Value Analysis
FR_{2223} = Assign teams and tasks
DP_{2223} = Human Resources Management

$$\begin{Bmatrix} FR_{2221} \\ FR_{2222} \\ FR_{2223} \end{Bmatrix} = \begin{bmatrix} x & & \\ & x & \\ & & x \end{bmatrix} \begin{Bmatrix} DP_{2221} \\ DP_{2222} \\ DP_{2223} \end{Bmatrix}$$

3.2.2.3 Effective Software Development Process

The development of a system is carried out over multiple periods in multiple phases [**184**]. SD is mainly constituted of four main phases: design, development, test and implementation. In the 1980's, development phase dominated an important part of the process; however, with emerging technologies, today SD is mainly constituted of the design phase, whereas the development phase generally only takes two or three weeks. Another major part of the SD is the testing phase requiring meticulous planning, while debugging is now a part of the coding. Implementation, the final phase, is essentially focused on the training efforts.

The goal to attain in the design process is the correct understanding of the customer demands. Efficient software goal is satisfied with the development phase. Assuring the quality respond to the flawlessness and efficient performance goal is assured by implementation. Requirements Engineering, which is the process of discovering, analyzing, modelling and specifying business and user requirements for an information system [**183**], is applied during the design. Developer teams are employed to develop the software. CMMI (Capability Maturity Model Integration), which represents a software engineering process improvement approach, is applied to assure software quality. The software product itself is utilized to implement the software.

Design strategy is divided into two branches: modelling the software specifications and getting approval of design from customer. Modelling the software specifications through UML (a common language for collaborative parties) requires careful consideration as it represents a highly complex process. Initially, customer demands are defined through meetings with customers. Then the aims and scope of the project is constituted through the project charter. Requirements are defined using Value Analysis. Interfaces between modules are determined via process flow of the customer, and meetings with software teams are utilized to define roles and authorizations. Interfaces along with roles and authorizations represent an important phase that requires thorough application, where the end user's role in organization and the authorizations required for these roles, as well as the intersection of these roles are determined. These specifications constitute the core of the software and require to be approved by the customer through agreement contract. Every contract includes the definition of the product (software, hardware and documentation), services (systems analysis, requirements analysis, interviews, design, programming, testing, conversion, implementation, consulting, documentation, supporting activities, maintenance, training, modification/enhancement assistance and progress reports), and delivery conditions (timetable for development cycles, installation dates (initial and final), conditions of hardware and premises, acceptance tests (including benchmark and test data), warranties (of software functions and operations) and disclaimers, fixes, and compatibility with other parts of the system) [**184**]. Prospective users cannot evaluate a system before they actually see the system; therefore, a prototype is built and users' feedback is reflected in the final design of the system [**184**]. The customer is provided with the screen simulation to get the approval for the screen and with the user process flow to get the approval for specifications.

After getting the approval from the customer, the development process starts. This phase is mainly constituted of coding. However, many projects involve complex or state-of-the-art technologies, and thus, the most appropriate hardware/software design has to be selected, the resources to commit to the development effort has to be estimated, and how the implemented product will perform has to be anticipated [**181**]. Therefore, before starting to code, SD environment has to be prepared by acquisition of hardware and decision on Integrated Development Environment. Common data structure must also be defined by choosing the most appropriate one among data structure types such as array, list, tree, hash, and graph. Then coding, along with debugging, begins through programming language. Backing up the system with Concurrent Versions System is another necessity during development. After the development phase, a comprehensive testing process starts. Before the integrated test is launched, each part is tested: test the functionality and database processing by test scenarios for functionality, test the interfaces between modules by test scenarios for interfaces, and test the roles and authorizations by test scenarios for roles and authorizations. Afterwards, integrated testing is performed through predefined test route.

Once integrated test is successfully completed, the software has to be implemented within the customer organization. Implementation implies more than setup. Trainings are organized through software teams. Trainers are educated, and training guides are prepared to instruct the end users about the software. Then a performance evaluation process, consisting of two parts begins. Trainers' performances are evaluated by end users through surveys in order to measure their ability to communicate the features of the software and end users' performances are evaluated by trainers through feedback in order to determine the acceptance and understanding toward the software. User performance evaluation is presented to the management level of the customer organization.

While the customer is being prepared for the software setup, data take on is performed using data transfer system of the current software in order to obtain existing data and upload to the upcoming system. From this moment on, software is set up and the focus is now on improving the system through add-ons. First action is to observe the system with issue tracking software. Then system is improved through feedbacks by updates. Even where evolution was not initially envisaged by the developer, it is necessitated by feedback from customers and users, by evolving requirements, and by competitive market pressures [**185**].

Figure 3.11 displays the branch of collaboration process while Table 3.5 presents the variables of the branch.

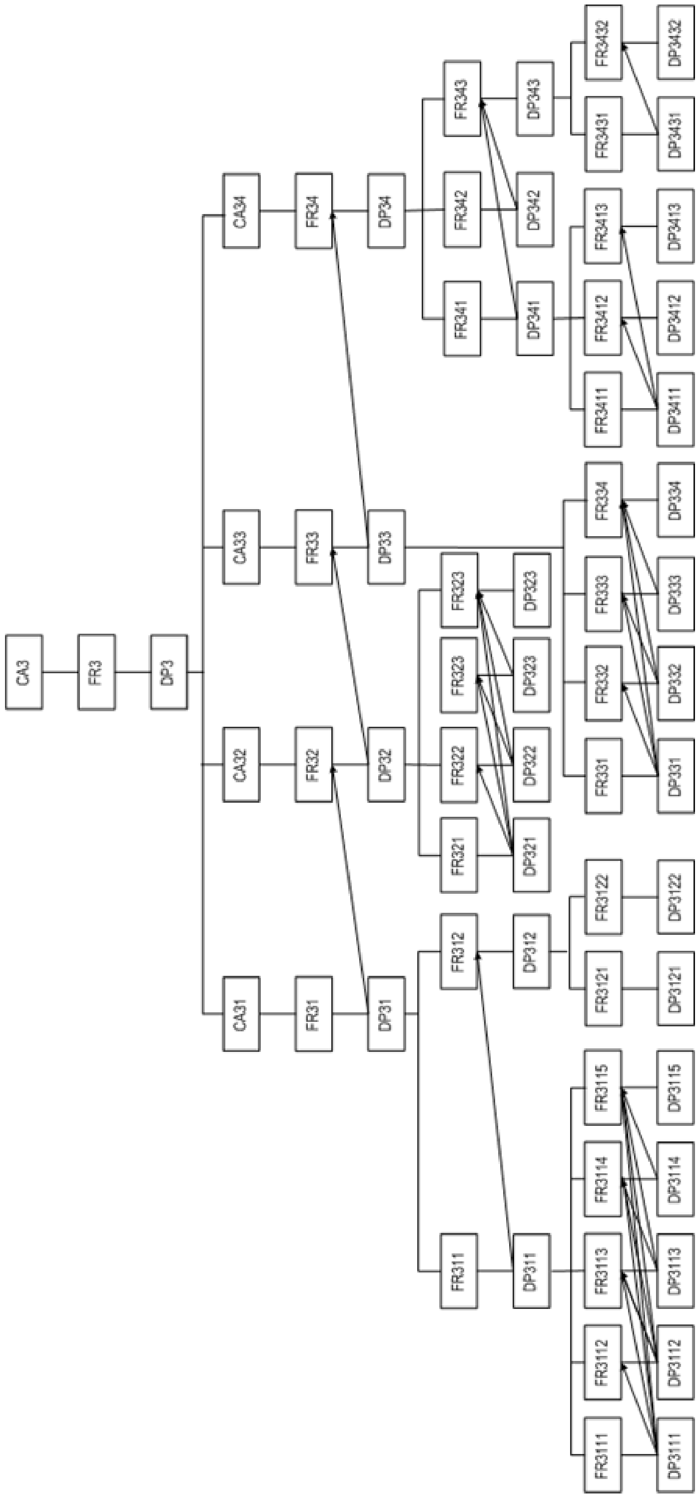


Figure 3.11 SD Process

Table 3.5 Decomposition for effective SD process

CA_{31}= Correct understanding of customer demands
FR_{31} = Design the software
DP_{31} = Requirements engineering
CA_{32} = Efficient software
FR_{32} = Develop the software
DP_{32} = Development server
CA_{33} = Flawlessness
FR_{33} = Test the software
DP_{33} = Test server
CA_{34} = Efficient performance
FR_{34} = Implement the software
DP_{34} = Live server

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

FR_{311} = Model the software specifications
DP_{311} = UML
FR_{312} = Get approval of design from customer
DP_{312} = Agreement contract

$$\begin{Bmatrix} FR_{311} \\ FR_{312} \end{Bmatrix} = \begin{bmatrix} x & \\ x & x \end{bmatrix} \begin{Bmatrix} DP_{311} \\ DP_{312} \end{Bmatrix}$$

FR_{3111} = Define customer demands
DP_{3111} = Meetings with customers
FR_{3112} = Define aims and scope of the project
DP_{3112} = Project charter
FR_{3113} = Define requirements
DP_{3113} = Value analysis
FR_{3114} = Define interfaces between modules
DP_{3114} = Process flow of the customer
FR_{3115} = Define roles and authorizations
DP_{3115} = Meetings with software teams

$$\begin{Bmatrix} FR_{3111} \\ FR_{3112} \\ FR_{3113} \\ FR_{3114} \\ FR_{3115} \end{Bmatrix} = \begin{bmatrix} x & & & & \\ x & x & & & \\ x & x & x & & \\ x & x & x & x & \\ x & x & x & x & x \end{bmatrix} \begin{Bmatrix} DP_{3111} \\ DP_{3112} \\ DP_{3113} \\ DP_{3114} \\ DP_{3115} \end{Bmatrix}$$

FR_{3121} = Get approval for screen
DP_{3121} = Screen simulation
FR_{3122} = Get approval for specifications
DP_{3122} = User process flow

$$\begin{Bmatrix} FR_{3121} \\ FR_{3122} \end{Bmatrix} = \begin{bmatrix} x & \\ & x \end{bmatrix} \begin{Bmatrix} DP_{3121} \\ DP_{3122} \end{Bmatrix}$$

FR_{321} = Prepare SD environment
DP_{321} = Hardware
FR_{322} = Define common data structure
DP_{322} = Data structures
FR_{323} = Code
DP_{323} = Programming language
FR_{324} = Backup
DP_{324} = Concurrent Versions System

$$\begin{Bmatrix} FR_{321} \\ FR_{322} \\ FR_{323} \\ FR_{324} \end{Bmatrix} = \begin{bmatrix} x & & & \\ x & x & & \\ x & x & x & \\ x & x & x & x \end{bmatrix} \begin{Bmatrix} DP_{321} \\ DP_{322} \\ DP_{323} \\ DP_{324} \end{Bmatrix}$$

FR_{331} = Test the functionality and database processing
DP_{331} = Test scenarios for functionality and database processing
FR_{332} = Test the interfaces between modules
DP_{332} = Test scenarios for interfaces
FR_{333} = Test the roles and authorizations
DP_{333} = Test scenarios for roles and authorizations
FR_{334} = Perform integrated testing
DP_{334} = Test route

$$\begin{Bmatrix} FR_{331} \\ FR_{332} \\ FR_{333} \\ FR_{334} \end{Bmatrix} = \begin{bmatrix} x & & & \\ x & x & & \\ x & x & x & \\ x & x & x & x \end{bmatrix} \begin{Bmatrix} DP_{331} \\ DP_{332} \\ DP_{333} \\ DP_{334} \end{Bmatrix}$$

FR_{341} = Organize trainings
DP_{341} = Software teams
FR_{342} = Perform data take-on
DP_{342} = Data transfer system
FR_{343} = Improve the software
DP_{343} = Add-ons

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

FR_{3411} = Train the users
DP_{3411} = Trainers and training guides
FR_{3412} = Evaluate trainers' performance
DP_{3412} = Survey (to users)
FR_{3413} = Evaluate users' performance
DP_{3413} = Feedback (from trainers)

$$\begin{Bmatrix} FR_{3411} \\ FR_{3412} \\ FR_{3413} \end{Bmatrix} = \begin{bmatrix} x & & \\ x & x & \\ x & & x \end{bmatrix} \begin{Bmatrix} DP_{3411} \\ DP_{3412} \\ DP_{3413} \end{Bmatrix}$$

FR_{3431} = Observe the system
DP_{3431} = Issue tracking software
FR_{3432} = Maintain system through feedback
DP_{3432} = Updates

$$\begin{Bmatrix} FR_{3431} \\ FR_{3432} \end{Bmatrix} = \begin{bmatrix} x & \\ x & x \end{bmatrix} \begin{Bmatrix} DP_{3431} \\ DP_{3432} \end{Bmatrix}$$

Figure 3.12 displays the AD based CSD model as a whole, including mapping between functional and physical domains, as well as FR-DP zigzagging. Lines represent the decomposition into hierarchies, while arrows symbolize the zigzagging between domains. As seen in Figure 3.12, though the three main domain of the CSD may seem independent, they are in fact interdependent given that the outcomes of the collaboration process is affected by partnership formation, and SD performance is dependent on the effective implementation of the collaboration.

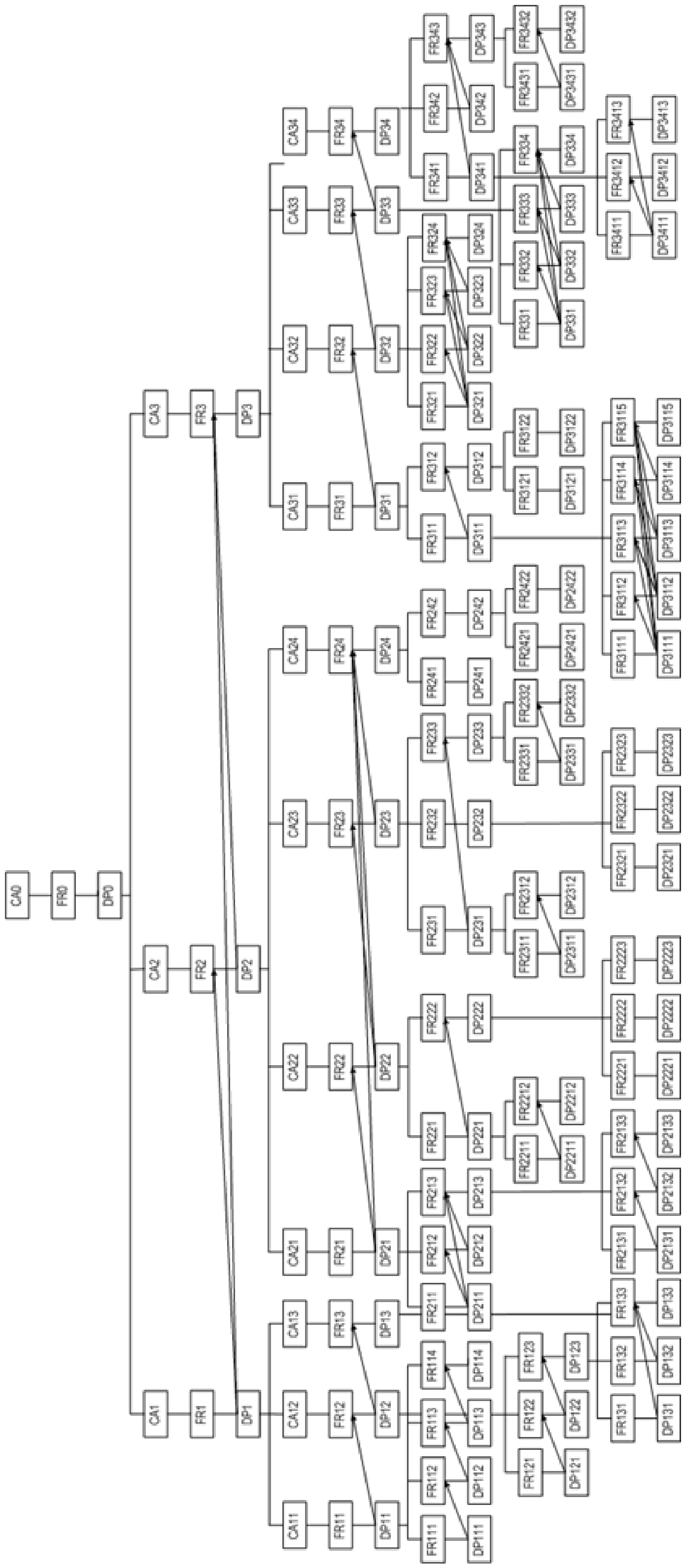


Figure 3.12 Modelling CSD using AD principles

3.3 VERIFICATION AND APPLICATION OF THE MODEL IN THE SOFTWARE INDUSTRY

The model proposed by Arsenyan and Buyukozkan [**166**] was revised through industrial feedback gathered from multiple experts involved in collaborative projects. The original model was fairly detailed and expanded. The notions mentioned throughout the model were clarified.

This study was conducted within the context of a CPD project sponsored by TUBITAK (Turkish Scientific and Technological Research Council). An industrial partner, an SD company named IDE Bilisim Destek Hizmetleri AS (IDE AS), assists the TUBITAK project in testing and verifying proposed models throughout the study.

Therefore, the AD based CSD model is brought to IDE AS for an evaluation and verification of the proposed model in industry. On the other hand, another expert from academia with strong industrial credentials, also a consultant for MESH Engineering and Software Co., was also consulted for another verification in Turkish SD environment. Both interviews are presented below. A case study is then conducted in order to observe the performance of the model in real life applications.

3.3.1 Interview with Expert X

Company and expert description

IDE AS, the industrial partner within the CPD project sponsored by TUBITAK, is selected from the software industry due to its dynamic and intrinsically collaborative nature. The company was founded in 1996 by SD experts in order to provide service and consultancy in IT sector. IDE AS aims to develop customized project for the requirements of each firm.

SD and consultancy in sales, distribution, pharmaceuticals, automotive, and finance are the company’s main expertise. However, they are also advancing in logistics sector through various projects since 2001 through their experience in various firms. IDE’s software services include software project with Java technologies, VB and C# projects with MS.net, web-based portal projects, consultancy for existing software, software projects for barcodes, RFID (Radio Frequency Identification) solutions, and customized software. Their modules include computability-finance, human resources, warehouse management, CRM, order tracking, shipping, sales and distribution, production planning, cross-docking, etc. They also provide consultancy for project-based software, ERP, outsourcing, and IT.

Expert X from IDE AS is a Management Engineer, who selected computer industry to start his career. He worked on projects where he could merge software business with Management Engineering while he strategically focused on logistics industry to profit from his profession. He is the co-founder of IDE AS, and he assisted in various projects since the company's foundation.

The interview

First of all, the expert is asked to describe the current practice for the CSD in order to examine the present situation. The three main domains of CSD presented to the expert, who is then enquired upon the course of events of these three domains.

- Partnership process

During the partnership formation of the firm in question, partners are generally selected among acquaintances. However, when the need for novel expertise arises, new partners are selected according to the new set of requirements. Each partnership requires another negotiation and agreement. Sustainable partnership is stressed out as a major issue given that the firm prefers repetitive partnership.

- Collaboration process

Trust is a major concern in collaboration and it is presented as the main reason why the firm chooses repetitive partnership. Nevertheless, the firm does not apply any formalized method to assure trust. Communication between partners is also emphasized by the expert though it is conducted through informal channels.

The expert also underlines the importance of co-learning and co-innovation in collaborative processes. Learning is secured through documentation of practices while innovation occurs with the development process and meetings on new projects.

- SD process

SD is basically the same for each project. The differences occur in the design phase, where the program type is selected, and where the integrated development environment (Visual Studio, Ecliplse, etc.) is decided upon. Few changes are observed according to the design decisions; however, the process remains the same. Each development process basically includes design, development, test, and implementation. The expert mentioned the training as a standalone process, rather than as a part of the implementation.

Model evaluation

Subsequently to the description of the current process in the firm, the expert was provided with the conceptual model presented in this study, and was asked to comment on the FRs. It was emphasized by the expert that the backgrounds of the firm managers include experience in major corporations. Therefore, the firm learns from its mistakes and experiences. Hence, current situation of the firm is close to ideal, which caused a high compatibility between the IDE AS case and the conceptual model. From 76 FRs presented, the only disagreement was upon the hierarchical position of FR_{341}= Organize trainings. The expert declared that implementation and training are independent of each other. On the other hand, FR_{341} and its subordinates were approved.

Then the expert asked to comment whether or not presented FRs are executed within the firm. First of all, the expert stated that they did not execute neither FR_{11} = Do market research nor its subordinates, given that they prefer to work with the same partners. However, the expert agrees with the FR for the collaboration cases when novel expertise is needed.

FR_{21} = Cultivate trust environment is another FR that is not executed within IDE AS, again due to the repetitive partnerships. FR_{211}= Provide fairness and reciprocity to the employees and FR_{212} = Engender team culture are not executed neither. However, FR_{213} = Resolve conflicts is executed, and its importance is emphasized.

Another FR that is not executed within IDE AS are FR_{2211}=Define communication channels and FR_{2212}= Document communication. The expert acknowledges the importance of the communication, and thus, the importance of FR_{221}. However, IDE AS does not define communication in a formalized manner. FR_{2222} = Define budget constraints is another strategy that is not applied within the firm.

Adopting best practices and creating innovative work environment are issues of minor concern for the expert. FR_{233} and its subordinates, as well as FR_{242} and its subordinates are not executed within IDE AS.

Finally, even though the expert agrees with the need for training, performance evaluation is not considered. FR_{3412}= Evaluate trainers' performance and FR_{3413}= Evaluate users' performance are not applied, or considered as a key issue. Table 3.6 displays the expert's discussions on DP suitability.

Table 3.6 DP discussions from Expert X

DP	Expert comments
DP241 = R&D department	The expert states that innovation occurs everywhere during CSD, not only in R&D department.
DP341 = Software teams	The expert affirms that trainers derived from end users are more adequate to train the users than the software teams.

3.3.2 Interview with Expert Y

Company and expert description

MESH Engineering and Software Co. is a technology company providing IT-based engineering and software solutions for various industries. The company was established in 2002 by a group of engineers including founders of a reputable Turkish Ship Design and Consultancy, Delta Marine and provides business solutions in advanced engineering and SD in two separate departments.

SD department was involved in development of software applications for ship design purposes in Delta Marine. Delta Marine's rapid expansion in terms of staff and the influence of the growing shipbuilding market conditions caused SD Department to go beyond developing software for ship design and to create solutions for project/document/process management. MESH also attempts to develop a database system. The company opted to adapt its ship design software to various industries. They allied with a consultant for process management and PD within MESH, mostly during partnership process and trainings. This consultant is our expert for Case II.

Expert Y has a Ph.D. degree in Engineering Management, and an M.Sc. in Electrical Engineering. He is a member of Referee Committee of Turkish Automation Revue, as well as a member of board of Internet Technologies Association. He provides publishing consultancy for automation journals, and resource planning consultancy for various firms. Expert Y is selected because of his vast expertise in IT consultancy in different industries, and because of his knowledge of behavioural motivations of Turkish IT firms.

The inverview

First of all, Expert Y is asked to describe the current practice for the CSD in Turkish SD market. The expert replied that CSD in Turkey generally lacks of trust between partners and it is conducted as an assignment process where tasks are assigned to teams within firms, rather than a collaboration process, where all firms are equally involved in SD. The expert states that MESH does not use component-based architecture, which enables concurrent engineering. He also states that Turkish firms, while not fully collaborating, occasionally opt for agile SD. Our expert underlines three main factors of SD:

- Functionality in order to respond to customer requirements,
- Right architecture in order to maintain reliability, speed and performance,
- Usability in order to assure intuitive learning of end user.

Our expert states that in every SD process, these factors must be assured. He also stresses the importance of integration platforms during collaboration, whether it is CAD/CAM integration for PD or integrated development environment for SD.

Model evaluation

Subsequently to the feedback on the CSD in Turkey, the expert was provided with the conceptual model presented in this study and was asked to comment on the FRs. The expert agreed on the three dimensions presented, however he again emphasized that collaboration is not a formal business process in Turkey and that the firms were inexperienced in collaborative aspects of SD. Hence, situations he is accustomed are far from ideal. From 76 FRs presented, the only disagreement was upon the position of FR_{21}= Cultivate trust environment. The expert states that trust is an issue that must be dealt with during FR_{13}= Maintain the partnership, within the partnership process. Even though being a very important FR, FR_{232}= Secure data should be implemented within IT Department, rather than as a part of the collaboration process. The expert also declared that FR_{3413}= Train the users was only meaningful for key users (which later train the end users), while FR_{3412}=Evaluate trainers' performance was unimportant.

Then the expert asked to comment whether or not presented FRs are executed within the firm. As stated before, the expert indicated that presented FRs were informally executed or not executed at all within SD companies in Turkey.

Table 3.7 DP discussions from Expert Y

DP	Expert comments
DP_{112} = Axiomatic Design	It is not practical to execute within a CSD process.
DP_{12} = Game Theory	It is excessively sophisticated.
DP_{213} = Cognitive mapping	It is not practical, especially when conflicts occur noticeably without the need to properly define them.
DP_{2221} = PERT	PERT is an old method which must be replaced with Critical Chain Method.
DP_{2311} = Data mining	The expert states that Data mining is an over-the-top technique and he proposes techniques such as reporting, queries and OLAP (Online analytical processing).
DP_{2422} = TRIZ	This technique requires deep understanding, so it is not practical.
DP_{3} = Product Lifecycle Management	PLM is a PD-oriented tool, our expert suggests integrated development environment as a suitable DP.
DP_{311} = UML	CASE (Computer Aided Software Engineering) tools are more appropriate.

The expert then was asked to perform an evaluation on the importance of the FRs as well as the suitability of its corresponding DP. A 5-level Likert scale was used for FRs, whereas a custom scale which consists of three options (Suitable, Not Suitable, No Comment) was used for DPs. Table 3.7 displays the expert's discussions on DP suitability.

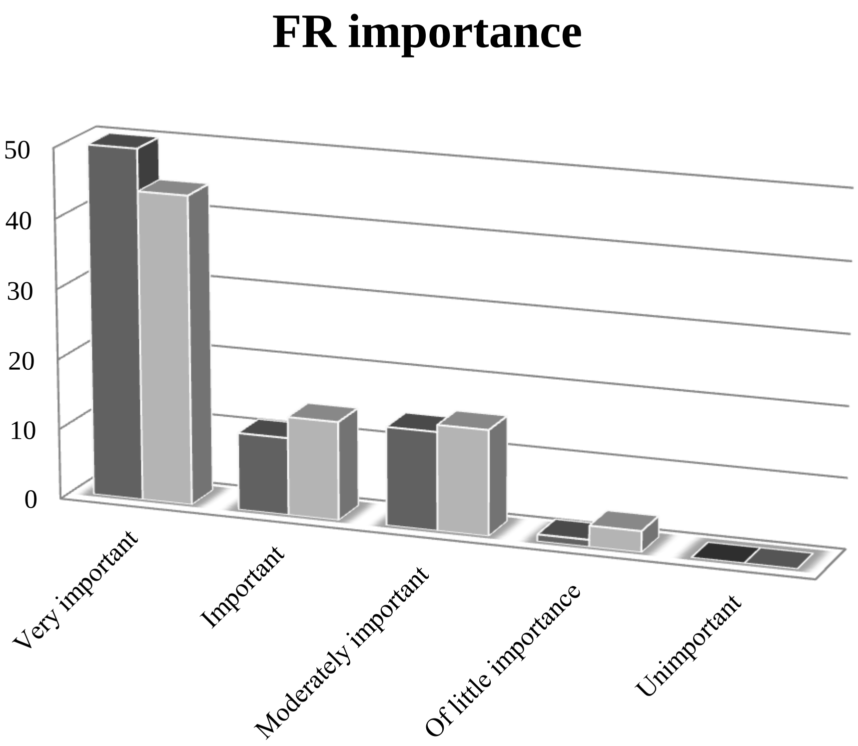
3.3.3 General Evaluation of the Proposed Model

The experts are then asked to perform an evaluation on the importance of the FRs and the suitability of its corresponding DP. A 5-level Likert scale (Very Important, Important, Moderately Important, Of Little Importance, Unimportant) was used for FRs, whereas a custom scale which consists of three options (Suitable, Discussed, No Comment) was used for DPs.

The outcome of the evaluation of Expert X shows that only 3% of FRs labelled "Very Important" are matched with discussed DPs, explained in Table 3.6. 87% of DPs are approved to be suitable, while the expert had no comment on the 10% of DPs.

On the other hand, the outcome of the evaluation of Expert Y shows that 4% of FRs labelled "Very Important", 1% of FRs labelled "Important", 4% of FRs labelled "Moderately Important" and 1% of FRs labelled "Of Little Importance" are matched with discussed DPs. Overall discussed DP rate is 10%, which slightly decreases the applicability of the proposed model. However, as explained in Table 3.7, the DP discussions are generally due to their impracticality, rather than their irrelativeness; which explains the overall rate. All of the DPs were familiar to the expert, therefore the chart does not include "not commented" DPs. 90% of DPs are approved to be suitable.

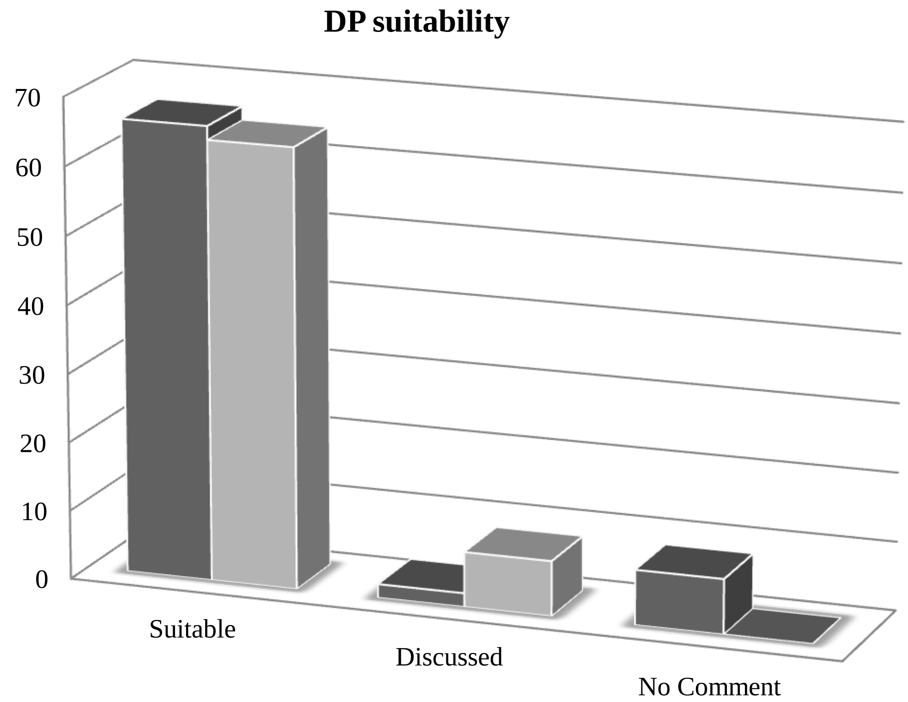
The final outcome on FR importance is visualized in Figure 3.13. It can be stated that Expert X attaches more importance to FRs than Expert Y does. However, the overall outcome clearly suggests that the experts acknolwedge the importance of the existence of all the FRs in the model.



	Very important	Important	Moderately important	Of little importance	Unimportant
Expert X	50	11	14	1	0
Expert Y	44	14	15	3	0

Figure 3.13 FR importance comparison

On the other hand, another comparison can be conducted on the DP suitability as shown in Figure 3.14. It is observed that both experts agrees on the ratio of suitable DPs. Expert Y puts more reservation on some DPs. Expert X makes no comment on some DPs while Expert Y expresses his opinion on each DP. Overall, proposed DPs respond effectively to the FRs.



	Suitable	Discussed	No Comment
Expert X	66	2	8
Expert Y	64	8	0

Figure 3.14 DP suitability comparison

Discussed DPs are not eliminated from the AD based CSD model. The experts state that these DPs, however impractical, may provide a motivation for CSD practitioners to seek consultancy on complicated requirements.

3.3.4 Case Study

Around the model was finalized, another industrial partner from software industry engaged in a new collaborative development process. The managers were asked to employ the conceptual model as a guideline to assist them throughout the collaboration. As they were used to conduct the process with an informal approach, developer teams were reluctant to formalize their activities. On the other hand, the manager was enthusiastic about structuring the process.

- Partnership process

CSD partner was already defined. It was a recurring partnership. Therefore market research through Strategic Analysis of the External Environment was not conducted to identify potential partners. SWOT analysis was performed in order to have a strategic breakdown before the development process. Decision analysis was skipped considering the partner was already selected. However, the company generally employed managerial experience, development competence, technologic capability and collaborative experience as selection criteria. Negotiation process was conducted formally. Company lawyers' employed a standard contract to all development alliances, with necessary adjustments to respond to unique features of each new alliance. SLA's were defined and property rights were assured through contract. The company did not employ any partnership management system in previous alliances. However, as the model required partnership maintenance, they opted to assign a *relationship manager*, with the responsibility to monitor teams' performance, satisfaction levels, and project progress through regular interviews. Another responsibility of the relationship manager was to maintain communication between project managers of partner companies.

The company also previously ignored the importance of a risk management system. They opted to implement Risk Matrix as an effective yet comprehensible tool. Balanced Scorecard was employed to assess the performance through key performance indicators such as meeting frequency, achieved short term goals and finances. The company did not employ any contract management system. Contract Maturity Model was implemented in order to handle issues such as contract change management, contract quality assurance, payment integrity assurance, and performance management.

The highlighted aspects of the partnership process are displayed in Figure 3.15.

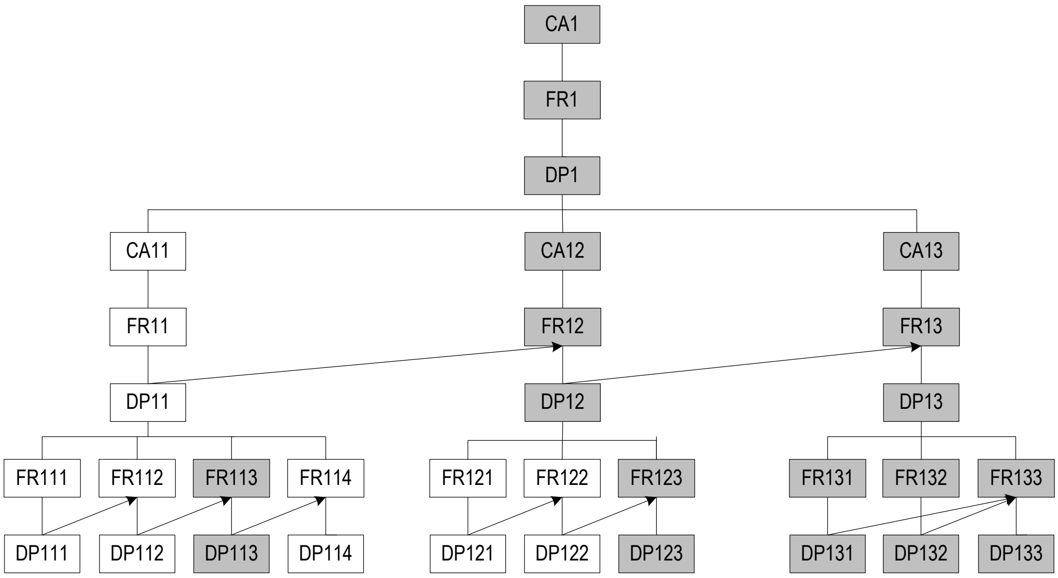


Figure 3.15 Highlighted aspects of the partnership process

- Collaboration process

The model was especially functional for the collaboration phase. As the development process was undertaken by a recurring partnership, trust environment was already established. However, the company decided to use the contract as a trust management tool. Confidentiality and privacy topics handled in the contract were monitored closely to prevent any contract breach. Inter-organizational brunches were organized to engender team culture. No personal conflict occurred during the development process. However the relationship manager was assigned to perform conflict management.

A Quality Circle (composed from two developers from the two companies) was selected in order to resolve development conflicts. They often employed cognitive mapping techniques where they drew conceptual maps where they visualized the problem. The Quality Circle then presented the problem to developer teams and they employed what-if analysis as a problem solving technique.

As the firms were already acquainted, coordination was an already resolved issue and previous success on interoperability was a driving motive for the choice of partner.

The two firms opted to have management level meetings once a month, operational level meetings once a week and development teams communicated through instant messaging (IM) services. They documented IM communications through chat logs and every meeting was documented with an official report.

Interoperability was assured by the use of common technology and IP. MS Project was employed as a collaborative project management tool. PERT and Earned Value Analysis tools in MS Project were employed to estimate task durations and cost performance. Development teams were already assigned; no Human Resource Management technique was needed.

The focal company puts much emphasis on learning; therefore there was an established learning organization. Both firms meticulously and collectively documented each issue occurred during the development process and the solution method on a simple knowledge management software developed internally, where business data is collected and analysed. The software supports data mining and managers employed the development data to improve the process. The focal firm's manager stated that the learning structure of their organization enabled them to adopt best practices given that they value knowledge created during each collaborative development.

Data security was not an issue. Being a SD company, they had established back-up systems, up-to-date anti-virus programs and firewall. Conversely, they had problem applying co-innovation requirements. Innovative management was undertaken by the focal firm's manager as he possessed an innovative vision for the company and he is involved in innovation management activities. The companies didn't have R&D departments, only developer teams. Brainstorming was employed in developmental meetings. However, developers were reluctant to employ TRIZ in their daily activities given that it is a rather demanding technique.

The highlighted aspects of the collaboration process are displayed in Figure 3.16, which clearly shows the importance of the implementation of the model within the collaboration dimension.

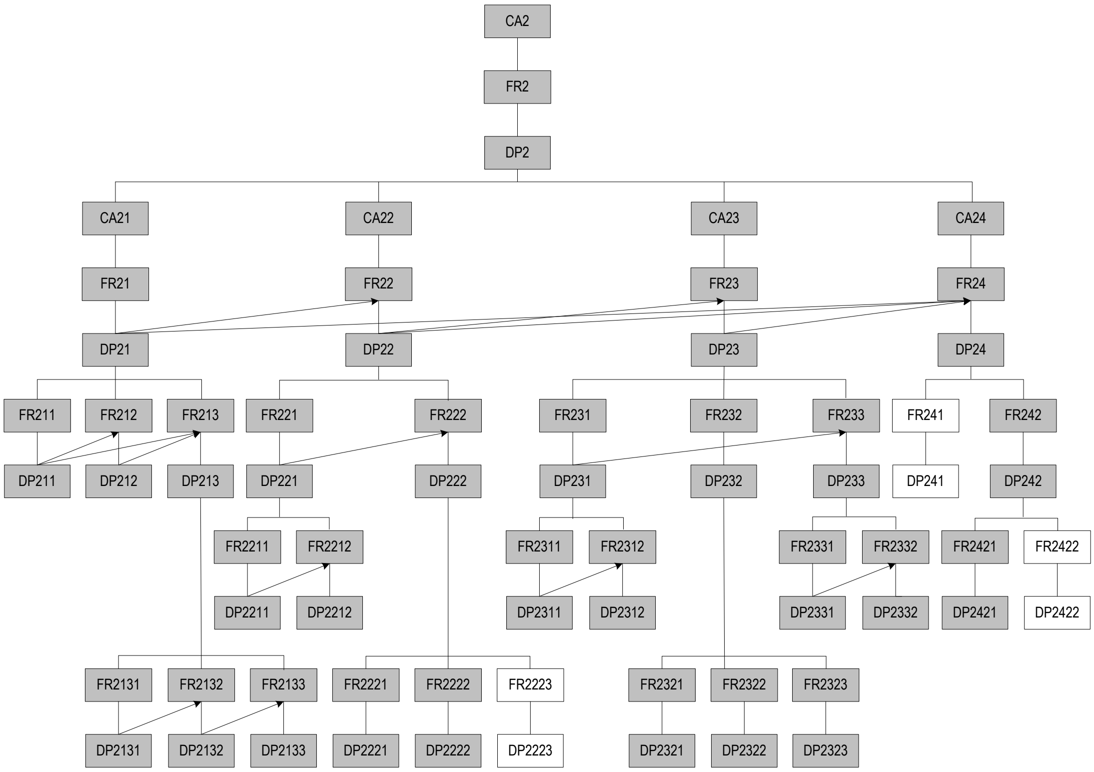


Figure 3.16 Highlighted aspects of the collaboration process

- SD process

During the development process, SD routine remained unchanged. Given that the model was developed with industrial feedback, the real life experience and the theoretical decomposition were substantially compatible. However, some instances were formalized according to the proposed model. The text-based modelling of software specifications were remodelled using UML in order to assure standardization. Also, the company decided to formalize trainings, especially trainers' and users' performance was evaluated through survey in order to detect failure points and learn from them for the next training session.

Each aspect is highlighted in SD process and this dimension emerges as the most practical dimension of the model, as shown in Figure 3.17.

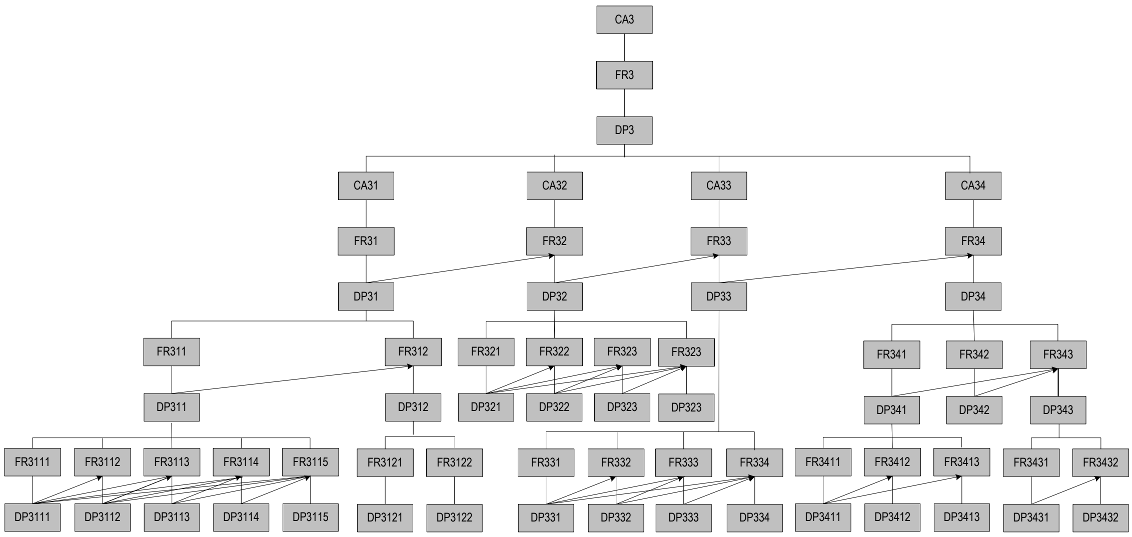


Figure 3.17 Highlighted aspects of the SD process

The manager claimed that the conceptual model was helpful during the project, even though they had managerial and operational experience in CSD. It was stated that theoretical support provided a guideline throughout the process, with special emphasis on the collaboration dimension.

3.4 SUMMARY

The increasing importance of collaboration efforts in PD processes is constantly highlighted by literature. Software industry is also leaning towards more formalized methods for collaboration. This emerging way of innovation and competition requires particular consideration, since joining two or more firms with one mutual aim creates a complex and conflicting environment. Therefore, a systematic approach is essential to analyze thoroughly all the aspects generated by both collaboration and development dimensions.

AD, and especially the Independence Axiom, offers an efficient methodology to design a conceptual system from scratch, and to consider all the requirements, even the minor factors, included in the system. AD does not prioritize the requirements as the other design techniques do. Instead, it considers all the variables of the system as a hierarchy and investigates the connections between requirements and design parameters with a top-down approach.

The main contribution of this study is the development of a detailed AD based collaboration model within the context of software industry. A three level hierarchic structure for CPD defining strategic goals to attain in collaborative efforts for PD, strategies to follow to fulfil these goals, and methodologies to implement to realize the strategies was introduced. However, since every industry possesses its own characteristics and the proposed model is very generic to be implemented for CPD efforts, an industry-specific approach was performed in order to detail the model. Given that software industry embraces a dynamic and innovative structure, the application was conducted for SD in order to decompose the proposed model to sub-levels. SD process has its specific steps, and consequently, it requires customized evaluation of its strategies and methodologies.

On the other hand, CSD does not differ from the CPD in partnership process and collaboration process, and a general decomposition applicable to various industries is proposed for these sub-levels. Goals were only investigated in the strategic levels, whereas strategies and methodologies to implement, i.e. FRs and DPs, were decomposed into hierarchies. The proposed model aims to present a managerial guideline. However, it does not aspire to handle project specifics such as profit sharing ratio, contracting details, SD strategy, etc. For example, the model states that effective coordination can be assured by IT; however it does not seek to explicitly define communication tools. The model rather collates academic findings and industrial feedback to cover all possible aspects of collaborative projects.

The proposed model was evaluated by interviews with experts from software industry. The major difference between the two interviews was that one firm operates near to ideal while other presents the cultural drawbacks of Turkish market and are far from ideal. However, both experts agree on the need to formalize the operations conducted during CSD within a structured model. Therefore, the model scores a high compatibility with informal applications of the software industry.

The results of the interview shows that the FRs are described accurately, while proposed DPs can evidently respond to the FRs. It can be concluded that the model captures correctly the current situation in collaborative efforts and develops an applicable model through real life practice.

The proposed approach has so far only been tested in one case study. However, it is safe to state that the detailed approach can help the project managers to concretely mitigate collaborative issues such as profit sharing, information sharing, and interoperability by defining each major aspect of CPD in general, and CSD in specific. These major aspects, however intuitively acknowledged, are not properly structured by researchers and CPD/CSD practitioners. It is expected to decrease collaboration failures by transforming industrial experience and empirical research into a conceptual framework.

The presented model offers a guideline for firms that venture or envisage effective CPD/CSD in order to evaluate their collaboration efforts. Since requirements are translated into strategies, and design parameters are translated into methodologies, the proposed AD based CSD model may form a guideline for entrepreneurs both to implement an efficient system and to assess their performance in collaboration. Also, the three main dimensions may be studied independently to develop new models in other contexts.

4 COLLABORATIVE PARTNER EVALUATION WITH MULTI-CRITERIA DECISION MAKING TECHNIQUES

CPD, by definition, consists of partners from different organizations joining forces for a common goal. The choice of a suitable partner is a very complex decision, involving many conflicting objectives as well as complex considerations. Ineffective partnerships can lead to the loss of core competencies and capabilities, exposure to unexpected risk and even business failure [**186**]. Thus, the partnership decision can affect the accomplishment of the whole collaboration process. Meticulous evaluation of potential partners with considerations from several perspectives holds a critical position in assuring the performance of the collaboration, even ensuring the success of the collaboration [**187**].

Researchers investigate this strategic problem with diverse methods and tools, focusing on different types of partnerships, such as PD collaborations, supply chains, and other collaboration types, including strategic alliances and virtual enterprises, which encompasses partnerships between independent organizations even though it does not specifically focus on the PD aspect of the collaboration. Even though there is a vast amount of literature regarding partner selection problems in many partnership contexts, the proposed work offers a new set of three-dimensional partner selection criteria based on the CPD model introduced by [**166**]. An integrated fuzzy MCDM is employed to evaluate more thoroughly the decision process.

MCDM refers to finding the best opinion from all of the feasible alternatives in the presence of multiple, usually conflicting, decision criteria [**188**]. The literature suggests that many MCDM methods such as ranking methods, rating methods, pairwise comparison, trade-off analysis, decision rules. On the other hand, the subjective nature of the decision-making problem and the uncertain environment which surrounds CPD and partner evaluation problems are analyzed under fuzzy judgments. Fuzzy decision-making is a powerful tool for decision-making in fuzzy environment. Classical decision-making methods work only with exact and ordinary data, whereas human judgment has a good ability for qualitative data processing, which helps the decision maker to make decisions in fuzzy environments [**188**]. Consequently, this chapter employs Fuzzy AHP to determine criteria weights and Fuzzy AD in order to evaluate and select partners. The Fuzzy AD technique enables decision makers to eliminate unsuitable alternatives, which cannot meet the decision makers' requirements, and then to present a detailed evaluation on each level of criteria in order to rank appropriate candidates. On the other hand, Fuzzy AHP is a clear yet sophisticated technique to translate decision makers' opinions on criteria into criteria weights.

Evaluation criteria are defined, and potential candidates are identified. Moreover, experts' judgments are employed in order to verify evaluation criteria and determine criteria weights. Afterwards, experts comment on the requirements and alternatives in linguistic terms, which result in partner evaluation and selection. Pidduck [**189**] indicates the drawbacks of a rigid set of criteria. Fuzzy AD offers an alternative to tackle this issue with the concept of the "design range," where decision makers can set the requirements on the provided criteria given the characteristics of the project, which gives a dynamic structure to the decision making problem.

This study aims to provide a criteria set able to cover all aspects of the CPD partner selection process as well as a methodology which can respond to the contingency of the decision-making process. Firstly, a thorough literature review is conducted on partner evaluation criteria and a three-dimensional criteria set is proposed. The proposed criteria set is verified by industrial experts. Subsequently, Fuzzy MCDM techniques are combined to develop a partner evaluation methodology. Two case studies are conducted and obtained results are discussed to observe the performance and the implications of the proposed methodology. The steps of the methodology are presented in Figure 4.1.

The next section depicts partner selection literature from different partnership contexts. Then partner selection methodology and partner selection criteria set are introduced. Fuzzy MCDM techniques employed in the evaluation are described. Subsequently, case studies are presented to illustrate the advantages of the three dimensional criteria set as well as the fuzzy techniques.

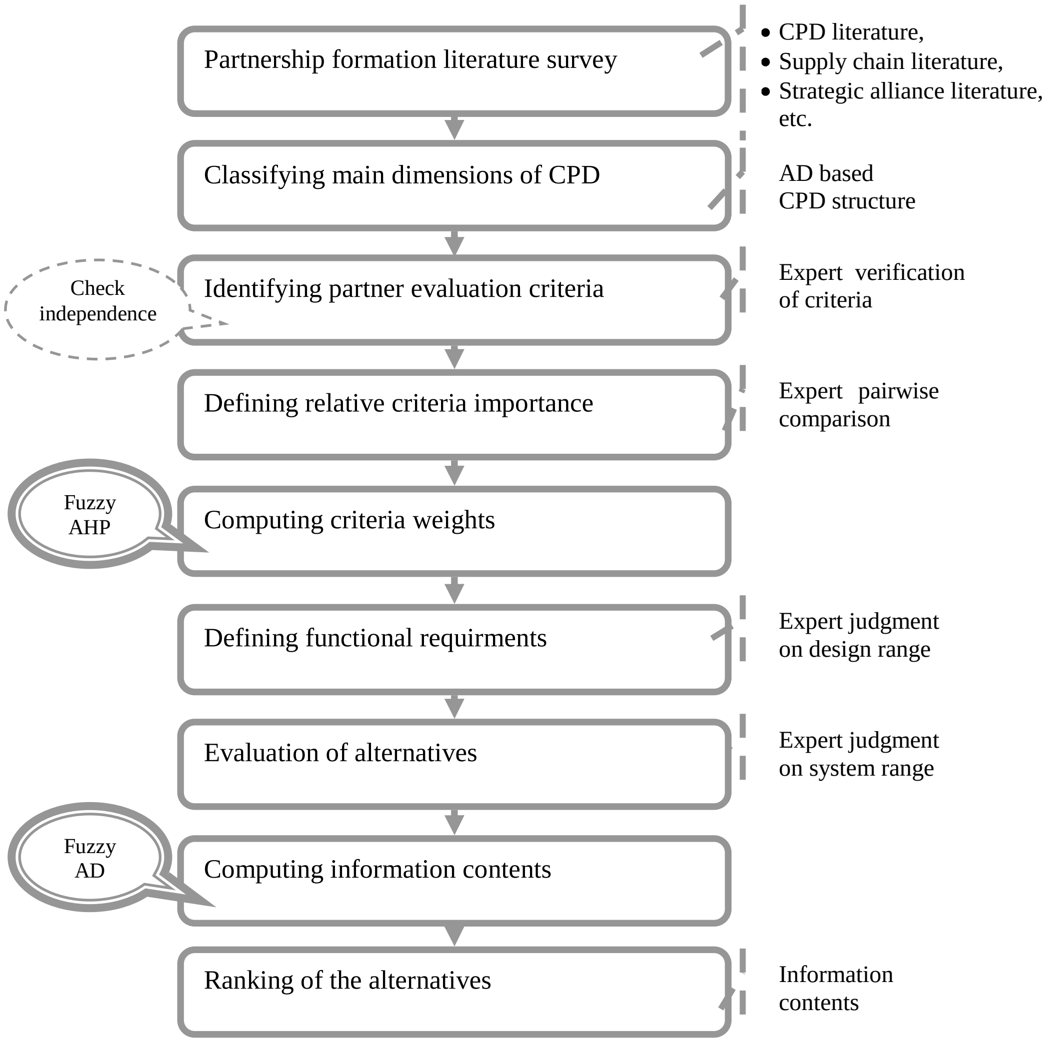


Figure 4.1 The steps of the fuzzy MCDM methodology

4.1 PARTNERSHIP FORMATION LITERATURE

Partner evaluation and selection is the key process in the establishment of a CPD project as highlighted by many authors [**190**], and it is critical in finding organizational matches that can effectively relate with each other [**27**]. Given that incompatibility between partners is one of the most important reasons why co-development partnerships fail [**191**], selecting a partner becomes a strategic issue for the firm. Individual attributes of firms as well as collaborative experience possess a value in the evaluation of potential partners. Each attribute gives a partnership value and plays an important role in determining the desirability of different partners [**192**]. Literature offers various methods and evaluation factors to select partners for different collaboration settings.

Even though literature on partner selection in CPD is limited [**193**], the problem of partner selection has been widely addressed in the contexts of other partnership agreements such as PD partnerships, alliances, as well as supply chains. Another classification can be made on the methods employed. Wang et al. [**194**] classify partner selection literature in three categories: fuzzy decision making algorithms, quantitative algorithms, and artificial intelligence planning based algorithms. In this study, the literature review is conducted according to partnership context and presented chronologically.

One of the basic concerns of CPD studies includes partnerships and partner selection[**167**]. Even though existing literature is relatively limited in this area, presented studies are more relevant considering that they focus on the specific context of CPD projects. There is also supplier selection in PD literature, of which a selection is also provided, given that the business trend evolves from a mere supplier selection to strategic partnerships.

Emden et al. [**27**] consider a process approach to partner selection. Technological alignment triggers the partner evaluation process, followed by strategic and relational alignment. After the three-phased process, partners with maximum potential to create value are selected. Hou et al. [**34**] employ en evaluation index for supplier selection in CPD. They analyze the supplier involvement, and they focus on measuring their developmental capabilities. Feng et al. [**193**] consider collaborative utility shared by pairwise partners versus individual utility of each partner in CPD. They present a partner selection framework considering both utilities, and they employ a fuzzy multi attribute decision-making approach to compute overall utility. Yoshimura et al. [**56**] present a decision support system with a different approach. Evaluation of partners is based on the technologies required for developing the new product, and they are classified into two groups: technologies already developed and technologies that must be developed.

Le Dain et al. [**79**] focus on the customer aspect of PD from the supplier point of view, and they propose an evaluation methodology for customer performance in the co-design process. The presented tool aims to evaluate the customer on three performance domains at three stages. In another work, Le Dain et al. [**78**] adopt a customer point of view. They propose a framework where the customer can measure the supplier performance in collaboration, and they evaluate supplier's involvement in the design process. Zolghadri et al. [**195**] introduce the "power assessment" concept to partner selection in PD context. They state that the bargaining powers of the suppliers are crucial in maintaining the stability of the partnership, and they introduce a selection procedure based on the dominance/subordination of the partners. Zolghadri et al. [**196**] extend the previous work to propose a selection framework. They transform selection criteria and metrics into a power factor, which are then aggregated in order to form a power value for each supplier. Fuzzy adaptive resonance theory is proposed by Ozkan et al. [**197**] to evaluate supplier involvement in PD process, and the mechanism is tested in Turkish automotive industry.

Supply chain literature also focuses on the partner selection problem given that supply chain management evolves towards collaboration rather than maintaining supplier-buyer relationships. Also, supply chain integration can be considered as a previous stage of CPD, where the importance of collaborating with suppliers is emphasized, project managers, product developers, and buyers. Essential supply chain partner selection studies are cited below.

Lin and Chen [**198**] introduce a fuzzy decision-making framework for selecting the most favourable supply chain partnership. They develop generic and industry-specific hierarchies, and then they formulate a 0-1 non-linear programming model to determine the optimal configuration hierarchy. Partners are selected through a fuzzy-rule based relationship intensity function integrated with a fuzzy relationship hierarchy.

Pidduck [**189**] investigates partner selection problems in supply chains. Qualitative techniques and research tools are employed to identify key issues and a Partner Negotiation Model is presented. Sha and Che [**199**] combine genetic algorithm, AHP, and multi-attribute utility theory to satisfy the preferences of suppliers and customers at each level of the supply chain network.

Yan et al. [**108**] investigate a clustered supply chain to support a heterarchical network of companies and their customers. They propose a bidding-based product conceptualization and partner selection (PCPS) system to help companies coordinate the two aspects. They employ general sorting for product platform generation and eliciting bidding criteria, a self-organizing map neural network to select preferred design options for bidding purposes and AHP to effectively select partners participating in a collaborative design and bidding process. Qi et al. [**200**] propose RVPK algorithm based on Particle Swarm Optimization and K-means clustering in order to select supply chain partners.

Wang [**201**] presents a two-phase ant colony algorithm for defective supply chain network design, focusing on the choice of the appropriate corporations from a number of potential participators to become involved in the network and to make optimal production–distribution planning decisions. Wang et al. [**202**] study the construction supply chain. They employ the method of combined radix determination as a method of partner selection by value assessment and performance assessment during invitation to bid and bidding. Another construction supply chain partner selection study is proposed by Zhang [**203**]. A new index system is constructed, and a theoretical model based on Support Vector Machine is proposed. Zhou et al. [**204**] combines AHP and fuzzy comprehensive evaluation techniques for the partner evaluation of the agile supply chain.

Wu et al. [**205**] study the final phase of partner selection in agile supply chains. They combine Analytic Network Process (ANP) and mixed-integer multi-objective programming methodologies to propose a model which identifies the priorities of different criteria and which handles the configuration of the supply network and the optimization of order quantity allocation. Another agile supply chain study is proposed by Wu and Barnes [**206**]. They present a three stage model for the formulation of partner selection criteria in agile supply chains by applying both the Dempster–Shafer and optimization theories.

Yeh and Chuang [**207**] focus on problems in green supply chain partner selection, and they propose a mathematical planning model to compromise conflicting objectives, such as cost, time, product quality, and green appraisal score. They employ two algorithms to obtain Pareto-optimal solutions for the supplier selection and product volume transportation problems.

Yue et al. [**208**] study the partner selection problems for the make-to-order supply chain and investigate the quantity allocation to each partner. They introduce a sourcing partner selection tool using information about cost, available capacity, and stochastic processing time. Shi and Bian [**209**] establish a Lean Logistics Alliance Partner Selection Index System, and they ensure profit margin optimization with a multi-objective linear programming model. Viswanadham et al. [**210**] develop a linear programming model for integrated partner selection and scheduling in a web-enabled global manufacturing network environment. Cao and Gao [**211**] describe the partner selection problem as a 0-1 integer programming model with nonlinear objective function to maximize project success probability within an agile manufacturing environment. They propose a penalty guided genetic algorithm approach in which the penalty function is dynamic and adaptive.

On the other hand, since the 1980s the problem of partner selection has been widely addressed in the contexts of strategic alliances [**212**], which can be described as the inter-organizational partnerships pursuing a common goal. Some recent studies in strategic alliance literature are summarized below.

Beckman et al. [**213**] consider partner selection in alliances from the network point of view, and they seek to predict when firms form new partnerships and when they will expand the existing relationships. They investigate the type of uncertainty (firm-specific or market-level) that causes exploration versus exploitation choices. Bierly and Gallagher [**214**] develop an understanding of how strategic fit, trust, and strategic expediency influences a firm's alliance partner selection in strategic alliances. They identify common problems that result because of the complexity of the partner selection decision process and give recommendations to managers that may help them make better decisions concerning partners in the future. Li et al. [**215**] consider partner selection a solution to preserve a firm's technological knowledge as an alternative to protective governance structure and narrow alliance scope. They investigate the transitivity of partner selection in R&D alliances, and they explore the dynamic relationships among three protection mechanisms (partner selection, governance structure, and alliance scope). Shah and Swaminathan [**41**] study factors affecting partner selection, and instead of using conventional criteria such as trust, commitment, etc., they propose an approach based on alliance project type. They utilised "process manageability" and "outcome interpretability" as evaluation criteria.

Büyüközkan et al. [**191**] focus on logistics value chain, and they construct an evaluation hierarchy with strategic alliance partner selection criteria. Holmberg and Cummings [**190**] present a strategic management-based process which provides a dynamic partner selection tool for evaluating target industries and specific firms for partner selection in strategic alliances.

Chen et al. [**187**] propose another study that focus on R&D strategic alliances where they present a mechanism for partner selection, which identifies the motivations, criteria, and measurable sub-criteria for evaluating the potential partners. The motivations for establishing strategic alliances differ from each firm, and thus, setting universal criteria weights becomes unproductive. They employ the Fuzzy AHP approach for weighting processes. Huang et al. [**212**] state that the conventional multi-objective programming method ignores the problems of objective synergies and resource allocations in strategic alliances, and they develop a new multi-objective programming model to determine the correct partners and corresponding resource allocations. Solesvik and Encheva [**216**] focus on the ship design industry. They explore previous qualitative and quantitative research on partner selection, and they analyze quantitative techniques employed in strategic alliance partner selection. Solesvik and Westhead [**217**] examine partner selection criteria in the Norwegian maritime industry, and they analyze how a maritime firm's competitive advantage can be enhanced by the selection of the right partner with reference to a strategic alliance.

Strategic alliance partner selection literature is extended by international strategic alliance studies. Focusing on UK international joint ventures, Glaister and Buckley [**44**] categorize partner selection criteria as task-related and partner-related. Tatoglu [**218**] studies international joint ventures between western firms and local partner firms in Turkey. He examines the relationship between the relative importance of selection criteria and the nationality of foreign partners. Hitt et al. [**219**] present a theoretical approach to international strategic alliances. They suggest that access to resources and organization learning are partner selection motivations. They examine the importance of specific market contexts (emerging versus developed), and they explain how firms' current resource endowments and needs motivate alliance partner selection. Hitt et al. [**220**] extend the previous research by comparing the characteristics of international strategic alliance partnerships preferred by managers in firms based in China and Russia, two transition economies with differing institutional environments. Hajidimitriou and Georgiou [**221**] present a quantitative approach, namely a goal programming model, to the partner selection problem in international joint ventures. Donga and Glaister [**222**] investigate the motivations in international strategic alliances and partner selection criteria within Chinese firms. Li and Ferreira [**223**] also focus on international strategic alliances of multinational corporations, and they examine the motivations and conditions under which multinational corporations prefer the repetition of prior partnerships in emerging economies. Specifically, they investigate the effects of the technological commitments, governance structure, and the institutional distance between the home and host countries.

Innovation networks are investigated by a few studies as well. Marxt and Link [**45**] determine different success factors for cooperative ventures in innovation networks, and they classify these factors as structure, culture, and risk with phases as initiation, partner selection, setup, realization, and termination.

Hacklin et al. [**55**] develop a decision support system for strategic innovation partner selection, which allows the decision-makers to evaluate or even benchmark potential partner firms autonomously and with instant feedback. They offer a multi-perspective and interactive overview of potential partners, and they categorise criteria as strategic, cultural, and structural. Borchert et al. [**224**] also investigate innovation networks, and they highlight the importance of technological resources and skills in partner selection. They state that there is a significant difference between the selection of known partners and new partners concerning the selection criteria and the information sources used. Cowan et al. [**192**] consider cognitive, relational, and structural embeddedness in the formation of innovation network. They analyze the effects of knowledge pooling and previous collaborations on the formation of the partnership. Baum et al. [**225**] focus on innovation networks emerging from R&D strategic alliances, and they design a partner selection model where the alliance motivations are learning and innovating.

A vast amount of literature can be found on partner selection in virtual enterprises. Talluri and Baker [**226**] develop a two-phase mathematical programming method to solve the partner selection problem in the formation of a virtual enterprise by taking factors such as cost, time, and distance into consideration. In a following study, Talluri et al. [**227**] propose a two-phase qualitative partner selection framework, first identifying the business type using Data Envelopment Analysis and then executing an integer goal programming model to determine the best portfolio. Wo et al. [**228**] propose an integer programming method for virtual enterprise partner selection based on minimum transportation costs according to geographic position and transportation approach.

Wang et al. [**229**] establish a fuzzy decision embedded genetic algorithm to solve the partner selection problem of virtual enterprise with due date constraint. Mikhailov [**230**] proposes a fuzzy programming method in AHP framework for partner selection in virtual enterprise, which is modelled as MCDM problem under uncertainty.

Ip et al. [**231**] develop a rule-based genetic algorithm with embedded project scheduling to solve a risk-based partner selection problem in virtual enterprise. Wu and Su [**232**] model the partner selection problem using an integer programming formulation to minimize the manufacturing cost with completing time constraint and develop a two-phase algorithm to solve this problem. Zeng et al. [**233**] prove that the partner selection problem with a due date constraint in a virtual enterprise is a NP-complete problem and establish a non-linear integer problem model to solve the partner selection problem. Liu et al. [**234**] draw theory of situation awareness into partner selection of virtual enterprise, and they analyze the support function of situation awareness theory and business intelligence technology to virtual enterprise partner selection. Zhao et al. [**235**] establish a non-linear integer program model to solve virtual enterprise partner selection problem with precedence and due date constraints and develop a particle swarm optimization algorithm. Yao et al. [**236**] develop a hybrid algorithm with particle swarm optimization and simulated annealing, combining local search (by self experience) and global search (by neighbouring experience) to solve partner selection problem in virtual enterprises. They focus on risk minimization and ensuring the due date for the success of the partnership. Feng and Yamashiro [**237**] present a comprehensive cost function and its mathematical formulation for optimal process and partner selection in a virtual enterprise. Hua et al. [**238**] analyze partner selection systems based on gray relation for an agile virtual enterprise, and they enumerate the advantages of partner selection based on gray relation analysis comparing to the other algorithms of partner selection.

Petersen [**239**] proposes an agent-based model of a virtual enterprise. Case studies are employed to analyze the partner selection process. Sarkis et al. [**240**] develop a framework and a decision model for agile virtual enterprise partner selection using ANP. Fu et al. [**241**] handle trust and reputation aspects of partner selection in virtual enterprises. They offer a trust and reputation model for networked manufacturing based on the ASP model where agents should be able to contract cooperation in virtual enterprises of best behaviour.

Junsan [**242**] employs a binary coded ant colony optimization algorithm for the partner selection optimization in virtual enterprises. The conceptual partner selection model includes criteria such as cost, quality, trust, credit, delivery time, and reliability.

Wang et al. [**194**] develop a genetic algorithm solution for collaboration cost optimization-oriented partner selection in virtual enterprises. They also analyze various collaboration patterns between distributed partners with the corresponding evaluation metrics for collaboration time and cost.

Ye and Li [**243**] propose two group multi attribute decision making methods for partner selection in virtual enterprises: TOPSIS group decision making based on deviation degree and TOPSIS group decision making based on risk factor. Yao et al. [**244**] present an integrated meta-heuristic algorithm, called a fused algorithm, integrating the genetic algorithm into the ant colony optimization algorithm to solve virtual enterprise partner selection problem, in which the core competencies required include the cost, time, and risk.

Jarimo and Salo [**245**] develop a mixed-integer linear programming model for the virtual organization partner selection problem, which is a multi-criteria optimization problem. Tang and Liu [**246**] focus on supply chain virtual enterprises, and they present an ANP based partner selection model with criteria such as cost, quality, and the ability to realize opportunities in the basic evaluation target and innovation, logistic support, and IT in the agile evaluation target.

Ye [**247**] focuses on partner selection in virtual enterprises under incomplete information and uncertain environment. An extended TOPSIS method for group decision making with interval-valued intuitionist fuzzy numbers is developed where considered criteria are low cost, short time, high trust, low risk, and high quality. Jiao et al. [**248**] propose two-layer ant colony optimization to overcome the shortcomings of previous ant colony optimization research in virtual enterprise partner selection problems.

Partnership selection is also covered in other contexts. Ha and Hong [**249**] investigate partner selection process in the e-business environment, and they propose a dynamic partner selection system selecting the optimal partners by maximizing revenue under a level of supply risk. Fan et al. [**250**] consider collaborative information versus individual information (such as members' availability, previous experience, individual needs and aspirations, and the ability to devolve responsibilities) in the formation of R&D teams. They propose a bi-objective 0-1 programming model and a multi-objective genetic algorithm to solve the model. Xu et al. [**251**] focus on the risk of failure and tardiness of cross-enterprise projects caused by the uncertainty of partner's resources, and they describe the partner selection problem with a 0-1 integer programming model considering the factors of process time, precedence of subprojects, and resource confidence. They propose a project scheduling algorithm embedded into a Tabu search algorithm to obtain the optimal partner selection solution.

This literature overview clearly suggests that partner selection literature is not neglected, and various approaches are presented for different partnership contexts. However, Holmberg and Cummings [**190**] state that "partner selection literature generally neglects to link partner selection to broader strategic management issues; fails to consider an overall partner selection process; focuses on general rather than specific motivations behind selection; tends to be conceptual, rather than offering operationalized analytical tools; pays insufficient attention to dynamic considerations and changes over time; and neglects the needs for weighting and rating the many specific elements embedded in an partner selection analysis". The existing literature fails to present methods that can be used by entrepreneurs to select appropriate partners who can sustain a firm's competitive advantage in the face of changing market, technological, and institutional conditions [**216**].

This study presents a partner selection model that considers all these issues. The partner selection hierarchy includes managerial as well as operational level criteria and takes into account the need for sustainability. Presented analytical tools possess a dynamic characteristic given the fact that requirements can be adapted to requirements of each specific case. Weighting the criteria and rating the alternatives have adaptability as well.

The study aims to fill the gaps in question by providing a CPD partner selection methodology with partner selection criteria set in order to guide CPD practitioners through the strategic process of partnership establishment. Partner selection criteria from different perspectives, as presented in Table 4.1, are gathered and integrated in order to present a criteria set incorporating various approaches. Partnership types consist of CPD, supply chains, strategic alliances, virtual enterprises, and joint ventures while employed methods include MCDM, Fuzzy MCDM, statistics, mathematical modelling, and qualitative analysis.

Table 4.1 Partner selection literature overview

Authors	***Partnership type***	***Method***	***Classification***	***Sub-criteria***
Bierly and Gallagher [**214**]	Strategic alliance	Qualitative	Factors influencing strategic alliance partner selection	Strategic fit, trust, strategic expediency
Büyüközkan et al. [**191**]	Strategic alliance	Fuzzy AHP, Fuzzy TOPSIS	Strategic dimension	Similar values and goals, similar size, financial stability, comparable culture, successful track record, fit to develop a sustainable relationship
			Business excellence dimension	Partners' technical expertise, partners' performance, partners' quality, managerial experience
Chen et al. [**187**]	Strategic alliance	AHP	Motivation	Strategy-oriented, cost-oriented, resource-oriented, learning-oriented
			Selection criteria	Organization compatibility, technology capability, resources for R&D, financial conditions
Donga and Glaister [**222**]	International strategic alliance	Qualitative	Factors of task-related selection criteria	Factor inputs and local knowledge, international knowledge and product knowledge, value chain access, production technology
			Factors of partner-related selection criteria	Reputation, trust and prior ties, business relatedness, company size, financial stability
Emden et al. [**27**]	CPD	Qualitative	Technological alignment	Technical capability, technical resource and market knowledge complementarity, overlapping knowledge bases
			Strategic alignment	Motivation correspondence, goal correspondence
			Relational alignment	Compatible cultures, propensity to change, long-term orientation
Fan et al. [**250**]	R&D teams	0-1 programming, genetic algorithm	Individual performances	Research, experience, activity, academic reputation
			Collaborative performances	Papers, projects

Authors	***Partnership type***	***Method***	***Classification***	***Sub-criteria***
Feng et al. [**193**]	CPD	Fuzzy MADM	Individual utilities	Technology capability, financial health, knowledge and managerial experience, capability to access new market
			Collaborative utilities	Resource complementarity, overlapping knowledge bases, motivation correspondence, goal correspondence, compatible cultures
Fu et al. [**241**]	Virtual enterprise	Mathematical model	Trust factors	Scale of the cooperation, satisfaction of the collaborators, time of the cooperation, trust value of the estimator, time-decreasing factor, initial trust value
Glaister and Buckley [**44**]	Joint ventures	Factor analysis	Task-related criteria	Knowledge of local market, distribution channels, links with major buyers, knowledge of local culture, technology, the product itself, knowledge of production processes, capital, regulatory permits, labour, local brand names, materials/natural resources
			Partner-related criteria	Trust between the top management teams, relatedness of partner's business, reputation, financial status/financial resources of the partner, complementarity of partner's resource contribution, established marketing and distribution system, the partner company's size, international experience, experience in technology applications, management in depth, degree of favourable past association between partners, partner's ability to negotiate with foreign government

Authors	***Partnership type***	***Method***	***Classification***	***Sub-criteria***
Ha and Hong [**249**]	Supply chains	Mathematical model	Partner selection criteria	Price, delivery, quality, quantity, reputation and position, warranties and claim, information share
Hitt et al. [**220**]	International strategic alliance	Qualitative	Partner selection criteria used in emerging and developed market contexts	Financial assets, complementary capabilities, unique competencies, industry attractiveness, cost of alternatives, market knowledge/access, intangible assets, managerial capabilities, capability for quality, willingness to share expertise, partner's ability to acquire skills, previous alliance experience, special skills to learn from partner, technical capabilities
Hou et al. [**30**]	Supply chain	Mathematical model	Satisfaction index	Product quality, product cost, technical capability, system support
			Flexibility index	Product standardization, quantity flexibility, developing capability, product modularization, information interchange, management level
			Risk index	Consistency, collaborative experience, technical risk, enterprise power, development perspective
			Confidence index	Business credit standing, after service, information sharing, information security
Hua et al. [**238**]	Virtual enterprise	Gray Relation Analysis	Task index	Project completion time, exception handling capability, project postponement term (completion quality grade, project bidding price, service after sale), task responding rapidity

Authors	***Partnership type***	***Method***	***Classification***	***Sub-criteria***
			General index	Production index (input/output ratio, value-added ratio, distribution ratio, recovery ratio, finished product turnover period, standardization, product market share, contract completion ratio, new product profit margin, technological development investment), income index (payoff rate of total assets, earning rate of funds, profit rate on funds, profit rate of product cost, profit rate of product sales income, profit rate of wage, profit rate of loan, retention ratio of development funds), liquidity index (turnover of total assets, turnover of current assets, turnover of merchandise, debt ratio of assets, constituent ratio of current fund, growth rate of increment value, growth rate of total industrial output value, growth rate of sales income)
			Natural index	Enterprise production capacity, enterprise production facility (enterprise trade status, enterprise geographical position, market share), accordance with project market share, enterprise credit standing
Huang et al. [**212**]	Strategic alliance	Multi-objective programming	Objective	Profit, quality, customer satisfaction
Jarimo and Salo [**245**]	Virtual organization	Integer programming	Selection criteria	Risk, collaboration, cost
Li and Ferreira [**223**]	International strategic alliance	Qualitative	Prior partner selection predictor	Technological commitments, governance structure, institutional distance
Marxt and Link [**45**]	Joint venture	Qualitative	Structure	Required profile, strategic fit, equality of all parties, similar structure, past experience
			Culture	Cultural compatibility, similar values, commitment to partnership; trust, openness and honesty; confidence in capabilities

Authors	***Partnership type***	***Method***	***Classification***	***Sub-criteria***
			Risk	Partner's readiness for risk and information sharing, similar premises of security and risk, partner risk analysis
Pidduck [**189**]	Supply chain	Qualitative	Selection criteria	Personal contact; previous knowledge, flexibility and willingness to adjust, communications, personal interest in the alliance, financial assets available to put into the partnership, technical capabilities, people or machines needed for the alliance, willingness to share expertise and teaching resources, unique competencies, local market knowledge, access
			Issues	Specific requirements or skills or constraints, resource availability, social network, reputation, politics, ambiguity
Sarkis et al. [**240**]	Virtual enterprise	ANP	Agility performance metrics	Cost, quality, time, and flexibility
Shah and Swaminathan [**41**]	Strategic alliance	Qualitative	Factors influencing partner selection in strategic alliances	Trust, commitment, complementarity, financial payoff
Tatoglu [**218**]	Joint venture	Factor analysis	Strategic motivations	Enable faster market entry, gain presence in new markets, maintain an adequate quality control, risk sharing, enable faster pay-back, potential problems with licensing and patents, conform to government policy, economies of scale, lack of patent and licence protection laws, avoid the risk of dissipation of knowledge, non-transferability of technology by licensing and patents, resource and capacity usage, exclusive access to inputs, cost of making and enforcing contracts

Authors	***Partnership type***	***Method***	***Classification***	***Sub-criteria***
Wu and Barnes [**206**]	Supply chain	Dempster–Shafer theory, optimization	Production and logistics management	Production volume flexibility, variation in types of products or services, post-sales service and support, order lead time, responsiveness to customer needs, condition of physical facilities, design capability, cost-reduction capability, quality philosophy, delivery capacity and reliability, distribution network performance and quality, quality assurance system, manufacturing network performance, order fulfilment rate, average defect rate, price/cost ratio, geographical location, production capabilities, sophistication of product lines, capabilities to provide quality product/service, quality stability, volatility of product mix, transportation cost, service level, consistent conformance to specifications, warranty period
(cont.)			Partnership management	Government relationships, information available on supplier, risk of failure of cooperation, easy communication, willing to invest in sales training, compatible management styles, industrial experience, cost to integration, alliance experience, willingness to resolve conflict, financial institution relationship, closeness of past relationship, data information, relationship building flexibility, power relative to potential partner, company’s reputation to integrity, the stability of the joint venture, time needed to integration, track record with past suppliers, compatible organization cultures, foreign experience, willingness to reveal financial records

Authors	*Partnership type*	*Method*	*Classification*	*Sub-criteria*
			Financial capability	Net operating margin, asset/liability ratio, gross profit margin, the growth rate of business income, stockholders' equity ratio, cash flow per share, earnings per share of stock, debt/equity ratio, inventory turnover, liquidity ratio, total revenue, assets rates of increment, net profits growth rates, accounts receivable turnover
			Technology and knowledge management	Technical capability, cost of alternatives, technical advice, knowledge of local business practices, information systems and communication, partner's ability to acquire your firm' special skills, obtain partner's local knowledge, patent security, willingness to share expertise, technology innovation, special skills that you can learn from partners, product familiarity, equipment status of the partners, repair turnaround time
			Marketing capability	Product/service brand value, brand loyalty, sales force, local political & cultural environments, customer demanded changes, rapid market entry, general reputation, better export opportunities, experience with target customers, market position, market share, variation in price, price level, culture of customer service, marketing competence, supplier representative's competence, variation in demand quantity, customer loyalty, marketing expertise/knowledge

Authors	*Partnership type*	*Method*	*Classification*	*Sub-criteria*
(cont.)			Industrial and organizational competitiveness	Strategic position in the marketplace, bargaining power of suppliers, industry attractiveness, strategic orientation, influence on industry, rivalry among existing firms, complementarity of product lines, corporate market position, functional competencies, bargaining power of buyers, relative power of organization, unique competencies, threat of substitute products
			Human resource management	Entrepreneurial creativity, quality of local personnel, human resource management skill, learning ability, organizational leadership, product and market expertise, corporate culture, quality of management team
Wu et al. [**205**]	Strategic alliance	ANP	Characteristics of the partner	Unique competencies, compatible management styles, compatible strategic objectives, higher or equal level of technical capabilities between manufacturers and distributors
			Marketing knowledge capability	Increase market share, better export opportunities, knowledge of local business practices
			Intangible assets	Trademarks, patents, licenses, or other proprietary knowledge, reputation, previous alliance experiences, technically skilled employees among partners
			Complimentary capabilities	Partners owned managerial capabilities, wider market coverage, diverse customer, the quality of distribution system to those of the strategic partners
			Degree of fitness	The compatible organization cultures, willingness to share expertise, equivalent of control, willingness to be flexible of partners compatible with that of strategic partners

Authors	*Partnership type*	*Method*	*Classification*	*Sub-criteria*
Wu et al. [**252**]	Supply chain	ANP, mixed-integer multi-objective programming	Cost	Raw materials cost, production cost
			Time	Transportation time, distribution time
			Quality	Production quality, service level
			Flexibility	Relationships with customers, relationship with suppliers
Ye [**247**]	Virtual enterprise	Fuzzy TOPSIS	Attributes	Low cost, short time, high trust, low risk, high quality
Ye and Li [**243**]	Virtual enterprise	TOPSIS	Attributes	Cost, time, trust, risk, quality
Zhou et al. [**204**]	Supply chain	AHP	Product quality	Quality management system, product life, product fault ratio
			Delivery date	On-time-delivery rate
			Quality of after sale service	Quality of after sale service, efficiency of after sale service
			Enterprise reputation	Product market share, enterprise industry influence
			Value adding processes	Logistics, design, manufacturing, service
			Technical level	Patents and awards

4.2 PARTNER EVALUATION CRITERIA

Since partner evaluation is crucial to success, identification of effective partner evaluation factors is essential prior to joining or developing any partnerships [**186**]. The existing literature offers many different approaches to categorize partner selection criteria. Chen et al. [**187**] classify criteria in four categories: organization compatibility, technology capability, resources for R&D, and financial conditions. Wu et al. [**205**] state that strategic partner selection criteria should include collaborative attributes as well as individual characteristics of partners. Feng et al. [**193**] also consider individual utilities versus collaborative utilities. They cite technology capability, financial health, knowledge and managerial experience, capability to access new market as individual utilities and resource complementarity, overlapping knowledge bases, motivation correspondence, goal correspondence, compatible cultures as collaborative utilities. Büyüközkan et al. [**191**] name two dimensions for strategic partner evaluation: strategic dimension (similar values and goals, similar size, financial stability, comparable culture, successful track record, and fit to develop a sustainable relationship) and business excellence dimensions (partners' technical expertise, partners' performance, partners' quality, and managerial experience). Sarkis et al. [**240**] categorize key need areas as cultural, business, and technical.

These various approaches are collected and analyzed to define partner selection criteria hierarchy. Firs the partner selection criteria set is defined. Based on the CPD architecture proposed by Arsenyan and Büyüközkan[**166**], the criteria set is categorized in three groups: partner focused, collaboration focused, and development focused. These three types of criteria are shaped by various measures. The alignment concept proposed by Emden et al. [**27**] is integrated into the framework as strategic alignment for partner focused criteria, relational alignment for collaboration focused criteria, and technological alignment for development focused criteria. These alignments prepare the necessary basis for a successful partnership; hence they affect the selection process. On the other hand, economic stability of both the market and the partners is another requirement [**193**], [**191**] in order to form and maintain partnership. Market and business conditions are related externalities as well. Potential partners' past experience with focal firm and other firms influence the trust formation between firms [**192**] and have an obvious effect on the selection process. Complementarity and compatibility between potential partners is another major factor affecting collaboration. Product/Software development focused criteria are formed concepts, such as R&D and innovation, as well as by more operational elements such as project and product characteristics. MCDM techniques are proposed to evaluate, rank, and select partners. Partner selection criteria set, summarized in Table 4.2Table 4.2, is identified through these various aspects influencing partner selection process, which enables the elaboration of the three main dimensions. The criteria hierarchy is presented in Figure 4.2.

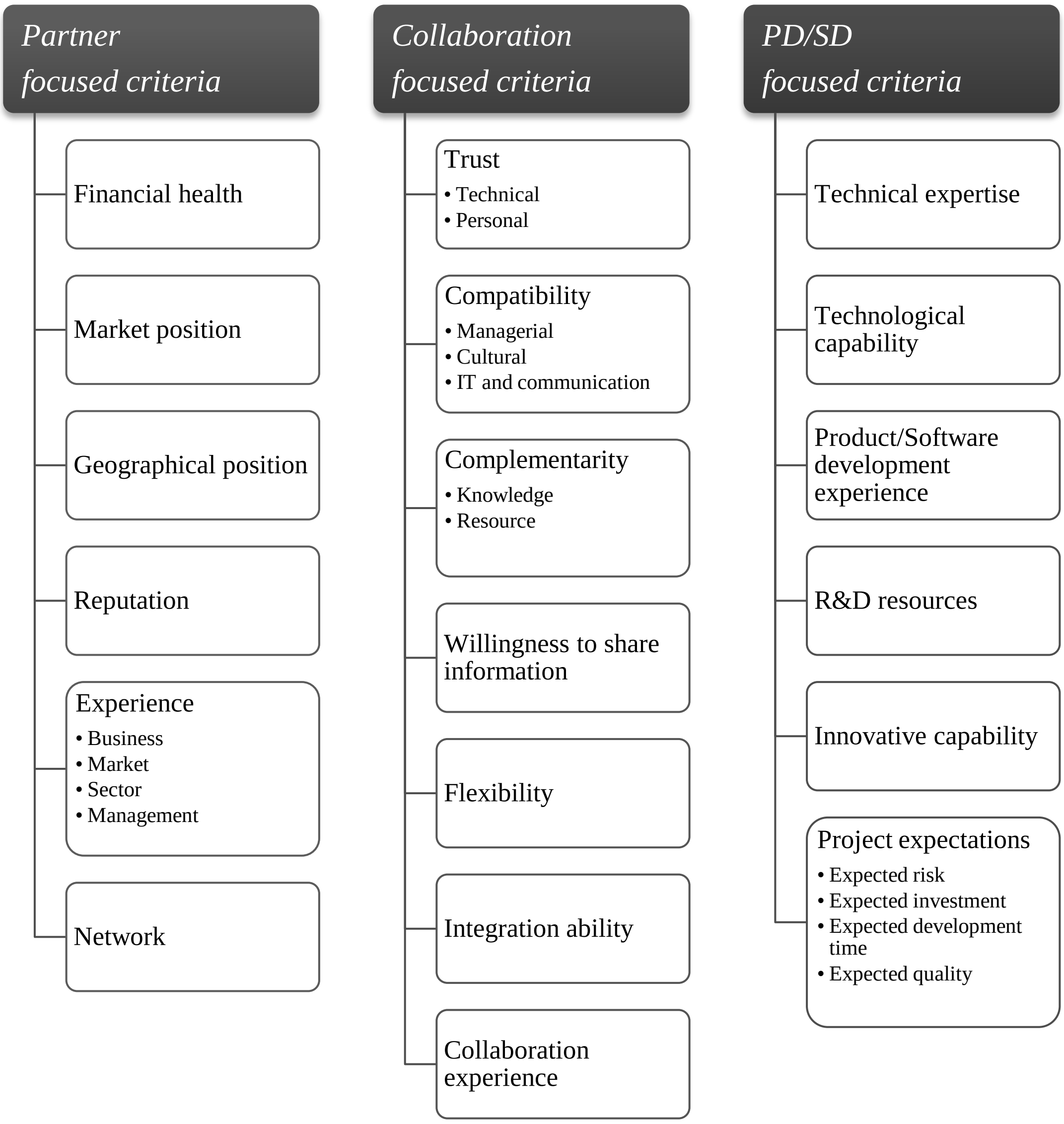


Figure 4.2 CPD partner evaluation criteria hierarchy

Table 4.2 Partner selection criteria

	Criteria	Description	Sources
C_1	*Partner focused criteria*	*This set of criteria describes the potential firm's organizational features independent of the collaboration process.*	
C_{11}	Financial health	Financial health is necessary to deal with technologic, project, and market uncertainties within a CPD project.	Glaister Buckley [**44**], Lederer-Antonucci et al. [**187**], Nguye and Shanks [**191**], Tun et al. [**193**], Wang et al. [**206**]
C_{12}	Market position	Given the project type, firm's market position influences the CPD project success.	Emden et al. [**27**], Glaister Buckley [**44**], Tun et al. [**193**], Wang [**205**], Wang et al. [**206**], Zmud [**189**]
C_{13}	Geographical position	Factors such as distance, culture, tax regulations, etc. defined by location affect partner selection.	Jarimo and Salo [**249**], Wang et al. [**206**]
C_{14}	Reputation	Reputation is expressed as an aggregation of opinions of members of the community about one agent.	Glaister and Buckley [**44**], Hou et al. [**34**], Jarimo and Salo [**249**], Wang [**205**],Wang et al.[**206**], Zmud [**189**]
C_{15}	Experience Business Market Sector Management	Potential partner's experience in four domains is a significant criterion in partner selection. Business experience depicts know-how; market experience describes customer focused aspect.	Nguye and Shanks [**191**], Tun et al. [**193**]
C_{16}	Network	A good network of firms may increase the business success of the partner.	Glaister and Buckley [**44**]
C_2	*Collaboration focused criteria*	*This set of criteria describes the features occurring from two firms' interactions.*	
C_{21}	Trust Technical Personal	Technical trust describes the trust that a firm will respect the agreement terms whereas personal trust is the trust between CPD managers.	Glaister and Buckley [**44**], Feng and Yamashiro [**241**], Marxt and Link [**45**], Shah and Swaminathan [**41**], Viswanadham et al. [**214**]
C_{22}	Compatibility Managerial Cultural IT and communication	Compatibility between firms would decrease conflicts and increase success probability.	Emden et al. [**27**], Lederer-Antonucci et al. [**187**], Marxt and Link [**45**], Nguye and Shanks [**191**], Tun et al. [**193**], Viswanadham et al. [**214**], Wang [**205**], Wang et al. [**206**], Zmud [**189**],
C_{23}	Complementarity Knowledge Resource	A high similarity between firms' knowledge and resources make the collaboration redundant, therefore complementarity is sought.	Emden et al. [**27**], Glaister and Buckley [**44**], Shah and Swaminathan [**41**], Tun et al. [**193**]
C_{24}	Willingness to share information	A firm open to collaborate and share increases CPD success probability.	Hou et al. [**34**], Jarimo and Salo [**249**], Marxt and Link [**45**], Wang [**205**], Zmud [**189**]

	Criteria	*Description*	*Sources*
C_{25}	Flexibility	Flexibility describes potential partner's ability to adapt its characteristic to its partner in order to improve collaborative process.	Hou et al. [**34**], Jiao et al. [**252**] Wang [**205**], Wang et al. [**206**], Yao et al. [**240**]
C_{26}	Integration ability	The more a firm is able to integrate its process to the partner's processes, the more CPD project tends to succeed.	
C_{27}	Collaboration experience	Prior collaborations can reduce uncertainty regarding the cooperative capabilities and reliability of potential members.	Glaister and Buckley [**44**], Hou et al. [**34**], Wang [**205**], Wang et al. [**206**]
C_3	*Product/Software development focused criteria*	*This set of criteria describes developmental characteristics of the potential partner.*	
C_{31}	Technical expertise	It differs from technological capability and it describes the ability to perform a particular task.	Emden et al. [**27**], Hou et al. [**34**], Nguye and Shanks [**191**], Wang [**205**], Wang et al. [**206**], Zmud [**189**],
C_{32}	Technological capability	This includes keeping up with the technological change, implementing up-to-date infrastructure improve development quality.	Lederer-Antonucci et al. [**187**], Tun et al. [**193**]
C_{33}	Product/Software development experience	Development experience increases developmental success.	Glaister and Buckley [**44**], Marxt and Link [**45**] , Wang et al. [**206**], Zmud [**189**]
C_{34}	R&D resources	Investment in R&D increases developmental capability.	Lederer-Antonucci et al. [**187**]
C_{35}	Innovative capability	CPD includes innovation as well as development, therefore innovative character provides distinction.	Wang et al. [**206**]
C_{36}	Project expectations Expected risk Expected investment Expected development time Expected quality	Expected outcomes of the project from collaborating with a potential partner also need to be considered during the selection process.	Fu et al. [**245**], Hou et al. [**34**], Jiao et al. [**252**], Marxt and Link [**45**], Petersen [**243**], Wang et al. [**206**], Yao et al. [**240**], Ye and Li [**247**],

4.3 MULTI-CRITERIA DECISION MAKING

MCDM is a powerful tool used widely for solving the problems with multiple and usually conflicting criteria. MCDM techniques help the decision maker to structure the problem clearly and systematically and easily examine and to scale the problem in accordance with their requirements [**188**]. Partner evaluation literature often refers to MCDM techniques to handle the problem. This paper employs MCDM techniques in a fuzzy environment given that the Fuzzy MCDM approach enables decision makers to quantify intangible criteria as well. Fuzzy environment emerges as a way to cope with uncertain judgments and to incorporate the vagueness that typifies human thinking [**186**]. The approach consists of Fuzzy AHP for the determination of criteria weights and Fuzzy AD for the evaluation of the alternatives. During the partner evaluation process, the decision makers are generally unsure of their preferences because the information about the candidates and their performances are incomplete and uncertain [**243**]. Fuzzy Set Theory [**253**] is employed to deal with this imprecision and subjectivity.

The presented methodology employs Fuzzy AHP to determine criteria weights from the decision makers' evaluation. Then Fuzzy AD is implemented to evaluate alternatives' performance in response to requirements, according to the decision makers. The determination of criteria weights through Fuzzy AHP is independent of the considered project and expresses the judgment of the decision maker on the criteria importance, regardless of the project. However, the Fuzzy AD evaluation is valid for a specific context, where the decision maker evaluates the alternatives for a given project and its requirements. Fuzzy AD evaluation may differ for different development collaborations, even with the same decision maker. Fuzzy AHP and Fuzzy AD techniques are described in detail in the following sections.

4.3.1 Fuzzy Analytic Hierarchy Process

Problems such as incomplete information and subjective uncertainty make it difficult for the experts to quantify the precise ratio of weights for the different criteria [**186**]. AHP is particularly useful for evaluating complex multi-attribute alternatives involving subjective criteria [**254**]. AHP solves complex decision problems based on three principles: decomposition, comparative judgments, and synthesis of priorities [**255**], i.e. determination of the weights. There exists another technique in literature, ANP, which is also employed to determine criteria weights. ANP is a generic form of AHP and it includes complex interdependent relations between criteria[**186**]. As the independence axiom of AD guarantees the independence of the FRs, AHP is a suitable technique as the independence of evaluation criteria is also assured.

AHP [**256**] offers the opportunity to tackle the complexity of the decision problem by means of a hierarchy of decision layers. In comparison with other MCDM methods, the AHP method has widely been used in multi-criteria decision-making and has been applied successfully in many practical decision-making problems, especially in determining the criteria weights [**188**].

However, given the vagueness and uncertainty in decision makers' judgments, the crisp pairwise comparison in the conventional AHP is too insufficient and imprecise to capture the solid judgments. Fuzzy logic in the pairwise comparison of the AHP, which is called Fuzzy AHP, makes up for this deficiency in the conventional AHP.

The existing literature proposes various approaches to determine weights, such as eigenvector, weighted least square, entropy methods and diverse MCDM methods. In this study, the fuzzy extension of a commonly accepted technique, namely AHP [**256**], is used to determine the decision criteria weights. Conventional AHP approach may not fully reflect a style of human thinking despite its wide range of applications and decision makers' judgments and knowledge concepts models contain subjectivity and uncertainty, causing assessment and evaluation to be more difficult. This difficulty is handled by applying AHP in a fuzzy environment to solve prioritisation and evaluation problems.

Literature includes numerous studies of Fuzzy AHP application. Recent literature on Fuzzy AHP employing the technique to determine criteria weights is summarized in Table 4.3.

Introduced by Zadeh [**253**], Fuzzy Set Theory has become important to deal with the ambiguity in a system. In this study, first linguistic terms are used to represent the expert assessments, then TFNs, $\tilde{1}$ to $\tilde{9}$ as given in Table 4.4, are used to represent subjective pairwise comparisons of evaluation processes in order to capture the vagueness.

Table 4.3 Recent Fuzzy AHP literature

Author(s)	***Topic***	***Fuzzy AHP contribution***
Büyüközkan and Çiftçi [**257**]	Analysis of electronic service quality in healthcare industry	Determining healthcare electronic service quality criteria weights
Zheng et al. [**258**]	Work safety evaluation and early warning rating	Evaluating the work safety in hot and humid environments
Chen and Chu [**259**]	Product design communication and evaluation from emotional perspectives	Quantifying the perception difference of emotional dimension
Bulut et al. [**260**]	Proposition of a fuzzy AHP modelling	Ranking the level of experience
Javanbarg [**261**]	Fuzzy AHP based MCDM technique with particle swarm optimization	Determining criteria weights
Özkır and Demirel [**262**]	Proposition of a fuzzy assessment framework for transportation investment projects	Calculating aggregate weights and ranking of the projects
Kutlu and Ekmekçioğlu [**263**]	Failure mode and effects analysis	Determining the importance of risk factors
Büyüközkan et al. [**264**]	Evaluation of mobile technologies for logistics industry	Determining criteria weights
Sarfaraz et al. [**265**]	Evaluation of web platform development	Ranking of the platforms
Rajput et al. [**266**]	Proposition of a MCDM technique integrating time dependency and ANOVA	Obtaining final scores and ranking of the alternatives
Duran [**267**]	Computer-aided maintenance management systems	Selecting the best suited system
Xia and Xu [**268**]	Proposition of multiplicative consistency	Obtaining final scores and ranking of the alternatives
Lee et al. [**269**]	Measuring the relative efficiency of hydrogen energy technologies	Determining criteria weights
Golestanifar et al. [**270**]	Assessment of tunnel excavation methods	Determining criteria weights
An et al. [**271**]	Railway risk management system	Determining the weight of hazardous event contribution

Table 4.4 Definition and membership function of fuzzy numbers

Importance	Fuzzy Number	Definition	Membership Function
9	$\tilde{9}$	Extremely more importance (EMI)	(8, 9, 10)
7	$\tilde{7}$	Very strong importance (VSI)	(6, 7, 8)
5	$\tilde{5}$	Strong importance (SI)	(4, 5, 6)
3	$\tilde{3}$	Moderate importance (MI)	(2, 3, 4)
1	$\tilde{1}$	Equal importance (EI)	(1, 1, 2)
2, 4, 6, 8	$\tilde{2},\tilde{4}, \tilde{6}, \tilde{8}$	Intermediate values	

The steps of the Fuzzy AHP methodology are presented below.

1. Compare the performance score. TFNs ($\tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$) are used to indicate the relative strength of each pair of elements in the same hierarchy.

2. Construct the fuzzy comparison matrix. By using TFNs, via pair-wise comparison, the fuzzy judgment matrix $\tilde{A}(a_{ij})$ is constructed as given below:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \quad (4.1)$$

where $\tilde{a}^{\alpha}_{ij} = 1$, if *I is equal to j*, and $\tilde{a}^{\alpha}_{ij} = \tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$ or $\tilde{1}^{-1},\tilde{3}^{-1},\tilde{5}^{-1},\tilde{7}^{-1},\tilde{9}^{-1}$, if *I is not equal to j*.

3. Solve the fuzzy eigenvalue. A fuzzy eigenvalue, $\tilde{\lambda}$, is a fuzzy number solution to:

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \quad (4.2)$$

where A is a $n \times n$ fuzzy matrix containing fuzzy numbers $\tilde{a}_{ij}$ and $\tilde{x}$ is a non-zero $n \times 1$ fuzzy vector containing fuzzy number $\tilde{x}_i$. To perform fuzzy multiplications and additions by using the interval arithmetic and α-cut, the equation $\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x}$ is equivalent to:

$$[a_{i1l}^{\alpha} x_{1l}^{\alpha}, a_{i1u}^{\alpha} x_{1u}^{\alpha}] \oplus \cdots \oplus [a_{inl}^{\alpha} x_{nl}^{\alpha}, a_{inu}^{\alpha} x_{nu}^{\alpha}] = [\lambda x_{il}^{\alpha}, \lambda x_{iu}^{\alpha}] \quad (4.3)$$

where:

$$\tilde{A} = [\tilde{a}_{ij}^{\alpha}], \tilde{x}^{t} = (\tilde{x}_1 \cdots \tilde{x}_n), \tilde{a}_{ij}^{\alpha} = [\tilde{a}_{ijl}^{\alpha}, \tilde{a}_{iju}^{\alpha}] \quad (4.4)$$

$$x_i^{\alpha} = [x_{il}^{\alpha}, x_{iu}^{\alpha}], \tilde{\lambda}^{\alpha} = [\lambda_l^{\alpha}, \lambda_u^{\alpha}] \quad (4.5)$$

$$\text{for all } 0 < a \leq 1 \text{ and all } i, j \text{ with } i = 1, 2, \cdots, n; j = 1, 2,$$

The *α-cut* is known to incorporate the experts or decision-maker(s) confidence over his/her preference or the judgments. The degree of satisfaction for the judgment matrix $\tilde{A}$ is estimated by the index of optimism μ. A larger value of the index μ indicates a higher degree of optimism. The index of optimism is a linear convex combination [**272**] defined as:

$$\tilde{a}_{ij}^{\alpha} = \mu \tilde{a}_{iju}^{\alpha} + (1 - \mu)\tilde{a}_{ijl}^{\alpha}, \forall \alpha \in [0, 1] \quad (4.6)$$

When α is fixed, the following matrix can be obtained after setting the index of optimism, μ, in order to estimate the degree of satisfaction:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12}^{\alpha} & \cdots & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & 1 & \cdots & \tilde{a}_{2n}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & \cdots & 1 \end{bmatrix} \quad (4.7)$$

The eigenvector is calculated by fixing the μ value and identifying the maximal eigenvalue. After defuzzification of each pair wise matrix, the consistency ratio *CR* for each matrix is calculated. The deviations from consistency are expressed by the following equation consistency index, and the measure of inconsistency is called the consistency index *CI*:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4.8}$$

The consistency ratio *CR* is used to estimate directly the consistency of pair wise comparisons. The *CR* is computed by dividing the *CI* by a value obtained from a table of Random Consistency Index *RI* to:

$$CR = \frac{CI}{RI} \tag{4.9}$$

If *CR* is less than 0.10, the comparisons are acceptable. *RI* is the average index for randomly generated weights [**256**].

4. The priority weight of each criterion can be obtained by multiplying the matrix of evaluation ratings by the vector of attribute weights and summing over all attributes.

4.3.2 Fuzzy Axiomatic Design

AD, a systematic method offering a scientific base for design, was introduced by Suh [**114**], and the technique is based on two axioms. The independence axiom states that the independence of functional requirements should be maintained, and the information axiom states that among the designs that satisfy the functional requirements the design with the minimum information content is the best design. These AD principles provide a powerful tool to measure how well alternatives respond to requirements. Decision makers employ a “design range” to define the requirements. Then the “system ranges” of the alternatives are assessed against this design range to analyze their suitability.

Table 4.5 Fuzzy AD applications

Authors	**Application area**
Kulak and Kahraman [**273**]	Selection among transportation companies
Kulak [**274**]	Choice of material handling equipments
Kulak et al.[**275**]	Multi-attribute equipment selection
Eraslan et al. [**276**]	Ranking of intercity bus passenger seats
Cebi and Celik [**277**]	Measuring customer satisfaction at ports
Ozel and Ozyoruk [**278**]	Supplier decision
Cebi and Celik [**279**]	Optimum configuration for ship machinery installation
Cebi et al. [**280**]	Ship design project approval
Yücel and Aktas [**281**]	Evaluation for ergonomic design of electronic consumer products
Büyüközkan and Arsenyan [**282**]	Evaluation of mobile technologies for logistics industry
Celik and Er [**283**]	Model selection paradigm
Celik [**284**]	Decision aid for integrated environmental management system
Celik et al. [**285**]	Shipyards' docking performance evaluation model
Celik et al. [**286**]	Strategy making towards container port development
Celik et al. [**287**]	Integrated fuzzy QFD model for shipping investment decisions in crude oil tanker market
Cevikcan et al. [**288**]	Comparison of Fuzzy VIKOR and Fuzzy Axiomatic Design versus to Fuzzy TOPSIS and application to candidate assessment
Kahraman et al. [**289**]	Renewable energy alternatives comparison
Cicek and Celik [**290**]	Selection of porous materials in marine system design
Kahraman and Cebi [**291**]	Teaching assistant selection problem
Kulak et al. [**292**]	Literature review for axiomatic design principles
Cebi and Kahraman [**293**]	Discussions on the adaptation of the current AD principles into fuzzy sets theory
Cebi and Kahraman [**294**]	Defining best design of indicator panel for passenger cars
Cicek and Celik [**295**]	Model selection interface for material selection
Cicek et al. [**296**]	Decision aid extension to material selection
Cebi et al. [**297**]	Ship design project approval mechanism
Celik [**298**]	Redesigning International Safety Management code s
Cebi and Kahraman [**299**]	Selecting best sites for real estate investment
Cebi and Kahraman [**300**]	Group decision support system
Chen et al. [**301**]	Knowledge demander and knowledge supplier matching
Büyüközkan et al. [**302**]	Evaluation of e-learning web-sites
Cheng and Huang [**303**]	Hybrid multi-attribute decision making with real number, interval number and linguistic labels

As the study includes incomplete information with subjective judgments, Fuzzy AD is preferred to conventional AD in order to operate in a fuzzy environment. Fuzzy AD has proven to be a powerful MCDM tool since first introduced [115]. Fuzzy AD literature summarized in Table 4.5 illustrates the versatility of Fuzzy AD and its usability in evaluation, ranking, and selection phases. Fuzzy AD enables evaluation of alternatives in linguistic terms and therefore allows the measurement of the intangible criteria as well. On the other hand, the design range concept gives Fuzzy AD a dynamic character, given that for each specific case, a new set of requirements can be defined on the criteria set, and redundant criteria may be dismissed without changing the criteria set. Fuzzy AD facilitates the elimination of the unsuitable alternatives also with the design range, given that an alternative that cannot meet an important requirement is eliminated directly, without the chance of compensating the deficiency at other criteria.

Information content, on which MCDM technique is based, represents a function of probability of satisfying a functional requirement *FR*. Therefore, the design with the highest probability to meet these requirements is the best design. Information content I_i of a design with probability of success p_i for a given FR_i is defined as follows:

$$I_i = log_2(\frac{1}{p_i}) \tag{4.10}$$

According to Suh [**144**], a logarithm is employed in calculating the information contents, so as to obtain additivity.

On the other hand, the probability of success is given by the design range (the requirements for the design) and the system range (the system capacity). Figure 4.3 illustrates the design and system ranges as well as the common area. The intersection of the ranges offers the feasible solution. Therefore, the probability of success can be expressed as:

$$p_i = \int_l^u p(FR_i)dFR_i \tag{4.11}$$

where l and u represent the lower and upper limits of the design range and where p represents the probability distribution function of the system for a given FR_i.

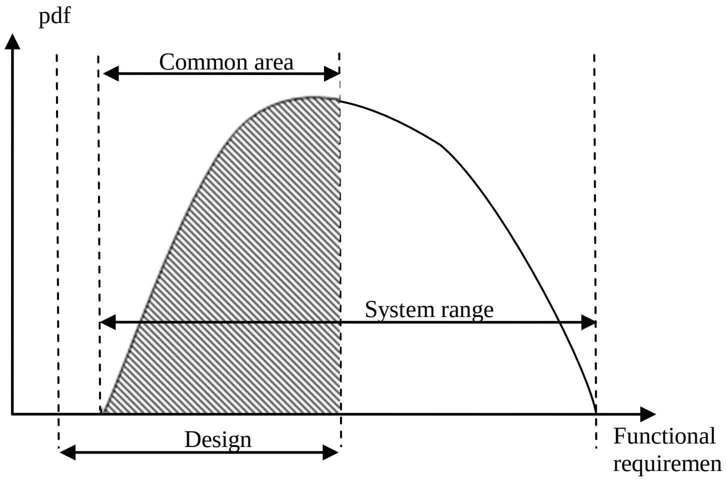


Figure 4.3 System-design ranges and common area

The probability of success p_i is equal to the common area A_c. Consequently, the information content can be expressed as follows:

$$I_i = log_2(\frac{1}{A_c}) \quad (4.12)$$

Also, if the probability distribution function is uniform, the probability of success becomes:

$$p_i = (\frac{common\ range}{system\ range}) \quad (4.13)$$

Therefore, the information content can also be written as:

$$I_i = log_2(\frac{system\ range}{common\ range}) \quad (4.14)$$

Fuzzy AD methodology is based on the conventional AD. However, crisp ranges are replaced by fuzzy numbers that represent linguistic terms Figure 4.4.

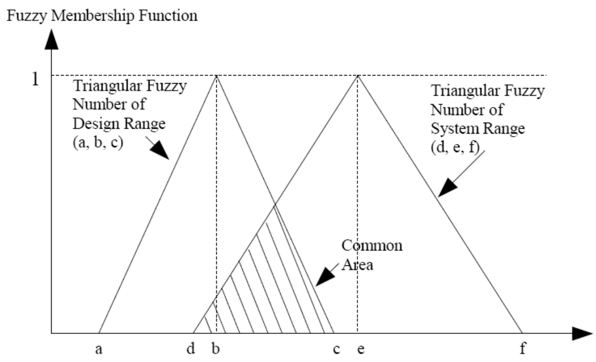


Figure 4.4 System-design ranges and common area in fuzzy environment

In this study, triangular fuzzy numbers (TFNs) are employed. Intersection of TFNs representing design and system ranges presents the common area [**304**]. First, the information content is calculated as in a non-fuzzy environment. Then information content in a fuzzy environment is calculated as follows:

$$I_i = \begin{cases} \infty & no \\ log_2\left(\frac{area\ of\ system\ range}{common\ range}\right) & otherwise \end{cases} \quad (4.15)$$

The calculation of the weighted information content is adapted from [**291**].

Given that this model requires determination of weights of criteria and sub-criteria. Total weighted information content for first level criteria is calculated as follows:

$$I = \sum_{i=1}^{n} w_i I_i \quad (4.16)$$

where n is the number of first level criteria and $\sum_{=1}^{n} w_i = 1$.

Likewise, information content for second level criteria (sub-criteria for criterion *i*) is calculated as follows:

$$I_i = \sum_{j=1}^{m} w_{ij} I_{ij} \quad (4.17)$$

where *m* is the number of sub-criteria for criterion *i* and $\sum_{j=1}^{m} w_{ij}=1$ for $i=1,\ldots n$. The technique is applied similarly at the lower levels. Finally, according to information axiom, alternatives are ranked with increasing order of information content.

System range evaluations are made on each level. If all alternatives except one (or alternatives altogether) are eliminated on a level, no further analysis is required. However, if more than two alternatives respond to the design range on a level, a more detailed analysis is conducted on a lower hierarchical level until all alternatives (or except one) are eliminated or alternatives are evaluated at all levels. Linguistic terms and their related fuzzy membership functions are presented in Table 4.6.

Table 4.6 Linguistic terms, their abbreviations, and membership functions

Term	**Abbrv.**	**Fuzzy Membership Function**	**Term**	**Abbrv.**	**Fuzzy Membership Function**
None	N	(0, 0, 1)	At least None	LN	(0, 1, 1)
Very low	VL	(0, 0.1, 0.2)	At least Very low	LVL	(0.05, 1, 1)
Low	L	(0.1. 0.2, 0.3)	At least Low	LL	(0.1, 1, 1)
Fairly low	FL	(0.2. 0.3, 0.4)	At least Fairly low	LFL	(0.2, 1, 1)
More or less low	ML	(0.3. 0.4, 0.5)	At least More or less low	LML	(0.3, 1, 1)
Medium	M	(0.4. 0.5, 0.6)	At least Medium	LM	(0.4, 1, 1)
More or less good	MG	(0.5, 0.6, 0.7)	At least More or less good	LMG	(0.5, 1, 1)
Fairly good	FG	(0.6, 0.7, 0.8)	At least Fairly good	LFG	(0.6, 1, 1)
Good	G	(0.7, 0.8, 0.9)	At least Good	LG	(0.7, 1, 1)
Very good	VG	(0.8, 0.9, 1)	At least Very good	LVG	(0.8, 1, 1)
Excellent	E	(0.9, 1, 1)	At least Excellent	LE	(0.9, 1, 1)

4.4 APPLICATION OF THE METHODOLOGY IN SOFTWARE INDUSTRY

The partner evaluation methodology is tested in two case studies, which aim to first verify the partner evaluation criteria, and then the usability of the proposed methodology. Two experts from the software industry with collaboration experience are selected and provided with an evaluation form. The form includes pairwise comparison matrices for Fuzzy AHP in order to determine criteria weights and an evaluation set of Fuzzy AD system and design ranges for the assessment of potential partners and project requirements. The Fuzzy AHP evaluation form contains 9 matrices whereas system range form contains one matrix where experts are expected to express their requirements from the potential partner for a specific project. The design range form also contains one matrix, where experts evaluate n partner alternatives according to the evaluation criteria.

The experts employ linguistic variables provided in the form for system and design ranges (Table 4.6), whereas they make pairwise comparisons according to the fuzzy scale in Table 4.4. The linguistic terms are then translated into TFNs, through which criteria weights and ICs are calculated.

Case studies aim to observe the performance and the managerial advantage the presented methodology provides. Both experts agree on the significance of the criteria set. However, each expert attributes different importance to the criteria. Fuzzy AHP becomes essential in this phase. Pairwise judgments of each expert are collected in fuzzy scale, and these judgments are translated into criteria weights through Fuzzy AHP. Each case has its unique criteria weight set. On the other hand, each project type requires different features and some criteria are prioritized over others in each case. The design range of Fuzzy AD serves this purpose by defining a requirement set on each criterion. Both techniques combine in presenting a final evaluation and ranking of the alternatives according to the judgments of the experts.

4.4.1 Expert X Evaluation and Obtained Results

The evaluation of Expert X is essential for the evaluation and the verification of the proposed methodology given that his company is the TUBITAK project partner. The company is about to start a new software development project and three alternatives are considered for the venture.

Table 4.7 Pairwise criteria comparisons by Expert X

	C_1	C_2	C_3
C_1	1	$1/\tilde{6}$	$1/\tilde{3}$
C_2	$\tilde{6}$	1	$\tilde{3}$
C_3	$\tilde{3}$	$1/\tilde{3}$	1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	$\tilde{3}$	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{5}$	$\tilde{1}$
C_{12}	$1/\tilde{3}$	1	$1/\tilde{3}$	$1/\tilde{5}$	$1/\tilde{9}$	$1/\tilde{3}$
C_{13}		$\tilde{3}$	1	$1/\tilde{3}$	$1/\tilde{5}$	$\tilde{1}$
C_{14}	$\tilde{3}$	$\tilde{5}$	$\tilde{3}$	1	$1/\tilde{3}$	$\tilde{3}$
C_{15}	$\tilde{5}$	$\tilde{9}$	$\tilde{5}$	$\tilde{3}$	1	$\tilde{5}$
C_{16}		$\tilde{3}$		$1/\tilde{3}$	$1/\tilde{5}$	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$
C_{152}	$1/\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$
C_{153}			1	$\tilde{1}$
C_{154}				1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$
C_{22}		1	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$
C_{23}	$1/\tilde{3}$	$1/\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$1/\tilde{3}$
C_{24}	$1/\tilde{3}$	$1/\tilde{3}$		1	$\tilde{1}$	$\tilde{1}$	$1/\tilde{3}$
C_{25}	$1/\tilde{3}$	$1/\tilde{3}$			1	$\tilde{1}$	$1/\tilde{3}$
C_{26}	$1/\tilde{3}$	$1/\tilde{3}$				1	$1/\tilde{3}$
C_{27}			$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	1

	C_{211}	C_{212}
C_{211}	1	$1/\tilde{2}$
C_{212}	$\tilde{2}$	1

	C_{221}	C_{222}	C_{223}
C_{221}	1	$\tilde{1}$	$1/\tilde{3}$
C_{222}		1	$1/\tilde{3}$
C_{223}	$\tilde{3}$	$\tilde{3}$	1

	C_{231}	C_{232}
C_{231}	1	$\tilde{1}$
C_{232}		1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	$\tilde{3}$	$\tilde{1}$	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$
C_{32}	$1/\tilde{3}$	1	$1/\tilde{3}$	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$
C_{33}		$\tilde{3}$	1	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$
C_{34}	$1/\tilde{3}$		$1/\tilde{3}$	1	$1/\tilde{3}$	$1/\tilde{3}$
C_{35}		$\tilde{3}$		$\tilde{3}$	1	$\tilde{1}$
C_{36}		$\tilde{3}$		$\tilde{3}$	$\tilde{1}$	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	$\tilde{1}$	$1/\tilde{2}$	$1/\tilde{2}$
C_{362}		1	$1/\tilde{2}$	$1/\tilde{2}$
C_{363}	$\tilde{2}$	$\tilde{2}$	1	$\tilde{1}$
C_{364}	$\tilde{2}$	$\tilde{2}$		1

Firstly, Expert X judgments on criteria are collected in order to obtain criteria weights. Table 4.7 displays pairwise comparisons of Expert X.

Table 4.8 Fuzzified pairwise judgments of Expert X

	C_1	C_2	C_3
C_1	1	(1/7, 1/6, 1/5)	(1/4, 1/3, 1/2)
C_2	(5, 6, 7)	1	(2, 3, 4)
C_3	(2, 3, 4)	(1/4, 1/3, 1/2)	1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	(2, 3, 4)	(1, 1, 2)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1, 1, 2)
C_{12}	(1/4, 1/3, 1/2)	1	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	1/10, 1/9, 1/8)	(1/4, 1/3, 1/2)
C_{13}	(1/2, 1, 1)	(2, 3, 4)	1	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1, 1, 2)
C_{14}	(2, 3, 4)	(4, 5, 6)	(2, 3, 4)	1	(1/4, 1/3, 1/2)	(2, 3, 4)
C_{15}	(4, 5, 6)	(8, 9, 10)	(4, 5, 6)	(2, 3, 4)	1	(4, 5, 6)
C_{16}	(1/2, 1, 1)	(2, 3, 4)	(1/2, 1, 1)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	(1, 1, 2)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(1, 1, 2)
C_{22}	(1/2, 1, 1)	1	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(1, 1, 2)
C_{23}	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	1	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)	(1/4, 1/3, 1/2)
C_{24}	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/2, 1, 1)	1	(1, 1, 2)	(1, 1, 2)	(1/4, 1/3, 1/2)
C_{25}	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/2, 1, 1)	(1/2, 1, 1)	1	(1, 1, 2)	(1/4, 1/3, 1/2)
C_{26}	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	1	(1/4, 1/3, 1/2)
C_{27}	(1/2, 1, 1)	(1/2, 1, 1)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	(2, 3, 4)	(1, 1, 2)	(2, 3, 4)	(1, 1, 2)	(1, 1, 2)
C_{32}	(1/4, 1/3, 1/2)	1	(1/4, 1/3, 1/2)	(1, 1, 2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
C_{33}	(1/2, 1, 1)	(2, 3, 4)	1	(2, 3, 4)	(1, 1, 2)	(1, 1, 2)
C_{34}	(1/4, 1/3, 1/2)	(1/2, 1, 1)	(1/4, 1/3, 1/2)	1	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
C_{35}	(1/2, 1, 1)	(2, 3, 4)	(1/2, 1, 1)	(2, 3, 4)	1	(1, 1, 2)
C_{36}	(1/2, 1, 1)	(2, 3, 4)	(1/2, 1, 1)	(2, 3, 4)	(1/2, 1, 1)	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	(2, 3, 4)	(1, 1, 2)	(1, 1, 2)
C_{152}	(1/4, 1/3, 1/2)	1	(1, 1, 2)	(1, 1, 2)
C_{153}	(1/2, 1, 1)	(1/2, 1, 1)	1	(1, 1, 2)
C_{154}	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	1

	C_{211}	C_{212}
C_{211}	1	(1/3, 1/2, 1)
C_{212}	(1, 2, 3)	1

	C_{231}	C_{232}
C_{231}	1	(1, 1, 2)
C_{232}	(1/2, 1, 1)	1

	C_{221}	C_{222}	C_{223}
C_{221}	1	(1, 1, 2)	(1/4, 1/3, 1/2)
C_{222}	(1/2, 1, 1)	1	(1/4, 1/3, 1/2)
C_{223}	(2, 3, 4)	(2, 3, 4)	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	(1, 1, 2)	(1/3, 1/2, 1)	(1/3, 1/2, 1)
C_{362}	(1/2, 1, 1)	1	(1/3, 1/2, 1)	(1/3, 1/2, 1)
C_{363}	(1, 2, 3)	(1, 2, 3)	1	(1, 1, 2)
C_{364}	(1, 2, 3)	(1, 2, 3)	(1/2, 1, 1)	1

These pairwise comparisons are first fuzzified according to the scale presented in Table 4.4. As stated before, TFNs are employed for the simplicity of calculations. The results are displayed in Table 4.8.

Table 4.9 α-cut on pairwise judgments of Expert X

	C_1	C_2	C_3
C_1	1	(13/84, 11/60)	(7/24, 5/12)
C_2	(11/2, 13/2)	1	(5/2, 7/2)
C_3	(5/2, 7/2)	(7/24, 5/12)	1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	(5/2, 7/2)	(1, 3/2)	(7/24, 5/12)	(11/60, 9/40)	(1, 3/2)
C_{12}	(7/24, 5/12)	1	(7/24, 5/12)	(11/60, 9/40)	(2/19, 2/17)	(7/24, 5/12)
C_{13}	(3/4, 1)	(5/2, 7/2)	1	(7/24, 5/12)	(11/60, 9/40)	(1, 3/2)
C_{14}	(5/2, 7/2)	(9/2, 11/2)	(5/2, 7/2)	1	(7/24, 5/12)	(5/2, 7/2)
C_{15}	(9/2, 11/2)	(17/2, 19/2)	(9/2, 11/2)	(5/2, 7/2)	1	(9/2, 11/2)
C_{16}	(3/4, 1)	(5/2, 7/2)	(3/4, 1)	(7/24, 5/12)	(11/60, 9/40)	1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	(1, 3/2)	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(1, 3/2)
C_{22}	(3/4, 1)	1	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(1, 3/2)
C_{23}	(7/24, 5/12)	(7/24, 5/12)	1	(1, 3/2)	(1, 3/2)	(1, 3/2)	(7/24, 5/12)
C_{24}	(7/24, 5/12)	(7/24, 5/12)	(3/4, 1)	1	(1, 3/2)	(1, 3/2)	(7/24, 5/12)
C_{25}	(7/24, 5/12)	(7/24, 5/12)	(3/4, 1)	(3/4, 1)	1	(1, 3/2)	(7/24, 5/12)
C_{26}	(7/24, 5/12)	(7/24, 5/12)	(3/4, 1)	(3/4, 1)	(3/4, 1)	1	(7/24, 5/12)
C_{27}	(3/4, 1)	(3/4, 1)	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	(5/2, 7/2)	(1, 3/2)	(5/2, 7/2)	(1, 3/2)	(1, 3/2)
C_{32}	(7/24, 5/12)	1	(7/24, 5/12)	(1, 3/2)	(7/24, 5/12)	(7/24, 5/12)
C_{33}	(3/4, 1)	(5/2, 7/2)	1	(5/2, 7/2)	(1, 3/2)	(1, 3/2)
C_{34}	(7/24, 5/12)	(3/4, 1)	(7/24, 5/12)	1	(7/24, 5/12)	(7/24, 5/12)
C_{35}	(3/4, 1)	(5/2, 7/2)	(3/4, 1)	(5/2, 7/2)	1	(1, 3/2)
C_{36}	(3/4, 1)	(5/2, 7/2)	(3/4, 1)	(5/2, 7/2)	(3/4, 1)	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	(5/2, 7/2)	(1, 3/2)	(1, 3/2)
C_{152}	(7/24, 5/12)	1	(1, 3/2)	(1, 3/2)
C_{153}	(3/4, 1)	(3/4, 1)	1	(1, 3/2)
C_{154}	(3/4, 1)	(3/4, 1)	(3/4, 1)	1

	C_{211}	C_{212}
C_{211}	1	(5/12, 3/4)
C_{212}	(3/2, 5/2)	1

	C_{231}	C_{232}
C_{231}	1	(1, 3/2)
C_{232}	(3/4, 1)	1

	C_{221}	C_{222}	C_{223}
C_{221}	1	(1, 3/2)	(7/24, 5/12)
C_{222}	(3/4, 1)	1	(7/24, 5/12)
C_{223}	(5/2, 7/2)	(5/2, 7/2)	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	(1, 3/2)	(5/12, 3/4)	(5/12, 3/4)
C_{362}	(3/4, 1)	1	(5/12, 3/4)	(5/12, 3/4)
C_{363}	(3/2, 5/2)	(3/2, 5/2)	1	(1, 3/2)
C_{364}	(3/2, 5/2)	(3/2, 5/2)	(3/4, 1)	1

Then α-cut operations in Equation 4.4 are applied to the fuzzy judgment matrix (Table 4.9) and then the index of optimism "μ" is applied according to Equation 4.6 (Table 4.10).

Table 4.10 Final judgment matrix of Expert X

	C_1	C_2	C_3
C_1	1	0.17	0.35
C_2	6	1	3
C_3	3	0.35	1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	3	1,25	0.35	0.20	1,25
C_{12}	0.35	1	0.35	0.20	0.11	0.35
C_{13}	0.88	3	1	0.35	0.20	1,25
C_{14}	3	5	3	1	0.35	3
C_{15}	5	9	5	3	1	5
C_{16}	0.88	3	0.88	0.35	0.20	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	3	1,25	1,25
C_{152}	0.35	1	1,25	1,25
C_{153}	0.88	0.88	1	1,25
C_{154}	0.88	0.88	0.88	1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	1,25	3	3	3	3	1,25
C_{22}	0.88	1	3	3	3	3	1,25
C_{23}	0.35	0.35	1	1,25	1,25	1,25	0.35
C_{24}	0.35	0.35	0.88	1	1,25	1,25	0.35
C_{25}	0.35	0.35	0.88	0.88	1	1,25	0.35
C_{26}	0.35	0.35	0.88	0.88	0.88	1	0.35
C_{27}	0.88	0.88	3	3	3	3	1

	C_{211}	C_{212}
C_{211}	1	0.58
C_{212}	2	1

	C_{221}	C_{222}	C_{223}
C_{221}	1	1,25	0.35
C_{222}	0.88	1	0.35
C_{223}	3	3	1

	C_{231}	C_{232}
C_{231}	1	1,25
C_{232}	0.88	1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	3	1,25	3	1,25	1,25
C_{32}	0.35	1	0.35	1,25	0.35	0.35
C_{33}	0.88	3	1	3	1,25	1,25
C_{34}	0.35	0.88	0.35	1	0.35	0.35
C_{35}	0.88	3	0.88	3	1	1,25
C_{36}	0.88	3	0.88	3	0.88	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	1,25	0.58	0.58
C_{362}	0.88	1	0.58	0.58
C_{363}	2	2	1	1,25
C_{364}	2	2	0.88	1

By solving the Equation 4.2 eigen vectors are found (Table 4.11). CRs, calculated according to Equations 4.8 and 4.9, are also included in the table. Fuzzy AHP matrices are all consistent. The highest inconsistency observed is 0.09 in C_{15i} matrix, which is still an acceptable consistency ratio.

Table 4.11 Eigen values for Expert X judgments

CR: 0.03	C_1	C_2	C_3
C_1	0.100	0.112	0.080
C_2	0.600	0.658	0.690
C_3	0.300	0.230	0.230

CR: 0.03	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	0.090	0.125	0.109	0.067	0.097	0.105
C_{12}	0.032	0.042	0.030	0.038	0.053	0.030
C_{13}	0.079	0.125	0.087	0.067	0.097	0.105
C_{14}	0.270	0.208	0.261	0.190	0.170	0.253
C_{15}	0.450	0.375	0.436	0.571	0.485	0.422
C_{16}	0.079	0.125	0.077	0.067	0.097	0.084

CR: 0.09	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	0.322	0.521	0.285	0.263
C_{152}	0.113	0.174	0.285	0.263
C_{153}	0.283	0.153	0.228	0.263
C_{154}	0.283	0.153	0.201	0.211

CR: 0.08	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	0.240	0.276	0.237	0.231	0.224	0.218	0.255
C_{22}	0.212	0.221	0.237	0.231	0.224	0.218	0.255
C_{23}	0.084	0.077	0.079	0.096	0.093	0.091	0.071
C_{24}	0.084	0.077	0.070	0.077	0.093	0.091	0.071
C_{25}	0.084	0.077	0.070	0.068	0.075	0.091	0.071
C_{26}	0.084	0.077	0.070	0.068	0.066	0.073	0.071
C_{27}	0.212	0.194	0.237	0.231	0.224	0.218	0.204

CR: 0.00	C_{211}	C_{212}
C_{211}	0.333	0.367
C_{212}	0.667	0.633

CR: 0.00	C_{221}	C_{222}	C_{223}
C_{221}	0.205	0.238	0.206
C_{222}	0.180	0.190	0.206
C_{223}	0.615	0.571	0.588

CR: 0.00	C_{231}	C_{232}
C_{231}	0.532	0.556
C_{232}	0.468	0.444

CR: 0.00	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	0.230	0.216	0.265	0.211	0.246	0.229
C_{32}	0.081	0.072	0.074	0.088	0.069	0.064
C_{33}	0.203	0.216	0.212	0.211	0.246	0.229
C_{34}	0.081	0.063	0.074	0.070	0.069	0.064
C_{35}	0.203	0.216	0.187	0.211	0.197	0.229
C_{36}	0.203	0.216	0.187	0.211	0.173	0.183

CR: 0.00	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	0.170	0.200	0.191	0.170
C_{362}	0.150	0.160	0.191	0.170
C_{363}	0.340	0.320	0.329	0.367
C_{364}	0.340	0.320	0.289	0.293

The criteria weights (Table 4.12) are calculated according to the eigen values in Table 4.11.

Table 4.12 Criteria weights of Expert X

	C_1	C_2	C_3						
w	0.097	0.649	0.253						
	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}			
w	0.099	0.037	0.093	0.226	0.457	0.088			
	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}		
w	0.240	0.228	0.085	0.081	0.077	0.073	0.217		
	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}			
w	0.233	0.075	0.220	0.070	0.207	0.195			
	C_{151}	C_{152}	C_{153}	C_{154}					
w	0.348	0.209	0.232	0.212					
	C_{211}	C_{212}		C_{221}	C_{222}	C_{223}		C_{231}	C_{232}
w	0.350	0.650		0.216	0.192	0.591		0.544	0.456
	C_{361}	C_{362}	C_{363}	C_{364}					
w	0.183	0.168	0.339	0.311					

Expert X is also consulted for his judgments on system and design ranges, which results are displayed in Table 4.13. These evaluations are then fuzzified (Table 4.14) according to the scale presented in Table 4.6. The highest requirements are set on willingness to share information and expected project quality.

Table 4.13 System and design range evaluation of Expert X

	C_1	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{151}	C_{152}	C_{153}	C_{154}	C_{16}				
FR	LM	LL	LVL	LMG	LM	LM	LFG	LM	LFL	LM	LM				
A_1	M	VL	VL	M	M	M	G	ML	M	ML	ML				
A_2	G	G	M	VG	M	ML	MG	ML	L	MG	FG				
A_3	ML	FL	L	G	FL	MG	G	G	M	ML	M				
	C_2	C_{21}	C_{211}	C_{212}	C_{22}	C_{221}	C_{222}	C_{223}	C_{23}	C_{231}	C_{232}	C_{24}	C_{25}	C_{26}	C_{27}
FR	LFG	LG	LG	LG	LG	LG	LFG	LG	LFG	LFG	LFG	LVG	LFG	LFG	LFG
A_1	G	G	FG	VG	G	FG	G	FG	G	G	G	G	G	MG	MG
A_2	G	G	G	G	G	G	MG	G	G	G	FG	G	G	G	FG
A_3	G	G	G	G	G	G	G	G	G	G	G	G	FG	G	FG
	C_3	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{361}	C_{362}	C_{363}	C_{364}				
FR	LFG	LG	LFG	LFG	LM	LMG	LG	LMG	LFL	LG	LVG				
A_1	MG	G	MG	VG	ML	M	G	G	L	G	VG				
A_2	G	G	VG	MG	G	G	G	G	G	VG	VG				
A_3	FG	FG	MG	G	FG	G	G	G	M	G	G				

Table 4.14 Fuzzified evaluations of Expert X

	C_1	C_{11}	C_{12}	C_{13}
FR	(0.4, 1, 1)	(0.1, 1, 1)	(0.05, 1, 1)	(0.5, 1, 1)
A_1	(0.4, 0.5, 0.6)	(0.0.1, 0.2)	(0.0.1, 0.2)	(0.4, 0.5, 0.6)
A_2	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.8, 0.9, 1)
A_3	(0.3, 0.4, 0.5)	(0.2, 0.3, 0.4)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)
FR		C_{14}	C_{15}	C_{16}
A_1		(0.4, 1, 1)	(0.4, 1, 1)	(0.4, 1, 1)
A_2		(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)
A_3		(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)	(0.6, 0.7, 0.8)
		(0.3, 0.4, 0.5)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)
	C_{151}	C_{152}	C_{153}	C_{154}
FR	(0.6, 1, 1)	(0.4, 1, 1)	(0.2, 1, 1)	(0.4, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.3, 0.4, 0.5)	(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)
A_2	(0.5, 0.6, 0.7)	(0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.5, 0.6, 0.7)
A_3	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.3, 0.4, 0.5)
	C_2	C_{21}	C_{211}	C_{212}
FR	(0.6, 1, 1)	(0.7, 1, 1)	(0.7, 1, 1)	(0.7, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)
A_2	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
A_3	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
	C_{22}	C_{221}	C_{222}	C_{223}
FR	(0.7, 1, 1)	(0.7, 1, 1)	(0.6, 1, 1)	(0.7, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)
A_2	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.5, 0.6, 0.7)	(0.7, 0.8, 0.9)
A_3	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
	C_{23}	C_{231}	C_{232}	C_{24}
FR	(0.6, 1, 1)	(0.6, 1, 1)	(0.6, 1, 1)	(0.8, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
A_2	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)
A_3	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
FR	C_{25}	C_{26}	C_{27}	
A_1	(0.6, 1, 1)	(0.6, 1, 1)	(0.6, 1, 1)	
A_2	(0.7, 0.8, 0.9)	(0.5, 0.6, 0.7)	(0.5, 0.6, 0.7)	
A_3	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	
	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	
	C_3	C_{31}	C_{32}	C_{33}
FR	(0.6, 1, 1)	(0.7, 1, 1)	(0.6, 1, 1)	(0.6, 1, 1)
A_1	(0.5, 0.6, 0.7)	(0.7, 0.8, 0.9)	(0.5, 0.6, 0.7)	(0.8, 0.9, 1)
A_2	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.5, 0.6, 0.7)
A_3	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.7, 0.8, 0.9)
		C_{34}	C_{35}	C_{36}
FR		(0.4, 1, 1)	(0.5, 1, 1)	(0.7, 1, 1)
A_1		(0.3, 0.4, 0.5)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)
A_2		(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
A_3		(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
	C_{361}	C_{362}	C_{363}	C_{364}
FR	(0.5, 1, 1)	(0.2, 1, 1)	(0.7, 1, 1)	(0.8, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)
A_2	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.8, 0.9, 1)
A_3	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)

Applying Equations 4.15, 4.16, and 4.17 on the data in Table 4.12 and Table 4.14, we obtain weighted information contents, i.e. Expert X evaluation on the partner alternatives (Table 4.15).

Table 4.15 Partner scores of Expert X

	I_{c1}	I_{c2}	I_{c3}							
A_1	0.174	0.292	0.834							
A_2	0.017	0.131	0.373							
A_3	0.366	0.059	0.493							
	I_{c11}	I_{c12}	I_{c13}	I_{c14}	I_{c15}	I_{c16}				
A_1	0.397	0.120	0.330	0.409	0.833	0.350	2.438			
A_2	0.007	0.018	0.006	0.409	1.754	0.039	2.233			
A_3	0.126	0.068	0.024	0.862	0.406	0.166	1.651			
	I_{c21}	I_{c22}	I_{c23}	I_{c24}	I_{c25}	I_{c26}	I_{c27}			
A_1	0.220	0.220	0.033	0.190	0.033	0.244	0.882	1.822		
A_2	0.220	0.220	0.033	0.190	0.033	0.033	0.351	1.080		
A_3	0.220	0.220	0.033	0.190	0.097	0.033	0.351	1.144		
	I_{c31}	I_{c32}	I_{c33}	I_{c34}	I_{c35}	I_{c36}				
A_1	0.214	0.237	0.021	0.272	0.768	0.214	1.727			
A_2	0.214	0.007	0.712	0.013	0.056	0.214	1.216			
A_3	0.643	0.237	0.096	0.031	0.056	0.214	1.277			
	I_{c151}	I_{c152}	I_{c153}	I_{c154}						
A_1	0.145	0.730	0.176	0.920	1.972					
A_2	1.080	0.730	1.008	0.213	3.030					
A_3	0.145	0.034	0.176	0.920	1.275					
	I_{c211}	I_{c212}		I_{c221}	I_{c222}	I_{c223}		I_{c231}	I_{c232}	
A_1	1.000	0.128	1.128	0.600	0.089	1.800	2.489	0.224	0.224	0.447
A_2	0.333	0.667	1.000	0.200	0.664	0.600	1.464	0.224	0.661	0.885
A_3	0.333	0.667	1.000	0.200	0.089	0.600	0.889	0.224	0.224	0.447
	I_{c361}	I_{c362}	I_{c363}	I_{c364}						
A_1	0.044	0.695	0.333	0.195	1.267					
A_2	0.044	0.016	0.064	0.195	0.319					
A_3	0.044	0.122	0.333	0.862	1.360					
	Level 1 scores	*Level 2 scores*	*Level 3 scores*							
A_1	1.300	1.858	1.284							
A_2	0.521	1.225	1.034							
A_3	0.917	1.226	0.958							

Final evaluations of Expert X depict ICs as well as final selection. Expert X clearly favours collaboration capabilities of the partner. Sub-criteria of collaboration-focused dimension are on the other hand approximately equivalent, with trust being the most important criteria, with personal trust being the more important sub-criterion. Compatibility and collaboration experience have also slightly higher importance than the rest of the criteria, of which IT and communication compatibility is favoured over the others. Development focused criteria is considered as of second importance. Technical expertise, development experience, and innovative capability are considered first. Expected development time is the most important project metric.

Partner focused criteria are not considered as important as the others. Experience, of which business experience is the most important, appears to be a dominant criterion. It is interesting to observe that managerial experience, though not neglected, is not as much important as the other three.

Alternative evaluation presents an interesting analysis. When only the first level criteria are considered, A_2 is clearly the most suitable alternative. As no alternative is eliminated at the first level, sub-criteria are considered as well. A_2 is still the most suitable alternative; however it can be observed that A_3 possesses the minimum information content on partner focused criteria. The low importance of this dimension fails to capture this characteristic of A_3. However, the ranking changes once all levels of hierarchy are considered. A_2 fails dramatically on *experience* sub-criteria, while it is not the best responder to compatibility and complementarity sub-criteria. Given the importance of collaboration focused criteria, A_3 comes out as the most suitable alternative when all hierarchical levels are considered.

4.4.2 Expert Y Evaluation and Obtained Results

The expert is in search of a reliable partner for a series of projects that requires collaboration. The alternatives are selected from acquaintances of the expert. Pairwise comparisons of Expert Y on the criteria are supplied in Table 4.16.

Table 4.16 Pairwise criteria comparisons by Expert Y

	C_1	C_2	C_3
C_1	1	$1/\tilde{3}$	$1/\tilde{3}$
C_2	$\tilde{3}$	1	$\tilde{1}$
C_3	$\tilde{3}$		1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$1/\tilde{3}$	$\tilde{1}$
C_{12}	$1/\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$
C_{13}	$1/\tilde{3}$		1	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$
C_{14}	$1/\tilde{3}$			1	$1/\tilde{3}$	$1/\tilde{3}$
C_{15}	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	1	$\tilde{3}$
C_{16}		$\tilde{3}$	$\tilde{3}$	$\tilde{3}$	$1/\tilde{3}$	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	$1/\tilde{3}$	$1/\tilde{3}$	$\tilde{1}$
C_{152}	$\tilde{3}$	1	$\tilde{1}$	$\tilde{3}$
C_{153}	$\tilde{3}$		1	$\tilde{3}$
C_{154}		$1/\tilde{3}$	$1/\tilde{3}$	1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$
C_{22}		1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$
C_{23}			1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$
C_{24}	$1/\tilde{3}$			1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$
C_{25}					1	$\tilde{1}$	$\tilde{1}$
C_{26}						1	$\tilde{1}$
C_{27}	$1/\tilde{3}$						1

	C_{211}	C_{212}
C_{211}	1	$\tilde{1}$
C_{212}		1

	C_{221}	C_{222}	C_{223}
C_{221}	1	$1/\tilde{3}$	$\tilde{1}$
C_{222}	$\tilde{3}$	1	$\tilde{3}$
C_{223}		$1/\tilde{3}$	1

	C_{231}	C_{232}
C_{231}	1	$\tilde{1}$
C_{232}		1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	$\tilde{1}$	$\tilde{1}$	$1/\tilde{3}$	$1/\tilde{3}$	$\tilde{3}$
C_{32}		1	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{3}$	$\tilde{3}$
C_{33}		$\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$
C_{34}	$\tilde{3}$	$\tilde{3}$		1	$\tilde{1}$	$\tilde{5}$
C_{35}	$\tilde{3}$	$\tilde{3}$			1	$\tilde{5}$
C_{36}	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{5}$	$1/\tilde{5}$	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	$1/\tilde{3}$	$1/\tilde{3}$	$1/\tilde{3}$
C_{362}	$\tilde{3}$	1	$\tilde{1}$	$\tilde{1}$
C_{363}	$\tilde{3}$		1	$\tilde{1}$
C_{364}	$\tilde{3}$			1

Similar to the previous case, firstly the pairwise comparisons are translated into TFNs according to the scale presented in Table 4.4 (shown in Table 4.17). Then α-cut operation in Equation 4.4 is applied to fuzzy judgments and Table 4.18 is obtained as a result. Then Equation 4.6 is applied for the final judgment matrix (Table 4.19).

Table 4.17 Fuzzified pairwise judgments of Expert Y

	C_1	C_2	C_3
C_1	1	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
C_2	(2, 3, 4)	1	(1, 1, 2)
C_3	(2, 3, 4)	(1/2, 1, 1)	1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(1/4, 1/3, 1/2)	(1, 1, 2)
C_{12}	(1/4, 1/3, 1/2)	1	(1, 1, 2)	(1, 1, 2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
C_{13}	(1/4, 1/3, 1/2)	(1/2, 1, 1)	1	(1, 1, 2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
C_{14}	(1/4, 1/3, 1/2)	(1/2, 1, 1)	(1/2, 1, 1)	1	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
C_{15}	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	1	(2, 3, 4)
C_{16}	(1/2, 1, 1)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(1/4, 1/3, 1/2)	1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	(1, 1, 2)	(1, 1, 2)	(2, 3, 4)	(1, 1, 2)	(1, 1, 2)	(2, 3, 4)
C_{22}	(1/2, 1, 1)	1	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)
C_{23}	(1/2, 1, 1)	(1/2, 1, 1)	1	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)
C_{24}	(1/4, 1/3, 1/2)	(1/2, 1, 1)	(1/2, 1, 1)	1	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)
C_{25}	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	1	(1, 1, 2)	(1, 1, 2)
C_{26}	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	1	(1, 1, 2)
C_{27}	(1/4, 1/3, 1/2)	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	(1/2, 1, 1)	1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	(1, 1, 2)	(1, 1, 2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(2, 3, 4)
C_{32}	(1/2, 1, 1)	1	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(2, 3, 4)
C_{33}	(1/2, 1, 1)	(2, 3, 4)	1	(1, 1, 2)	(1, 1, 2)	(1, 1, 2)
C_{34}	(2, 3, 4)	(2, 3, 4)	(1/2, 1, 1)	1	(1, 1, 2)	(4, 5, 6)
C_{35}	(2, 3, 4)	(2, 3, 4)	(1/2, 1, 1)	(1/2, 1, 1)	1	(4, 5, 6)
C_{36}	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1, 1, 2)
C_{152}	(2, 3, 4)	1	(1, 1, 2)	(2, 3, 4)
C_{153}	(2, 3, 4)	(1/2, 1, 1)	1	(2, 3, 4)
C_{154}	(1/2, 1, 1)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	1

	C_{211}	C_{212}
C_{211}	1	(1, 1, 2)
C_{212}	(1/2, 1, 1)	1

	C_{231}	C_{232}
C_{231}	1	(1, 1, 2)
C_{232}	(1/2, 1, 1)	1

	C_{221}	C_{222}	C_{223}
C_{221}	1	(1/4, 1/3, 1/2)	(1, 1, 2)
C_{222}	(2, 3, 4)	1	(2, 3, 4)
C_{223}	(1/2, 1, 1)	(1/4, 1/3, 1/2)	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)
C_{362}	(2, 3, 4)	1	(1, 1, 2)	(1, 1, 2)
C_{363}	(2, 3, 4)	(1/2, 1, 1)	1	(1, 1, 2)
C_{364}	(2, 3, 4)	(1/2, 1, 1)	(1/2, 1, 1)	1

Table 4.18 α-cut on pairwise judgments of Expert Y

	C_1	C_2	C_3
C_1	1	(7/24, 5/12)	(7/24, 5/12)
C_2	(5/2, 7/2)	1	(1, 3/2)
C_3	(5/2, 7/2)	(3/4, 1)	1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(7/24, 5/12)	(1, 3/2)
C_{12}	(7/24, 5/12)	1	(1, 3/2)	(1, 3/2)	(7/24, 5/12)	(7/24, 5/12)
C_{13}	(7/24, 5/12)	(3/4, 1)	1	(1, 3/2)	(7/24, 5/12)	(7/24, 5/12)
C_{14}	(7/24, 5/12)	(3/4, 1)	(3/4, 1)	1	(7/24, 5/12)	(7/24, 5/12)
C_{15}	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	1	(5/2, 7/2)
C_{16}	(3/4, 1)	(5/2, 7/2)	(5/2, 7/2)	(5/2, 7/2)	(7/24, 5/12)	1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	(1, 3/2)	(1, 3/2)	(5/2, 7/2)	(1, 3/2)	(1, 3/2)	(5/2, 7/2)
C_{22}	(3/4, 1)	1	(1, 3/2)	(1, 3/2)	(1, 3/2)	(1, 3/2)	(1, 3/2)
C_{23}	(3/4, 1)	(3/4, 1)	1	(1, 3/2)	(1, 3/2)	(1, 3/2)	(1, 3/2)
C_{24}	(7/24, 5/12)	(3/4, 1)	(3/4, 1)	1	(1, 3/2)	(1, 3/2)	(1, 3/2)
C_{25}	(3/4, 1)	(3/4, 1)	(3/4, 1)	(3/4, 1)	1	(1, 3/2)	(1, 3/2)
C_{26}	(3/4, 1)	(3/4, 1)	(3/4, 1)	(3/4, 1)	(3/4, 1)	1	(1, 3/2)
C_{27}	(7/24, 5/12)	(3/4, 1)	(3/4, 1)	(3/4, 1)	(3/4, 1)	(3/4, 1)	1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	(1, 3/2)	(1, 3/2)	(7/24, 5/12)	(7/24, 5/12)	(5/2, 7/2)
C_{32}	(3/4, 1)	1	(7/24, 5/12)	(7/24, 5/12)	(7/24, 5/12)	(5/2, 7/2)
C_{33}	(3/4, 1)	(5/2, 7/2)	1	(1, 3/2)	(1, 3/2)	(1, 3/2)
C_{34}	(5/2, 7/2)	(5/2, 7/2)	(3/4, 1)	1	(1, 3/2)	(9/2, 11/2)
C_{35}	(5/2, 7/2)	(5/2, 7/2)	(3/4, 1)	(3/4, 1)	1	(9/2, 11/2)
C_{36}	(7/24, 5/12)	(7/24, 5/12)	(7/24, 5/12)	(11/60, 9/40)	(11/60, 9/40)	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	(7/24, 5/12)	(7/24, 5/12)	(1, 3/2)
C_{152}	(5/2, 7/2)	1	(1, 3/2)	(5/2, 7/2)
C_{153}	(5/2, 7/2)	(3/4, 1)	1	(5/2, 7/2)
C_{154}	(3/4, 1)	(7/24, 5/12)	(7/24, 5/12)	1

	C_{211}	C_{212}
C_{211}	1	(1, 3/2)
C_{212}	(3/4, 1)	1

	C_{231}	C_{232}
C_{231}	1	(1, 3/2)
C_{232}	(3/4, 1)	1

	C_{221}	C_{222}	C_{223}
C_{221}	1	(7/24, 5/12)	(1, 3/2)
C_{222}	(5/2, 7/2)	1	(5/2, 7/2)
C_{223}	(3/4, 1)	(7/24, 5/12)	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	(7/24, 5/12)	(7/24, 5/12)	(7/24, 5/12)
C_{362}	(5/2, 7/2)	1	(1, 3/2)	(1, 3/2)
C_{363}	(5/2, 7/2)	(3/4, 1)	1	(1, 3/2)
C_{364}	(5/2, 7/2)	(3/4, 1)	(3/4, 1)	1

Table 4.19 Final judgment matrix of Expert Y

	C_1	C_2	C_3
C_1	1	0.35	0.35
C_2	6	1	1.25
C_3	6	0.88	1

	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	1	6	6	6	0.35	1.25
C_{12}	0.35	1	1.25	1.25	0.35	0.35
C_{13}	0.35	0.88	1	1.25	0.35	0.35
C_{14}	0.35	0.88	0.88	1	0.35	0.35
C_{15}	6	6	6	6	1	6
C_{16}	0.88	6	6	6	0.35	1

	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	1	0.35	0.35	1.25
C_{152}	6	1	1.25	6
C_{153}	6	0.88	1	6
C_{154}	0.88	0.35	0.35	1

	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	1	1.25	1.25	6	1.25	1.25	6
C_{22}	0.88	1	1.25	1.25	1.25	1.25	1.25
C_{23}	0.88	0.88	1	1.25	1.25	1.25	1.25
C_{24}	0.35	0.88	0.88	1	1.25	1.25	1.25
C_{25}	0.88	0.88	0.88	0.88	1	1.25	1.25
C_{26}	0.88	0.88	0.88	0.88	0.88	1	1.25
C_{27}	0.35	0.88	0.88	0.88	0.88	0.88	1

	C_{211}	C_{212}
C_{211}	1	1.25
C_{212}	0.88	1

	C_{221}	C_{222}	C_{223}
C_{221}	1	0.35	1.25
C_{222}	6	1	6
C_{223}	0.88	0.35	1

	C_{231}	C_{232}
C_{231}	1	1.25
C_{232}	0.88	1

	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	1	1.25	1.25	0.35	0.35	6
C_{32}	0.88	1	0.35	0.35	0.35	6
C_{33}	0.88	6	1	1.25	1.25	1.25
C_{34}	6	6	0.88	1	1.25	10
C_{35}	6	6	0.88	0.88	1	10
C_{36}	0.35	0.35	0.35	0.20	0.20	1

	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	1	0.35	0.35	0.35
C_{362}	6	1	1.25	1.25
C_{363}	6	0.88	1	1.25
C_{364}	6	0.88	0.88	1

Table 4.20 Eigen values for Expert Y judgments

CR: 0.00	C_1	C_2	C_3
C_1	0.077	0.157	0.135
C_2	0.462	0.448	0.481
C_3	0.462	0.395	0.385

CR: 0.08	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{11}	0.112	0.289	0.284	0.279	0.127	0.134
C_{12}	0.039	0.048	0.059	0.058	0.127	0.038
C_{13}	0.039	0.042	0.047	0.058	0.127	0.038
C_{14}	0.039	0.042	0.042	0.047	0.127	0.038
C_{15}	0.672	0.289	0.284	0.279	0.364	0.645
C_{16}	0.099	0.289	0.284	0.279	0.127	0.108

CR: 0.00	C_{151}	C_{152}	C_{153}	C_{154}
C_{151}	0.072	0.136	0.119	0.088
C_{152}	0.432	0.388	0.424	0.421
C_{153}	0.432	0.341	0.339	0.421
C_{154}	0.063	0.136	0.119	0.070

CR: 0.05	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}
C_{21}	0.192	0.188	0.178	0.494	0.161	0.154	0.453
C_{22}	0.169	0.150	0.178	0.103	0.161	0.154	0.094
C_{23}	0.169	0.132	0.142	0.103	0.161	0.154	0.094
C_{24}	0.067	0.132	0.125	0.082	0.161	0.154	0.094
C_{25}	0.169	0.132	0.125	0.072	0.129	0.154	0.094
C_{26}	0.169	0.132	0.125	0.072	0.113	0.123	0.094
C_{27}	0.067	0.132	0.125	0.072	0.113	0.108	0.075

CR: 0.00	C_{211}	C_{212}
C_{211}	0.532	0.556
C_{212}	0.468	0.444

CR: 0.00	C_{221}	C_{222}	C_{223}
C_{221}	0.127	0.206	0.152
C_{222}	0.761	0.588	0.727
C_{223}	0.112	0.206	0.121

CR: 0.00	C_{231}	C_{232}
C_{231}	0.532	0.556
C_{232}	0.468	0.444

CR: 0.04	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}
C_{31}	0.066	0.061	0.265	0.087	0.080	0.175
C_{32}	0.058	0.049	0.074	0.087	0.080	0.175
C_{33}	0.058	0.291	0.212	0.310	0.284	0.036
C_{34}	0.397	0.291	0.187	0.248	0.284	0.292
C_{35}	0.397	0.291	0.187	0.218	0.227	0.292
C_{36}	0.023	0.017	0.074	0.050	0.045	0.029

CR: 0.00	C_{361}	C_{362}	C_{363}	C_{364}
C_{361}	0.053	0.113	0.101	0.091
C_{362}	0.316	0.322	0.359	0.325
C_{363}	0.316	0.283	0.287	0.325
C_{364}	0.316	0.283	0.253	0.260

Table 4.21 Criteria weights of Expert Y

	C_1	C_2	C_3						
w	0.123	0.464	0.414						
	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}			
w	0.204	0.062	0.059	0.056	0.422	0.198			
	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_{27}		
w	0.260	0.144	0.137	0.117	0.125	0.118	0.099		
	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}			
w	0.122	0.087	0.199	0.283	0.269	0.040			
	C_{151}	C_{152}	C_{153}	C_{154}					
w	0.104	0.416	0.383	0.097					
	C_{211}	C_{212}		C_{221}	C_{222}	C_{223}		C_{231}	C_{232}
w	0.544	0.456		0.161	0.692	0.146		0.544	0.456
	C_{361}	C_{362}	C_{363}	C_{364}					
w	0.089	0.330	0.303	0.278					

Table 4.20 displays the eigen vectors and consistency ratios calculated by Equations 4.2 and 4.9, respectively. Criteria weights obtained by the eigen vectors are displayed in Table 4.21. Pairwise comparison matrices are all consistent, six out of nine of which have 0.00 consistency ratio. Highest consistency is observed in C_1 matrix, which is an acceptable consistency ratio of 0.08.

Table 4.22 System and design range evaluation of Expert Y

	C_1	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{151}	C_{152}	C_{153}	C_{154}	C_{16}				
FR	LFG	LG	LML	LL	LML	LM	LN	LN	LN	LM	LM				
A_1	FG	G	VG	FG	G	G	G	G	G	G	FG				
A_2	FG	G	G	FG	G	ML	ML	ML	ML	ML	FG				
A_3	FG	G	G	VL	G	ML	FL	ML	ML	ML	FG				
	C_2	C_{21}	C_{211}	C_{212}	C_{22}	C_{221}	C_{222}	C_{223}	C_{23}	C_{231}	C_{232}	C_{24}	C_{25}	C_{26}	C_{27}
FR	LG	LVG	LVG	LVG	LG	LG	LG	LG	LG	LFG	LFG	LVG	LG	LG	LFL
A_1	G	VG	VG	G	G	G	G	G	G	VG	FG	G	G	G	G
A_2	G	G	VG	VG	FG	FG	VG	G	G	FG	G	VG	VG	G	G
A_3	G	G	VG	VG	VG	VG	VG	VG	FG	MG	MG	VG	VG	VG	M
	C_3	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{36}	C_{361}	C_{362}	C_{363}	C_{364}				
FR	LG	LG	LMG	LG	LMG	LVG	LML	LFL	LM	LFG	LG				
A_1	VG	G	M	VG	G	VG	G	L	G	G	VG				
A_2	VG	VG	M	VG	G	VG	G	L	G	G	VG				
A_3	VG	FG	M	VG	G	VG	G	L	G	G	VG				

Expert Y clearly favours collaboration focused criteria over the partner and development focused criteria. This is clearly the result of the fact that partner alternatives are predefined; whatever their partner focused criteria scores may be. Trust appears to be the most important issue for Expert Y, without substantially preferring technical over personal trust. Collaboration experience comes out as the least important collaboration focused criteria, along with willingness to share information. The expert also attributes much importance on cultural compatibility, whereas managerial and IT & communication compatibility are not much emphasized. On the other hand, development focused criteria are dominated by innovative capability and R&D resources, followed by the development experience. Interestingly, the expert attributes almost no importance to project expectations. Experience is incontestably the most important criteria of partner focused attributes, though of lower importance. Market and sector experiences are twice as much important than business and management experience.

Expert Y judgments on system and design ranges are displayed in Table 4.22. These evaluations are then fuzzified (Table 4.23) according to the scale presented in Table 4.6. Highest requirements are set on collaboration focused criteria compatibility and willingness to share information, and also innovative capability. Applying Equations 4.15, 4.16, and 4.17 on the data in Table 4.21 and Table 4.23, we obtain weighted information contents, i.e. Expert Y evaluation on the partner alternatives (Table 4.24).

Table 4.23 Fuzzified evaluations of Expert Y

	C_1	C_{11}	C_{12}	C_{13}
FR	(0.6, 1, 1)	(0.7, 1, 1)	(0.3, 1, 1)	(0., 1, 1)
A_1	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)
A_2	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)
A_3	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0, 0.1, 1, 0.2]
		C_{14}	C_{15}	C_{16}
FR		(1, 0.3, 1, 1)	(0.4, 1, 1)	(0.4, 1, 1)
A_1		(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)
A_2		(0.7, 0.8, 0.9)	(0.3, 0.4, 0.5)	(0.6, 0.7, 0.8)
A_3		(0.7, 0.8, 0.9)	(0.3, 0.4, 0.5)	(0.6, 0.7, 0.8)
	C_{151}	C_{152}	C_{153}	C_{154}
FR	(0, 1, 1)	(0, 1, 1)	(0, 1, 1)	(0.4, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
A_2	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)
A_3	(0.2, 0.3, 0.4)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)	(0.3, 0.4, 0.5)
	C_2	C_{21}	C_{211}	C_{212}
FR	(0.7, 1, 1)	(0.8, 1, 1)	(0.8, 1, 1)	(0.8, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)
A_2	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.8, 0.9, 1)
A_3	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.8, 0.9, 1)
	C_{22}	C_{221}	C_{222}	C_{223}
FR	(0.7, 1, 1)	(0.7, 1, 1)	(0.7, 1, 1)	(0.7, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)
A_2	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)
A_3	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)
	C_{23}	C_{231}	C_{232}	C_{24}
FR	(0.7, 1, 1)	(0.6, 1, 1)	(0.6, 1, 1)	(0.8, 1, 1)
A_1	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)
A_2	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)
A_3	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0.5, 0.6, 0.7)	(0.8, 0.9, 1)
	C_{25}	C_{26}	C_{27}	
FR	(0.7, 1, 1)	(0.7, 1, 1)	(0.2, 1, 1)	
A_1	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	
A_2	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	
A_3	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.4, 0.5, 0.6)	
	C_3	C_{31}	C_{32}	C_{33}
FR	(0.7, 1, 1)	(0.7, 1, 1)	(0.5, 1, 1)	(0.7, 1, 1)
A_1	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.8, 0.9, 1)
A_2	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.4, 0.5, 0.6)	(0.8, 0.9, 1)
A_3	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.4, 0.5, 0.6)	(0.8, 0.9, 1)
		C_{34}	C_{35}	C_{36}
FR		(0.5, 1, 1)	(0.8, 1, 1)	(0.3, 1, 1)
A_1		(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)
A_2		(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)
A_3		(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)
	C_{361}	C_{362}	C_{363}	C_{364}
FR	(0.2, 1, 1)	(0.4, 1, 1)	(0.6, 1, 1)	(0.7, 1, 1)
A_1	(0., 1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)
A_2	(0., 1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)
A_3	(0., 1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)

Table 4.24 Partner scores of Expert Y

	I_{c1}	I_{c2}	I_{c3}							
A_1	0.185	0.430	0.083							
A_2	0.185	0.430	0.083							
A_3	0.185	0.430	0.083							
	I_{c11}	I_{c12}	I_{c13}	I_{c14}	I_{c15}	I_{c16}				
A_1	0.201	0.002	0.014	0.010	0.062	0.086	0.376			
A_2	0.201	0.010	0.014	0.010	1.348	0.086	1.670			
A_3	0.201	0.010	0.350	0.010	1.348	0.086	2.007			
	I_{c21}	I_{c22}	I_{c23}	I_{c24}	I_{c25}	I_{c26}	I_{c27}			
A_1	0.118	0.139	0.139	0.315	0.139	0.139	0.012	0.999		
A_2	0.522	0.416	0.139	0.071	0.027	0.139	0.012	1.325		
A_3	0.522	0.027	0.416	0.071	0.027	0.027	0.089	1.178		
	I_{c31}	I_{c32}	I_{c33}	I_{c34}	I_{c35}	I_{c36}				
A_1	0.122	0.352	0.040	0.069	0.153	0.006	0.742			
A_2	0.024	0.352	0.040	0.069	0.153	0.006	0.643			
A_3	0.366	0.352	0.040	0.069	0.153	0.006	0.986			
	I_{c151}	I_{c152}	I_{c153}	I_{c154}						
A_1	0.007	0.022	0.022	0.022	0.074					
A_2	0.082	0.245	0.245	0.476	1.046					
A_3	0.123	0.245	0.245	0.476	1.088					
	I_{c211}	I_{c212}		I_{c221}	I_{c222}	I_{c223}		I_{c231}	I_{c232}	
A_1	0.292	1.292	1.585	0.200	0.600	0.200	1.000	0.050	0.661	0.711
A_2	0.292	0.292	0.585	0.600	0.116	0.200	0.916	0.661	0.224	0.885
A_3	0.292	0.292	0.585	0.039	0.116	0.039	0.193	1.661	1.661	3.322
	I_{c361}	I_{c362}	I_{c363}	I_{c364}						
A_1	0.417	0.053	0.134	0.058	0.662					
A_2	0.417	0.053	0.134	0.058	0.662					
A_3	0.417	0.053	0.134	0.058	0.662					
	Level 1 *scores*	*Level* 2 *scores*	*Level* 3 *scores*							
A_1	0.700	0.800	0.961							
A_2	0.633	1.082	0.664							
A_3	0.620	1.214	0.725							

Final evaluation analysis presents remarkable variations on each level. No elimination of alternative occurs on a higher level, therefore the Fuzzy AD analysis is conducted at each level of the hierarchy, and evaluation at each level presents a different ranking of alternatives.

First level evaluation, where only functional requirements on the three main dimensions are considered, results in the equality of all three alternatives. It is an ordinary outcome, given that all three alternatives respond exactly the same to the first level requirements. A further analysis is conducted on the second level. At this stage, it is observed that A_1 is the most suitable alternative. A_2 is the most suitable alternative with only respect to the development focused criteria. However, as A_1 scores better on the two other criteria set, especially when collaboration focused criteria weight enables A_1 to be the most suitable alternative. However, once all sub-criteria are considered for the alternative evaluation, A_2 comes out as the most suitable alternative overall. This is due not to the A_2 performance, but rather to A_3 performance on lower levels of criteria such as trust and compatibility. A_3 is able to compete with A_2 on the third level, whereas A_1 fails to score well on significant criteria such as trust, compatibility, flexibility, and willingness to share information. Consequently, A_2 comes out as the most suitable alternative as a long term partner for Expert Y.

4.4.3 Discussions

Level 1 scores consider the information content solely at the first hierarchical level. Level 2 scores consider experts' evaluation of the second level criteria. Level 3 scores include the sub-criteria in the assessment. On both cases, further analysis results in a different ranking of alternatives, which confirms that a thorough evaluation leads to a more valid outcome. Therefore, it is important to present a hierarchical structure for partner evaluation.

In the first case, ranking on the first and second levels designate A_2 as the most suitable alternative. However, the final ranking, which considers all criteria on three levels, shows that A_3 is the best respondent to all requirements. In the second case, all three alternatives score the same. However, a more detailed evaluation on second level favours A_1, while A_2 scores the best overall.

The evaluation of Expert X is collaboration focused given his innovative character. Partners' own attributes and developmental capabilities are not as important as their collaborative abilities. He is looking for a partner with willingness to share information, and also he’s expecting high quality from the project. Criteria weight and requirement differs especially on willingness to share information. While its weight is not as high, the expert requires learning from the specific project and therefore seeks openness in his potential partner.

The weights according to Expert Y are equal for collaboration focused and development focused criteria. Like Expert X, Expert Y does not attribute as much importance to a partner’s own features as to the other two dimensions. On the other hand, Expert Y is in pursuit of a long-term partnership and the requirements are higher on the collaboration focused criteria. This outcome expresses his willingness to find a compatible partner on a corporate level, rather than a short term partner with developmental credentials. The compatibility aspect is also displayed in the high importance of cultural compatibility criteria. Expert Y sets a high requirement on innovative capability, given that the projects are not predefined, and he intends participation in innovative ventures.

The experts’ approach differs on trust criteria. It has almost the same weight; however it is the most important criteria for Expert Y while it is not as important for Expert X. Both experts do not favour managerial experience, which mostly results from the fact that both experts are accustomed to *lead* projects and have managerial experience themselves. Collaboration experience is highly important for Expert X, while Expert Y does not emphasize this feature. However, they both agree on the importance of innovative capability. It can be stated that innovative features of a partner makes him more appropriate whether or not he has the necessary experience in collaborative activities. Weights on R&D resources differ as well. Given that Expert X has a resourceful company, he believes he can cover the lack of R&D resources of the partner, while Expert Y values this aspect more as he acts as a consultant.

Both experts were satisfied with the results. Their evaluations and outcomes were provided, and analysis was explained. They agreed with the outcome and decided to proceed according to the analysis.

It is obvious that the presented hierarchy provides a thorough partner evaluation and selection scheme for CPD practitioners. Decision makers have the freedom to define their set of criteria weights and functional requirements as well as their linguistic assessments of potential partners. The outcome varies according to the decision maker's strategic inclination and managerial approach. Fuzzy AD allows decision makers to express their expectations from potential CPD partners and examine how well these potential partners respond to their expectations. Fuzzy AHP sets a common criteria weight set for all project types while Fuzzy AD is employed to evaluate each alternatives in their own context. The presented methodology offers a dynamic partner evaluation scheme for different types of partnerships. Criteria sets cover all aspects of the partner evaluation process, identified in the literature, and Fuzzy AD provides a tool to alternate requirements according to characteristic of each project type. The methodology handles the partner evaluation process on a scientific basis and provides an analytical tool for CPD practitioners at a critical phase of the collaboration process.

4.5 SUMMARY

This chapter introduced a three dimensional partner evaluation criteria set and proposed a fuzzy MCDM methodology, combining Fuzzy AHP and Fuzzy AD, in order to select the most suitable partner for a CPD project. The three dimensional criteria set covers the partner evaluation process from all perspectives. Partner focused criteria consider the individual attributes of the potential partner; whereas collaboration focused criteria consider the interaction between the focal firm and the partner candidate, as well as the ability of the partner candidate to collaborate. Finally, development focused criteria consider the capability of the potential partner in the product/software development area.

Fuzzy MCDM techniques, namely Fuzzy AHP and Fuzzy AD were combined to evaluate this three-dimensional criteria set. The proposed methodology helps decision makers to consider criteria from two perspectives: defined criteria weights reflect the approach of the decision maker towards the importance of the criteria in general. On the other hand, design range of Fuzzy AD provides a project based evaluation on the criteria. Consequently, decision makers can express their project-dependent and project-independent opinion separately.

The case studies proved that the methodology is efficient in the identification of the adequate partner and the criteria set considers all aspects of the CPD partnership. It is aimed to expand the methodology and adapt it to group decision making, in order to take into account the judgments of all the main CPD actors of the focal firm and reflect the collective opinion about criteria weights and design ranges. It is also foreseen to perform a comparison between individual and group decisions.

5 MODELLING COLLABORATION FORMATION WITH GAME THEORY

With the increasing market competition and globalization, as well as high product differentiation, collaboration between firms becomes more and more frequent to share PD costs and to significantly reduce time-to-market. The incentive to collaborate is not limited with the aim of enhancing PD project and the implication of collaboration goes beyond the revenue sharing [**5**]. It includes the creation and sharing of knowledge about the markets and technologies, setting the market standards, the sharing of facilities, etc [**305**]. Innovation also is a part of the CPD projects.

The benefits of the collaboration efforts can be exposed only by analyzing the conditions that enabled the collaboration formation. Negotiating the collaboration terms holds a strategic importance, and therefore, the strengths and weaknesses of the parties need to be meticulously investigated before establishing the contract. In this respect, a decision aid mechanism is required to choose the level of investment, knowledge, trust, development cost and innovation revenue, as well as the level of profit sharing and collaboration.

In this study, we develop a collaboration formation model and analyze it for various scenarios. The following principles are adopted while drafting the model. Not only monetary terms but also other aspects of the collaboration should be included, given that the collaborating firms seek to learn and innovate by joining knowledge and technology, cultivating trust and assuring coordination. It should assist in identifying how collaborative parties should negotiate and interact with each other to improve the total process effectiveness. Accordingly, our mathematical model is based on the conceptual CPD model introduced in [**166**] and integrates trust, coordination, co-learning, and co-innovation concepts.

Our model reflects a negotiation environment where each party benefits from collaborating, i.e., a win-win situation. The win-win situation is required to balance the contribution of each factor from each party by defining the level of sharing. Game theory is a known tool to model the conflict and/or collaboration between individuals and/or institutions, and its principles are applied in our study to analyze collaboration efforts in PD. In sum, our aim is to provide insight for the product developers on how to negotiate and collaborate under particular conditions by proving the equilibrium solutions.

This chapter is organized as follows: the next section introduces briefly the game theory applications in the collaboration literature and Nash Bargaining theory. The following section describes our mathematical model for CPD. The numerical analysis section includes several scenarios to illustrate the details of the model and to make inferences. Some remarks and research perspectives are given in the conclusion section.

5.1 LITERATURE REVIEW

Forming groups and collaborations is an essential problem in game theory [**305**]. Introduced by von Neumann and Morgenstern [**306**], game theory is an applied mathematics branch used in many domains such as economics, politics, management and organization, etc. Various applications of the game theory are used in the collaboration formation domain. The next section introduces game theory applications in collaboration formation domain.

5.1.1 Game Theory for Collaboration Formation

Early studies date back to the appearance of strategic ventures in 1990's. Parkhe [**307**] develops a model incorporating game theory and cost economics in order to analyze the formation, management and completion of strategic ventures. Larsson et al. [**308**] integrate game theory, strategic venture, institutional learning and collective action studies in order to observe the development, performance and longevity of strategic ventures.

There is also game theory literature on strategic partnerships in supply chain. Studies on the collaboration among supply chain actors [**309**], modelling the buyer-supplier relationships with cooperative/non cooperative games [**310**], and modelling of customer-supplier relationships with game theory [**311**] provide a research basis for partnership formation conditions in CPD.

Game theory literature also includes collaboration and competition of R&D projects. Martin [**312**] investigates the effects of R&D spill-overs and pre-innovation efforts on post-innovation success for non-cooperative R&D and R&D joint ventures. Amir et al. [**313**] analyze non-cooperative and cooperative R&D cartels where firms jointly invest in R&D. Lambertini et al. [**314**] focus on the spill-overs in R&D cooperation by analyzing information sharing and technological externalities. Wiethaus [**315**] analyze how innovation versus imitation affects the non-cooperative and cooperative incentives to invest in cost reduction. Cowan et al. [**192**] study the network formation where partnerships are defined as embedded cognitively (ability to integrate knowledge), relationally (experience with the partner), and structurally (partner's past experience with others). Erkal and Minehart [**316**] dynamically model the R&D process and investigate the knowledge sharing incentives through R&D stages. They state that the R&D behaviour of the firms is determined by the firms' willingness to compete and the intensity of the competition. Bourreau and Dogan [**317**] analyze the cost sharing versus reduced product differentiation in PD cooperation between competitors.

The mentioned studies generally cover issues of partnerships under a competition setting and analyze the cost sharing, knowledge sharing (instead of pooling) and pricing mechanisms. On the other hand, CPD literature is much more limited when considering game theory studies. Xiao et al. [**61**] model the relationships between engineering teams using the game theory principles in order to facilitate the collaborative decision making and they investigate the effect of design competence on design freedom. Phelan et al. [**318**] model the behaviour of an opportunistic partner using the prisoner's dilemma with an exit option. They conclude that the opportunistic partner should be given a second chance if high expectations are involved. Arend [**319**] also employs the prisoner's dilemma to observe two-firm collaboration and argues that while literature suggests that reputation is an enabler of the collaboration, the empirical evidence shows that collaboration diminishes as the reputation increases.

Cai and Kock [**67**] employ evolutionary game theory in order to determine whether or not companies should collaborate and how much they should collaborate. They use the prisoner's dilemma and Snowdrift game theory notions including social punishment, and they investigate e-collaboration game with discrete strategies. Another important game theory research is introduced by Bhaskaran and Krishnan [**5**], where they define three collaboration models (revenue sharing, investment sharing and innovation sharing) and they attain equilibrium points with the Nash Bargaining game under technology and timing uncertainties. In CSD literature, Hazzan and Dubinsky [**320**] investigate Extreme Programming in the prisoner's dilemma framework. They analyze SD methods not only by their benefits but also from a perspective of team members.

Amaldoss focuses on strategic partnerships in his game theory applications. Amaldoss et al. [**321**] investigate the concept of "coopetition" (collaboration to compete) and they observe the control of the resources attributed to collaboration. Non-cooperative non-zero sum games are used to model and analyze equilibrium in various types of partnerships. Amaldoss and Rapoport [**322**] analyze the effect of the number of networks competing to develop a product, the number of alternative technology platforms, and the market sensitivity to PD expenditures on the investments of partnering firms using game theory principles. Amaldoss and Staelin [**323**] employ a Game Theoretical model to investigate investment behaviours in cross-functional and same-function alliances.

Chen and Li [**324**] model team behaviour of multifunctional product design teams toward design alternatives using fuzzy sets theory. Strategic team paradigms derived from game theory principles as well as the responsibility and controllability notions are employed to ensure the team agreement. Takai [**325**] analyzes the collaboration in engineering design using game theory and defines collaboration conditions of two engineers in order to maximize product performance within the prisoner's dilemma framework.

Table 5.1 Game Theory literature on partnerships

Author(s)	***Topic***	***Focus***	***Approach***
Xiao et al. [**61**]	CPD	The effect of design competence on design freedom	Non-cooperative, cooperative, leader-follower
Phelan et al. [**318**]	CPD	Behaviour towards an opportunistic partner	Prisoner's dilemma
Arend [**319**]	CPD	Reputation in collaboration	Prisoner's dilemma
Cai and Kock [**67**]	CPD	Collaboration decision and the amount of collaboration.	Prisoner's dilemma, Snowdrift
Bhaskaran and Krishnan [**5**]	CPD	Revenue sharing, investment sharing and innovation sharing	Nash Bargaining
Chen and Li [**324**]	CPD	Team behaviour toward design alternatives	Non-cooperative, cooperative, leader-follower
Takai [**325**]	CPD	Collaboration in engineering design	Prisoner's dilemma
Samaddar and Kadiyala [**326**]	CPD	Knowledge creation	Stackelberg leader-follower
Ding and Huang [**327**]	CPD	Knowledge spill-over	Stackelberg leader-follower
Hazzan and Dubinsky [**320**]	CSD	Extreme programming	Prisoner's dilemma
Martin [**312**]	R&D partnership	Spill-overs and pre-innovation efforts effects on post-innovation success	Non-cooperative, cooperative
Amir et al. [**313**]	R&D partnership	R&D cartels	Non-cooperative, cooperative
Lambertini et al. [**314**]	R&D partnership	Spill-overs, information sharing and technological externalities	Cournot-Nash, Cournot-Stackelberg
Wiethaus [**315**]	R&D partnership	Innovation versus imitation, cost reduction	Non-cooperative versus cooperative
Cowan et al. [**192**]	R&D partnership	Knowledge sharing effect on innovation networks	Network formation
Erkal and Minehart [**316**]	R&D partnership	Knowledge sharing incentives	Markov Perfect Equilibria
Bourreau and Dogan [**317**]	R&D partnership	Cost sharing versus reduced product differentiation	Bertrand competition, Cournot competition
Nagajaran and Sosic [**309**]	Supply chain	Collaboration among supply chain actors	Nash Bargaining
Esmaeili et al.[**310**]	Supply chain	Buyer-supplier relation	Non-cooperative, cooperative
Laaksonen et al. [**311**]	Supply chain	Customer-supplier relation	Trust game
Amaldoss et al. [**321**]	Strategic partnerships	Coopetition (collaboration to compete)	Non-cooperative non-zero sum games
Amaldoss and Rapoport [**322**]	Strategic partnerships	Competing networks, technology platforms, market sensitivity	Nash equilibrium
Amaldoss and Staelin [**323**]	Strategic partnerships	Cross-functional versus same-function alliances	Nash equilibrium
Parkhe [**307**]	Strategic alliance	Formation, management and completion	Prisoner's dilemma, cost economics
Larsson et al. [**308**]	Strategic alliance	Development, performance and longevity	Game Theory, institutional learning and collective action

Samaddar and Kadiyala [**326**], focus on collaborations aiming to create knowledge and they investigate conditions to share resources and maintain collaboration. They analyze models with and without prior knowledge using Stackelberg leader-follower framework. Ding and Huang [**327**] employ this study and investigate the effect of knowledge spill-over using the same framework.

Table 5.1 displays a summary of game theory literature with a summary of the focus and the employed approach. The studies are ordered from the most relevant domain to the least significant. Even though these studies form a basis for CPD modelling, they do not fully cover the collaboration dimensions introduced in the previous section. With this respect, the need of a more elaborated CPD model is apparent to integrate these collaboration dimensions.

5.1.2 Nash Bargaining Game

Nash Bargaining game, proposed by Nash [**328**], adopts a cooperative approach to the bargaining problem. In cooperative games, agents bargain with each other before the game is played. If an agreement is reached, agents act according to this agreement. Otherwise, agents act non-cooperatively. Nash Bargaining game aims to analyze how agents should cooperate when non-cooperation leads to Pareto-inefficient results, i.e. if the results are dominated by other alternatives.

Nash Bargaining game involves two agents and these agents are assumed to be rational and perfectly informed about agreement alternatives. They have the opportunity to collaborate for mutual benefit in more than one way [**328**] and choose among the set A of alternatives. The aim is to find a solution upon which both agents agree. Bargaining theory assumes that the resulting solution in unbiased.

The principle is that if two agents do not agree on an alternative a, there is a fixed disagreement point d. The utility functions of the agents are presented as u_1 and u_2. It should be noted that utility achieved by any agreement point has to be equal or greater than the utility achieved at the disagreement point. Let the problem be described by (S, d) consisting of solution set and disagreement point. Let S be the set of utilities resulting from an agreement between the players and let *d* be the set of disagreement points.

$$S = (u_1(a), u_2(a)|a \in A) \quad (5.1)$$

$$d = (d_1, d_2) \quad (5.2)$$

Nash Bargaining solution can be obtained by solving the following maximization problem:

$$max = (u_1 - d_1)(u_2 - d_2) \quad (5.3)$$

Nash [**328**] states that the solution of this problem is unique if it satisfies the following axioms:

- *Pareto optimality*: There exists no feasible solution where one agent can improve its payoff without decreasing the other agent's payoff.
- *Invariance to affine transformations*: If both the feasible region of the bargaining model and the disagreement point are subjected to an affine transformation on the payoff space, then the bargaining payoffs satisfy the same affine transformation.
- *Independence of irrelevant alternatives*: If the feasible region is shrunk but still includes the Nash Bargaining solution, the payoffs will not change.
- *Symmetry:* Identical players receive identical utility payoffs.

Nash Bargaining theory is a central topic in game theory studies [**329**]. Existing literature offers many Nash Bargaining studies from mathematics and economics points of view. On the other hand, CPD literature lacks an analysis with Nash Bargaining principle which might offer managerial implications for CPD practitioners. Nevertheless, some studies apply Nash Bargaining solution to supply chain problems to investigate *coordination* mechanisms.

Nagajaran and Sosic [**309**] present a review on the cooperative bargaining in supply in chain management. Baron et al. [**330**] investigate the Nash Equilibrium within an industry with two supply chains. They apply Nash Bargaining over the wholesale price and they investigate the power structure of the chains. Wu et al. [**331**] extend the previous work to include demand uncertainty. They conclude that while the vertical integration solution is a unique Nash equilibrium for one period, Stackleberg game where the manufacturer is the leader and bargaining on the wholesale price are Nash equilibriums on the long term. Li et al. [**332**] investigate Nash Bargaining for elastic and linear demand in a decentralized supply chain. The retailer and the manufacturer bargain on the retail price, production quantity and revenue share. Hezarkhani and Kubiak [**333**] investigate shipment of an identical product between two independent companies. They propose a coordinating contract where two firms first set the shipment prices and then decide on production quantities. Competitive green supply chains are investigated by Sheu [**334**] where negotiation between producers and reverse logistics suppliers under government intervention is considered. A bargaining framework is proposed with a three-stage game model. These studies offer a basis to advance coordination mechanism further into full collaboration.

5.2 MODELLING COLLABORATION FORMATION

In this section, the profit (utility) functions of the firms that must decide on the level of collaboration, investment sharing, and profit sharing are formulated. The model includes the four dimensions of the collaboration process described in Effective collaboration process section, and also the revenues and the costs anticipated from CPD efforts. Only the collaboration of two firms, namely the focal (F) and partner (P) firms, are considered in a Nash Bargaining framework, and it is supposed that these partners jointly put their efforts into the PD [**5**]. Moreover, the following assumptions, which are widely adopted in the literature and verified by the industrial experts, form the basis of our study.

Assumption 1: Collaboration creates added value for the PD process [**5**]. It is obvious that the synergy of the collaboration is a natural motivation for a firm to search for other firms having complementary capabilities.

Assumption 2: Collaboration incurs a collaboration cost, which results from the coordination efforts and knowledge spill-overs. When the development effort is distributed between the firms, additional money is spent for integration [**5**]. In an optimal arrangement, firms choose the level of the spill-over parameter in order to maximize their joint profit [**313**]. Amir et al. [**313**] state that firms decide on the level of information sharing according to the sophistication of the R&D project. In this study, we assume that there is no competition in the market and therefore knowledge spill-over is in function of knowledge complementarity only.

Assumption 3: Collaboration reduces the overall development cost. Division of the innovation between multiple companies lowers development costs in comparison to the case where innovation is the responsibility of a single firm [**5**]. R&D costs are typically postulated to be quadratically increasing [**313**].

The following notation is used through the rest of this chapter.

Indices

i: knowledge type, $i = \{1, \ldots, N\}$

j: firm type, $j = \{F, P\}$

Parameters

a: product initial value

b_i: value added to the product in relation with knowledge type i

v: efficacy of the new product

$t_{jj'}$: trust level of firm j to other firm j'

z_i^j: type i knowledge stock of firm j

$\bar{z}_i$: type i knowledge stock of collaborating firms*j*

M_i^j: investment of firm j*j* in knowledge type i

β_i: knowledge complementarity for knowledge type i

$\gamma^j(\,)$: knowledge absorption capacity function of firm j

$s(\,)$: coordination cost function

$c^j(\,)$: development cost function of firm j

Variables

θ: collaboration level between firms

k: coordination cost sharing ratio

ϕ: revenue sharing ratio

When two firms collaborate, they pool their knowledge and use that as input into the new knowledge production. In accordance with the work of Cowan et al.[**192**], we will assume that each firm holds N distinct types of knowledge. Besides, the stock of knowledge is the result of a firm's own investments into knowledge and the knowledge shared or spilled over by the other company [**335**]. More precisely, the stock of knowledge of type i is a concave function of the collaboration level θ and is defined for firm j as

$$z_i^j = M_i^j + \gamma^j(M_i^j, \beta_i)\theta(M_i^{j'})^{t_{j'j}} \tag{5.4}$$

where j' represents the other company.

The literature shows that trust has a positive effect on the information sharing, and is important not only for effective partnerships, but also for the collaborative venture performance [**336**]. This idea is reflected in equation 5.4 where the knowledge $M_i^{j'}$ of firm j' will be more revealed to firm j as the trust level, $t_{j'j}$, and/or the collaboration level, θ, are high. Here, it is assumed that $t_{j'j} \in [0, 1]$ and $\theta \in [0, 1]$. Note that trust can be mutual or not, in other words the management of each firm has its own degree of trust towards its partners.

Knowledge can be revealed by the partner, but how much of that knowledge is actually captured is another concern. In equation 5.4, γ^j is the fraction of partner's knowledge that the firm is able to assimilate and exploit. It thus represents the firm's learning capability or absorptive capacity. γ^j depends on two factors: one is its own knowledge investment, M_i^j, and the other is the complementarity of its knowledge with that of the other firm, denoted as β_i. Knowledge complementarity can be defined as the degree of difference in knowledge that the firms possess. To put it another way, complementary knowledge may be defined as low degrees of redundancy in the form of dissimilar PD knowledge and skills. As two firms are distant in the technology space, β_i will become larger. In line with Sakakibara [45], we assume that the knowledge investments of a firm increase its learning capability, $\partial\gamma^j/\partial M_i^j > 0$ but at a constant or decreasing rate, $\partial^2\gamma^j/\partial(M_i^j)^2 \leq 0$. As the knowledge of other firm becomes more complementary or more distant, learning will be more difficult, $\partial\gamma^j/\partial\beta_i < 0$. This can be attributed to the fact that firms will not possess the elementary knowledge to understand a distant technology at that case. However, we will also suppose that the marginal effect of the firm's own knowledge investments on the absorption capacity will be larger, i.e. $\partial^2\gamma^j/\partial\beta_i\partial M_i^j > 0$, as β_i increases. This is because the contribution of more complementary knowledge to learning is greater compared to more similar knowledge, once it is learned. As a last remark, when β_i approaches to zero, learning capability will less depend on firm's knowledge investments, and γ^j will approach 1.

We can express the co-learning of the focal and partner firms as

$$\theta(\gamma^F(M_i^F, \beta_i)\theta(M_i^P)^{t_{PF}} + \gamma^P(M_i^P, \beta_i)\theta(M_i^F)^{t_{FP}}) \tag{5.5}$$

and the pooled knowledge due to collaboration as

$$\bar{z}_i = M_i^F + M_i^P + \theta(\gamma^F(M_i^F, \beta_i)\theta(M_i^P)^{t_{PF}} + \gamma^P(M_i^P, \beta_i)\theta(M_i^F)^{t_{FP}}) \tag{5.6}$$

for each knowledge type $i = \{1, 2, \ldots, N\}$.

When firms make their investment decisions, we assume that they only have an estimate of the success of the new product project. There is a technology uncertainty and thus how much firms can exploit the new innovation is also uncertain. If we denote the efficacy as $\tilde{v}$, the final value added to the product would be $\tilde{v}\mathbf{b}\bar{\mathbf{z}}$. Thus whether or not the costs borne by the firms for innovation would be recovered is uncertain. This type of uncertainty is referred as translational uncertainty in the literature [**5**], and it represents the ability of a firm to translate an idea into a commercially viable product. We suppose that $\tilde{v}$ is uniformly distributed between v and 1, and consequently, less translational uncertainty is faced as v increases.

Firms can build development partnerships in many different ways. To investigate how issues related to PD influence the collaboration between firms, we consider a case in which firms are currently in a revenue sharing agreement. This implies that the focal and partner firms get ϕ and $(1-\phi)$ of the total revenue respectively where $\phi \in [0, 1]$.

Revenue sharing is a proven useful technique to increase the total profit in supply chain partnerships. Here we are interested in exploring its relations with cost sharing and collaboration decisions.

The costs incurred because of the collaboration are identified as knowledge investment cost, coordination cost and development cost. The total knowledge investment cost is evidently equals to $\sum_i M_i^j$ for firm j. The coordination costs may arise from the interdependence of tasks assigned to partners. The higher the interdependence or collaboration level, the greater the information they must possess while the development is in progress. The interdependence level is especially high in technology alliances where partners aim to share complementary technology and jointly reduce the time needed for innovation. All these alliances require continuous inputs and information updates from all partners. This generally indicates high coordination costs. In this study, the coordination cost is a function of the collaboration level, and $\partial s/\partial\theta > 0$, $\partial^2 s/\partial\theta^2 > 0$, $s(0) = 0$ and $s(1) < +\infty$. The coordination cost is shared by the firms. We refer to $k \in [0, 1]$ as the fraction of the cost borne by the focal firm. In that case, $(1 - k)$ is the fraction of the coordination cost borne by the partner firm. Development costs are mostly associated with resource usage. As the stock of knowledge held by a firm increases, resources are used less and more efficiently managed. This clearly reduces the development cost, $\partial c_i^j/\partial z_i^j < 0$, but at a decreasing rate, $\partial^2 c_i^j/\partial(z_i^j)^2 > 0$. The development cost would always exist despite a large stock of knowledge, thus c_i^j will take finite positive values.

Based on this reasoning, the profit functions of the focal and partner firms can be derived as

$$\pi^F = \phi\left(a + \mathbf{b}\bar{\mathbf{z}}\tilde{v}\right) - (1-k)s(\theta) - \sum_{i=1}^{N}\Big(M_i^F + c_i^F\left(z_i^F\right)\Big) \tag{5.7}$$

and

$$\pi^F = \phi\left(a + \mathbf{b}\bar{\mathbf{z}}\tilde{v}\right) - (1-k)s(\theta) - \sum_{i=1}^{N}\Big(M_i^F + c_i^F\left(z_i^F\right)\Big) \tag{5.8}$$

respectively. In equations 5.5 and 5.6, the revenue is formulated as a sum of the initial product value and the value added by the collaboration. Therefore, $a = 0$ corresponds to the new PD case while $a > 0$ corresponds to the product improvement case. We must note that the profit functions are concave as the cost functions are convex.

As the decision on the collaboration level should be made before it is known how well the innovation can be translated into a product, as proposed in Arsenyan et al. [**337**], the expected profit function of the focal firm can be written as:

$$\begin{aligned} \pi^F &= E[\phi(a + b\bar{\mathbf{z}}v) - (1-k)s(\theta) - \textstyle\sum_{i=1}^{N}(M_i^F c_i^F(z_i^F))] \\ &= \phi(a + b\bar{\mathbf{z}}(\tfrac{v+1}{2})) - (1-k)s(\theta) - \textstyle\sum_{i=1}^{N}(M_i^F c_i^F(z_i^F)) \end{aligned} \quad (5.9)$$

Similarly, the expected profit function of the partner firm would be

$$\pi^P = (1-\phi)\left(a + \mathbf{b}\bar{\mathbf{z}}(\tfrac{v+1}{2})\right) - ks(\theta) - \sum_{i=1}^{N}\Big(M_i^P + c_i^P(z_i^P)\Big) \quad (5.10)$$

5.2.1 Solution to the Nash Bargaining Problem

Without loss of generality, only one type of knowledge is considered to simplify the analysis. The knowledge absorption capacity function of firm j is selected as $\gamma(M^j, \beta) = M^j\beta + (1-\beta)$, and accordingly, the learning of firm j when collaborating with firm j' is $L^j = \big(M^j\beta + (1-\beta)\big)(M^{j'})^{t_{kj}}$. Based on this definition, the co-learning can be expressed as $\theta\,(L^F + L^P)$ and the total accumulated knowledge can be expressed as $\bar{z} = M^F + M^P + \theta\,(L^F + L^P)$. The development cost function for firm j is assumed to be linear and modelled as $(c^j - (M^j + d^j\theta L^j))$. The condition $c^j > (M^j + d^j L^j)$ should be satisfied by definition. The collaboration cost is convex, quadratic and increasing in θ and is given as $s(\theta) = I\theta^2$ where I is the associated cost. Finally, we simplify the notation of the ease of exposition such that

$\bar{a} = a + b(\frac{v+1}{2})(M^F + M^P)$, $\bar{b} = b(\frac{v+1}{2})(L^F + L^P)$, $\bar{c}^j = c^j - M^j$ and $\bar{d}^j = d^j L^j$ for $j \in \{F, P\}$. The profit functions in Equations 5.9 and 5.10 can be now reformulated as

$$\pi^F = \phi\left(\bar{a} + \bar{b}\theta\right) - (1-k)I\theta^2 - \left(\bar{c}^F - \bar{d}^F\theta\right) \tag{5.11}$$

and

$$\pi^P = (1-\phi)\left(\bar{a} + \bar{b}\theta\right) - kI\theta^2 - \left(\bar{c}^P - \bar{d}^P\theta\right) \tag{5.12}$$

respectively.

To find the Nash Bargaining solution, a three-stage solution procedure is suggested:

1. At the *first stage*, the focal firm makes the decision on the collaboration level. Given that the focal firm initiates the collaborative activities, it is normal to suppose that the collaboration level is determined according to the requirements of the focal firm. Therefore, optimal θ is calculated through the profit function of the focal firm in Equation 5.11.

$$\theta^* = \frac{\bar{d}^F + \bar{b}\phi}{2I(1-k)} \tag{5.13}$$

2. At the *second stage*, the partner firm decides how the collaboration cost would be shared. The optimum θ^* is plugged to the profit function of the partner firm in Equation 5.12 to compute the optimal cost sharing ratio k in response to the given collaboration level. This ratio is expressed as a function of profit sharing ratio ϕ but it is a so complex closed expression that it is not given here.

3. At the *third* and final *stage*, the profit sharing ratio ϕ is determined as a Nash Bargaining solution. The optimal solutions θ^* and $k^*$are now plugged to the profit functions in Equations 5.11 and 5.12 and the equilibrium solution ϕ^* would be obtained by solving the Nash Bargaining problem

$$\max_{0 \leq \phi \leq 1} \ \pi^F \times \pi^P \tag{5.14}$$

ϕ^* has a complex closed form which we cannot provide in this study. The effects of several model parameters on the optimum solution of the problem in Equation 5.14 are investigated in the next section.

5.2.2 Scenario Analysis

The developed mathematical model is tested within various instances with the scenarios provided by Expert X, our industrial expert and TUBITAK project partner. The parameters within these scenarios and the corresponding figures are presented in Table 5.2. The scenario analysis was conducted with the involvement of our expert throughout the study. The parameters employed in the MATLAB analysis were collected from the collaboration experience of IDE AS and reflect real-life experience of a SD company. The *x*-axis in all the figures represents the revenue sharing ratio ϕ while the *y*-axis in all the figures represents the total profit.

Table 5.2 Legend for the scenarios

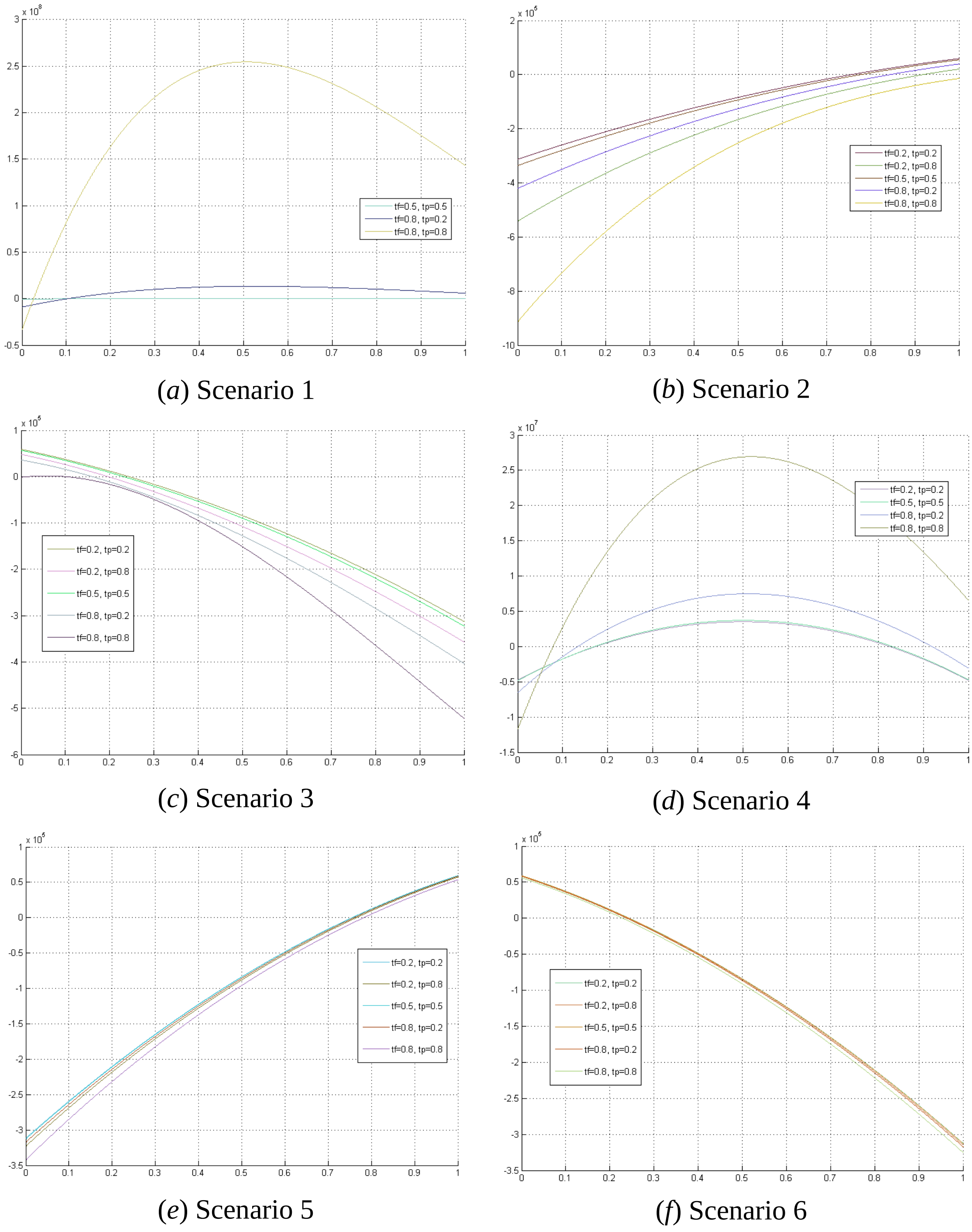
Scenario no	***Figure***	***Trust***	***Knowledge investment***	c^F/c^P	d^F/c^F	d^P/c^P	***Project type***	β
1	Figure 5.1	-	Equal and high	=1	<<1	<<1	New revenue	High
2	Figure 5.1	-	Uneven	=1	<<1	<<1	New revenue	High
3	Figure 5.1	-	Uneven	=1	<<1	<<1	New revenue	High
4	Figure 5.1	-	Equal and high	=1	<<1	<<1	New revenue	Low
5	Figure 5.1	-	Uneven	=1	<<1	<<1	New revenue	Low
6	Figure 5.1	-	Uneven	=1	<<1	<<1	New revenue	Low
7	Figure 5.2	Equal and high	Equal and low	=1	>>1	>>1	New revenue	-
8	Figure 5.2	Equal and high	Uneven	=1	>>1	<<1	New revenue	-
9	Figure 5.2	Equal and high	Equal and low	>1	<<1	<<1	New revenue	-
10	Figure 5.2	Equal and high	Equal and low	>1	<<1	<<1	New revenue	-
11	Figure 5.2	Equal and high	Equal and low	>1	>>1	>>1	New revenue	-
12	Figure 5.2	Equal and high	Equal and standard	<1	<<1	<<1	New revenue	-
13	Figure 5.3	Equal and high	Equal and standard	=1	<<1	<<1	-	Standard, low efficacy
14	Figure 5.4	Equal and high	-	>1	<<1	<<1	New revenue	Standard
15	Figure 5.4	Equal and high	-	=1	>>1	<<1	New revenue	Standard
16	Figure 5.4	Uneven	-	>1	>>1	<<1	New revenue	Standard
17	Figure 5.4	Uneven	-	>1	>>1	<<1	Improvement	Standard

5.2.2.1 The Effect of Trust

The CPD model introduced by Arsenyan and Büyüközkan [**166**] clearly suggests that trust between the collaborating firms is a major success factor. In this section, Scenarios 1-6 given in Figure 5.1 are analyzed in details to observe the effect of this factor for the negotiation. According to Scenario 1, highest profit is attained if the collaborating firms have high level of trust to each other, and low or unbalanced levels of trust decrease the profit significantly. The case where prior knowledge investments of the firms are unequal is investigated in Scenarios 2 and 3. The results indicate that the firm having significantly greater knowledge investment does not need cooperate, and should undertake the development project alone and take all the profit whatever the trust level is. Similar reasoning applies to Scenarios 4-6. Despite low knowledge complementarity, trust has a major role on the profit generated and the level of collaboration when firms have both high knowledge stock, and it has a minor role when the knowledge stocks among firms differ considerably.

5.2.2.2 The Effect of Knowledge Complementarity

Knowledge absorption capacity is an important issue for our model and it favours knowledge complementarity as a collaboration motivation. Six different scenarios displayed in Figure 5.2 are considered to identify the effect of knowledge complementarity on the profit generated and how it is shared. The results for Scenario 7 clearly show how much complementarity is important to increase profit. Moreover, the highest profit is always attained when revenue is equally distributed between firms. This reasoning slightly changes when collaborating firms differ in their knowledge stocks and development costs (Scenario 8). The firm with less knowledge accumulation should collect less of the revenue, and collaboration is no more required when knowledge of firms are less complementary. Similar arguments can be made for Scenario 9 where only the effect of development costs is considered. However, when prior knowledge of both firms is few (Scenario 10), there is almost nothing to learn from the partner whether its knowledge is complementary or not, and the firm with less development cost structure takes the almost the whole revenue.

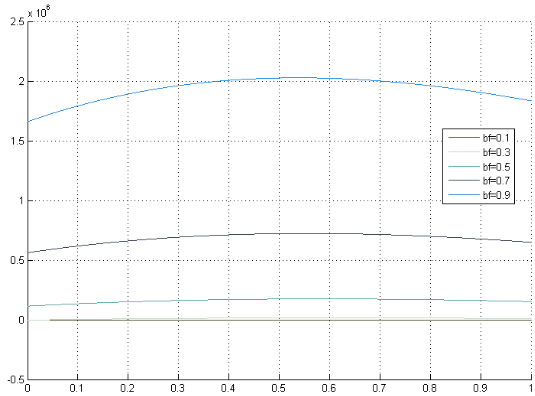


(*a*) Scenario 1 (*b*) Scenario 2

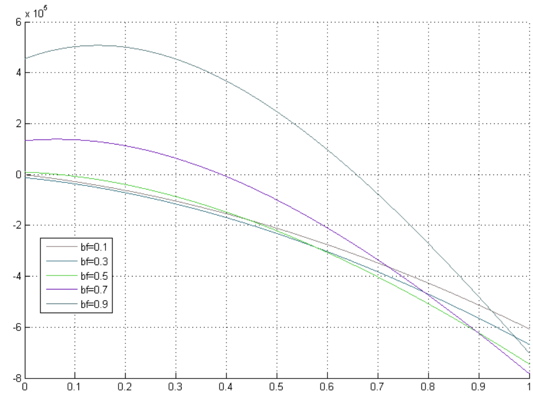
(*c*) Scenario 3 (*d*) Scenario 4

(*e*) Scenario 5 (*f*) Scenario 6

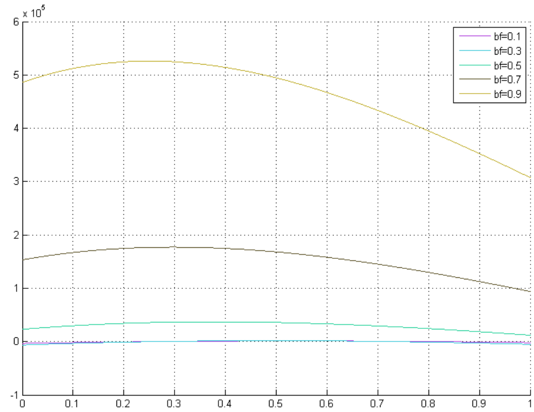
Figure 5.1 Results obtained for Scenarios 1-6



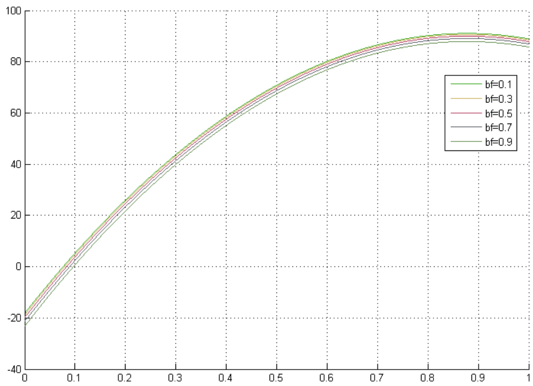
(*a*) Scenario 7



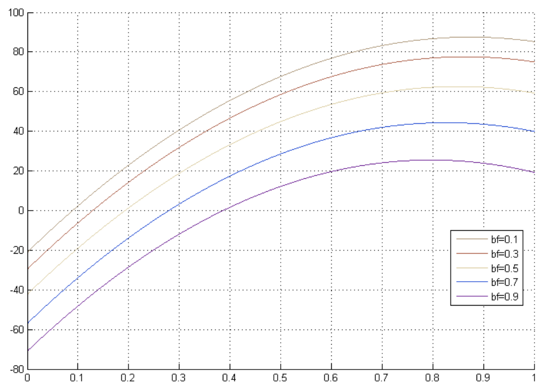
(*b*) Scenario 8



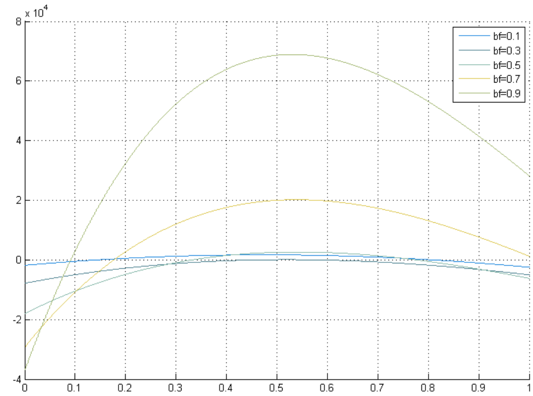
(*c*) Scenario 9



(*d*) Scenario 10



(*e*) Scenario 11



(*f*) Scenario 12

Figure 5.2 Results obtained for Scenarios 7-12

In Scenario 11, the importance of co-learning together with the knowledge complementarity is investigated by setting the development cost parameter d^j to higher values for both the firms. When complementarity is low, the focal firm which has a favourable development cost structure takes much of the revenue. On the other hand, when knowledge stocks of companies are more complementary, their learning also increases and the disadvantageous cost structure of the partner firm becomes less effective. This slightly raises the revenue share of the partner firm, but the total profit curve shifts down as complementarity is higher. Whatever the case is, the companies should always collaborate under these scenario conditions. The development cost parameters are determined such that $d^F = d^P$ and $c^F < c^P$ in the last Scenario 12. Similar to Scenario 7, positive profit is obtained when complementarity is high, and the associated revenue should be distributed equally. Meanwhile, collaboration becomes useless when complementarity is low. In sum, it can be concluded that knowledge complementarity is another key issue to consider when collaborating. It has especially great effect on total profit, especially when development costs are high.

5.2.2.3 The Effect of Product Type and Efficacy

To analyze whether the initial value of the product and the value added to the product by the development project have a consequence on the profit, we focus on three cases: new PD with an innovation aspect ($a = 0$), minor product update ($a > 0, a > \mathbf{b}\bar{\mathbf{z}}\tilde{v}$) and major product update ($a > 0, a < \mathbf{b}\bar{\mathbf{z}}\tilde{v}$). Moreover, these cases are investigated under the high and low efficacy of the product. The solutions associated six scenarios (13-18) are plotted on Figure 5.3. Though total profits differ, the optimal revenue ratios are equal to 0.5 for all scenarios as the collaborating firms cost structures and knowledge stocks are equal. Low efficacy of the product causes the total profit to decrease, especially when the development project involves a major product update. The project type seems to be the decisive factor, but this outcome cannot be interpreted as there can be no benefit from CPD for new revenue projects. This type of projects can also lead to high profits with different combinations of learning, value added and efficacy. Other cases with dissimilar collaborators did not yield to any significant outcome and thus are not included in this analysis.

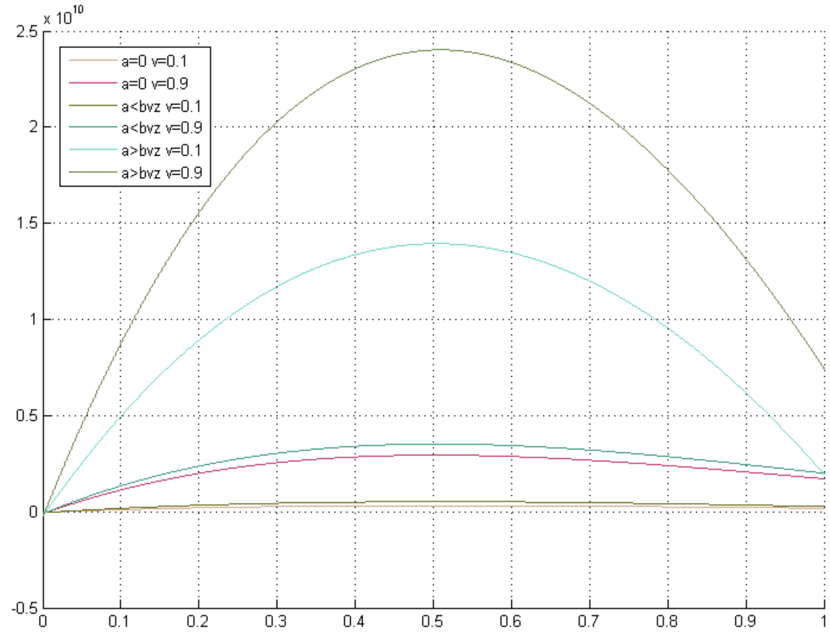
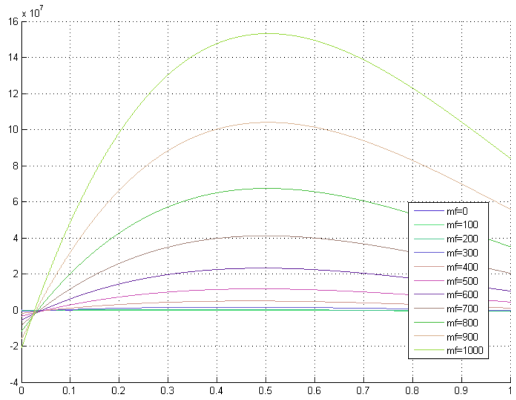


Figure 5.3 Results obtained for Scenarios 13

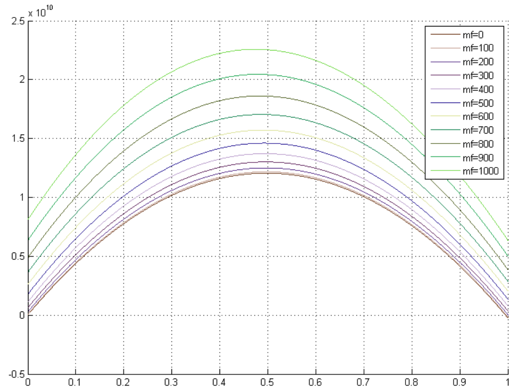
5.2.2.4 The Effect of Knowledge Investment

Knowledge investment of the firms is an important parameter in the model given that it influences both cost and revenue at the same time. This section considers the scenarios where the initial knowledge investment of the partner firm is preset while the knowledge investment of the focal firm varies.

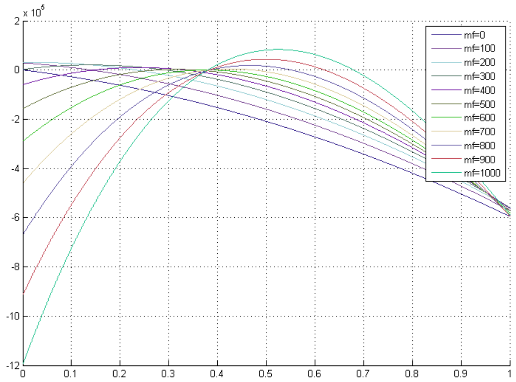
A new revenue PD project is considered in Scenario 14. The development cost function parameters for the partner firm are selected such that learning will have almost no effect in reducing this cost. Moreover, partner firm has a high knowledge stock. The scenario is arranged such that focal firm could only attain that level of stock at most. The results show that the optimal revenue sharing is almost equal in every case, while collaboration is beneficial only if both firms have comparable knowledge stocks. If one of the firms has a notably low knowledge stock while the other firm could not reduce its own development costs due to learning, then there is no foundation for partnership.



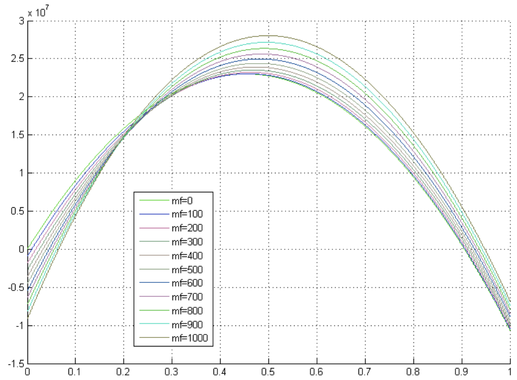
(*a*) Scenario 14



(*b*) Scenario 15



(*c*) Scenario 16



(*d*) Scenario 17

Figure 5.4 Results obtained for Scenarios 14-17

In Scenario 15, an innovation project is considered, i.e. the product has no initial value. Initial development costs of both firms are equal, and the focal firm benefits more from learning as its initial development cost decrease at a much higher rate compared to the partner firm. In general, total profit increases as the knowledge investment of the focal firm is larger but surprisingly the revenue share of the focal firm decreases in the meantime. This occurrence can be explained by the growing knowledge spillover towards partner firm as the knowledge stock of the focal firm expands. It can be concluded that the effect of the co-learning is more significant than the effect of development cost on the optimal revenue sharing. This inference also highlights that the model put more emphasize on the co-learning and co-innovation than the monetary benefits of the collaboration.

Scenario 16 is designed so that the development cost structure, knowledge complementarity and trust of firms differ; and one party benefits from the collaboration in terms of development costs while the benefits of other party occur from the co-learning. It is obvious that collaboration is feasible only if the focal firm's knowledge investment level matches the knowledge investment of the partner firm. This also increases the revenue sharing of the focal firm. Once the prior knowledge investments are equal, focal firm gets a slightly higher profit share. This outcome justifies the importance of co-learning over the improvement of the development costs for collaboration formation.

The distinction of Scenario 17 to 16 is the higher initial value of the product. This made the feasible revenue sharing ratio range larger. In line with the previous observations, the revenue sharing shift in favour of the focal firm as its knowledge investment is larger. As the total profit amounts are almost the same for all levels of knowledge stock of the focal firm, it can be deduced that prior knowledge investment of the firms loses its significance in generating profit when the initial value of the product is high. Equal revenue sharing is optimum when both companies have equal knowledge investment despite the differences in development cost structures and trust levels. In sum, co-learning is a highly effective factor for collaboration in the development of new products, but becomes a minor concern for development projects aiming to upgrade an existing product.

5.2.3 Analysis Review

A final analysis is conducted with a fixed parameter set in order to identify combinations where similar strategies can be followed. 288 instances in 72 groups are investigated. Investigated instances are:

- New versus upgrade product development
- High versus low knowledge complementarity

- High versus low stability
- Mutually high versus varying levels of trust, focal firm with low level of trust versus mutual low levels of trust
- High development costs decrease rates for both firms versus uneven development costs decrease rates, F with higher development cost decrease rate versus low development costs decrease rates.
- Mutually large versus varying knowledge investments, greater knowledge investment of F versus varying levels of knowledge investments, greater knowledge investment of P versus small knowledge investments.

72 groups consist each of four states of knowledge investment. Optimum strategies are defined according to the optimum state of knowledge investment that generates maximum profit. As displayed in Table 5.3, five strategies emerge as an outcome out of 12 possible strategies. These can be summarized as:

- S-1. *Equal revenue sharing with both firms having large knowledge investments*: Higher profit is made when both parties have large knowledge investments. Maximum profit is made when the collaborators have equal share of the revenue.
- S-2. *Equal revenue sharing with both firms having small knowledge investments*: Higher profit is made when both parties have small knowledge investments. Maximum profit is made when the collaborators have equal share of the revenue.
- S-3. *Greater revenue share for F with large knowledge investment of F*: Higher profit is made when F has a greater investment of knowledge than P. Maximum profit is made when the revenue share of F is greater.
- S-4. *Greater revenue share for P with large knowledge investment of P*: Higher profit is made when P has a greater investment of knowledge than F. Maximum profit is made when the revenue share of P is greater.
- S-5. *Greater revenue share for F with both firms having large knowledge investments*: Higher profit is made when both parties have large knowledge investments. Maximum profit is made when the revenue share of F is greater.

It is clear that two strategies, namely S-1 and S-2, are largely dominant. For the product upgrade projects, if there is a lack of trust, and knowledge complementarity and product efficacy is low, then collaboration becomes valuable particularly when firms have low levels of knowledge investment (strategy S-2). Firms benefit from CPD even though the conditions are not favourable. However, if one of the potential partners has a relatively higher level of knowledge investment, collaboration is not justified. As the conditions improve -i.e. trust levels, complementarities, and product efficacy increase- it becomes more profitable to collaborate for higher levels of knowledge investments (strategy S-1). That is to say, total profit is proportional to knowledge investments. Revenue is shared equally as well.

For the new PD projects, all five strategies are possible to implement. Unlike the product upgrade projects, even though there is a lack of trust among partners, the knowledge stocks are not complementary, and the efficacy of the product is uncertain, it is still profitable to collaborate when parties have high initial knowledge investments. As the partnership conditions become more favourable, various optimal strategies emerge. For the most optimistic case (i.e. mutual high trust, product efficacy predictable, high development cost decrease rates), the maximum total profit is made when the focal firm has a higher share of the revenue (S-5). For new revenue PD projects, it is the focal firm's advantage to collaborate with a trustworthy partner having high prior knowledge investment and with whom a high knowledge complementarity exists.

S-2 strategy is optimal for four combinations, namely A2, A4, C1, and D8, where the total profit decreases when knowledge investments increase. This is due to the unevenness in the first two instances and due to the low complementarity in the last instance. Parties share the revenue equally.

As shown in Table 5.3, S-3 strategy is optimal for combinations A3 and D1. This is the result of improved learning for F for the first combination, and high development cost decrease rate for the second. Thus, P appears as a performance improvement agent of CPD.

S-4 strategy is optimal for five combinations: A5, B2, B4, B5, C2. Considering the similarity of the firm's profit functions, it is not difficult to observe that strategies S-4 and S-3 are equivalent. Even though total profit diminishes in the latter strategy, it is the optimal solution for the focal firm, given that the analysis is conducted from the focal firm's point of view.

Seven strategies turn out not to be optimal in Nash Bargaining equilibrium. These strategies are as follows:

- Equal revenue sharing with larger knowledge investment of F
- Equal revenue sharing with larger knowledge investment of P
- Greater revenue share for F with larger knowledge investment of P
- Greater revenue share for P with larger knowledge investment of F
- Greater revenue share for P with both firms having large knowledge investments
- Greater revenue share for F with both firms having small knowledge investments
- Greater revenue share for P with both firms having small knowledge investments

It is clear why there is no profit in favour of one party when knowledge investment is higher for the other party. On the other hand, it is interesting to observe that uneven knowledge investments always yield to unequal revenue sharing no matter how other factors are valued.

Table 5.3 Analysis summary

			Uncertain product efficacy				Existing product upgrade			
			High knowledge		Low knowledge		High knowledge		Low knowledge	
			Predictable product	Uncertain product	Predictable product	Uncertain product	Predictable product	Uncertain product	Predictable product	Uncertain product
			(A)	**(B)**	**(C)**	**(D)**	**(E)**	**(F)**	**(G)**	**(H)**
High levels of trust for both F and P	High development cost decrease rates for both F and P	**(1)**	S-5	S-5	S-2	S-3	S-1	S-1	S-1	S-2
	Uneven development cost decrease rates, F with higher rate	**(2)**	S-2	S-4	S-4	S-1	S-1	S-1	S-2	S-2
	Low development cost decrease rates for both F and P	**(3)**	S-3	S-1	S-1	S-1	S-1	S-2	S-2	S-2
Uneven levels of trust, F with lack of trust	High development cost decrease rates for both F and P	**(4)**	S-2	S-4	S-1	S-1	S-1	S-1	S-2	S-2
	Uneven development cost decrease rates, F with higher rate	**(5)**	S-4	S-4	S-1	S-1	S-1	S-2	S-2	S-2
	Low development cost decrease rates for both F and P	**(6)**	S-1	S-1	S-1	S-1	S-2	S-2	S-2	S-2
Low levels of trust for both F and P	High development cost decrease rates for both F and P	**(7)**	S-1	S-1	S-1	S-1	S-2	S-2	S-2	S-2
	Uneven development cost decrease rates, F with higher rate	**(8)**	S-1	S-1	S-1	S-2	S-2	S-2	S-2	S-2
	Low development cost decrease rates for both F and P	**(9)**	S-1	S-1	S-1	S-1	S-2	S-2	S-2	S-2

5.3 SUMMARY

The presented model integrated four dimensions of collaboration process in CPD and presented a mathematical profit model that captured both the revenue generated by the innovation and the cost resulting from the collaboration. The mathematical model provides an understanding on the working of the collaboration dimensions, expressed as parameters. It provides visualization of the effect of collaboration level on revenues and costs occurred from collaboration.

Game theory principles are applied to investigate the CPD negotiation conditions. Its ability in analyzing strategic situations enables game theory to study the effects of various factors included in the model. Nash Bargaining is employed to define negotiation points between two parties, focal firm and partner firm, by defining profit sharing ratio, investment sharing ratio and collaboration level.

The mathematical model put forward a unique tool for CPD practitioners to understand how important the collaboration dynamics are while negotiating. Given that the factors such as trust level, knowledge investment, collaboration effect on development cost, and integration cost are known to the collaborative parties reciprocally, this knowledge can be used by the managers to negotiate the collaboration formation by analyzing the mathematical model's behaviour.

The model provides insights on the outcomes of a partnership, not particularly on a monetary basis, but on the learning and innovation levels it may generate with regard to the project parameters such as knowledge types, knowledge complementarity, or added value from co-learning. It is important to receive revenue from PD but this is not enough. Combining knowledge bases in order to extract new knowledge results in added value for PD and is of at least importance.

Model analysis demonstrates that trust is a major concern in CPD projects and it indicates that no collaboration is preferable with the lack of trust. Knowledge complementarity and prior knowledge investments are significant parameters as well, considering they contribute to learning, which generates additional revenue and reduces development costs.

Whether the collaboration is for new product or upgrade PD is another major factor; few strategies are optimal for the product upgrade projects, while more can be implemented for new product projects. The mathematical model yields to a more meaningful outcome when an innovation is foreseen. These results justify the increase in the number of CPD projects to offer new products to the market with an increased speed.

The future work includes some variations on the mathematical model. First of all, scenario analysis was conducted under some assumptions of the cost and absorption functions. The model can be extended to analyze the scenarios where the functions present various behaviours. On the other hand, the model needs to incorporate an analysis on the collaboration and coordination ratios. Given that both ratios had complex closed forms, it was out of scope of this study to investigate them. Further analysis therefore is required to study the behaviour and the feasible regions of these ratios. On the other hand, different Game Theory approaches can be adopted to analyze scenarios with more than two firms and with different types of knowledge.

6 INFORMATION TECHNOLOGIES PLANNING FOR COLLABORATION NETWORK THROUGH INTEGRATED FUZZY METHODOLOGY

Being a technology-centric process, the collaboration process in PD as well as SD is built upon technological infrastructures. Accordingly, technology planning in collaborative development activities holds a strategic position given that it not only implies a major decision from an economical standpoint, but also the right technology investment supports the whole collaborative network. The accurate planning of the technology investment therefore holds a critical position in gaining and maintaining a competitive advantage [**338**,**339**]. Appropriate implementation of tools and technologies enabling collaboration is necessary to assure the efficiency and effectiveness of the collaborative development projects [**11**]. Various information systems are proposed by literature and commercial ventures to facilitate collaboration, integration, co-design, and co-development processes within the collaboration network consisting of the PD and SD teams. However, as collaborative requirements increase with high rates, current tools become insufficient in responding to this change, and new tools are needed to satisfy emerging requirements.

In this highly uncertain environment where requirements are various and technological response is numerous, the accurate planning of technological requirements thus becomes important in improving the collaborative development performance. Determining and weighting the requirements is an important phase in IT planning given that the process should understand the new technology and processes in order to offer a general system solution [**340**]. Even though each project has its own characteristics and specific requirement sets, the generic framework must cover all possible infrastructures. Moreover, systematic methodology is essential to planning the IT infrastructure needed to start and maintain the collaborative process within the collaboration network.

Literature fails to propose a comprehensive review of collaborative systems; the main reason being that these systems, including various applications, tools, platforms, and plug-ins, are numerous, easily outdated by new research, and known only to a limited community. Therefore, it is within the scope of this study to identify the features presented by these systems, instead of identifying the systems themselves.

Additionally, this study introduces a comprehensive and detailed IT planning methodology to help CPD practitioners in their effort to a successful development and collaboration process. A well known and widely applied planning technique, namely HoQ within the QFD framework is employed for this purpose, as its mapping grids provide a supporting tool for the planning process [**341**]. The HoQ diagram presents a suitable tool for mapping needs of the collaboration network into existing tools and technologies. Additionally, the target concept included in HoQ is employed with the Fuzzy AD technique in order to measure how well the project partners respond to the project targets. Then a FRBS is implemented with the purpose of deploying a knowledge base for investment decisions within the CPD project.

The study is organized as follows: the next section introduces the technology planning literature, which ranges from technology roadmapping in general to IT planning in CPD. Then the integrated fuzzy methodology background is established with an introduction on employed techniques, namely fuzzy HoQ, Fuzzy AD, and FRBS. Afterwards, a collaborative technologies overview is presented, including commonly used standards and environments, technology requirements and system features in collaboration infrastructure, as well as the sophistication levels of the IT systems. Then IT planning methodology is introduced, followed by an application of the methodology in the context of a case. The study concludes with a few remarks.

6.1 TECHNOLOGY PLANNING LITERATURE

Technology planning problems present an important study domain in the literature given the dynamic nature of the technological progress. Studies are numerous, from the general technology roadmapping to the technology framework for CPD. Qualitative as well as quantitative techniques are employed to tackle the technology planning issue from a strategic perspective. The first studies date back to the early 1990, with the successful implementation of technology roadmapping of Motorola in the mid 1980 [**342**]. The framework proposed by Porter et al. [**343**] includes technology forecasting as well as environmental analysis and aims to design organizational actions. As it is in this study, the value adding chain concept requires the implementation of technology within all aspects of the business. This book is constantly reviewed by its authors and it provides a starting point for various studies as a practical roadmap for technology planning.

Another early study proposed by Nauda and Hall [**338**] highlights the importance of aligning business strategies with technology planning in order to gain a competitive advantage. They follow a classification-evaluation-selection-analysis path in order to develop an implementation plan. Martin [**344**], on the other hand, starts with technology forecasting and applies scenario analysis to define technology allocations according to short term and long term needs. Rip and Camp [**345**] propose a four-step methodology, which starts with market research and continues with determining product features and technology options for these features and finally finishes with future consideration of technology resources. Wexelblat and Srinivasan [**340**] highlight the importance of IT strategic planning by offering a structure for the the IT planning process inspired by a government model where the core drive is the justification of a predetermined budget.

Pretorius and Wet [**346**] define a framework based on the hierarchy of the enterprise, business processes and functions. They state that technological assessment can be mapped on the relationship between technology and processes in this three dimensional framework. Curry and Ferguson [**347**] focus on global organizations for strategic IT planning and propose to correlate the IT planning horizon and technology lifecycle in order to decrease the planning horizon.

Kim et al. [**348**] tackle the problem of IT investment from a strategic point of view. They employ the priority grid technique in QFD, and by identifying the degree of flexibility required, they construct a decision path for IT investments with respect to the firm's business strategy. Talluri [**349**] approaches the efficient IT use from a supply chain perspective at strategical, tactical, and operational levels. A multi-objective mathematical model is proposed for the effective acquisition and justification of IT systems. Schniederjans and Hamaker [**350**] expand the previous work by investigating the cases, where only one solution is required and solution justification is desired. They employ a simple ranking/scoring method for the first one while they employ a more elaborate modelling approach for the latter to identify economic tradeoffs that can be used to improve an existing solution.

In a technology evaluation study proposed by Babar et al. [**351**], collaborative technologies instead of face-to-face meetings are proposed as a cost and time effective mechanism to evaluate software architecture. This study is interesting in both the proposal of the evaluation framework and the effect of collaborative technology use.

Koc and Mutu [**339**] present a technology planning methodology, from selection of competitive priorities to designing the activities, by integrating different system design perspectives through AD. Lee et al. [**352**] handle the subject from the R&D investment perspective, and they aim to integrate management tools into technology roadmaps in order to assure alignment with managerial concerns. The proposed framework identifies six stages of technology roadmapping, and it describes inputs and outputs as well as the techniques employed to prepare the roadmap. Gokhale and Myers [**353**] handle the technology roadmapping process from a competence perspective. The study aims to present an understanding of how the technology can be developed or acquired on a time scale with respect to alignment of the competence sourcing to the strategic goals.

Rueda and Kocaoglu [**354**] state that market and technology performance uncertainty make technological investment highly risky, and they focus on diffusion of emerging technologies. They combine bibliometrics analysis, the Delphi method, utility curves, and scenarios to define a composite indicator for diffusion. Shengbin et al. [**355**] focus on the technology roadmap concept, and they present a visual guide to map market, product, and technologies to achieve technology selection. The three-phased design process includes trend discussion, industrial and academic investigation, and expert feedback on technological demand. It also provides a tool to make strategic level technology selection decisions. An et al. [**341**] develop a produce-service integration roadmap for the mobile communications industry where they employ QFD for the integration process.

Gerdsri et al. [**356**] discuss the initiation, development, and integration stages of technology roadmapping implementation, and then they identify the roles and responsibilities to match the requirements of implementation. Chen et al. [**357**] present a strategic technology planning framework that provides technology assessment and technology scenarios by a hierarchical decision model along with a sensitivity analysis based on competitive goals and technology strategies. The framework is highly dependent on expert judgments. Hou et al. [**342**] conduct exploratory case studies in China in order to identify critical factors in technology roadmapping. They state that the support from senior leaders of the company is a crucial factor as it assures easy adoption of new technologies. Geum et al. [**358**] propose a generic structure of product–service integrated roadmap based on the concept and typology of technological interface, and they investigate the usage, characteristics, and roadmapping processes.

Recently, Cho and Lee [**359**] presented taxonomy on technology roadmaps in service areas and they established that there were five dominant types of standardized roadmaps which could be listed as product-focused, service-focused, product-service integration, technology-driven, and finally product-service technology roadmaps.

In addition to technology planning studies from a generic perspective, there are also limited but essential studies on technology use in PD and CPD projects. Krishnan and Bhattacharya [**360**] study PD technology selection under technology uncertainty. They model the decision process mathematically from *proven* technology and *prospective* technology angles and they propose *parallel path* and *sufficient design* approaches to design flexibility. Gerdsri and Kocaoglu [**361**] propose an analytical approach for technology selection for PD by combining the Delphi method and a hierarchical decision making model. The model consists of technology forecasting, technology characterization, technology assessment, hierarchical modelling, technology evaluation, and formation of strategic Technology Development Envelope (TDE) steps. In an extended work, Gerdsri and Kocaoglu [**362**] improve the TDE framework by incorporating AHP for the hierarchical decision making model to measure intangible criteria impact as well as tangible criteria impact. Büyüközkan et al. [**11**] present a comprehensive review on tools, techniques, and technologies enabling agile manufacturing in concurrent PD. Luh et al. [**363**] combine Design Structure Matrix (DSM) with Fuzzy Sets Theory into FDSM to present a dynamic planning method for PD, increasing PD efficiency and decreasing development time. Ko [**364**] also employs FDSM to present a methodology that enhances PD management by organizing design activities and measuring dependency strength. Oliveira and Rozenfeld [**365**] integrate technology roadmapping into product portfolio management and utilize the complementary features of these two techniques to support front-end PD activities.

A more restricted sub-domain of technology planning is the CPD/CSD literature. Research is very limited in this area. Kumar and Midha [**93**] employ the QFD approach to compare a company's requirements in CPD with different functionalities of PDM systems, and technical specifications are then compared to a specific PDM system. Rodriguez and Al-Ashaab [**24**] identify CPD supporting system characteristics and classify corresponding technological requirements. They also perform a survey in the injection mould industry, and they propose a knowledge-based CPD system architecture responding to industrial requirements. Palacio et al. [**366**] present a tool to facilitate collaboration in distributed SD teams that aims to increase collaboration awareness by focusing on individuals and their activities.

The literature overview clearly points to the importance of the technology planning in a strategic management context.

Technology planning literature also contains a sub-domain, which is the technology planning for the PD/SD process. This literature, on the other hand, includes the CPD technology planning literature, which, as manifested in the review, is very limited. Overall, there are only a few studies on technology planning for PD whereas there are no studies on the technology problem for SD. On the other hand, only two studies handle the technology planning in CPD while CSD literature presents a single publication on the technology issue.

Accordingly, this study aims to fill two gaps in literature. First, a comprehensive review on requirements and available systems supporting the collaboration is introduced in order to identify *what has to be done* and *how can it be done* to support the collaboration of PD and SD teams. Second, this study aims to introduce a planning tool that covers *technology needs assessment*, *technology development plans*, and *implementation* stages of the technology roadmapping process, which consists of six stages (initiation, subject selection, technology needs assessment, technology development plan, implementation, and follow-up activities, such as environmental scanning and updates) according to Lee et al. [**352**]. Figure 6.1 presents the position of the presented study in the literature.

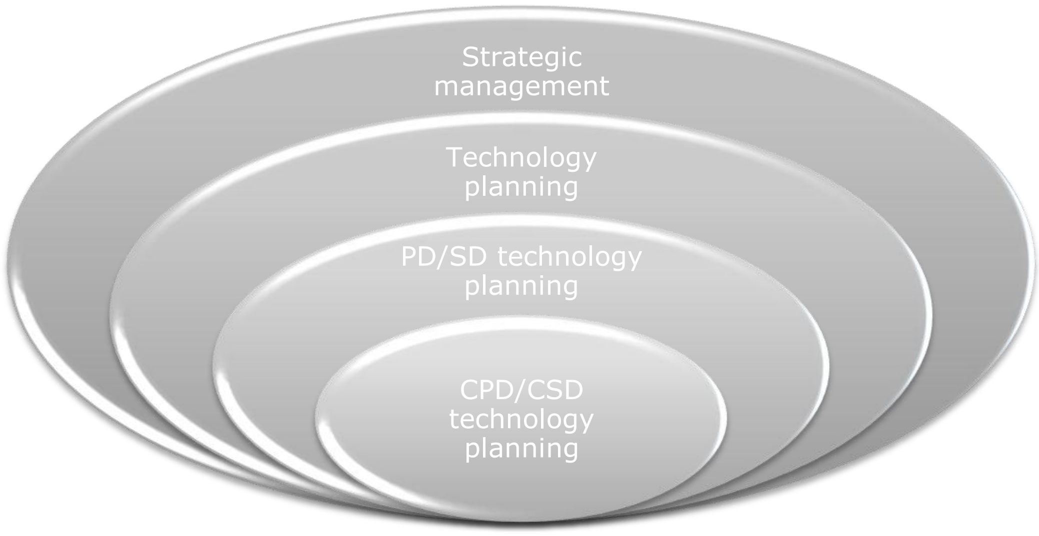


Figure 6.1 Current state of the technology planning literature

The planning phase involves the implementation of various techniques, including QFD. The review of Cho and Lee [**359**] suggest that QFD is widely employed as a supporting strategic planning tool in technology roadmapping, while Lee et al. [**352**] emphasize QFD as a widely employed technique in the technology needs assessment stage. It is apparent that QFD and the corresponding planning tools within present a recurring methodology in literature, given the effectiveness and the ease of use of planning matrices. It enables mapping of the requirements in the planning scheme while providing a systematic method. Therefore, this study employs the HoQ tool within the QFD methodology combined with Fuzzy AD and FRBS for IT planning purpose. These techniques are described in the following section.

6.2 METHODOLOGY BACKGROUND

Introduced by Akao in Japan in late 1960's, QFD provides specific methods for ensuring quality throughout the PD process, from design to production[**113**]. The methodology can be considered as a targeting technique for planning and development, an outline of events required during development, a comprehensive development plan, a means to emphasize important relationships, and a performance enhancer for the development process [**367**]. Basically, four stages can be identified: "Phase I translates the voice of the customer into corresponding engineering characteristics. Phase II moves one step further back in the design process by translating the engineering characteristics into parts' characteristics. Phase III identifies critical process parameters and operations. Finally, phase IV identifies detailed production requirements" [**348**].

QFD adopts a "design approach", where positive feedbacks from customers as well as the negative feedbacks are incorporated into the quality plan. The "Voice of Customer" is translated into design specifications using a planning matrix called HoQ. Although it constitutes a mere tool in QFD methodology, this planning matrix is widely implemented in QFD studies. Accordingly, this study opts to employ HoQ tool for IT planning. However, given that expert based evaluation is considered for the planning process, the methodology is developed in a fuzzy environment. Fuzzy AD and FRBS are also employed in order to develop an integrated fuzzy methodology, which puts forward an investment decision plan for IT investments in a CPD network. The three techniques are described in the following sections.

6.2.1 Fuzzy House of Quality

The HoQ can be described as a "conceptual map that provides the means of inter-functional planning and communications" [**368**]. It seeks to gather customer needs and translate them into customer attributes (CAs) in order to meet them through engineering characteristics (ECs). The HoQ utilizes "a weighted-sum multi-objective decision criterion, entailing technical test measures (benchmarking) analysis, technical importance rankings, and estimates of technical difficulty to enable a decision maker to set performance targets for a designed artefact" [**369**]. An illustrative example is displayed in Figure 6.2.

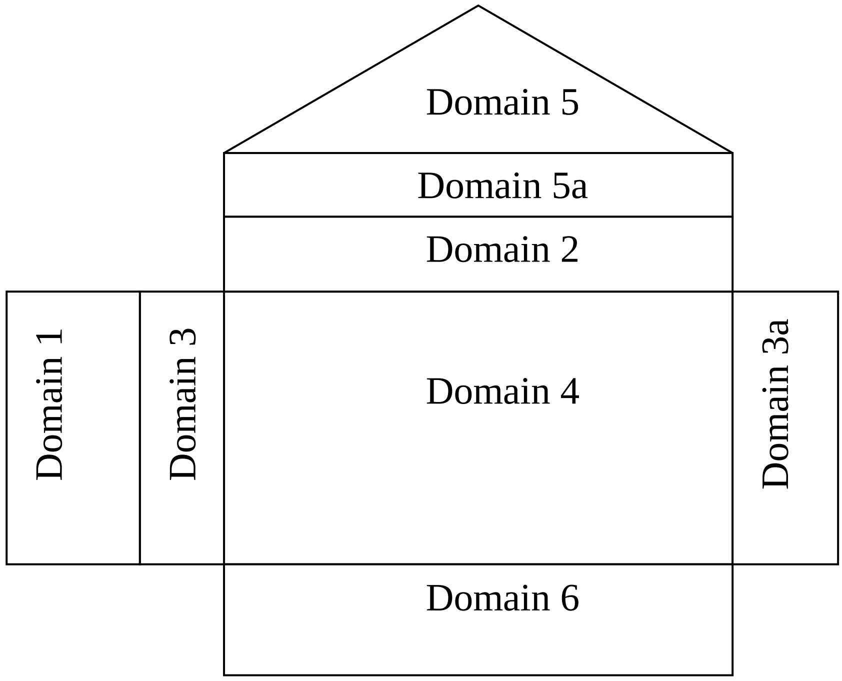


Figure 6.2 Main domains of HoQ

First, CAs are collected from customers (Domain 1). Customer may include suppliers, retailers, vendors, engineering teams, as well as end users. These attributes are categorized into groups to assure traceability. Then engineering teams try to answer the question "how to do it". ECs that affect CAs are listed accordingly (Domain 2).

Considering that not all needs are of equal importance, CAs are prioritized in order to have a trade off basis, when there are conflicting objectives (Domain 3). Weightings derive from assessors' own experience with customers as well as from analytic techniques. The right hand side of HoQ offers a benchmarking tool where customer perception of other brands in response to CAs is depicted (Domain 3a).

Then relationships between CAs and ECs are represented in symbols according to the strength of the relationship (strong positive, medium negative, etc.). This step of the methodology serves to identify how an EC can affect a specific CA (Domain 4).

ECs effect on each other is represented in the roof matrix of the HoQ (Domain 5). Interdependent characteristics are thus displayed and the total outcome of engineering change is visualized. ECs are also marked regarding the direction of the change in that specific characteristic (Domain 5a). Finally, target values and the degree of technical difficulty are set for ECs in order to present the amount of work and its complexity (Domain 6).

The majority of QFD applications stop at the planning stage, i.e., the HoQ. Nevertheless, many benefits can be achieved through the first matrix [**370**].

Overall, HoQ is a renowned planning tool utilized not only in PD but also in managerial context. However, applications show that QFD fails to incorporate uncertainty of decision making into design; importance ranking and target performances are deterministic [**369**]. Limitations of QFD indicate the need for incorporating a decision-making framework into the planning tool [**369**].

Many studies propose the integration of other methodologies into QFD framework. The integration of Fuzzy sets theory into the QFD concept is a recurrent topic in literature. Researchers develop approaches including conventional QFD computation using *fuzzy variables, fuzzy outranking, entropy, fuzzy tendency analysis, fuzzy MCDM, fuzzy integral, fuzzy analytical network process, fuzzy expected value, fuzzy goal programming,* and *fuzzy expert systems* [**371**]. MCDM techniques as well as design methodologies are also employed. In the following section, some hybrid approach examples are reviewed below in order to give an idea of the QFD extensions.

Iranmanesh et al. [**372**] propose an approach, which considers both cost constraints and customer requirements. In a two-phased QFD method, initially design teams set customer satisfaction goals and then a mixed integer structure is employed to minimize cost while satisfying customer requirements. Iranmanesh and Tabrizi [**373**] propose a three phase approach using QFD, the Kano model, and ANP in order to satisfy customer needs by translating them into engineering characteristics.

Yung et al. [**374**] present a PD decision-making model based on QFD, improved by the integration of other techniques. While AHP prioritizes customer requirements; a function-oriented approach verbally describes the functions. Also linear programming is employed for resource optimization, and TRIZ allows innovation. Shaobo et al. [**375**] state that QFD includes some drawbacks such as deficiency for innovative demand, lack of focus on technology planning, as well as technical issues. They propose to integrate TRIZ into QFD in order to reflect invention design.

Hoyle and Wei [**369**] incorporate a mathematical decision making framework into QFD, which extends the QFD mapping matrix concept to qualitatively identify relationships and interactions among product design attributes and provides quantitative assessment through decision-based design principles. Liu [**371**] also focuses on the uncertainty of design decisions in QFD and proposes to employ Fuzzy MCDM to select the best prototype through α-cut operations and fuzzy pairwise comparisons.

Literature shows that the conventional QFD approach is not sufficient for the mapping process in the cases where subjective and vague judgments of experts are involved. Therefore, another direction of QFD extension tends to be towards Fuzzy Sets Theory [**253**]. Fuzzy QFD is employed in cases where conventional HoQ matrix is not sufficient in describing the relationships between the CAs and ECs. Working in a fuzzy environment enables the vagueness of the relationships and subjectivity of the evaluator to be translated into quantifiable data.

Many examples for fuzzy QFD applications are available in the literature. Some recent studies include Ding [**376**] who applies fuzzy QFD to a maritime problem and identifies service solutions for port customers employing fuzzy relationship matrix. Another fuzzy QFD application is proposed by Luu et al. [**377**], who employ the framework to capture imprecise customer opinions on improvement of apartment projects.

Şen and Baraçlı [**370**] investigate enterprise software selection requirements with fuzzy QFD. Linguistic variables are employed to prioritize non-functional criteria in order to provide a decision making framework to determine the order of criteria to be satisfied during software selection decisions of a company.

Malekly et al. [**378**] employ fuzzy QFD to describe CR-EC relationships in linguistic terms in their two-phased methodology for evaluating bridge design. In the second phase, they employ priorities of the first phase to rank the design alternatives with fuzzy TOPSIS.

Yan et al. [**379**] propose the implementation of fuzzy QFD as a group decision support system in the transportation of hazardous materials. Requirements and correlations are defined in linguistic variables to attain a ranking of design schemes.

In their two concurrent studies, Vinodh and Chintha [**380**,**381**] investigate the enabling effect of fuzzy QFD to leanness and agility in a manufacturing organization. Fuzzy QFD is employed to prioritize the lean competitive bases, lean attributes, and lean enablers in one case and agile decision domains, agile attributes and agile enablers in the other by employing linguistic terms for both relationship matrix and correlations.

Lee and Lin [**382**] employ fuzzy QFD in PD. They incorporate fuzzy Delphi, fuzzy Interpretive Structure Modelling and fuzzy ANP into the QFD framework. Linguistic variables are employed for relationships between CAs and ECs. The correlation between CAs is also studied to investigate priorities of PD in CAs, ECs, part characteristics, key process operations, and production requirements.

Liu [**383**] employs fuzzy QFD to investigate priorities in product design and selection by computing the relative importance of CRs, computing the final importance of CRs, and computing the final importance of ECs through linguistic variables. The proposed methodology is also two-phased, with the second phase adopting a MCDM approach. Jia and Bai [**384**] apply fuzzy QFD in manufacturing strategy development. Fuzzy integrated HoQ helps to capture the highly imprecise and vague nature of strategy decisions. Tseng and Lin [**385**] employ fuzzy QFD as a planning tool to deploy and link agility drivers, capabilities and providers for an enterprise. Recent fuzzy HoQ applications in the literature are recapitulated in Table 6.1.

Given that IT planning of CPD projects is dependent on the subjective judgments of CPD managers on requirements and features, our study also employs fuzzy QFD. The integration of fuzzy sets theory into HoQ aims to translate subjective and linguistic judgments of evaluators into quantifiable relationships. In the proposed methodology, CA weightings, CA-EC relationships, and EC correlations are defined in linguistic terms and then translated into triangular fuzzy numbers (TFNs) in the form of (l, m, u). After defining CAs and ECs for the study, an industrial expert is consulted for his judgments. Collected linguistic judgments are thus fuzzified.

Table 6.1 Fuzzy HoQ integrated QFD literature

Author	Technique	Focus
Vinodh and Chintha [**380**]	Fuzzy HoQ	Lean manufacturing
Vinodh and Chintha [**381**]	Fuzzy HoQ	Enhancing agility improvement
Jia and Bai [**384**]	Fuzzy HoQ	Manufacturing strategy development process
Ding [**376**]	Fuzzy HoQ	Service delivery system for ports
Liu [**383**]	Fuzzy HoQ	Prototype product selection
Şen and Baraçlı [**370**]	Fuzzy HoQ	Enterprise software selection
Luu et al. [**377**]	Fuzzy HoQ	Improvement of apartment projects
Malekly et al. [**378**]	Fuzzy HoQ	Creation of bridge superstructure
Tseng and Lin [**385**]	Fuzzy HoQ	Agility development planning
Yan et al. [**379**]	Fuzzy HoQ	Transportation of hazardous materials

Fuzzy computation processes for this study are adapted from Vinodh and Chintha [**380**,**381**],. Relationship matrix and the weights of CAs are employed to compute relative importance of ECs as follows:

$$RI_j = \sum_{i=1}^{n} w_i \otimes R_{ij},\ j = 1, \cdots m. \tag{6.1}$$

Then the correlation matrix is constructed. The final score of the jth EC is computed by the following equation:

$$score_j = R_{ij} \oplus \sum_{j' \neq j} T_{jj'} \otimes RI_{j'},\ j = 1, \cdots m. \tag{6.2}$$

The final score is defuzzified in order to obtain a final crisp score:

$$S_j = \frac{l + 2m + u}{4} \tag{6.3}$$

The ECs are ranked in decreasing order of crisp scores. A higher score of EC implicates a higher priority to consider. Priorities are then normalized in order to be employed as criteria weights in the next phase of the methodology.

The technique offers EC priorities according to CA relationships and importance. It assures identification and prioritizing stages, but it fails to respond to target setting and the following stages. Yet, proper technology planning includes the steps of identification of gaps, prioritisation of issues, target setting/creating action plans, and communication across the organisation [**352**]. Therefore, Fuzzy AD is employed to enhance Fuzzy HoQ with the target concept. In this study, domains 3a and 5a are not considered. Domain 6 is considered in the Fuzzy AD phase.

6.2.2 Fuzzy Axiomatic Design

AD is a frequently employed technique within the QFD framework. Existing literature proposes several studies integrating AD into QFD in order to overcome its design drawbacks. Suh [**114**] recommends the use of AD with a quality matrix, while Manchulenko [**386**] proposes "Axiomatic HoQ" in order to overcome dependence issues of QFD with independence axiom of AD. Table 6.2 summarizes AD integrated QFD studies.

Gonçalves-Coelho et al. [**146**] suggest improving the use of QFD through AD principles. They state that the product design decomposition does not consider product architecture and they propose AD decomposition with FRs and DPs to overcome the dependence issues. Krishnapillai and Zeid [**388**] focus on customizable design and employ QFD integrated with AD. QFD is applied to link "customer functional requirements" (imprecise) into "technical functional requirements" (definite), which are mapped into each product family functional requirements through AD. Also a value is given to the correlation to measure dependency strength. Dickinson [**389**] proposes to integrate AD into Design for Six Sigma (DFSS) for the concept generation phase in order to achieve robustness in design. AD concepts are employed in HoQ to translate customer requirements into specifications, but also they are integrated in other methodologies such as TRIZ, Pugh Analysis, and Robust Engineering for a better DFSS deployment.

Table 6.2 AD integrated QFD literature

Author	Technique	Focus
Manchulenko [**386**]	AD (Independence Axiom)	Conceptual design model
Gonçalves-Coelho et al. [**387**]	AD (Independence Axiom)	Concurrent Engineering
Krishnapillai and Zeid [**388**]	AD (Independence Axiom)	Mass customization
Dickinson [**389**]	AD (Independence Axiom)	Conceptual design model
Zhang et al. [**390**]	AD (Independence Axiom)	Conceptual design model
Carnevalli et al. [**391**]	AD (Independence Axiom)	Facilitating QFD usage
Zhang et al. [**392**]	AD (Independence Axiom)	Requirements analysis
Torres et al. [**393**]	AD (Independence Axiom)	Information flow in CAD systems
Sun et al. [**394**]	AD (Independence Axiom)	Conceptual design model
Runliang and Hui [**395**]	AD (Independence Axiom with Information Axiom prospect)	Energy saving
Tchidi and Zhen [**396**]	AD (Independence Axiom with Information Axiom prospect)	Conceptual design model
Celik et al. [**287**]	AD (Information Axiom)	Shipping investment decisions

Zhang et al. [**390**] develop a conceptual design model integrating AD, TRIZ, QFD and functional basis. HoQ is employed to obtain product design specifications, and then a function-structure model is built through AD, where FRs and DPs are described through a functional basis. If there is a design problem (i.e. a coupled design), TRIZ is employed to handle the issue. Çelik et al. [**287**] develop a decision aid mechanism based on QFD under a fuzzy environment, with the specific context of route investment decisions in crude oil tanker markets. The mechanism includes two other techniques, where Fuzzy AHP derives the weights of performance characteristics of each market while Fuzzy AD ensures selection of the suitable market alternative.

Runliang and Hui [**395**] handles the product energy saving issue with the Design for Energy Saving approach integrating TRIZ, AD, and QFD. Each domain is decomposed through AD, and mapping between adjacent domains is assured by QFD. If there is a contradiction in QFD matrix, the conflict is redefined through TRIZ.

Carnevalli et al. [**391**] define difficulty in interpreting voice of customer, defining and prioritizing quality characteristics, and working with large matrices as QFD drawbacks. They integrate AD principles to establish a QFD application sequence and propose solution alternatives to the problem at hand. Zhang et al. [**392**] combine QFD and AD to handle the limitations of QFD in requirements analysis. Operation tasks, operation abilities, and measures of performance are represented as customer attributes, functional requirements, and design parameters. Mapping between domains is assured through HoQ.

Tchidi and Zhen [**396**] also propose to achieve mapping process through HoQ. They develop an AD model for Six Sigma based on QFD. It is stated that the model reduces design variables of QFD process and loss of information through the PD process. Torres et al. [**393**] present a knowledge-based framework integrating QFD, AD, and FMEA (Failure mode and effects analysis) into a commercial Computer Aided Design system for Product Lifecycle Management. The aim is to increase effectiveness of the information flow while it is being transferred from customer needs to functional requirements, key characteristics, and DPs to geometric DPs.

Sun et al. [**394**] also prefer to integrate multiple methodologies, such as AD, QFD, TRIZ and the Taguchi method, in order to design in response to the actual needs of the users by combining the strengths of each methodology. Accordingly, AD provides a theoretical framework for mapping between domains, QFD serves to translate customer needs into specifications, TRIZ is employed to solve technical problems and the Taguchi method provides parameter optimization techniques.

The most beneficial function of AD methodology lies in its versatility: some QFD integrated approaches employ the design function of AD while others employ the technique as a decision making tool using the information axiom. Two studies [**395**,**396**] consider to integrate information axiom into QFD methodology as future work. Çelik et al. [**287**] integrate information axiom into QFD in a fuzzy environment as Fuzzy AD methodology.

This study employs Fuzzy AD as a MCDM tool to select the most suitable alternative in two stages, according to performance characteristics and technical characteristics.

Fuzzy AD is preferred to conventional AD given that the study is conducted in a fuzzy environment,. As seen in Table 6.2, previous work does not integrate Fuzzy AD into the QFD methodology, nor into the HoQ. The only study that employs Fuzzy AD within the QFD methodology [**287**] does not combine the two techniques but rather it employs them separately to compute the outcome. In this study, Fuzzy AD is employed for the target setting process due to its design range concept. As the study includes incomplete information with subjective judgments, Fuzzy AD is preferred to conventional AD in order to operate in a fuzzy environment. For the detailed description of the methodology, please refer to Section 4.3.2.

In order to apply Fuzzy AD, the independence of the EC's must be assured. This requires that the "roof" of the HoQ must be empty. If this condition cannot be satisfied, then the correlation matrix should comply with an ordered dependence, which assures a decoupled design.

6.2.3 Fuzzy Rule Based Systems

Fuzzy HoQ enhanced with Fuzzy AD puts forward a weighted ranking for the implementation importance of ECs. However, this combined methodology fails to provide a "planning technique" as it fails to capture supporting aspects that are not included in the EC set. Hence, the integrated fuzzy methodology is enhanced by a third technique. The "creating action plans" stage proposed by Lee et al. [**352**] is assured by FRBS, which provide a simple yet effective way to capture fuzzy and imprecise knowledge and translate this knowledge into a decision output. IF-THEN rules are employed to map the fuzzy inputs into fuzzy outputs through fuzzy inference process.

In terms of rule-based process, there are two main types of Fuzzy Inference Systems the Mamdani model and the Takagi-Sugeno model [**397**]. This study considers Mamdani-type FRBS, given that the Takagi-Sugeno model calculates the output with a simple weighted average formula while the Mamdani model operates in fuzzy environment [**398**]. Additionally, a Mamdani type system is suitable to integrate into the proposed methodology due to the intuitive and interpretable nature of the rule base [**397**].

A Mamdani FRBS employs a combination of fuzzification, defuzzification and fuzzy inference. Inputs are translated into linguistic variables through membership functions and then these inputs are mapped by the rule set in order to produce an output through defuzzification. The knowledge base in the Mamdani model is constructed *based on the expert knowledge* and the outcome is not optimized, thus making the model suitable for IT planning methodology. Also, Figure 6.3 depicts a Mamdani-type FRBS.

A Mamdani FRBS can be described by a few simple steps:

- Define the input and output variables
- Determine the linguistic variables and associated fuzzy membership functions
- Design the knowledge base -i.e., the rule set [**399**].

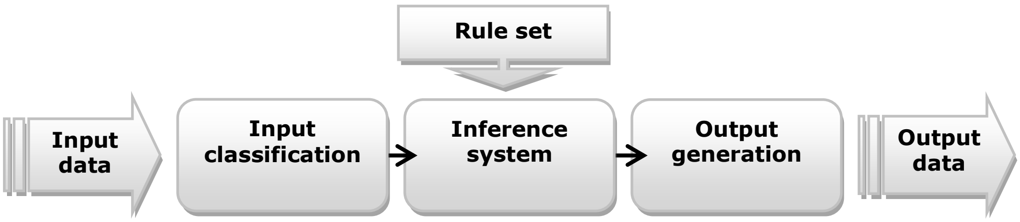


Figure 6.3 Mamdani type FRBS

The Mamdani type fuzzy logic rule can be expressed as follows [**400**]: IF x_1 is A_1 AND x_2 is A_2 AND ... AND x_n is A_n THEN y is B. x_i $(i = 1, 2, \ldots, n)$ are input variables and y is the output variable. A_i $(i = 1, 2, \ldots, n)$ and B are linguistic terms translated into fuzzy membership functions. In this study, the MATLAB Fuzzy Logic Toolbox is employed to implement the technique.

FRBS are employed within various contexts such as railway traffic control, flow time prediction in semi conductor manufacturing systems, urban development modelling, bankruptcy risk assessment, fire support planning, medical diagnoses, geologic slope stability assessment, risk assessment in nuclear power plants, etc [**400**]. However, FRBS literature is very limited in the technology planning domain. Hamundu and Budiarto [**401**] employ the FRBS in knowledge management tools selection while

Üstündağ et al. [**400**] perform an economic analysis of RFID investments using fuzzy inference. Yücel et al. [**402**] employ a combination of ANP, reality-design gap evaluation, and FRBS techniques for risk assessment of hospital information systems implementation.

There are also limited applications of FRBS within the QFD framework; however some studies combine both methodologies. Kuo and Hung [**403**] tackle the problem of eco-design PD, and they employ a fuzzy inference system in the HoQ while translating the voice of the customer into environmental technical measurements. Cheng and Chiu [**404**] state that QFD does not consider the negative relations and limited resources. They propose a two-dimensional QFD framework derived from Kano's model and fuzzy logic. The framework employs fuzzy inferences to identify the customer attributes proposed by Kano's model in order to quantify the relationships in the HoQ. Liu [**405**] extends the Fuzzy QFD from product planning to part deployment. Failure Mode and Effect Analysis is integrated into the methodology within FRBS to derive the risk level of potential failure modes for high importance group part characteristics.

Table 6.3 FRBS integrated QFD literature

Author	Technique	Focus
Kuo and Hung [**403**]	FRBS	Eco-design product development
Cheng and Chiu [**404**]	FRBS, Kano model	Integration of negative relations and limited resources into QFD
Liu [**405**]	FRBS, FMEA	Risk level of potential failure modes
Yaqiong et al. [**406**]	FRBS	Quality management of distributed manufacturing systems

Yaqiong et al. [**406**] present a recent review on quality management of distributed manufacturing systems where they emphasize that both QFD and FRBS are techniques employed in the planning dimension. Recent literature on FRBS integrated QFD studies is presented in Table 6.3. In this study, FRBS are employed to enhance the methodology for the deployment of investment planning decision route.

6.3 INFORMATION TECHNOLOGIES FOR COLLABORATIVE NETWORK

Technological change, especially in PD and collaborative technologies domains, is increasingly rapid and challenging to track. However, services offered by various systems do not transform with the same pace, even though the complexity level of the requirements increases. This section discusses the technological requirements in a collaboration network, available systems and the features of these systems that are considered to be indispensable in a collaborative infrastructure as reviewed in literature and supported by industrial experts.

Collaborative IT systems are generally built on various infrastructures. Commercial software and academic projects based on these infrastructures are numerous to cite and easily outdated. Therefore they were kept out of the scope of this research. Nevertheless, some systems and commercial packages, summarized in [**24**] and [**59**], can be a reference of the services offered by researchers and industry. Frequently employed standards, formats and environments to develop these services present an idea of the technological background upon which CPD is functioning. Commonly used standards, formats, and environments are introduced below in order to offer a guide of the technology upon which collaboration systems are built:

- *IGES (Initial Graphics Exchange Specification):* Vendor neutral data format that allows the digital exchange of information among CAD systems [**407**].
- *STEP (Standard for the Exchange of Product Model Data):* "ISO 10303 Industrial Automation Systems – Product Data Representation", CAD/CAM data exchange standard [**408**].
- *CORBA (Common Object Request Broker Architecture):* Multiple-platform supporting standard that enables software components written in multiple computer languages and running on multiple computers to work together [**409**].
- *VRML (Virtual Reality Modelling Language):* 3D concise representation file format for web-based visualization systems [**410**].
- *X3D:* XML based 3D concise representation file format, successor of VRML [**411**].

- *OpenHSF:* Open format for lightweight 3D visualization using the HOOPS Stream Format (HSF) from Tech Soft 3D [**412**].
- *MPEG-4:* Compression of audio and visual (AV) digital data, includes 3D Graphics Compression Model and 3D Graphics conformance [**413**].
- *J2EE (Java 2 Platform, Enterprise Edition):* Java standard for developing multi-tier enterprise applications; basing them on standardized, modular components and handling many details of application behaviour without complex programming [**414**].
- *Microsoft.Net:* Microsoft's platform for building applications that have the ability to model a range of business processes, applying common skills across a variety of devices, application types, and programming tasks [**415**].

The next sections describe requirements that must be met in a collaborative system and system features supported by the aforementioned technologies that respond to these requirements.

6.3.1 IT Requirements for the Collaboration Network

CPD literature as well as industrial experts express similar opinions when it comes to technological requirements in a CPD project, despite different priorities. These requirements, as presented in the literature and confirmed by our experts, are reviewed in this section.

Two studies consider technological requirements from a conceptual aspect. Li and Su [**416**] state that CPD environment should comprise *scalability, openness, heterogeneity, resources access and inter-operation, legacy codes reusability, and artificial intelligence* as features. According to Rodriguez and Al-Ashaab [**24**], who support a collaborative design view, the requirements to be supported by collaborative technologies are common access of design information, collaborative visualization of the component, and collaborative design of the component. Palacio et al. [**366**] classify SD requirements in four groups: *scale, uncertainty, interdependence, and* *communication.* These requirements form a starting point for both collaboration and development processes.

A recapitulative study by Shen et al. [**76**] suggests requirements such as ontology and semantics based integration, interoperability of product models, product-centric design methodology, knowledge management, collaborative intelligent user interfaces, distributed design project management, drag and drop functionality, security/privacy, self-management, and social software for CPD. These requirements, although highly generic, can provide an idea on the categorization of the requirements.

Requirements of CSD, which can be viewed as a CPD sub-domain, include: *interaction* among members inside and outside the work unit, *knowledge* regarding progress status per work unit, work units assigned to other people, general objective of the programme, goals on which the work units make an impact, programme charter that drives the programme, *awareness* of the status of resources and members per work unit as well as the people collaborating in the programme, *coordination* in common or dependent work units and among members of the work unit, adequate and acceptable means of *communication*, and *control* of the project specifications [**366**].

The literature overview clearly points out to the importance of some common topics. These commonalities are categorized in nine groups under the *Requirements* domain.

Awareness is a constantly underlined issue in technological requirements studies [**59**] and it is defined as the understanding of others' activities [**417**]. *Communication* therefore emerges as a principal requirement in technological planning. On the other hand, Arsenyan and Büyüközkan [**166**] highlight IT as a must to assure coordination and effective collaboration.

Project Management and *Knowledge Management* are two essential requirements as stated in the CPD structure various studies [**11**,**24**,**76**]. These studies clearly suggest that these two requirements should be considered within any type of project, regardless of its collaborative aspect. However, collaboration strengthens the importance of project and knowledge management.

Another important requirement while planning the technological infrastructure of CPD is the *product model* itself. While a collaborative project may implicate products that cannot be modelled (such as software), it generally includes a concrete product to be represented on a 3D level. Therefore, the technological infrastructure should comprise a system that enables the representation, visualization, modification of the product model, as well as other similar activities.

The *Data Integration & Analysis* requirement can be described as a mechanism to integrate data available on different sites from different collaborating teams and to analyze the data in the most efficient manner [**417**]. Integrating all data does not suffice; it is also important to integrate various available infrastructures. Therefore, the *Interoperability* requirement emerges as a natural result of collaboration in order to assure diverse systems work together.

Security and privacy issues arise as CPD projects become a part of the business routine. The security requirement involves data protection as well as system back-up, as mentioned in [**418**]. Accordingly, risk management appears to be another requirement in CPD infrastructure. Defined by ISO 31000 as the effect of uncertainty on objectives, *Risk Management*, which is a requirement to control uncertainties, may result in project failures if unattended. Lastly, CPD infrastructure requires *Technical Support* given that collaborative infrastructure consisting of technology products may often necessitate maintenance and repair services.

6.3.2 Collaborative System Features

Nine requirement groups described in the previous section are met by various tools presented by commercial applications and academic research. These tools are gathered in ten groups, and labelled as *features* of collaborative systems. These groups are identified through the tools introduced by academic research and commercial software and are approved by our industrial experts. Sophistication levels, also approved by our experts, are described following the description of features.

Many academics investigate the means to respond to technological requirements. Palacio et al. [**366**] state that technological infrastructure to meet the specified requirements should include features such as *communication service, a mechanism to share and filter relevant information, a mechanism to spot individual project progress, an interaction mechanism for team members, status updates and tasks progress, a search tool based on profile, status, and activity,* and *synchronous and asynchronous communication*. According to Rodriguez and Al-Ashaab [**24**], key technological requirements for CPD include information *system architecture, communication tool, virtual team management, product model, engineering applications, product geometric representation, and integration with CAD/CAM/CAE commercial software, knowledge representation,* and *project management tools*. These can be labelled as *system features* instead of "requirement."

Computer supported collaborative design applications categorized by Shen et al. [**76**] include *web-based collaborative design, agent-based collaborative design, integration of web and agent technologies, representation schemes, representation systems,* and *PDM/PLM systems (with team management, product structure management, workflow and process management, design change management, visualization based collaborative workspace, integration interface functionalities)*. These applications are considered as features introduced in collaborative systems.

PD oriented studies are also reviewed to support development process at IT planning. Sky and Buchal [**419**] categorize tools to support PD in six groups: *information gathering, drawing and design, analysis and evaluation, general documentation, planning and scheduling, synchronous workspace sharing*. Büyüközkan et al. [**11**] classify concurrent PD tools as *networking and management tools, modelling and analysis tools, predictive tools,* and *intelligent tools*.

Studies clearly suggest the importance of the communication tools. Issues such as frequency, synchronization mode, or authorization levels are secondary topics while discussing the deployment of communication tools. However, it is essential to assure coordination with IT [**418**], and therefore communication tools are considered as primary features in a CPD system.

Literature shows that synchronous and asynchronous communication tools are nearly always included in any collaborative system. *Synchronous communication tools* (instant messaging, chat rooms, videoconferencing, web conferencing, audio conferencing, application sharing, etc.) assure real-time communication while temporally and spatially different communication happens by *asynchronous communication tools* (e-mail, faxing, discussion boards, streaming audio, streaming video, document libraries, etc.). Synchronous communication's drawbacks are large bandwidth requirements and conflicting schedules. Impersonal style and outdated information are listed as asynchronous communication's drawbacks[**59**].

System integration mechanisms are also widely studied in the literature. Some propose web-based interfaces to integrate various design models while others emphasize unification of modelling schemes [**167**]. Shen et al. [**76**] state that encapsulating data and models instead of standardization assures the use of the most appropriate models for the intended tasks.

A *Project management tool* is indispensable in a CPD project and it serves to control and coordinate the virtual team and their tasks [**24**]. Applications such as managing time, cost, human resources, task scheduling, and resource planning is assured through a project management tool presented by CPD systems. It may include scheduler, calendar, etc.

Product visualization is another feature of CPD systems. Collaborative visualization and collaborative design of the product allow collaboration teams to view, design, modify, mark-up, and measure the 3D virtual geometric model. Each application differs in the functions they are presenting. Some CPD systems are reviewed and analyzed according to the features they are supporting in the study presented by Rodriguez and Al-Ashaab [**24**]. Li and Qiu [**59**] analyze commercial visualization systems according to their characteristics and functions.

Document management tools systems aim to store electronic documents and images. Related functions include metadata creation, integration with other applications, indexing, distribution among engineering teams, publishing, and reproduction. This approach enables engineering teams to create knowledge out of the information shared throughout the CPD project.

Content management tools, often mistaken for data management tools serve to manage the workflow in collaborative environments. Working units' roles and authorizations are used as a determinant in data access and modification. They also assure version control and manage the organization's unstructured information flow appearing from different sites and engineering teams.

Described as tools to keep track of the history of a dataset [**417**], *Data Tracking & Analysis Tool* enables the collaborating teams to comprehend the data they are handling. It is an issue related with metadata, which provides contextual description of the data. Data tracking is therefore important as it provides a detailed history of data and its origin. The purpose of the analysis is to handle relevant data by categorizing and modelling, and to transform it in order to extract useful information. The functions of these tools involve the collection, organization, and interpretation of data.

Archiving tools are also important features, where large data is shared by distributed teams as storing, retrieving, and accessing the data are assured by archiving. With appropriate tagging and an effective search tool, engineering teams can exchange data created through the CPD project.

It is important to be able to utilize the information created during the collaboration process. *Decision support tools* become necessary at this stage. From design process to human resource management, decisions are made at each step of the CPD. Therefore a system is required to analyze all data and present a comprehensible report to assist decision makers.

These system features cover all six groups listed by Sky and Bouchal [**419**] and therefore encompass general categories available in current systems.

CPD requirements and system features are recapitulated in Figure 6.4, which emphasizes that both the requirement list and feature list are formed through literature review and finalized by expert reviews.

Table 6.4 presents the sophistication levels of these features as low (L), medium (M), and high (H) and includes a summary of the content at each level.

Table 6.4 System feature sophistication levels

System features		***Sophistication levels***	
1	Synchronous communication tools	L	Only telephone services
		M	Telephone services and IM
		H	Teleconferencing included
2	Asynchronous communication tools	L	Only mailing
		M	Enhanced with discussion boards
		H	Enhanced with wikis
3	System integration mechanisms	L	Integration partly at file transfer level
		M	Integration by universal gateways
		H	Integration at database level
4	Project management tool	L	Spreadsheets
		M	Software such as MS Project
		H	Project tool connected to finance tools
5	Product visualization	L	Only visualization
		M	Visualization and mark-up
		H	Collaborative modelling
6	Document management tools	L	Software such as SharePoint
		M	Enhanced with scanning and imaging
		H	Web based document sharing and publishing
7	Content management tools	L	Basic system without modification
		M	Connection to project management
		H	Enhanced with logistics and finance system
8	Data tracking & analysis	L	In-house data mining systems
		M	Data mining in integrated systems
		H	Executive information systems
9	Archiving tools	L	Local archiving by individuals
		M	In-house archiving tool
		H	Integrated archiving
10	Decision support tools	L	Weighted calculations on spread sheets
		M	Decision trees
		H	Scenarios and simulations

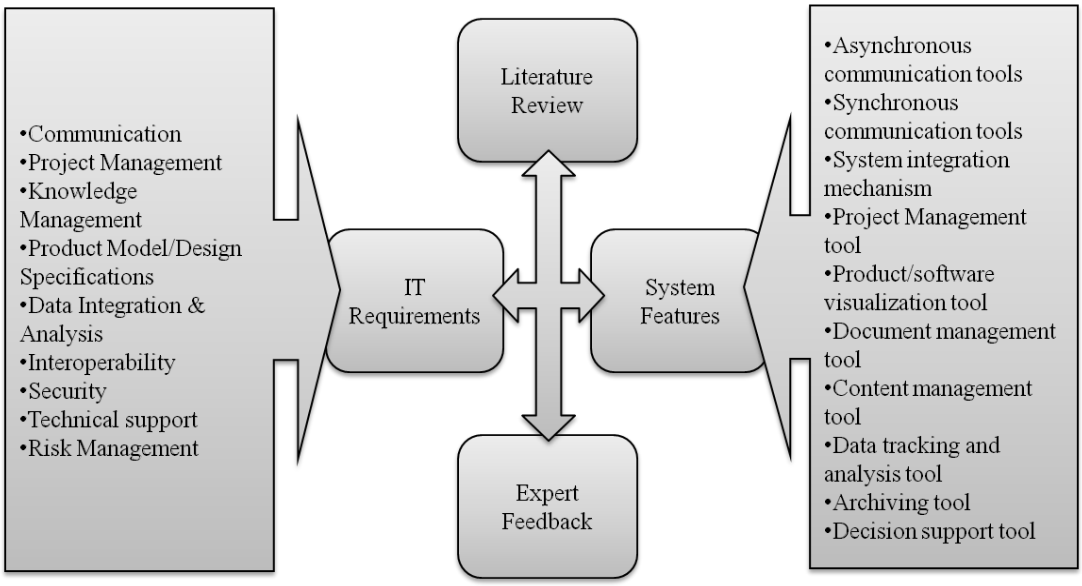


Figure 6.4 CPD requirements and system features

6.4 PROPOSED INFORMATION TECHNOLOGIES PLANNING METHODOLOGY

IT planning includes identifying the subject and the critical requirements, specifying major technology areas and technology targets, and determining the solutions to be pursued [**420**]. The proposed IT planning methodology covers all these stages with three phases: Fuzzy QFD (identifying the subject, identifying the critical requirements, specifying major technology areas), Fuzzy AD (specifying technology targets), and FRBS (identifying the solutions to be pursued). First, fuzzy QFD is applied in order to map the technology requirements into system features and thus to prioritize these features. Then in the next stage, the Fuzzy AD technique is employed to measure how well the collaborative project partners respond to the targets required by the project. The outcome of these two techniques, combined with budget index and usability index are employed to construct IF-THEN rules within the FRBS framework. The outcome of the methodology presents a decision roadmap on improvement priorities of the system features. The proposed methodology is recapitulated in Figure 6.5 and further detailed below.

The literature survey and experts' feedback form the basis of the Fuzzy QFD. The requirements, the system features and their corresponding sophistication levels are defined through review. The requirements and the system features are placed in the HoQ as CRs and ECs. Then the expert is provided with the evaluation form.

First, the HoQ is filled according to the linguistic scales provided within the form, presented in Table 6.5. The weights of the requirements are determined according to the *fuzzy scale for importance levels*. Then the relationships between the requirements and the system features are evaluated with the linguistic variables in *fuzzy scale for relationships*. The correlation scale is used for the "roof" of the house, i.e. definitions of the correlations. This step requires a meticulous evaluation given that the Fuzzy AD technique is employed and the independence of the system features must be assured. Therefore the correlation matrix is constructed on the condition that an uncoupled or decoupled design is assured. Otherwise, system features are reorganized to avoid a coupled design. Then a computation algorithm is employed in order to calculate the priorities of the system features. This phase of the methodology provides the *weight index*.

Table 6.5 Scales for the HoQ

Fuzzy scale for importance levels		
Linguistic variable	***Abbreviation***	***TFN***
Very low	VL	(0, 1, 2)
Low	L	(2, 3, 4)
Medium	M	(4, 5, 6)
High	H	(6, 7, 8)
Very high	VH	(8, 9, 10)
Fuzzy scale for relationships		
Linguistic variable	***Symbol***	***TFN***
Strong	Θ	(7, 10, 10)
Moderate	O	(3, 5, 7)
Weak	▲	(0, 0, 3)
Fuzzy scale for correlations		
Linguistic variable	***Abbreviation***	***TFN***
Strong positive	⊕	(3, 5, 7)
Positive	+	(0, 3, 5)
Negative	−	(-5, -3, 0)
Strong Negative	⊖	(-7, -5, -3)

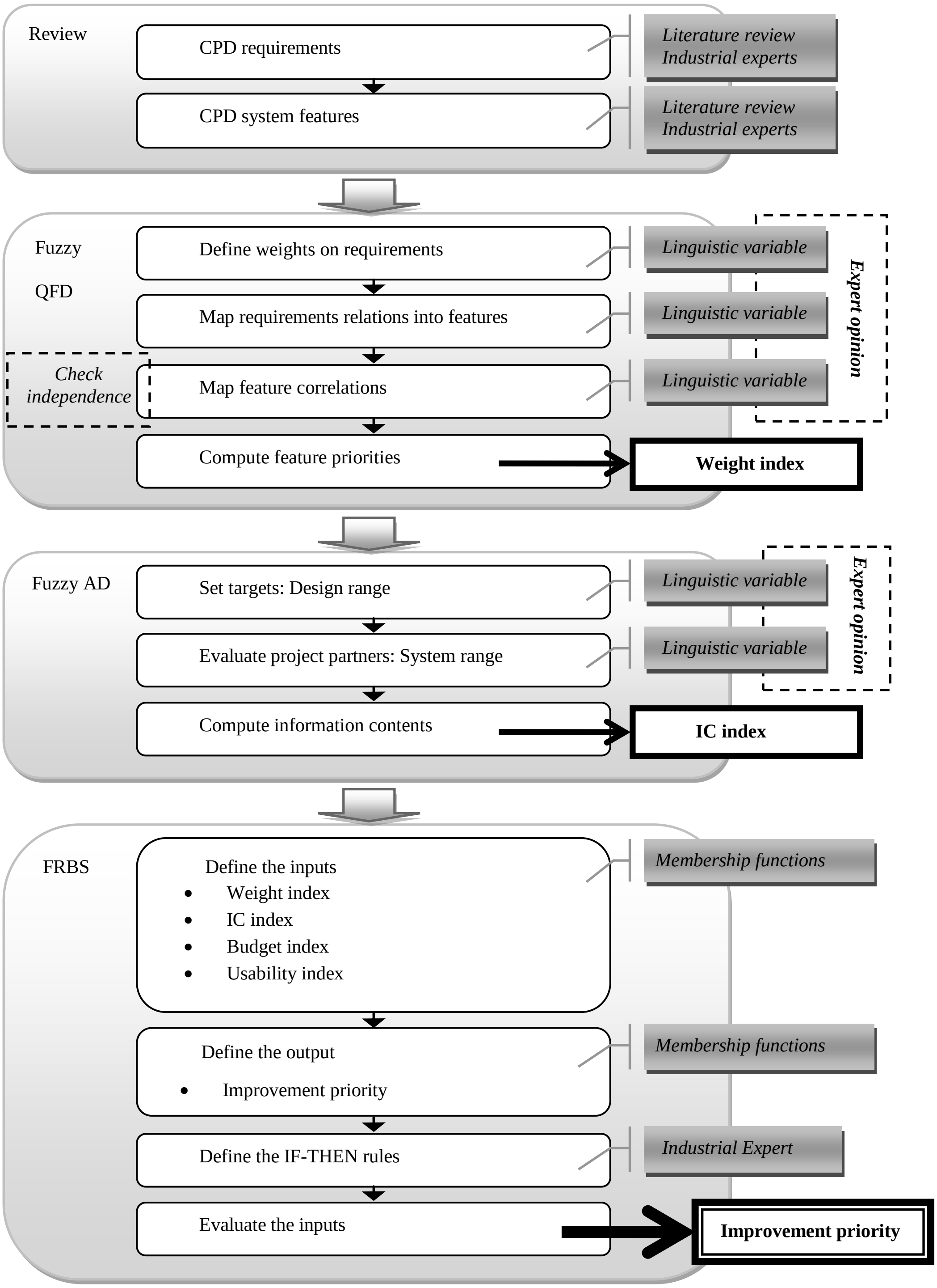


Figure 6.5 The steps of the integrated fuzzy methodology

The second phase includes Fuzzy AD methodology, where the expert is asked to determine the targets for the project. The design range linguistic variables presented in Figure 6.6 are employed to set the targets for each system feature for the specific CPD project considered. Then each partner of the project is evaluated according to the fuzzy scale in Figure 6.7 for its current state regarding each system feature. The Fuzzy AD computation algorithm is then implemented in order to calculate ICs of the system features for each partner. This phase of the methodology provides the *IC index*.

Then the expert is asked to evaluate the budget and usability indices of the partners for each system feature. *Budget index*, for which the membership function is displayed in Figure 6.10, describes how much of the total budget the specific technology investment consumes. If a specific investment consumes a major portion of the budget, it can be said that *the budget index is high*. It is important to notice the membership function of the budget index: it does not range from 0 to 1, but rather from 0 to 0.6 given that an investment that will consume the total budget cannot be envisaged.

The same logic is also valid for the *weight index*. On the other hand, *Usability index*, the membership function of which is displayed in Figure 6.11, defines the time horizon for the technology investment in terms of usability. If a specific investment is useful for more than eight projects, it can be stated that *the usability index is high*. The membership functions of the Weight index and IC index are displayed in Figure 6.8 and Figure 6.9, respectively.

After the indices are defined, they constitute the inputs for the FRBS. The FRBS for the IT planning methodology is constructed in MATLAB Fuzzy Logic Toolbox. Inputs (Weight index, IC index, Budget index, Usability index) are labelled and fuzzy membership functions are established according to the fuzzy membership functions displayed in Figure 6.8, Figure 6.9, Figure 6.10, Figure 6.11, and Figure 6.12, respectively. Then the output is defined to be the improvement priority of the system feature. This constitutes the final outcome of the IT planning methodology. The FRBS is constructed with the intention of providing a technology improvement roadmap. Therefore the improvement priority provides a sequence of improvement for the CPD project. Figure 6.12 represents the fuzzy membership function for the *Improvement priority*.

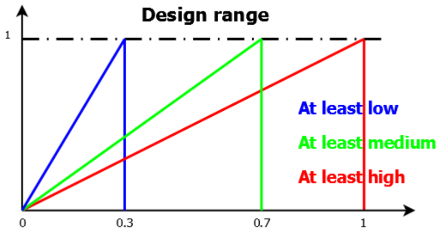


Figure 6.6 Design range for the targets (Fuzzy AD phase)

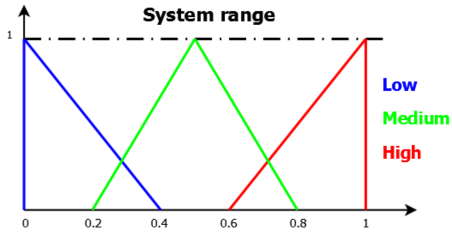


Figure 6.7 System range for the partners (Fuzzy AD phase)

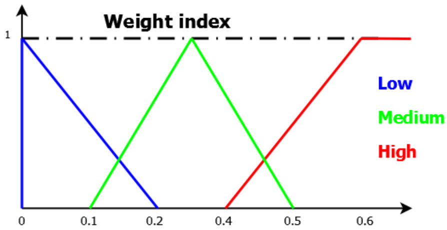


Figure 6.8 Weight index for the technology (FRBS phase)

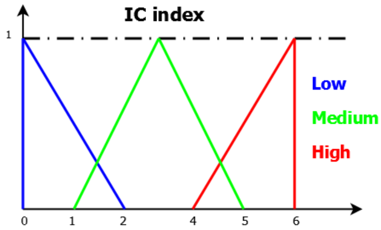


Figure 6.9 IC index for the technology (FRBS phase)

Figure 6.10 Cost/Budget index for the technology (FRBS phase)

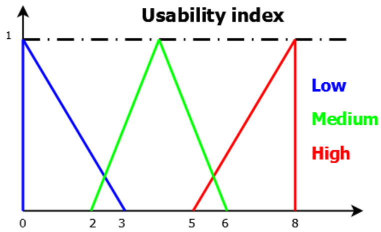


Figure 6.11 Usability index for the technology (FRBS phase)

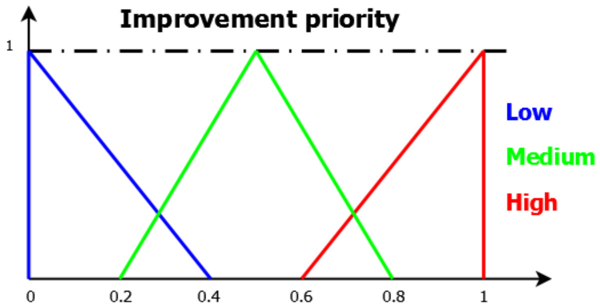


Figure 6.12 Improvement priority for the technology (FRBS phase)

According to Gacto et al. [**421**], the set of rules must be as small as possible under conditions in which the model performance is preserved to a satisfactory level and the number of conditions should be as small as possible in order to ease the readability of the rules. An IF-THEN rule set must be limited to the most essential rules in order to assure the performance of the decision scheme.

The knowledge base is constructed by the assistance of the industrial expert and nine rules are generated. The basic idea is that weight and information indices are the primary decision variables. Therefore, if an IC is high on a system feature, i.e., the feature is not at the required sophistication level, and/or the weight is high on that particular feature, then supplementary indices are employed. A summary is presented in Table 6.6 for the nine rules employed in the methodology.

- RULE 1: IF Weight is high AND IF IC is high THEN Improvement priority is high.
- RULE 2: IF Weight is low AND IF IC is low THEN Improvement priority is low.
- RULE 3: IF Weight is high AND IF IC is medium AND IF Budget index is low THEN Improvement priority is high.
- RULE 4: IF Weight is medium AND IF IC is high AND IF Budget index is low THEN Improvement priority is medium.
- RULE 5: IF Weight is high AND IF IC is low AND IF Budget index is low AND IF Usability index is high THEN Improvement priority is high.
- RULE 6: IF Weight is medium AND IF IC is high AND IF Budget index is NOT high AND IF Usability index is NOT low THEN Improvement priority is medium.
- RULE 7: IF Weight is medium AND IF IC is medium AND IF Budget index is medium AND IF Usability index is medium THEN Improvement priority is medium.
- RULE 8: IF Weight is low AND IF IC is high AND IF Budget index is low AND IF Usability index is NOT low THEN Improvement priority is medium.
- RULE 9: IF Weight is low AND IF IC is medium AND IF Budget index is NOT low AND IF Usability index is NOT high THEN Improvement priority is low.

Table 6.6 Decision rules (FRBS phase)

Rule	Weight index	IC index	Budget index	Usability index	Improvement priority
1	High	High	-	-	High
2	Low	Low	-	-	Low
3	High	Medium	Low	-	High
4	Medium	High	Low	-	Medium
5	High	Low	Low	High	High
6	Medium	High	Not high	Not low	Medium
7	Medium	Medium	Medium	Medium	Medium
8	Low	High	Low	Not low	Medium
9	Low	Medium	Not low	Not high	Low

The FRBS constructed for the IT planning is recapitulated in Figure 6.13. On the other hand, Figure 6.14, Figure 6.15, and Figure 6.16 display surface view of the interactions among indices Weight-IC, Weight-Budget, and Weight-Usability, respectively. Surface views present the effect of rules on the combination of the indices.

The evaluation form is employed to identify the inputs. The outcome of the FRBS emphasizes the importance of the investment for the specific system feature. The IT planning for CPD is performed accordingly. The next section introduces an application of the methodology in a case study.

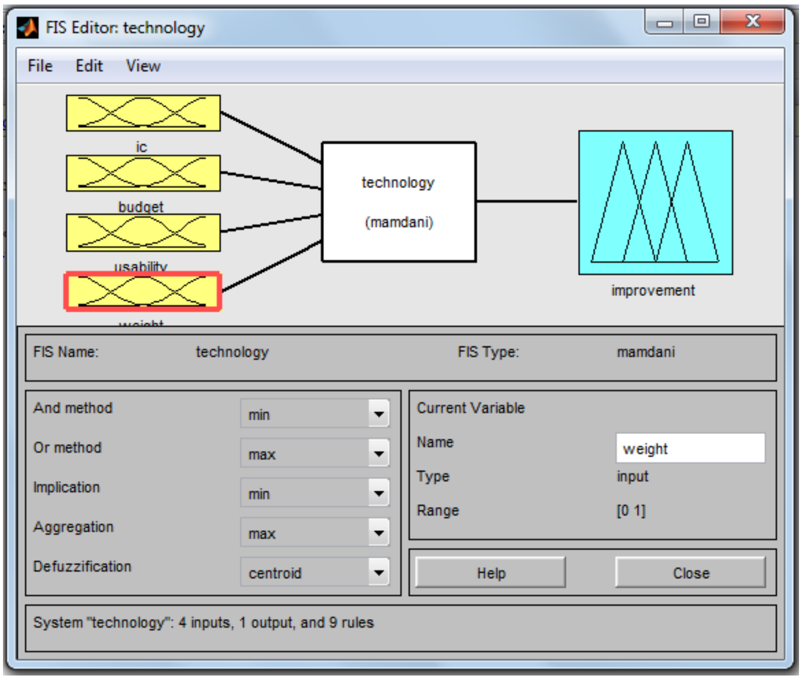


Figure 6.13 FRBS constructed in MATLAB

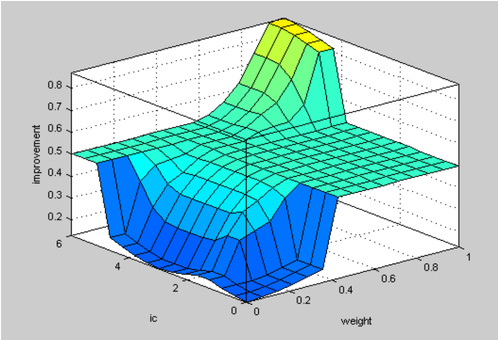


Figure 6.14 Surface view for weight versus IC

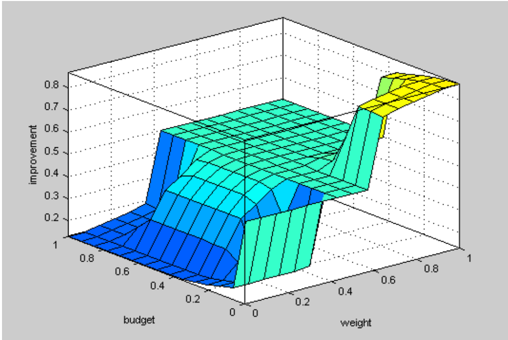


Figure 6.15 Surface view for weight versus budget

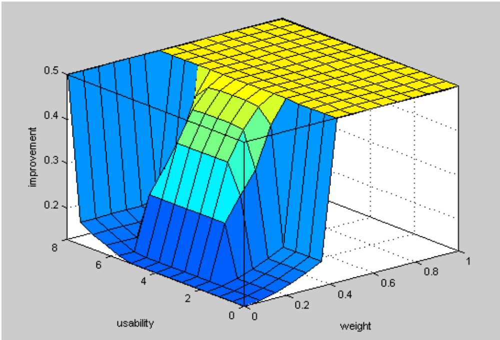


Figure 6.16 Surface view for weight versus usability

6.5 APPLICATION OF THE METHODOLOGY IN A CASE STUDY

Company XYZ wants to develop a library information system (LIS) with three SD companies for a Turkish university. The project basically implies that the entire system must be based on the tools that use newer technology. Today, most of the LIS perform on barcode technologies but this is not an efficient technique given that it requires a lot of time for both the operators and the managers. Consequently, the new project proposes the use of a much faster and easy-to-use RFID technology.

An integrated LIS consists of modules such as cataloguing, circulation, acquisitions, and such, which share a common database and a common interface. In many cases, there is only one entry point for the system and there is no need to access, for example, the cataloguing module or the circulation module. Although these modules are integrated in the system itself, usually they are sold separately. Nearly all systems come with a cataloguing and a circulation module. Only a few systems include Acquisitions and Serials modules at no extra charge. All systems come with Reporting capabilities, but these vary greatly both in the number of reports and in the ability to create custom reports. Some systems also offer an Inventory feature. In a typical client-server system, the Web-based OPAC (Online public access catalogue) constitutes an additional cost, whereas it comes standard in an ASP (active server pages) solution.

Thus, LIS consists of a middleware (RFID software layer), a server (heart of the RFID application system), an application software, an encoder, several tags and readers. The system defines four types of users: students, academic staff, library staff, and the library administrator. A general view is provided in Figure 6.17 in order to present a snapshot of the CSD process.

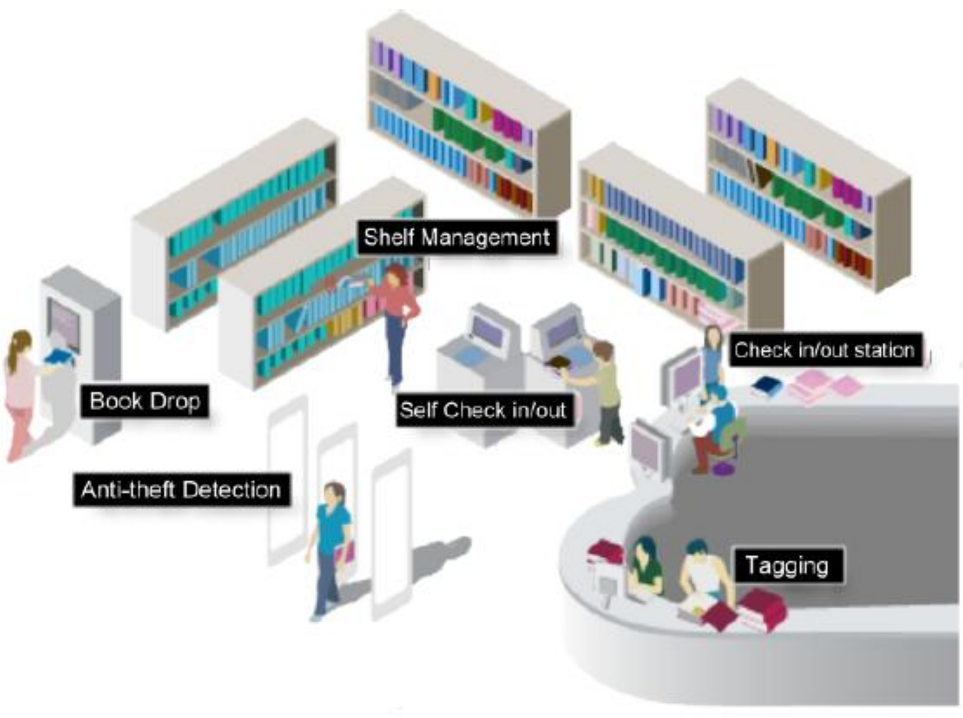
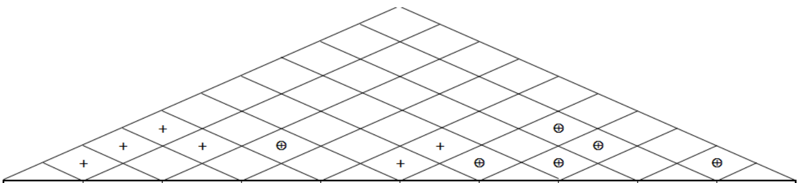


Figure 6.17 General view of the LIS

In order to develop this system, four companies are united for a CSD project. The partners, all being SMEs (Small/Medium size enterprises), are defined as follows:

- *Partner A (Company XYZ):* The party that structures the database schema and that develops the service communicating directly with the database
- *Partner B:* The party that develops the software, which is used by employees and which communicates with the service developed by Partner A.
- *Partner C:* The party that develops the web application, which assures online access for the end user and communicates with the service developed by Partner A
- *Partner D:* The party that assures communication of the applications with hardware.

Before the initiation of the project, the aim is to determine the improvement priorities of system features for each collaboration partner. Our expert, the project manager from Company XYZ, is consulted on the current state of the partners in order to evaluate the system and determine the improvement priorities. The expert makes the evaluation on the from provided, which consists of the extended HoQ described in the methodology section. The outcome on the Fuzzy HoQ is presented in Figure 6.18.



	W	Asynchronous communication tools EC1	Synchronous communication tools EC2	System integration mechanism EC3	Project Management tool EC4	Product visualization tool EC5	Document management tool EC6	Content management tool EC7	Data tracking and analysis tool EC8	Archiving tool EC9	Decision support tool EC10
CA1 Communication	VH	Θ	Θ	O	Θ	O	O	O	O	O	O
CA2 Project Management	VH	Θ	Θ	O	Θ	Θ	Θ	Θ	Θ	Θ	Θ
CA3 Knowledge Management	L	O	O	▲	O	▲	▲	▲	▲	▲	O
CA4 Product Model/Design Specifications	H	Θ	Θ	▲	Θ	O	▲	O	O	▲	Θ
CA5 Data Integration & Analysis	M	Θ	Θ	Θ	O	▲	▲	▲	O	▲	▲
CA6 Interoperability	H	O	O	O	Θ	▲	▲	▲	▲	▲	▲
CA7 Security	VH	O	O	Θ	O	▲	▲	▲	▲	O	▲
CA8 Technical support	H	Θ	Θ	Θ	▲	O	▲	▲	O	▲	▲
CA9 Risk Management	VL	▲	▲	▲	O	▲	▲	▲	O	▲	O

Figure 6.18 Expert evaluation and outcome

The evaluation consisting of CA weights, CA-EC relationships and EC correlations, is translated into TFNs according to Table 6.5 and the fuzzified version of the evaluation is displayed in Table 6.7.

Table 6.7 Fuzzified HoQ Evaluation

	Weight	EC_1	EC_2	EC_3	EC_4	EC_5
CA_1	(8, 9, 10)	(7, 10, 10)	(7, 10, 10)	(3, 5, 7)	(7, 10, 10)	(3, 5, 7)
CA_2	(8, 9, 10)	(7, 10, 10)	(7, 10, 10)	(3, 5, 7)	(7, 10, 10)	(7, 10, 10)
CA_3	(2, 3, 4)	(3, 5, 7)	(3, 5, 7)	(0, 0, 3)	(3, 5, 7)	(0, 0, 3)
CA_4	(6, 7, 8)	(7, 10, 10)	(7, 10, 10)	(0, 0, 3)	(7, 10, 10)	(3, 5, 7)
CA_5	(4, 5, 6)	(7, 10, 10)	(7, 10, 10)	(7, 10, 10)	(3, 5, 7)	(0, 0, 3)
CA_6	(6, 7, 8)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(7, 10, 10)	(0, 0, 3)
CA_7	(8, 9, 10)	(3, 5, 7)	(3, 5, 7)	(7, 10, 10)	(3, 5, 7)	(0, 0, 3)
CA_8	(6, 7, 8)	(7, 10, 10)	(7, 10, 10)	(7, 10, 10)	(0, 0, 3)	(3, 5, 7)
CA_9	(4, 5, 6)	(0, 0, 3)	(0, 0, 3)	(0, 0, 3)	(3, 5, 7)	(0, 0, 3)
	Weight	EC_6	EC_7	EC_8	EC_9	EC_{10}
CA_1	(8, 9, 10)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)
CA_2	(8, 9, 10)	(7, 10, 10)	(7, 10, 10)	(7, 10, 10)	(7, 10, 10)	(7, 10, 10)
CA_3	(2, 3, 4)	(0, 0, 3)	(0, 0, 3)	(0, 0, 3)	(0, 0, 3)	(3, 5, 7)
CA_4	(6, 7, 8)	(0, 0, 3)	(3, 5, 7)	(3, 5, 7)	(0, 0, 3)	(7, 10, 10)
CA_5	(4, 5, 6)	(0, 0, 3)	(0, 0, 3)	(3, 5, 7)	(0, 0, 3)	(0, 0, 3)
CA_6	(6, 7, 8)	(0, 0, 3)	(0, 0, 3)	(0, 0, 3)	(0, 0, 3)	(0, 0, 3)
CA_7	(8, 9, 10)	(0, 0, 3)	(0, 0, 3)	(0, 0, 3)	(3, 5, 7)	(0, 0, 3)
CA_8	(6, 7, 8)	(0, 0, 3)	(0, 0, 3)	(3, 5, 7)	(0, 0, 3)	(0, 0, 3)
CA_9	(4, 5, 6)	(0, 0, 3)	(0, 0, 3)	(3, 5, 7)	(0, 0, 3)	(3, 5, 7)
		EC_1	EC_2	EC_3	EC_4	EC_5
	EC_1		(0, 3, 5)	(0, 3, 5)	(0, 3, 5)	
	EC_2	(0, 3, 5)			(0, 3, 5)	
	EC_3	(0, 3, 5)				(3, 5, 7)
	EC_4	(0, 3, 5)	(0, 3, 5)			
	EC_5			(3, 5, 7)		
	EC_6				(0, 3, 5)	
	EC_7				(0, 3, 5)	
		EC_6	EC_7	EC_8	EC_9	EC_{10}
	EC_5	(0, 3, 5)	(0, 3, 5)			
	EC_6		(3, 5, 7)		(3, 5, 7)	
	EC_7	(3, 5, 7)		(3, 5, 7)	(3, 5, 7)	
	EC_8		(3, 5, 7)			(0, 3, 5)
	EC_9	(3, 5, 7)	(3, 5, 7)			(3, 5, 7)
	EC_{10}			(0, 3, 5)	(3, 5, 7)	

Equation 6.1 is applied in order to obtain RI and then Equation 6.2 is applied on RI to obtain scores for each EC. Fuzzy scores are then defuzzified using Equation 6.3. The final fuzzy and crisp scores are displayed in Table 6.8.

Table 6.8 Fuzzy HoQ priorities

	EC_1	EC_2	EC_3	EC_4	EC_5
Fuzzy score	(272, 4155, 8832)	(272, 3150, 6382)	(432, 2405, 5690)	(250, 4135, 9846)	(656, 1810, 3750)
Crisp score	4354	3239	2733	4592	2007
Fuzzy score	0.13	0.10	0.08	0.14	0.06
	EC_6	EC_7	EC_8	EC_9	EC_{10}
Fuzzy score	(686, 2290, 6904)	(1070, 3425, 9736)	(434, 1840, 4976)	(1058, 2930, 7976)	(452, 1910, 5096)
Crisp score	3043	4414	2273	3724	2342
Fuzzy score	0.09	0.13	0.07	0.11	0.07

Assessing the system feature priorities resulted from the Fuzzy HoQ suggests that the *Project management tool* is the most important system feature according to the evaluation of our expert. This tool is followed by *Asynchronous communication tools* and *Content management tool*, which portray the second important system features according to the evaluation. The *visualization tool* is the least important one given that the project involves SD.

The second stage of the methodology is the computation of Fuzzy AD evaluation. Table 6.9 displays the evaluation of the judgment of the expert on design and system ranges.

Table 6.9 Evaluation for Fuzzy AD

	EC_1	EC_2	EC_3	EC_4	EC_5
Design range	LH	LH	LH	LM	LH
Partner A	M	M	L	L	L
Partner B	H	H	H	M	H
Partner C	M	M	M	M	H
Partner D	H	H	H	M	L
	EC_6	EC_7	EC_8	EC_9	EC_{10}
Design range	LM	LH	LM	LL	LL
Partner A	L	M	H	M	L
Partner B	L	L	L	L	L
Partner C	M	L	L	L	L
Partner D	M	M	M	L	L

Fuzzy AD evaluation is fuzzified according to the membership functions given in Figure 6.6 and Figure 6.7. Corresponding TFNs are displayed in Table 6.10. Three levels of sophistication are labelled as High, Medium, or Low and the design range is labelled according to the minimum level required for each system feature.

Table 6.10 Fuzzified AD evaluation

	EC_1	EC_2	EC_3	EC_4	EC_5
Design range	(0, 1, 1)	(0, 1, 1)	(0, 1, 1)	(0, 0.7, 0.7)	(0, 1, 1)
Partner A	(0.2, 05, 0.8)	(0.2, 05, 0.8)	(0, 0, 0.4)	(0, 0, 0.4)	(0, 0, 0.4)
Partner B	(0.6, 1, 1)	(0.6, 1, 1)	(0.6, 1, 1)	(0.2, 05, 0.8)	(0.6, 1, 1)
Partner C	(0.2, 05, 0.8)	(0.2, 05, 0.8)	(0.2, 05, 0.8)	(0.2, 05, 0.8)	(0.6, 1, 1)
Partner D	(0.6, 1, 1)	(0.6, 1, 1)	(0.6, 1, 1)	(0.2, 05, 0.8)	(0, 0, 0.4)
	EC_6	EC_7	EC_8	EC_9	EC_{10}
Design range	(0, 0.7, 0.7)	(0, 1, 1)	(0, 0.7, 0.7)	(0, 0.3, 0.3)	(0, 0.3, 0.3)
Partner A	(0, 0, 0.4)	(0.2, 05, 0.8)	(0.6, 1, 1)	(0.2, 05, 0.8)	(0, 0, 0.4)
Partner B	(0, 0, 0.4)	(0, 0, 0.4)	(0, 0, 0.4)	(0, 0, 0.4)	(0, 0, 0.4)
Partner C	(0.2, 05, 0.8)	(0, 0, 0.4)	(0, 0, 0.4)	(0, 0, 0.4)	(0, 0, 0.4)
Partner D	(0.2, 05, 0.8)	(0.2, 05, 0.8)	(0.2, 05, 0.8)	(0, 0, 0.4)	(0, 0, 0.4)

Equation 4.15 is applied to the fuzzy values of AD evaluation in order to compute information contents *IC*. The results are displayed in Table 6.11. In this study, ICs are not weighted given that weight and IC indices are employed separately in the FRBS phase.

Table 6.11 Information contents

IC	EC_1	EC_2	EC_3	EC_4	EC_5
Partner A	0.43	0.43	1.59	1.17	1.59
Partner B	0.00	0.00	0.00	0.00	0.00
Partner C	0.43	0.43	0.43	0.00	0.00
Partner D	0.00	0.00	0.00	0.00	1.59
IC	EC_6	EC_7	EC_8	EC_9	EC_{10}
Partner A	1.17	0.43	0.00	0.00	0.00
Partner B	1.17	1.59	1.17	0.00	0.00
Partner C	0.00	1.59	1.17	0.00	0.00
Partner D	0.00	0.43	0.00	0.00	0.00

While considering the weaknesses of the partners with regards to project targets, null information contents imply an appropriate or higher level of sophistication. Accordingly, it can be stated that all partners have a strong IT infrastructure, with Partner D being the best invested party.

Last, supplementary indices are collected from the expert. The results for budget and usability indices are displayed in Table 6.12.

Table 6.12 Budget and usability indices

Budget index	EC_1	EC_2	EC_3	EC_4	EC_5
Partner A	0.05	0.05	0.35	0.05	0.15
Partner B	0.1	0.1	0.2	0.15	0.25
Partner C	0.1	0.1	0.2	0.15	0.25
Partner D	0.15	0.15	0.2	0.2	0.1
Budget index	EC_6	EC_7	EC_8	EC_9	EC_{10}
Partner A	0.05	0.1	0.1	0.1	0
Partner B	0.05	0.05	0.1	0	0
Partner C	0.05	0.05	0.1	0	0
Partner D	0.05	0.05	0.05	0.05	0
Usability index	EC_1	EC_2	EC_3	EC_4	EC_5
Partner A	6	5	5	6	2
Partner B	6	5	4	6	1
Partner C	5	3	3	5	3
Partner D	6	4	3	6	2
Usability index	EC_6	EC_7	EC_8	EC_9	EC_{10}
Partner A	6	5	3	6	4
Partner B	6	6	2	6	5
Partner C	6	6	3	6	5
Partner D	6	6	3	6	4

The improvement priorities are computed through MATLAB. The results on the improvement priorities are displayed in Table 6.13.

Table 6.13 Improvement priorities

	EC_1	EC_2	EC_3	EC_4	EC_5
Partner A	0,16	0,15	***0,17***	0,17	***0,17***
Partner B	0,16	0,15	0,15	0,17	0,14
Partner C	0,16	0,15	0,15	0,17	0,14
Partner D	0,16	0,15	0,15	0,17	***0,17***
	EC_6	EC_7	EC_8	EC_9	EC_{10}
Partner A	***0,16***	0,16	0,14	0,16	0,14
Partner B	***0,16***	***0,17***	***0,16***	0,16	0,14
Partner C	0,15	***0,17***	***0,16***	0,16	0,14
Partner D	0,15	0,16	0,14	0,16	0,14

Required ameliorations are observed in *system integration mechanism* for Partner A, in *product visualization tool* for Partner A and Partner D, and in content management tool for Partner B and Partner C. However, this does not imply a definite improvement; it only provides an input for the planning methodology.

Investments with the highest priorities are displayed in Figure 6.19 with the visualization on the inputs as well as on the output.

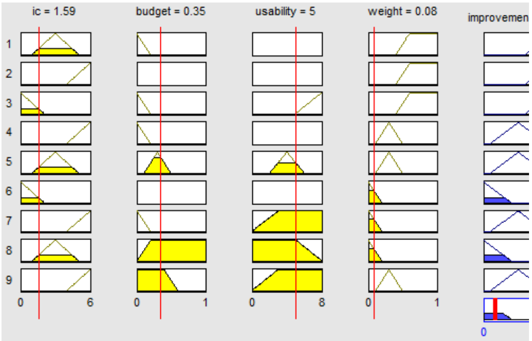
Results show that given the project partners, no improvement has high priority in this project. This is mainly due to the fact that all partners possess well established infrastructures, since they are already in the software business.

However, some improvements may be considered. First of all, all partner should improve their *project management* infrastructure. This is an evident issue, mainly due to the lack of systematic working schemes of partners. On the other hand, Partner A should focus on *system integration mechanism*, and Partners A and D should improve their infrastructure for *product visualization tool*. Partners B and C should improve their *content management tools* for better collaboration performance. Consequently, all features score more or less similarly and result in low priority investment.

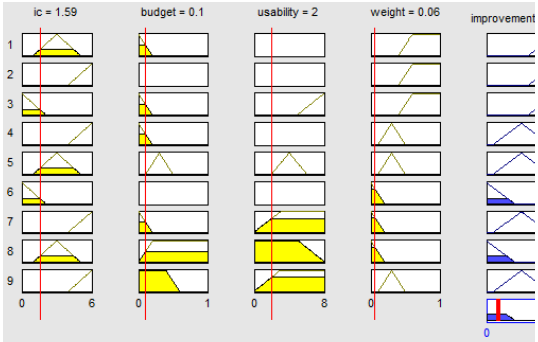
It can also be observed that the communication tools, both synchronous and asynchronous, do not score as high priority investments. This is mainly due to the fact that all partners are within the software industry and the basic requirements for the collaboration are already developed since SD is an intrinsically collaborative process.

Also, decision support tools rank as the lowest in investment priority scores given that all four partners possess the required sophistication levels and the budget index for this tool is null.

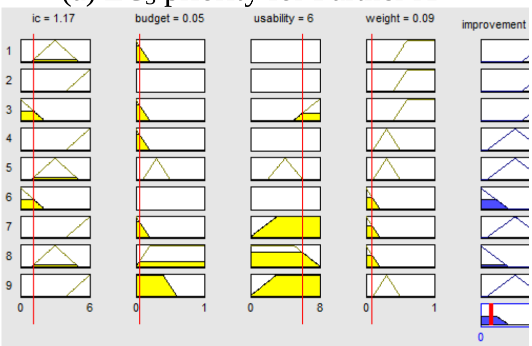
The project manager judged the outcome to be useful in IT planning process of collaborative parties. However, it was stated that the evaluation form, which consists of five different scales and seven different fields, was a challenge to fill. Nevertheless, the evaluation was performed in only two hours, which is an acceptable duration for IT planning of a CSD project.



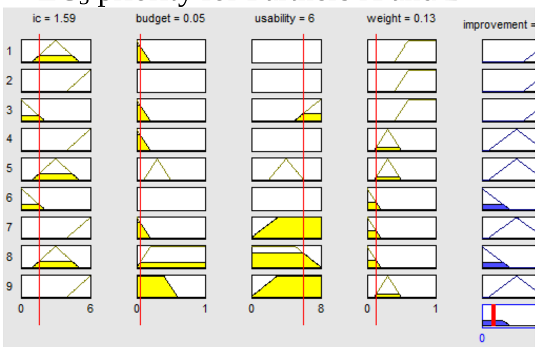
(a) EC_3 priority for Partner A



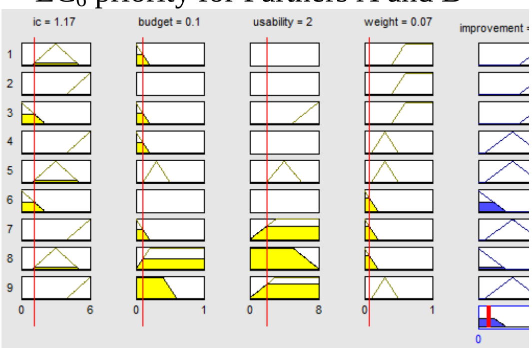
EC_5 priority for Partners A and D



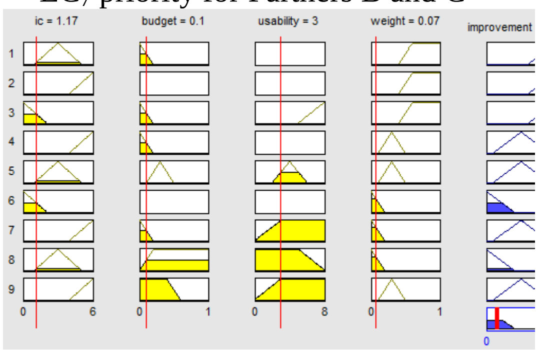
EC_6 priority for Partners A and B



EC_7 priority for Partners B and C



EC_8 priority for Partner B



EC_8 priority for Partner C

Figure 6.19 High priority investments

6.6 SUMMARY

This study presented a Fuzzy QFD based methodology for IT planning in CPD projects. Given that CPD is a highly technology-centric process, it is important to identify the requirements correctly, and plan the implementation of the technologies appropriately.

The contribution of the presented work lies in two aspects. First, it tackles the CPD technology requirements issue by presenting a requirement set that is mapped into the system features available in the technology market. Also it identifies sophistication levels of system features, considering the systems presented by the commercial packages and research project do not respond to identical levels of requirements and therefore, the levels need to be differentiated.

The second contribution of this work derives from the methodology presented. Fuzzy HoQ, Fuzzy AD, and FRBS are combined in order to present a planning framework for the technology improvement decisions. Fuzzy HoQ is employed in order to map requirements into system features and derive system feature priorities. The current state of the partners is matched against the targets of the CPD project in order to measure the information content, i.e. the improvement extent. The outcome of these two methodologies, combined with the budget and usability indices, operate as inputs for FRBS. Nine rules are then developed to translate these four indices into an improvement priority, which constitutes the outcome of the methodology.

Consequently, an improvement priority is identified for each system feature for each project partner, generating an IT planning framework. The outcome of the case study is two-fold. Fuzzy HoQ provides visualization on the relationships of the requirements and the system features and it guides the project manager through the IT aspect of the CSD. IT also acts as a decision support tool for the IT planning phase of the CSD partners. In summary, the feasibility of the methodology is demonstrated through the case study, where the only criticism is on the extent of the evaluation. As a future work, the presented methodology is considered to be adapted to different collaborative projects to verify its performance within other CPD networks.

7 CONCLUSION

In a globally competing business environment where collaboration becomes an obligation, SMEs need to successfully venture and manage CPD projects to maintain a competitive advantage. This research aspired to provide a roadmap for CPD practitioners and especially for SME managers in the Software Industry by structuring and decomposing the process as well as by proposing tools and methodologies for major high points. While the generic approach focused on CPD projects as a whole, the emphasis was on CSD process while structuring and conducting applications.

This research aimed to fill the lack of a holistic approach for CPD by presenting a top-down systematic approach to decompose the process into its requirements and methodologies in order to structure the process for a better management. The objective was to develop a structure to improve the CPD and CSD performance and four sub-problems were defined accordingly. These four sub-problems were tackled separately. The conceptual model provided a holistic view of the CPD/CSD process with a top-down approach, and it showed that CPD/CSD consists of three major dimensions: partnership process, collaboration process, and PD/SD process. Collaboration processes emerges as the most complicated of these three with its four main dimensions, namely trust, coordination, co-learning, and co-innovation. The model was detailed for CSD process, and interviews with industrial experts showed that, apart from some tools qualified as extravagant, the model reflects the whole process from a managerial perspective. On the other hand, the case study confirmed that the conceptual model can be employed as a guideline, with some reservation on the more sophisticated tools, such as TRIZ. The conceptual model is functional in both the introduction of a roadmap and the proposition of a three-dimensional approach.

The second stage of the research used the CPD/CSD model as an input and offered a partner selection framework for CPD/CSD practitioners. Criteria sets were formed according to three-dimensional structure. Partner focused, collaboration focused, and development focused criteria were gathered from the literature and enhanced by experts' reviews. It was established that the type of CPD project defines the importance of criteria dimension. Collaboration focused criteria was considered to be more significant for long-term and repetitive partnerships, whereas development focused was considered to be more substantial for short-term projects where the product itself is more important than the collaboration. The collaboration vision of the evaluator also plays an important role in the evaluation. An innovative and entrepreneur behavior favors collaboration focused criteria while solution focused behavior favors partner focused and development focused criteria.

In the following phase, a mathematical model was developed in order to analyze the collaboration conditions under which CPD negotiations are conducted. The model employed the four main dimensions of collaboration process as an input. These four dimensions, namely trust, coordination, co-learning, and co-innovation, were endorsed by other features such as knowledge investment, knowledge complementarity, development cost, absorption cost, etc. The model investigated the conditions of each partner pair in a collaborative network. Scenario analysis was conducted to observe the model under game theoretical principles, specifically Nash Bargaining game. The analysis put forward that the amount of knowledge investment and the symmetries between the firms acts as a major factor on the revenue sharing decision. Trust, as emphasized before in the conceptual model, emerges as another major factor that needs to be carefully examined while negotiating the collaboration conditions.

The last phase of the research included technological planning for CPD. As highlighted in the conceptual model, the development process is initiated by the successful implementation of the collaboration process, which includes the establishment of a technology infrastructure. One contribution of this stage was the identification the technological requirements and the responding system features within CPD. Another contribution was to develop a QFD based methodology, enhanced with Fuzzy Sets Theory, Fuzzy AD, and FRBS for the planning of the technology investment path. The methodology helps to map the requirements to the system features and develop an investment planning route accordingly. The evaluation is project-based and therefore the outcome varies according to the specific needs of each CPD project.

This research showed that CPD is a highly complex but manageable process within the software industry if a systematic approach is adopted. The intrinsic complexity occurring from diverse teams and organizations working together can be overcome by carefully decomposing the process and analyzing its components. The four stage research provided a roadmap for CSD practitioners and the applications in the software industry noticeably supported the assistance of the methodologies developed throughout the collaboration. In addition, the presented work being in the scope of a TUBITAK project, it can safely be stated that the outcome of this research will have industrial implications beyond the theory and limited CSD applications. It is anticipated that this research will be applied in further cases in CPD scope.

This research aspired to put forward a holistic approach for the CPD, and it covered the general guidelines, partnership formation, negotiating conditions, and planning the infrastructure issues. CSD process was emphasized throughout the study within the applications and case studies. Nevertheless, being a dynamic and strategic process, CPD requires further attention. The proposed approaches need to be applied and verified in CPD processes. Investigating the behavior of the proposed model in various CPD environments from different industries can be considered as a future work. Application of the proposed models in further case studies may help the development of performance metrics in order to measure CPD performance. Network perspective and time concept can be considered as perspective approaches in order to enhance the practicality of the proposed models. Also, group decision making can be applied during the expert evaluations to consider and combine different perspectives.

On a final note, the proposed models and approaches can be considered separately or as a whole to develop new models for different network structures.

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