

**COLLABORATIVE-CROWDSOURCING PRODUCT
FULFILLMENT FOR OPEN DESIGN AND MANUFACTURING**

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by

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COLLABORATIVE-CROWDSOURCING PRODUCT
FULFILLMENT FOR OPEN DESIGN AND MANUFACTURING

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LIST OF SYMBOLS AND ABBREVIATIONS

A^I	Open innovator
A^D	Design agents
A^M	Manufacturing agents
B^D	Design contracting brokers
B^M	Manufacturing contracting brokers
C^0	Customer orders
F^0	Product specs
F	Function structure
f_p	Functional subtask
F_i	Design request for quotation
p_i^D	Design bids
D	Design bids set
D*	Design spec set
p_i^{D*}	Selected design bids
D^0	Design specs
Δ	Product structure
δ_q	Manufacturing subtask
Δ_j	Manufacturing request for quotation
p_j^M	Manufacturing bids
M	Manufacturing bids set
M*	Manufacturing spec set
p_j^{M*}	Selected manufacturing bids
P^0	Process specs
Γ^D	Design configuration broker
I^D	Design agent invitation broker
E^D	Design evaluation broker
ψ^i	Bidding design agents
ψ^N	Non-bidding design agents

Γ^M	Manufacturing configuration broker
I^M	Manufacturing agent invitation broker
E^M	Manufacturing evaluation broker
μ^j	Bidding manufacturing agents
μ^N	Non-bidding manufacturing agents
C^D	Design supply contracts
ψ^{i*}	Preferred bidding design agents
C^M	Manufacturing supply contracts
μ^{j*}	Preferred bidding manufacturing agents
$X(t)$	Fraction of bidding agents in design agents
$Y(t)$	Fraction of bidding agents in manufacturing agents
c_u	Capacity unbalance index
π_d	Design fundamental income
π_m	Manufacturing fundamental income
b_d	Design bidding cost
b_m	Manufacturing bidding cost
b_d^*	Corrected design bidding cost
b_m^*	Corrected manufacturing bidding cost
Π	Extra income
$\Delta\pi$	Corrected extra income
g	Distribution coefficient
D_1	Design agents bidding states
D_2	Design agents non-bidding states
M_1	Manufacturing agents bidding states
M_2	Manufacturing agents non-bidding states
S	States space
f_d^S	Fitness of design agents
f_m^t	Fitness of manufacturing agents
\bar{f}_d	Average fitness of the design agents
\bar{f}_m	Average fitness of the manufacturing agents

e_1, e_2, e_3, e_4, e_5	Equilibrium points
(X^*, Y^*)	Coordinates of the fifth equilibrium point
J	Jacobian matrix
τ	Trace of Jacobian matrix
Δ_J	Determinant of Jacobian matrix
ρ_1, ρ_2, ρ_3	Variables for the Jacobian matrix simplification
F_{fr}	Design fulfillment range
F_{pr}	System performance range
D_{fr}	Supplying fulfillment range
D_{pr}	Production performance range
$c_{r_i}^{F_i}$	Design evaluation criteria
$c_{s_j}^{P_j}$	Manufacturing evaluation criteria
$DoS_{c_{r_i}^{F_i}}(p_i^D m_i)$	Degree of satisfaction of $p_i^D m_i$ with $c_{p_i}^{F_i}$
w	Weighting factor
$TDoS(p_i^D m_i)$	Total degree of satisfaction of $p_i^D m_i$ with F_i
$UDoS(p_i^D m_i)$	Normalized degree of satisfaction of $p_i^D m_i$ with F_i
I	Information content
$u(F_{fr})$	Preference of design fulfillment range
$u(D_{fr})$	Preference of system fulfillment range
$p(F_{pr})$	PDF of design bids performance
$p(D_{pr})$	PDF of manufacturing bids performance
$P(F_{pr})$	The probability of success of F_{pr}
$P(D_{pr})$	The probability of success of D_{pr}

CM	Cloud Manufacturing
CBDM	Cloud-Based Design and Manufacturing
CNs	Customer Needs
CPF	Collaborative Product Fulfillment
C ² PF	Collaborative-Crowdsourcing Product Fulfillment
CPS	Cyber-Physical System
CUI	Capacity Unbalance Index
DoS	Degree of Satisfaction
DPs	Design Parameters
ECC	Evolutionary Competition-cooperation
ESS	Evolutionary stable strategy
FRs	Functional Requirements
ICT	Information and Communications Technology
IoT	Internet of Things
MAS	Multi-Agent System
MC	Mass Customization
MTTF	Mean Time to Failure
NE	Nash Equilibrium
OBM	Open Business Model
OD	Open Design
ODM	Open Design and Manufacturing
OI	Open Innovation
OM	Open Manufacturing
PDF	Probability Distribution Function
PVs	Process Variables
RFQ	Request for Quotation
SME	Small and Medium Enterprise

SUMMARY

The open business model has attracted much attention from academia and industries alike. It implies many new opportunities for product innovation to transcend traditional boundaries and leverage diverse capabilities and resources by coherently integrating external partners into the design and manufacturing processes. Such trends lead to the decentralization of the product fulfillment process. Particularly, the open business model offers the opportunities for the small and medium enterprises to fulfill various customer needs in an innovative crowdsourcing manner.

While open design and manufacturing sounds appealing, research on formal formulation of crowdsourcing product fulfillment has been very limited. The underlying challenge for adoption and reversion of the open business strategy is the difficulty in justification of the population dynamics of crowdsourcing. This thesis puts forward *collaborative-crowdsourcing product fulfillment (C²PF) for open design and manufacturing*. This work proposes a new product fulfillment workflow to accommodate the decentralized yet collaborative product fulfillment process.

The research focus is geared towards the instantiation of the open design and manufacturing with a highly individualized dental braces fulfillment process as a case study. The thesis investigates the fundamental issues underpinning open design and manufacturing. A game-theoretic decision framework is proposed to deal with such critical issues as (1) group decision-making in the product fulfillment processes, (2) dynamics analysis of the external partners' population, and (3) collaboration-negotiation contracting scheme based on an information contents measure.

Since the boundaries are opened to the external partners, the product fulfillment decision-making processes must be reengineered to adapt the collaborative-crowdsourcing process. The workflow of C²PF is established. The supply contracting mechanism is identified as the key pillars to support the product fulfillment flow.

In addition, to model the population dynamics of the partners, an evolutionary competition-cooperation game theoretic model is established. The relationships among participation fraction of the partners, the balance of inter-domain capacity, and income and distribution have been established. It reveals a competition-cooperation relationship between the external partners and a co-evolutionary characteristic of the entire population. This model provides a guideline for the management of the open enterprise, with considering of the long-time prosperity.

Moreover, to achieve the collaborative crowdsourcing, a generalized supply contracting evaluation mechanism has been proposed. This mechanism supports the collaborative-negotiation from the bidding perspective. The evaluation mechanism handles the uncertainty, aggregates multi-criteria evaluation results and ensures the satisfaction of the requirements. The proposed theory is applied to the open design and manufacturing, respectively.

Furthermore, a case study of the dental brace product fulfillment process is reported to demonstrate the feasibility and potential of the proposed C²PF framework. The case study illustrates the roles of the stakeholders through C²PF and shows the steps of the execution of the proposed process. This case study serves as a validation of the proposed open physical product fulfillment methodology.

CHAPTER 1. INTRODUCTION

This chapter provides an overview of background knowledge leading to this research topic. Through the discussion of research motivation, the topic of research is identified as C²PF for open design and manufacturing. It suggests itself as a critical enabler of physical product fulfillment under the open business model, which should suggest companies apply the open approach in design and manufacturing via collaboratively crowdsourcing. Accordingly, the research objectives and scopes are defined, along with a technical roadmap of this research.

1.1 Emerging of Open Business Model

Manufacturing companies are confronted with challenges for satisfying individual customer needs while efficiently managing product variety in order to fulfill product development better than their competitors (Brettel et al. , 2014, Jiao et al. , 2003). The extent of market-of-one has been foreseen as a prospective driving force for the next transformation of the global economy (Pine, 2009). The traditional mass production paradigm has been shifted towards mass customization (MC) (Pine, 1993, Tseng et al. , 1996). Customer involvement in value creation through innovative product fulfillment becomes imperative for manufacturers to address customer satisfaction (Koomsap, 2013).

On the other hand, nowadays information and communications technologies (ICT) are undergoing exponential growth. Many disruptive technologies have been advocated for manufacturing industries and are continuously emerging, such as cloud computing, Internet of Things (IoT), big data analytics, cyber-physical systems (CPS), to name but a few. These new technologies are nowadays penetrating manufacturing and serving as critical enablers

for the manufacturing industry to address current challenges for customization and quick response. For example, the vision of industry 4.0 describes the synergy of IoT and CPS in manufacturing environments to make manufacturing systems smarter and more autonomous, leading to high agility and flexibility of the production system (Weyer et al. , 2015). This trend brings pervasive connectivity to the manufacturing environment and allows the collection of a significant amount of real-time information (Monostori et al. , 2016).

In such information explosion age, the “Big Data” has been introduced to the industry to support the decision-making (Brown et al. , 2011). As a result, the application of the “Big Data” can not only excellence the quality of the product design and production, but also usher in the socialization product design and the predicting of the supplier’s performance (Li et al. , 2015). The emerging cloud computing helps the real-time collaboration of various stakeholders and creates intelligent networks for efficient fulfillment (Xu, 2012). The smart manufacturing technologies like additive manufacturing significantly reshape the realization of the digitalized knowledge (Ratto and Ree, 2012) and reorganize the traditional supply chain to the network (Holland et al. , 2017). Thanks to the advancement of CAx software, collaborative product fulfillment (CPF) opens the access of the group’s simultaneously modification of the digital files and serves the organization of distributed knowledge to ensure successful outcomes (Zhen et al. , 2011). Because the collaboration across entities can increase the competitiveness of companies, it has been recognized as one core characteristic of Industry 4.0 (Schuh et al. , 2014).

The fusion of these state-of-the-art technologies brings together the ease of integration process, which marks the advent of the pervasive increasing willingness of

invite external partners to the product and service development (Füller, 2010, Malhotra and Majchrzak, 2014). The widespread of such willingness intrigue a growing amount of enterprises are choosing the open approach as their entire business model (Kortmann and Piller, 2016). This trend of applying open business model (OBM) has been recognized as a paradigm shift (Chesbrough, 2006b). By applying OBM, the enterprise can concentrate on their core competing activities, while crowdsourcing the peripheral activities to their external collaborators. The open design and manufacturing (ODM) is the extension of the instantiation of the OBM in manufacturing industries, and the open designer and open manufacturers are invited to contribute the product fulfillment.

Different from traditional outsourcing, crowdsourcing utilizes an open call to a crowd for exploring the external resources maximally, instead of an assignment to a designated agent (Bücheler and Sieg, 2011). Collaborative-Crowdsourcing is developed as the extension of crowdsourcing, which includes a population of heterogeneous workers to work complementarily and collaboratively to handle a complex task (Pan et al. , 2016). This approach highlights the collaboration among the heterogeneous collaborators to ensure the accomplishment of the task, which is essential for the physical product fulfillment. Inspired by the collaborative-crowdsourcing, the traditional CPF should be reengineered to a C²PF to adopt the open approach in physical products' design and manufacturing.

1.2 Research Objective

The traditional product fulfillment flow is an all-in-one and cascading decision-making process, the integration of the external partners is incompatible with it. In order to

implement the ODM, which collaboratively crowdsource the product fulfillment jobs to the external partners, several crucial technical issues and corresponding research tasks are identified.

(1) Proposing of the group decision model for C²PF. The proposing model is compatible with the collaborative crowdsourcing, which supports the team construction under the ODM and negotiation for the group decision making. Corresponding research tasks are conducted as follows:

- a. Formulate the workflow along C²PF;
- b. Identify the stakeholders and their roles in C²PF;
- c. Develop the contracting mechanism to support the team construction and negotiation.

(2) Establishment of a dynamics model for the agents' population to serve the decision-making in open enterprise. This model reveals the inherent mechanism of the participation and reversion to the ODM and can be taken as a guideline to seek the prosperity in a long time span. The related tasks are:

- a. Establish an evolutionary competition-cooperation game model to describe the relationships of the agents in open enterprise;
- b. Derive the replicator equations to model the dynamics of the agents' population;
- c. Analyze the stability of the equilibrium points in the state's space and derive the revision protocol as a guideline of the decision-making in open enterprise.

(3) Formulation of the supply evaluation mechanism to support the supply contracting. The C²PF requires a collaborative team, which is constructed by open call and contracting. This contracting mechanism requires a generalized evaluation of the bids based on the satisfaction of the requirement and handle the uncertainty. This evaluation mechanism is compatible to ODM. The related researching tasks are:

- a. Establish the bids selection methodology;
- b. Formulate the degree of satisfaction as the foundation of the evaluation process;
- c. Instantiate through ODM.

1.3 Research Scope

The C²PF is proposed as a new product fulfillment paradigm through design and manufacturing of physical products. It attempts to open the boundaries of traditional product fulfillment processes to crowdsource the jobs to the collaboration crowds. First, the research is motivated by the emergence of OBM which leads to a pervasive willing of applying the open business strategy in manufacturing industries. Then, the scope narrows down to the formulation of the workflow of the C²PF, the contracting mechanism is entailed, and the evaluation has been highlighted. Next, the key to the long-time prosperity of the open enterprise is identified as an agents' population dynamics. An evolutionary population dynamics model is established to model the adoption and reversion of the C²PF. The third step is the development of a supply contracting evaluation mechanism based on the information contents measurement. Such evaluation is a crucial enabler of the

collaborative-negotiation contracting with designers and manufacturers. At last, to validate the C²PF through ODM, a case study of dental braces fulfillment is conducted.

1.4 Organization of This Thesis

In this regard, this research proposes the C²PF to achieve open design and manufacturing of physical products. Therefore, the fundamental issues are examined in Chapter 3. A frame of the workflow of C²PF is established in Chapter 4. An evolutionary game theoretic model is developed for the analysis of the population of designers and manufacturers in Chapter 5, to seek the prosperity of the open enterprise. The evaluation mechanism for the supply contracting is the foundation of the collaborative-negotiation for contracting, which is established in chapter 6. The technical threads underlying this thesis are organized as Figure 1.1.

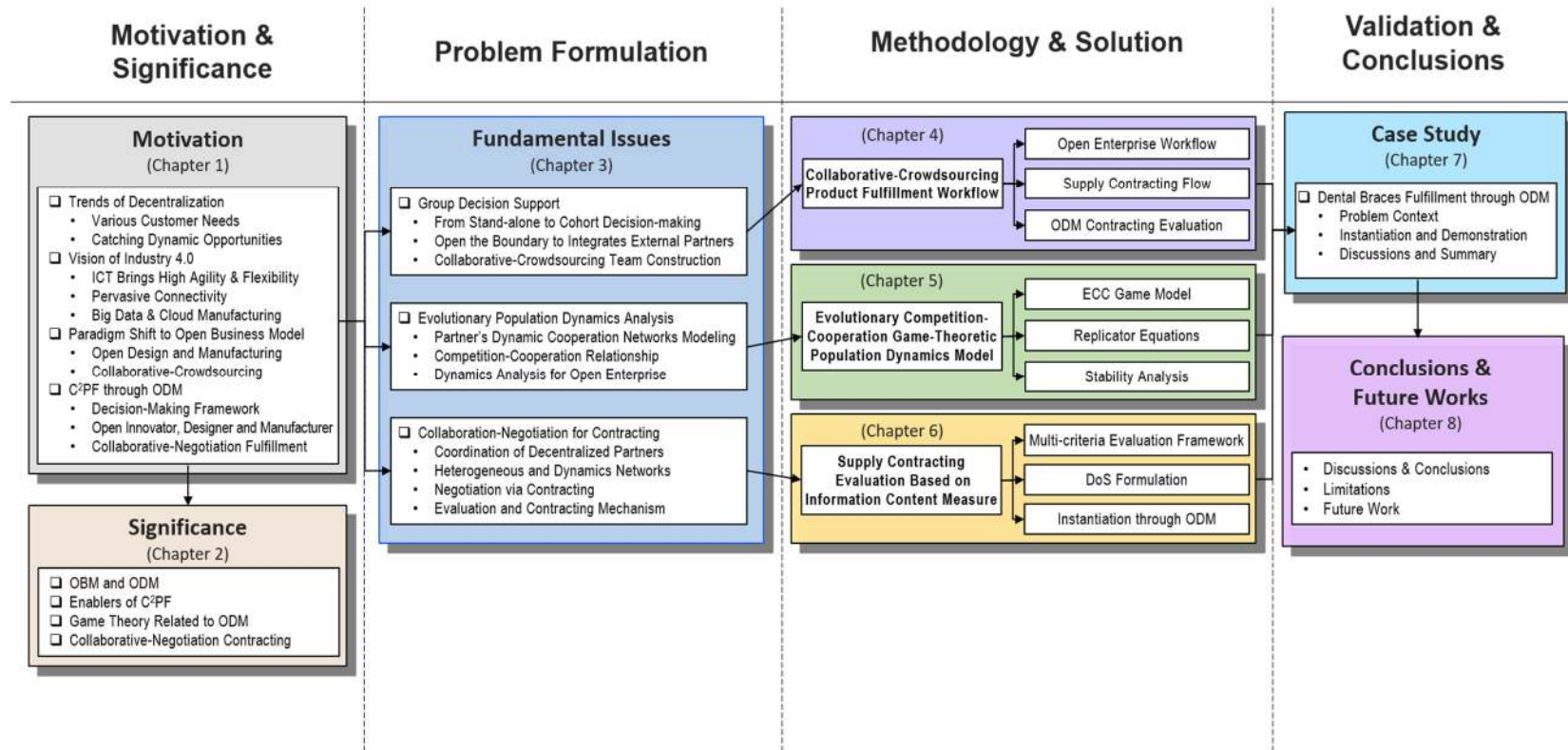


Figure 1.1 Organization of this thesis

CHAPTER 2. LITERATURE REVIEW

The background leading to the application of the ODM covers five areas, namely from open business model to open design and manufacturing (Section 2.1), enablers of collaborative crowdsourcing (Section 2.2), game-theoretic decisions in design and manufacturing (Section 2.3), and collaborative-negotiation contracting (Section 2.4). A framework of reference will be elaborated to point out their relevance and limitation, which leads to the significance of this research.

2.1 From Open Business Model to Open Design and Manufacturing

OBM is defined as utilizing the external partners' assets to develop own business model (Chesbrough, 2006a). OBM enhances the firm's efficiency by leveraging external resources in value-creating processes and achieving high utilization of not only the firm's key assets but also the external partners' resources in value capture process (Chesbrough, 2007). As a later supplementary of the OBM, open innovation (OI) is applied to depict the distributive innovation process based on purposively managed flows across the organization's boundaries (Bogers et al. , 2017). OI has been recognized as an opposite of the traditional vertical integration model, regarding develops and distributes the products by one firm (Chesbrough et al. , 2006). OI horizontally structures a dynamic interaction network of various clusters of autonomous firms throughout the innovation process (Dhanaraj and Parkhe, 2006). Moreover, from a platform-based view, an increasing amount of the industries organize the firms as a central platform structure, the core firm seeks the inflow of the external knowledge, while the other firms are surrounding them to outflow their knowledge (Gawer and Cusumano, 2014). Among the accesses to the external

knowledge, crowdsourcing is highlighted and described as the open innovator broadcasts the problem to the crowd and select the best solution, instead of outsourcing a problem to a designated agent or solving it internally (Afuah and Tucci, 2012, Howe, 2006).

Focusing on the context of product fulfillment in open enterprise, the open design (OD) and open manufacturing (OM) is introduced to depict the collaboration with the external designers and manufacturers crowds through the product design and manufacturing processes, respectively (Bauwens, 2009). The conception of OD origins from the open source method from the software industry, which has created the legends like Linux and Wikipedia (Weber, 2004). OD often entails the collaboration of external designers to design the subsystem, which can be integrated by an open architecture harmoniously (Vallance et al. , 2001). The practice of OD is enabled by a designer community and the internet-based communication technologies, which significantly reduce the cost of virtually team structuring and collaboratively operating (Koch and Tumer, 2009). However, since the physical products are increasingly data-centric and digitalized, the OBM propagates from software development to the fulfillment of tangible products (Raasch et al. , 2009). Because of the indispensable role of manufacturing in the physical products' value realization process (Koufteros et al. , 2014), the manufacturing process is assessed as a challenge for the implementation of the OBM through physical product fulfillment process (Maurer and Scotchmer, 2006).

Recent studies highlight a series of perspectives to support the collaboration of a crowd of manufacturers, which utilizes OM and cloud manufacturing (CM). OM depicts an enterprise structure which integrates the knowledge of manufacturing from the distributed manufacturer community to support the manufacturing operation (Maurer and

Scotchmer, 2006). CM is a new manufacturing paradigm which integrates the network, cloud computing and smart manufacturing technologies into the transformation process of manufacturing resources and capabilities to the manufacturing services (Zhang et al. , 2014). Both approaches pave the way for the collaboration of the manufacturer crowds in the context of the physical product fulfillment. Thus, with the support of an open-source platform, the crowds of designers and manufacturers can be configured as a collaborative team to fulfill the physical product (Banerjee et al. , 2015).

However, with an increasing interest in the OBM and related issues, there is limited research shed light on the underlying dynamics of the adoption of the OBM. Several factors in this field are highlighted, which includes partner's anticipation payoffs, value capture ability, the prosperity of the collaborator crowds, and coordination inner the open enterprise. (Appleyard and Chesbrough, 2017, Brunswicker and Chesbrough, 2018, Van de Vrande et al. , 2009). Furthermore, there is still an absence of formulated ODM workflow (Bogers, Zobel, 2017).

2.2 Enablers of Collaborative Crowdsourcing

For the achievement of C²PF, the coordination of the designer and manufacturer crowds requires pervasive connectivity, which is offered by the spread implementation of industrial IoT, mobile internet, and smart sensor technologies (Gil et al. , 2016). Thanks to the quick advancement and spread of ICT, the technological foundations of the decentralized and networked cooperation product fulfillment process are constructed (Wulfsberg et al. , 2011).

Meanwhile, the traditional standalone CAx systems have been developed to support the multi-user adoption and CPF (Hao et al. , 2006). This technology trend enables

operative profit enhancement and lead time reduction in product design, manufacturing, and supply chain management (Chen et al. , 2004, Shen et al. , 2008, Wang et al. , 2009). Additionally, by applying cloud-computing technologies, the cloud-based design and manufacturing (CBDM) builds up the bridges between the individual design partners while offers the opportunities of inter-organizational real-time communication and coordination in the design modeling, analysis, optimization, and validation process (Wu et al. , 2013a). Because of the support from the cyber platform, the paradigm of CBDM enables the rapid finding of the optimal resources allocation among the crowds for various demands and smooths the path of the collaboration (Wu et al. , 2013b). Meanwhile, the cloud-based manufacturing helps the design team exploiting a set of various and distributed available manufacturing resources for efficiency enhancement of the realization of product design (Wu et al. , 2015).

However, the collaboration of C²PF highly depends on the service and communication platforms throughout the product fulfillment process (Richardson, 2016). The trends of digitization of product design process and smart manufacturing technologies enable the implementation of these platforms in the C²PF process (Boisseau et al. , 2018). As a result, a massive amount of data will be generated along the whole process, and the efficiency of utilizing these data is the critical factor for the success of the C²PF in this big data era (LaValle et al. , 2011). In this era, the CPS can be applied to the management of the big-data, leverage the interconnectivity of the physical manufacturing equipment, to achieve an agile and intelligent manufacturing system (Lee et al. , 2015). This technological idea also leads to the conception of “Digital Twin,” which is a seamlessly integrated simulation model along the C²PF process to mirror the life of the physical

product twin to achieve high competitiveness (Tao et al. , 2017). From a supervisory level, this concept can also boost the replacement of the central re-planning process in the production system, with an autonomous process of the reconfiguration of product and production units (Rosen et al. , 2015). Thus, a simulation model of C²PF can be established, and the optimal configuration of the C²PF process can be searched based on the performance of the digital twins. The synergy of these cutting-edge technologies consists a set of enablers of C²PF.

2.3 Game-theoretic Decisions in Design and Manufacturing

Research in decision support for C²PF includes decision-based design, set-based reasoning, distributed problem solving and the negotiation mechanism. The decision-based design is a perspective that the designer's decision-making process is bridging the gap from idea to reality by finding satisfying solutions (Hazelrigg, 1998, Mistree et al. , 1990). The current research about decision-based collaborative design includes the adoption of linear programming method to solve the continuous variable problem (Mistree et al. , 1993) and discrete method to model the demands (Wassenaar and Chen, 2003). Meanwhile, the set-based reasoning expands the optimal solution of the parameters from single points to a range, to handle the uncertainty (Davin and Modi, 2005). The distributed problem solving considered the entire design process to a consolidated problem and solve it by decomposing it hierarchically, while minimizing system level inconsistency and maintaining discipline-level feasibility (Kroo, 1995). Thus, a collaborative product development problem can be modeled as a multi-objective optimization to seek a Pareto efficiency with distributed constraints satisfaction (Binnekamp et al. , 2006, Petrie, 1996). The negotiation mechanism among the agents can be modeled based on the decision-making process considering multi-

target negotiation protocol, which includes price, lead time and parameters (Ganguly et al. , 2008, Lin et al. , 2012, 2014).

Among these methods, game theory has been highlighted as a solution of supporting the decision-making of a decentralized system. The classic game theory focuses more on the decision-making of rational individuals under a static setting. The classic game theory can be categorized into cooperative game, competitive game and hierarchical game (Liu et al. , 2013), and all of these three can be applied to support the decision-making in product development (Tang, 2006). In practice, game theory can model an equilibrium to support the analysis of the behaviors of the MAS, considering the interactions among the agent population (Xiao et al. , 2005). However, the evolutionary game extends this theory to the dynamic circumstance. Since the agents who cannot approach a maximum fitness in a dynamic environment will be driven out, the evolutionary game can be applied to predict the population which is playing a game (Mailath, 1998). Based on the previous decisions made by the agents, their fitness will be evaluated based on the payoff, and the population will update the proportion of making decisions to reach an evolutionary steady state in a long-time scale (Friedman, 1998). The evolutionary stable states formulate the equilibrium situation, which means the composition of the population can be restored after the disturbance (Smith, 1988). The evolutionary game theory has been recognized as a powerful predictor in the analysis of the population dynamics in the decentralized system, since the decision from a group with a higher fitness will be selected after a long-time scale interaction with agents from other groups (Feng et al. , 2008, Wang et al. , 2011, Zhang et al. , 2007). The evolutionary behavior of the agents under dynamic circumstances can be

modeled, and the results can be applied as a guideline of the decision examination (Xiao and Yu, 2006).

2.4 Collaborative-Negotiation Contracting

The mechanism of collaborative-negotiation supply contracting has been studied extensively, which can be divided into two streams, included centralized optimization (Arntzen et al. , 1995) and distributed problem-solving (Pena-Mora and Wang, 1998). Because of the autonomous agents in practice subject to the different set of constraints and targets, the distributed problem-solving shows a superiority, where the agents collaborate and negotiate dynamically and achieve equilibrium as an overall functionality (Sadeh et al. , 2001). The MAS technology is a paradigm for the researching of the organizational architecture, decision-making processes and cooperation and coordination mechanism for the distributed, knowledge-based, autonomous problem-solving modules (Brenner et al. , 2012, Gupta et al. , 2001). MAS collects a set of agents to consist an agent population; each agent has their perspective and incentives to maximize its utility in a dynamic circumstance (Jennings et al. , 1998). The individual agents work independently or interactively and cooperatively to solve the problem, and their local goals and objectives can be integrated by the negotiation of the supply contracts to achieve the system's overall goals (Kaihara, 2001). The MAS can be applied to analyze the supply chain coordination issue considering information, material, and financial flow (Dudek and Stadtler, 2005, Gaonkar and Viswanadham, 2001, Govindan and Popiuc, 2014). With the combination of evolutionary game theory, the coordination mechanism and the behavior of the agents in an evolutionary environment can be modeled (Xiao et al. , 2007).

The systematical tasks are decomposed into subtasks, and a crowd of the agents can bid based on their individual constraints from a communication channel (Jiao et al. , 2006). Based on the requirement of the specific subtask, the bids will be evaluated, and the incentives will be awarded to the winning contributor (Simula and Ahola, 2014).

2.5 Chapter Summary

The topics reviewed in this chapter provide the guidance to solve the fundamental issues involved in C²PF in open design and manufacturing in the next chapter. The limitations of various topics are explored and reviewed in this chapter. The proposed methodologies and solutions overcome their respective limitations and address a specific step of the C²PF processes in Chapters 4, 5 and 6.

CHAPTER 3. FUNDAMENTALS OF C²PF

Recognizing the importance of collaborative crowdsourcing in the ODM, this chapter examines the fundamental issues underlying C²PF for the physical products, which includes the group decision model for C²PF, evolutionary population dynamics analysis, and collaboration-negotiation contracting. Understanding these fundamental issues is crucial to this research and thus leads the way of the formulation of the workflow of C²PF in the next chapters and the underlying population dynamics model and contracting mechanism in the later chapters.

3.1 From Conventional Fulfillment Flow to C²PF

In a traditional view, a manufacturer implements a series of activities to develop the product, and thus, fulfill the customer needs. This process is depicted as a cascading mapping of “what-how” relationship across four domains, which is named as the axiomatic design (Suh, 2001). Such design framework includes customer, functional, physical and process domain, respectively, and the mapping relationship starts from customer needs (CNs) to functional requirements (FRs), to design parameters (DPs), and to process variables (PVs), consecutively (Jiao et al. , 2007). Traditionally, the mapping from domain to domain is processed centrally.

However, with the acceptance of the OBM, the open enterprise must cooperate with the external partners in different aspects of the product fulfillment process, includes OI, OD, and OM. OI is a value-creation strategy, which is defined as a distributed innovation process with the management of inter-organizational knowledge flows across the boundaries (Chesbrough et al. , 2014). After this term was coined in 2003 (Chesbrough,

2003), several modes of OI have been observed from the practices, which differentiate from the spectrum of partners and number of phases (Lazzarotti and Manzini, 2009). Among these modes, the open innovator has higher partner variety and more open phases, besides, the partners are involved in the activities of the product fulfillment process, includes the function specification, design, and manufacturing.

Besides, the application of the open strategy requires the collaboration of external partners, which challenges the traditional fulfillment flow management. The partners are embedded in an inter-organizational network, and the relationships are contractually tied to collaboration for the fulfilling of the knowledge along the flow (Simard and West, 2006). The supply contracts can formally formulate the transaction between the stakeholders to pursue the coordination of decision-maker and organize them into a supply chain networks (Giannoccaro and Pontrandolfo, 2004). In the real practice, every organization and entities are operating under heterogeneous environment, objectives, and constraints (Swaminathan, 1996). As a result of collaboration scheme, the entities have to consider the cohort behavior, rather than the individual operation, to achieve the general functionality along product fulfillment flow and negotiate with the peers to find a compromise solution (Sadeh, Hildum, 2001). Such negotiation works involve the supply contracting that coordinates the material and knowledge flow, which can be depicted in the agent-based model (Jiao, You, 2006).

A house-pillar-foundation diagram is shown in Figure 3.1 to explain the organization of an open enterprise, taking C²PF as its essential workflow. The open innovator, open designer, and open manufacturer are three pillars of the house of open enterprise. Because

of the C²PF forms the relationship between the pillars, it supports three pillars as the base of the house.

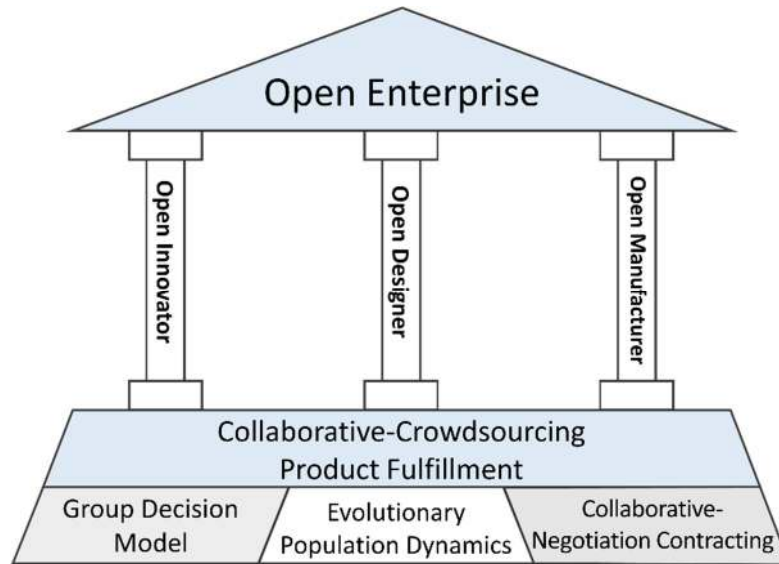


Figure 3.1 Technical pillars for C²PF

An illustrative example is introduced to demonstrate the proposing theory. An orthodontist fulfills his patients' order of braces, which are highly individualized and required to apply latest technologies and respond rapidly. The orthodontist can plan the treatment, which is the translation of the CNs to FRs and can manage the design and manufacturing processes. However, the orthodontist lacks the knowledge and resources to execute the appliance design and manufacturing. Thus, the orthodontist implements the ODM and crowdsources the product fulfillment jobs to the external partners. The collaborative network of the autonomous external partners can be viewed as a multi-agent system (MAS). The orthodontist plays the role as an open innovator, which is responsible for the treatment planning and the final implementation and delivery, the external partners

include open designers and open manufacturers, which cooperate as agents. They consist the open enterprise, which applies the ODM by applying the C²PF.

3.2 The Group Decision for C²PF

The traditional design framework is a series of actions centrally cascading across the domains. However, such decision framework is proposed for the traditional enterprise, which fulfills the product all-in-one instead of crowdsourcing to the partners. However, besides the traditionally open call to invite a global crowd to solve a job, constructing a collaborative-crowdsourcing team has been highlighted to ensure the effectiveness from the practice perspective (Tazzini et al. , 2013). The job crowdsourcing process constructs a collaborative team, which centers around the context of product development. It is essential to reengineer the centralized product fulfillment flow to a collaborative group decision-making scheme to support the effectiveness of this team. Because the partners in the C²PF are working simultaneously, the job distribution, team construction, coordinated planning and collaborative group decision-making has been identified as the critical challenges for the effectiveness collaborative-crowdsourcing team construction (Li et al. , 2018, Red et al. , 2013). An ideal C²PF team structure should ensure the achievability of product fulfillment, and collaborative group decision-making process to maximize the efficiency.

3.3 Evolutionary Population Dynamics Analysis

The dynamical partners' cooperation network is crucial to C²PF, because of the inherent openness. Thus, the governance of the networks is critical to the effectiveness of the implementation of OBM (Tiwana et al. , 2010). However, the relationship among the

community is multi-fold, and the analysis of the crowd dynamics are complicated. The physical products fulfillment requires collaboration between designers and manufacturers. Besides, after the open call to the crowd, if the agents decide to bid, they will compete with their peers for the rewarding from supply contracts. The open enterprise's fulfillment capacity relies on the willingness of the bids from both design and manufacturing domains.

However, this willingness is based on the operational success of the open enterprise and the individual partner's revenue. Thus, from a long time span, the proportion of making bidding decision in the population of designers and manufacturers show a strong co-evolution. If the bidding decisions can bring an excessive profit, the proportion of bidding agents will increase. Otherwise, a decrease will be observed. To sum up, the significance of a population dynamics model has identified. Such model should be able to depict the adoption and reversion of the ODM in the agent population. The corresponding population dynamics analysis can be taken as a critical guideline for the individual decision making and the open enterprise management in ODM.

3.4 Collaborative-Negotiation for Contracting

Since the partners in C²PF are decentralized and organized in a network, the C²PF can be viewed as a supply chain with knowledge and material flow which fulfill the product design and manufacturing, respectively. In a dispersed supply chain network, decision-making of the autonomous partners highly depends on the decisions from other partners (Swaminathan et al. , 1998). However, because the crowdsourcing partners operate in heterogeneous environments, the negotiation and coordination among the contracting can be identified as a dynamic and varying process (Gaonkar and Viswanadham, 2001). To

fulfill a customer order, an individual partner has to coordinate with downstream and upstream partners via a set of contracts (Jiao, You, 2006). Thus, the negotiation problem can be summarized as a multi-contract negotiation problem with a context of product fulfillment.

In the typical supply contracting process, the candidate agents bid with their bids, and the selection of awarding partners is based on the evaluation. This evaluation process is the foundation of the awarding activities in the contracting, and the preferred agents will be involved as collaborative partners to fulfill the product in the open enterprise. A poor selection of the agents and bids can give rise to a significant amount of cost (Ahlmann, 2002, Pahl and Beitz, 2013). Thus, evaluation is the key to the prosperity of the open enterprise and evaluation criteria for the design and manufacturing bids should be established to serve the open enterprise's operation. However, neither design nor manufacturing evaluation is based on single criterion process, the multi-criteria evaluation criteria for the bids should be established.

3.5 Chapter Summary

This chapter examines the fundamental issues underlying C²PF for the physical products. These issues include the group decision model for C²PF, evolutionary population dynamics analysis, and collaboration-negotiation contracting. Their correlations and the influence of the C²PF has also been elaborated. Such profound understanding provides us a clear direction of the methodologies and solutions in the following chapters.

CHAPTER 4. PRODUCT FULFILLMENT THROUGH COLLABORATIVE CROWDSOURCING

Recognizing a paradigm shift to ODM, this chapter proposes a product fulfillment workflow through the ODM and explains the fundamental mechanism underlying the fulfillment process, which includes the supply contracting mechanism, and evaluation for design and manufacturing. Understanding these fundamental issues is crucial to this research and thus achieve the product fulfillment in the open enterprise structure.

4.1 Workflow of Collaborative-Crowdsourcing Product Fulfillment

The paradigm shift to ODM implies offering the integration path of external partners into all activities in the value creation and capture, such as product design and manufacturing. With the involvement of the external partners, the product fulfillment is achieved based on the collaboration of multi-parties in four physical domains: open product innovation domain, C²PF platform, open design domain, and open manufacturing domain. The open innovator A^I has been identified as a stakeholder in open product innovation domain, who takes in charge of collecting the CNs, specify the FRs and final product delivery. The stakeholder in open design domain has been identified as the design agents A^D , who generate design solutions. The stakeholder in open manufacturing domain is manufacturing agents A^M , who generates the manufacturing plans considering the processes capability constraints and resources utilization limitation.

The C²PF platform is the fourth domain, it is a bridge to the open product innovation domain in the front end and the open design and manufacturing domain at the back end. It has two virtual fields, includes C²PF management and open supply contracting

mechanism. The C^2PF management field is responsible for the management of the specs in the fulfillment process. The open supply contracting mechanism is responsible for the negotiation and contracting with A^D and A^M . Two stakeholders are identified as design contracting brokers B^D and manufacturing contracting broker B^M , who take in charge of the open calls, negotiation and contracting with the A^D and A^M .

Based on the roles in the fulfillment workflow, the stakeholders in C^2PF can be categorized into five agents cluster: open innovator A^I , design contracting brokers B^D , design agents A^D , manufacturing contracting brokers B^M , manufacturing agents A^M .

Inspired by the axiomatic design model, the workflow of C^2PF through open design and manufacturing is shown in Figure 4.1.

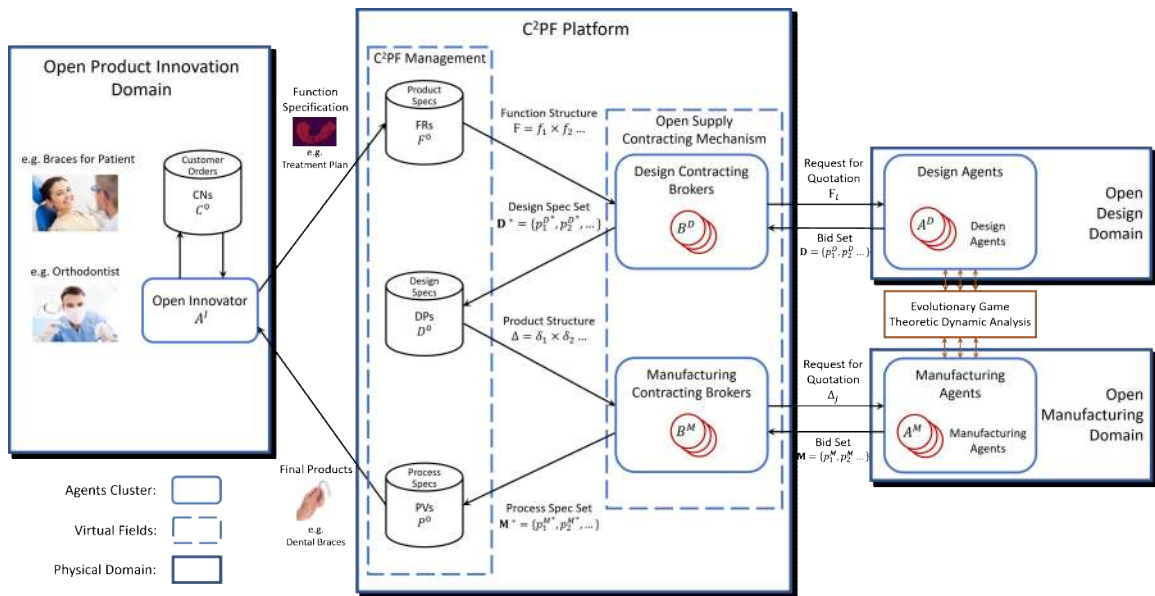


Figure 4.1 Product fulfillment process in the open design and manufacturing

The CNs represents a set of the customer orders, includes the expectations of the open enterprise's products. The CNs are collected and saved as customer orders C^0 by A^I and then translated to the functional domain as FRs. A^I considers the engineering concerns and develops the FRs based on the related technologies. The FRs are saved as

product specs F^0 , after the data processing, the FRs are structured as a Cartesian product named function structure: $F = f_1 \times f_2 \dots$, where $f_p, p \in \mathbb{N}$, depicts a specific functional subtask, and will be sent to the B^D . The function structure is restructured to design request for quotation $F_i \in F$, includes a set of structured f_p . A^D are the design agents in the open design domain, they receive F_i , analyze the structured f_i and response with the design bids $p_i^D, i \in \mathbb{N}$, all the p_i^D are collected in the bids set $\mathbf{D} = \{p_1^D, p_2^D, \dots\}$. The B^D receive \mathbf{D} and evaluate all the p_i^D based on the corresponding F_i . After the bids evaluation finished, the B^D select the preferred bids and send them to the open product innovation domain in the design spec set $\mathbf{D}^* = \{p_1^{D*}, p_2^{D*}, \dots\}$. \mathbf{D}^* contains all the selected design bids p_i^{D*} . \mathbf{D}^* is saved as the design specs D^0 in the product fulfillment flow management.

Based on the understanding of the manufacturing industry, the D^0 are structured to the product structure $\Delta = \delta_1 \times \delta_2 \dots$, where $\delta_q, q \in \mathbb{N}$, depicts a specific manufacturing subtask. The structured Δ depicts the inner relationship of the product, e.g., the assembly structure, and will be sent to the B^M . Δ is restructured to manufacturing request for quotation $\Delta_j \in \Delta$, where $j \in \mathbb{N}$, includes a set of the manufacturing subtask δ_q , and will be sent to the A^M by B^M . A^M receive the P_j , analyze the specs and response with manufacturing bids $p_j^M, j \in \mathbb{N}$. All the p_j^M are collected in the manufacturing bids set $\mathbf{M} = \{p_1^M, p_2^M, \dots\}$. After the bids evaluation finished, the B^M select the preferred bids and send them to the open product innovation domain in the manufacturing spec set $\mathbf{M}^* = \{p_1^{M*}, p_2^{M*}, \dots\}$. \mathbf{M}^* contains all selected manufacturing bids p_j^{M*} . \mathbf{M}^* is saved as the process specs P^0 in the product fulfillment flow management.

Different to the “cascading” model, the product fulfillment process in open enterprise is shown as “zigzagging.” The reason for this changing is the involvement of the external partners, and the fulfillment is achieved by the collaboration of all the stakeholders in the fulfillment process. However, this kind of collaboration is forged in the form of contracting, and the negotiation involves the supply contracting which coordinates the product design and the material flow (Jiao, You, 2006, Subramanian et al. , 2009). Thus, the product fulfillment process in open enterprise can be characterized as collaborative-negotiation based product fulfillment process.

4.2 Supply Contracting Flows

The contracting in the open enterprise is the agreement of the collaborative relationship, which can be decomposed into three activities: 1) request for quotation (RFQ); 2) bids proposing; 3) contracting. Based on the different role in the contracting mechanism, the B^D can be categorized into design configuration broker Γ^D , the negotiation broker in open design domain includes design agent invitation broker I^D and design evaluation broker E^D . Based on the applied policy states, the A^D can be categorized into bidding design agents ψ^i and non-bidding design agents ψ^N . Similarly, the B^M can be categorized into manufacturing configuration broker Γ^M , and the negotiation broker in manufacturing domain includes manufacturing agent invitation broker I^M and manufacturing evaluation broker E^M . According to the applied policy states, the A^M can be categorized as bidding manufacturing agents μ^j and non-bidding manufacturing agents μ^N . Figure 4.2 and Figure 4.3 shows the design and manufacturing supply contracting mechanism, respectively.

The design supply contracting mechanism receives the function structure F and delivers the design spec sets \mathbf{D}^* as the result of negotiation. The collaborative relationship with the A^D is formed with the design supply contracts C^D . The design configuration broker Γ^D receives the F from F^0 and decomposes the F and restructures f_p to F_i , after that, they will be sent to the negotiation brokers. Inner the negotiation brokers in open design domain, the design invitation broker I^D takes in charge of the invitation of A^D to bid and issue the RFQ to them. According to the one-to-one relationship of F_i to the I_i^D , where $i \in \mathbb{N}$, each I_i^D takes in charge of the invitation a cluster of bidding design agents ψ^i for a specific RFQ. Every design agent cluster have a total number of m_i agents, thus, a generic expression of the bidding design agents is $\psi_{m_i}^i$. There are also a cluster of A^D choose a non-bidding policy, named as ψ^N . The index of the non-bidding design agents is m , $m \in \mathbb{N}$, and each of them can be expressed as ψ_m^N .

Every bidding design agent $\psi_{m_i}^i$ proposes a bid, named as $p_{m_i}^D$. The bids are collected in the set: $\mathbf{D} = \{p_1^D, p_2^D, \dots, p_i^D\}$, where $p_i^D = \{p_{i_1}^D, p_{i_2}^D, \dots, p_{i_{m_i}}^D\}$. All the p_i^D are sent one-to-one to the design evaluation broker E_i^D . After the evaluation process, the preferred design agents ψ^{i*} are selected from every design agents cluster i , thus, the contracts are generated subsequently. The design supply contracts are noted as $C^D = \psi^{1*} \times \psi^{2*} \dots$, it will be sent to the open design domain to award the ψ^{i*} , and design configuration broker Γ^D . Γ^D processes the C^D , synthesize the ψ^{i*} and their bids to the design spec set $\mathbf{D}^* = \{p_1^{D*}, p_2^{D*}, \dots\}$. \mathbf{D}^* is sent to the open product innovation domain and saved as design specs D^0 .

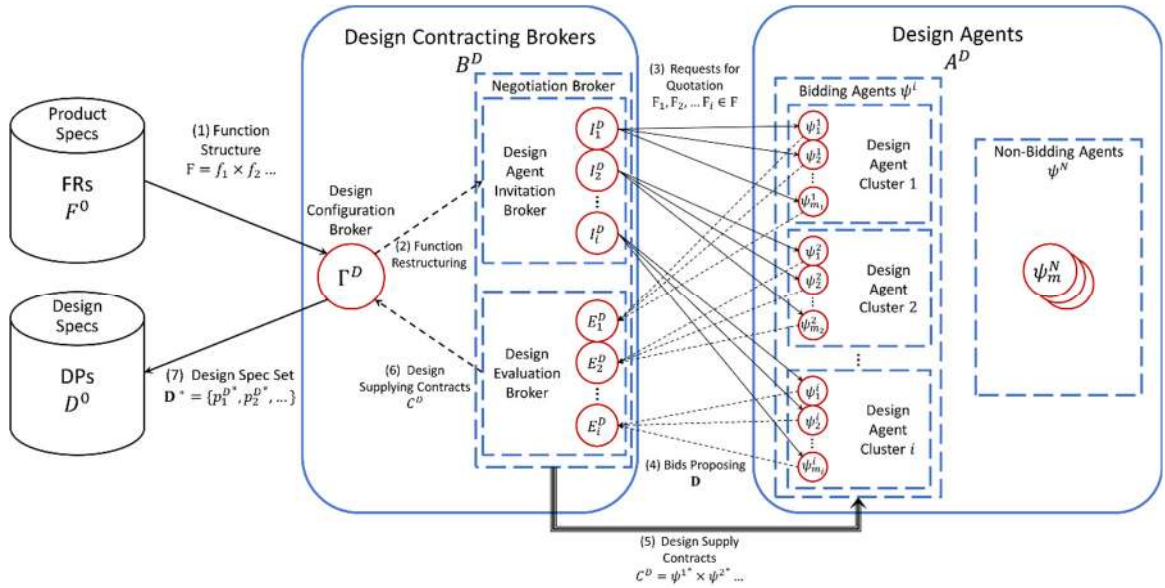


Figure 4.2 Design supply contracting mechanism

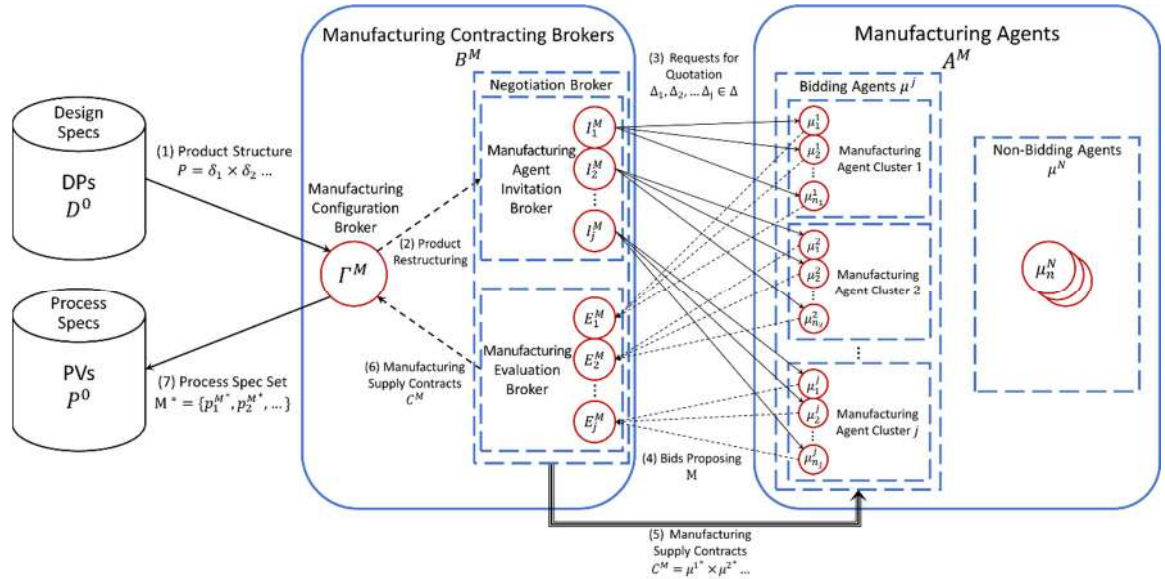


Figure 4.3 Manufacturing supply contracting mechanism

The manufacturing supply contracting mechanism receives the product structure P and delivers the manufacturing spec set M^* after the negotiation process. Besides, it also generates the manufacturing supply contracts, which formulates the collaborative relationship with A^M . The manufacturing configuration broker Γ^M receives the Δ from D^0 and decomposes the Δ and restructures δ_q to Δ_j , after that, they will be sent to the

negotiation brokers. Inner the negotiation brokers in open manufacturing domain, the manufacturing invitation broker I^M manage the invitation of A^M to bid and issue the RFQ to them. According to the one-to-one relationship of P_j to the I_j^M , where $j \in \mathbb{N}$, each I_j^M takes in charge of the invitation a cluster of bidding manufacturing agents μ^j for a specific RFQ. Every manufacturing agent cluster have a total number of n_j agents, thus, a generic expression of the bidding design agents is $\mu_{n_j}^j$. There are also a cluster of A^M choose a non-bidding policy, named as μ^N . The index of the non-bidding design agents is n , $n \in \mathbb{N}$, and each of them can be expressed as μ_n^N .

Every bidding manufacturing agent $\mu_{n_j}^j$ proposes a bid, named as $p_{n_j}^M$. The bids are collected in the set: $\mathbf{M} = \{p_1^M, p_2^M, \dots, p_j^M\}$, where $p_j^M = \{p_{j_1}^M, p_{j_2}^M, \dots, p_{j_{n_j}}^M\}$. These bids are sent to the manufacturing evaluation broker E_j^M . After the evaluation process, the preferred manufacturing agent μ^{j^*} are selected from every manufacturing agents cluster j , thus, the contracts are generated subsequently. The manufacturing supply contracts are noted as $C^M = \mu^{1^*} \times \mu^{2^*} \dots$, it will be sent to the open manufacturing domain to award the μ^{j^*} , and manufacturing configuration broker Γ^M . Γ^M processes the C^M and synthesize the μ^{j^*} and their bids to the process specs set $\mathbf{M}^* = \{p_1^{M^*}, p_2^{M^*}, \dots\}$. \mathbf{M}^* is sent to the open product innovation domain and saved as process specs P^0 .

4.3 Design Contracting Evaluation

From the OD perspective, the p_i^D is the response of the F_i , and the selection of preferable p_i^D should base on the evaluation of the variables, which is formulated as having the lowest deviation of the p_i^D to the expected fulfillment.

However, there is a subjectiveness lying in the evaluation process, and in practice, the experts evaluate based on their heuristic “rule of thumb,” which have been historically done on an ad hoc basis (Thurston and Crawford, 1994). Establishing a model of the preference of the bids and the decision-making in the evaluation process to serve the contracting mechanism is critical to the realization of C²PF.

Since the evaluation is an interdisciplinary decision-making process, a series of trade-offs must be evaluated by knowledge from the various domain (Jiao and Tseng, 1998). Thus, the adaptability in regarding the multi-discipline and the aggregability of these evaluation results is crucial to the evaluation mechanism.

At last, the goal of evaluating process is the assessment of the product performance, which regarding maximizing the customer’s degree of satisfaction (DoS). However, the chance of the satisfaction is not deterministic, and the uncertainty comes from the customer’s value perceiving and physical tolerance and fluctuation. A performance-based evaluation approach are required to handle this uncertainty.

4.4 Manufacturing Contracting Evaluation

From the OM perspective, the realization of a product Δ is restructured to the manufacturing jobs P_j , and the external manufacturers A^D are reconfigured into a production system in the supply contracting C^M . The evaluation of the bids seeks the maximal overlap to the RFQs. This characteristic requires the evaluation should base on the performance of the reconfigured system. However, several challenges lie on the development of the evaluation process.

The evaluation of the production system has various variables, which subject to change in the later development, such as processes setting, machine, tooling, and routings.

A method to able the process these variables, and easy to reconfigure the system has been highlighted in the evaluation process.

On the other hand, the performance of the production system shows strong dynamic and stochastic characteristic in the real manufacturing environment, which regarding the fluctuation of the throughput time, tolerance and rejection rate. Moreover, these fluctuations propagate to the overall performance of the system, which includes cost and lead time and throughput. A method to mimic the uncertainty of the performance is critical in the development of evaluation mechanism.

4.5 Chapter Summary

In this chapter, the workflow of C²PF is established. From a traditional product fulfillment view of the axiomatic model and combined with the characteristics from ODM, the product fulfillment flow is reengineered from cascading to zigzagging. To serve the collaborative characteristic of crowdsourcing process, the supply contracting mechanism is highlighted and developed. The negotiation process is highlighted as realizing based on the evaluation and contracting, and the multi-criteria evaluation criteria are introduced.

CHAPTER 5. EVOLUTIONARY COMPETITION-COOPERATION

GAME MODEL FOR POPULATION DYNAMICS

From the constructed supply contracting mechanism, the partners in the open enterprise are confronting a massive impact of competition. Because of the existence of the selection of ψ^{i^*} and μ^{j^*} , only the best performed agent in each cluster can be awarded and selected in the C^D and C^M . Besides, due to the “zigzagging” product fulfillment flow in the open enterprise, the fulfillment process requires the involvement of the multi-parties, thus, the prosperity of the open enterprise heavily relies on the participation of all the parties. From this view, the relationships between the agents are not only the competition but also the cooperation.

On the one hand, there is an inter-domain cooperation relationship shown between A^D and A^M , due to the significance of the capacity matching. Because of the bidding manufacturing agents μ^j is invited one-to-one by I_j^M , for the P_j the revenue of the design agents A^D is highly related to the number of the μ^j . The D^0 can be only realized in the case that the capacity of the manufacturing domain is matched with the capacity of the design domain, by manufacturing process. Otherwise, some of the P_j will not get any feasible bid. The similarly mechanism is also applicable to the revenue analysis of manufacturing agents A^M .

On the other hand, there are inner-domain cooperation relationships among the A^D or A^M , because of the willing of the participation in one domain is triggered by the participation from another domain. The higher number of bidding agents from one domain shows an abundant capacity to the counterpart domain. Such richness implies a higher

number of generating RFQ, and therefore, a high likely of awarding in the counterpart domain. Thus, the agents in design and manufacturing domain need to cooperate with their peers to participate the bidding to attract the μ^N to bid, and to achieve the revenue maximization.

Besides, there is a robust co-evolutionary relationship in the entire population of A^D and A^M in open enterprise. The decision-making process of applying bidding or non-bidding policy for the agents is actually based on the revenue of their peers at the current situation. A higher revenue of bidding induces the agents applying bidding policy high likely, and low revenue of bidding will increase the probability of applying non-bidding policy. Additionally, the revenue is highly depending on the participation of the other domain. This kind of fitness-decreasing behavior can be categorized in the evolutionary puzzle and has been considered using the game theory to model it (Roca et al. , 2009). To find the equilibrium of the evolutionary dynamic supply contracting mechanism, the evolutionary game model is widely applied (Reeves et al. , 2005, Tian et al. , 2014). In this study, the system dynamics analysis based on the evolutionary competition-cooperation (ECC) game model is applied to find the equilibrium of the agents' population.

5.1 Model Development

The ECC game model is established to imitate the relationship between the agents. This model has considered the cooperation, which is the result of capacity matching and participation abundant, the competition of the agents' peers in their domain, and the co-evolutionary based on the payoff of the states. Based on the evolutionary game theory (Roca, Cuesta, 2009), several assumptions have been set to formulate the model.

Assumption 1: The population of the A^D and A^M is large enough.

Assumption 2: The variation of the total amounts of the A^D and A^M is minimal.

Assumption 3: The contracts can be formed with every agent in the population.

Assumption 4: The agents can only select bidding or non-bidding as their states.

Assumption 5: The capacity of the open design domain and open manufacturing domain is matched.

Based on these assumptions, the model is established as follows. The $X(t)$ and $Y(t)$ are the fraction of the agents who chose bidding strategy in A^D and A^M , respectively. Which $0 < X(t) < 1$ and $0 < Y(t) < 1$. Based on the capacity matching thinking, the capacity unbalance index (CUI) c_u is introduced to the model, as defined as follow:

$$c_u = \frac{X(t)}{Y(t)}. \quad (5.1)$$

From Eq. 5.1, the CUI can be interpreted as the proportion of the $X(t)$ and $Y(t)$, it measures the unbalance of the capacity of different domains.

The cost structure of the agents is modeled in three parts. The first part is the fundamental income of the agents, which can be categorized as design fundamental income π_d and manufacturing fundamental income π_m . This pair of variables depict the basic operation status of the agents. The second part is the bidding cost, which can be categorized as design bidding cost b_d and manufacturing bidding cost b_m . This pair of the variables are modeled based on the cost of generating bids. However, this cost is not only related to the fixed cost of making bids, but also the coast resulted from the unbalanced capacity. For instance, in the case the $X(t)$ is high and $Y(t)$ is low, the bidding cost for A^D is relatively high, because the probability of awarding in this case is minimal. Meanwhile, the bidding cost of the A^M is relatively low, because in such case, the probability of awarding is high. In the worst case, the c_u is approximate to positive infinity, the bidding cost of the A^D will

approximate to positive infinity, and the bidding cost of the A^M will approximate to b_m . Thus, the variable corrected design bidding cost b_d^* and corrected manufacturing bidding cost b_m^* is introduced as follows:

$$\begin{cases} b_d^* = b_d \cdot (1 + c_u) \\ b_m^* = b_m \cdot \left(1 + \frac{1}{c_u}\right) \end{cases} \quad (5.2)$$

The third part of the cost structure is the income from the open product fulfillment flow. The extra income Π is the highest extra income the open enterprise can reach, and the corrected extra income $\Delta\pi$ is the extra income considering the participation abundant:

$$\Delta\pi = \Pi \cdot X(t) \cdot Y(t). \quad (5.3)$$

To measure the income distribution between the A^D and A^M , the distribution coefficient g is introduced, which $g \cdot \Delta\pi$ will be sent to the A^D , and $(1 - g) \cdot \Delta\pi$ will be sent to A^M .

5.2 Replicator Equations for Agents' Population

The agents A^D and A^M make the decision to be bidding or non-bidding states based on their information. The states of the A^D includes $\{D_1, D_2\}$, which are design agents bidding states and design agents non-bidding states, respectively. Similarly, the states of the A^M include $\{M_1, M_2\}$, which are manufacturing agents bidding states and manufacturing agents non-bidding states, respectively. Thus, applying the method from Daniel Friedman (Friedman, 1991), the state's space S is yielded as $S = \{\{D_1, M_1\}, \{D_2, M_2\}\}$. S can be expressed by $(X(t), Y(t))$ in the square of $[0,1] \times [0,1]$. The payoff of the agents in different states can be established in the Table 5.1.

Table 5.1 The game payoff matrix of the design and manufacturing agents

Design Agent A^D	Manufacturing Agent A^M	
	$Y(t)$ Choose Bidding	$1 - Y(t)$ Choose Non-bidding
	M_1	M_2
$X(t)$ Choose Bidding	$\pi_{d_1} = \pi_d - b_d^* + \Delta\pi \cdot g$	$\pi_{d_2} = \pi_d - b_d^* + \Delta\pi \cdot g$
D_1	$\pi_{m_1} = \pi_m - b_m^* + \Delta\pi \cdot (1 - g)$	$\pi_{m_2} = \pi_m$
$1 - X(t)$ Choose Non-bidding	$\pi_{d_3} = \pi_d$	$\pi_{d_4} = \pi_d$
D_2	$\pi_{m_3} = \pi_m - b_m^* + \Delta\pi \cdot (1 - g)$	$\pi_{m_4} = \pi_m$

Table 5.1 can determine the fitness of applying a state by measuring the corresponding income. Thus, the fitness functions of A^D and A^M can be defined as f_d^s and f_m^t , respectively, where $s \in \{D_1, D_2\}$, $t \in \{M_1, M_2\}$. The f_d^s and f_m^t can be defined in Eq. 5.4 and 5.5.

$$\begin{cases} f_d^{D_1} = Y(t) \cdot \pi_{d_1} + (1 - Y(t)) \cdot \pi_{d_2} \\ f_d^{D_2} = Y(t) \cdot \pi_{d_3} + (1 - Y(t)) \cdot \pi_{d_4} \end{cases} \quad (5.4)$$

$$\begin{cases} f_m^{M_1} = X(t) \cdot \pi_{m_1} + (1 - X(t)) \cdot \pi_{m_3} \\ f_m^{M_2} = X(t) \cdot \pi_{m_2} + (1 - X(t)) \cdot \pi_{m_4} \end{cases} \quad (5.5)$$

Based on the Eq. 5.4 and 5.5, the average fitness function of A^D and A^M is noted as \bar{f}_d and \bar{f}_m , respectively, and is depicted as follows:

$$\bar{f}_d = X(t) \cdot f_d^{D_1} + (1 - X(t)) \cdot f_d^{D_2}, \quad (5.6)$$

$$\bar{f}_m = Y(t) \cdot f_m^{M_1} + (1 - Y(t)) \cdot f_m^{M_2}. \quad (5.7)$$

The replicator dynamics describes the frequencies of states in a population, and the increasing rate of applying a strategy is proportional to its relative fitness (Hofbauer and Sigmund, 1998). Thus, the replicator equations are yielded:

$$X\dot{(t)} = \frac{dX(t)}{dt} = X(t) \cdot (f_d^{D_1} - \bar{f}_d) = X(t) \cdot (1 - X(t)) \cdot (f_d^{D_1} - f_d^{D_2}), \quad (5.8)$$

$$Y\dot{(t)} = \frac{dY(t)}{dt} = Y(t) \cdot (f_m^{M_1} - \bar{f}_m) = Y(t) \cdot (1 - Y(t)) \cdot (f_m^{M_1} - f_m^{M_2}). \quad (5.9)$$

Substitute the Eq. 5.4 and 5.5, the replicator equations can be simplified to Eq. 5.10.

$$\begin{cases} \frac{dX(t)}{dt} = X(t) \cdot (1 - X(t)) \cdot [\pi_{d_1} - \pi_{d_3}] \\ \frac{dY(t)}{dt} = Y(t) \cdot (1 - Y(t)) \cdot [\pi_{m_1} - \pi_{m_2}] \end{cases} \quad (5.10)$$

Let the Eq. 5.10 equal to zero, we can find five equilibrium points: $e_1(0,0)$, $e_2(0,1)$, $e_3(1,0)$, $e_4(1,1)$ and the fifth equilibrium point is $e_5(X^*, Y^*)$. Where X^* and Y^* are:

$$\begin{cases} X^* = \frac{\sqrt{b_m(b_d(1-g) + b_m \cdot g)}}{\sqrt{b_d(g-1)^2 \Pi}} \\ Y^* = \frac{\sqrt{b_m(b_d(1-g) + b_m \cdot g)} \cdot \sqrt{b_d(g-1)^2 \Pi}}{b_m \cdot g(1-g)\Pi} \end{cases} \quad (5.11)$$

The e_5 is also an equilibrium point when $(X^*, Y^*) \in [0,1] \times [0,1]$, the constraints can be expressed as follows:

$$\begin{cases} 0 < b_d < \frac{g \cdot \Pi}{2} \\ \frac{b_d^2}{b_d - g \cdot \Pi} \cdot \frac{g-1}{g} < b_m < \frac{b_d(g-1) + \sqrt{b_d(g-1)^2(b_d + 4g \cdot \Pi)}}{2g} \end{cases} \quad (5.12)$$

5.3 Stability Analysis

The concept of Evolutionary Stable Strategies (ESS) is introduced to observe the dynamic behavior of this kind of population (Smith, 1976). In the evolutionary game theory, the ESS is a refinement of Nash Equilibrium (NE), and all games played have an ESS as an optimal solution (Smith, 1988). The ESS can be interpreted as a stable condition after a long time of evolution, and such stability can resist the mutation of small invasion of the population (Friedman, 1991). At an ESS condition, the composition of the agents' populations keeps stable and can prevent the turbulence of alternative strategies.

5.3.1 Jacobian Matrix

The population games describe the interactional behaviors among a considerable number of anonymous agents; such behaviors are based on the simple rules called revision protocol (Sandholm, 2015). Over a long time span, the aggregate behavior can be well modeled by the differential equations. Because the proposed evolutionary game is a 2×2 planar system, the stability of the equilibrium points in replicator equations can be analyzed by applying the trace-determinant plane analysis of the Jacobian matrix of the replicator equations. The Jacobian matrix J of the replicator equations is established in Eq. 5.13. The trace and the determinant of J is noted as τ and Δ_J . The stability of equilibrium points can be evaluated by the following criteria (Hirsch et al. , 2012):

- (1) The equilibrium point is ESS when $\Delta_J > 0$ and $\tau < 0$;
- (2) The equilibrium is unstable when $\Delta_J > 0$ and $\tau > 0$;
- (3) The equilibrium is saddle when $\Delta_J < 0$.

5.3.2 Equilibrium Points Stability Analysis

Based on these criteria, the stability analysis of the $e_1 (0^+, 0^+)$, $e_2(0^+, 1)$, $e_3(1,0^+)$, $e_4(1,1)$ is shown in Table 5.2. From Table 5.2, the e_1 is an ESS, which can be interpreted as no agents decide to bid in this population. Although a small fraction of the agents decides to bid, the population will maintain the stable situation at $(0,0)$ in a long-time span. The equilibrium points e_2 and e_3 are the case that almost all the agents in A^D or A^M decide for bidding, while all the agents in the counterpart cluster choose non-bidding. The stability analysis shows these two are saddle points, which can be interpreted as trajectory has both inner and outer directions, these situations are not evolutionary stable.

$$\begin{aligned}
J &= \begin{bmatrix} \frac{\partial X \dot{(t)}}{\partial X(t)} & \frac{\partial X \dot{(t)}}{\partial Y(t)} \\ \frac{\partial Y \dot{(t)}}{\partial X(t)} & \frac{\partial Y \dot{(t)}}{\partial Y(t)} \end{bmatrix} \\
&= \begin{bmatrix} \frac{b_d \cdot (3X^2(t) - Y(t) + 2X(t) \cdot (-1 + Y(t)))}{Y(t)} + g \cdot (2 - 3X(t)) \cdot X(t) \cdot Y(t) \cdot \Pi & X(t) \cdot (1 - X(t)) \cdot \left(\frac{b_d \cdot X(t)}{Y^2(t)} + g \cdot X(t) \cdot \Pi \right) \\ Y(t) \cdot (1 - Y(t)) \cdot \left(\frac{b_m \cdot Y(t)}{X^2(t)} - (g - 1) \cdot Y(t) \cdot \Pi \right) & b_m \cdot \left(-1 + 2Y(t) + \frac{Y(t) \cdot (3Y(t) - 2)}{X(t)} \right) + (g - 1) \cdot (3Y(t) - 2) \cdot X(t) \cdot Y(t) \cdot \Pi \end{bmatrix} \quad (5.13)
\end{aligned}$$

$$\begin{aligned}
J|_{(X^*, Y^*)} &= \begin{bmatrix} \frac{-b_m^2 \cdot g \sqrt{b_d(g-1)^2 \Pi} + b_d \cdot (g-1) [(g-1) \sqrt{b_m(b_d(1-g) + b_m \cdot g)} \cdot \Pi + b_m \cdot \sqrt{b_d(g-1)^2 \Pi}]}{(g-1)^2 \cdot \sqrt{b_m(b_d(1-g) + b_m \cdot g)} \cdot \Pi} & \frac{-b_m \cdot g \cdot \Pi [b_d(1-g) + 2b_m \cdot g] \cdot (\sqrt{b_m(b_d(1-g) + b_m \cdot g)} - \sqrt{b_d(g-1)^2 \Pi})}{(b_d(g-1)^2 \Pi)^{\frac{3}{2}}} \\ \frac{b_d [2b_d(g-1) - b_m \cdot g] \cdot [b_m \cdot g(g-1) \Pi + \sqrt{b_m(b_d(1-g) + b_m \cdot g)} \sqrt{b_d(g-1)^2 \Pi}]}{b_m^2 \cdot g^3 \cdot \Pi} & b_m + \frac{b_d(g-1) \sqrt{b_m(b_d(1-g) + b_m \cdot g)}}{g \sqrt{b_d(g-1)^2 \Pi}} \end{bmatrix} \quad (5.14)
\end{aligned}$$

Table 5.2 The stability analysis of the first four equilibrium points

Equilibrium Points	J	$\tau = \text{tr}(J)$	$\Delta_J = \det(J)$	Stability
$e_1(0^+, 0^+)$	$\begin{bmatrix} -3b_d & b_d \\ b_m & -3b_m \end{bmatrix}$	$-3b_d - 3b_m$	$8b_d \cdot b_m$	ESS
$e_2(0^+, 1)$	$\begin{bmatrix} -b_d & 0 \\ 0 & \infty \end{bmatrix}$	∞	$-\infty$	Saddle Points
$e_3(1, 0^+)$	$\begin{bmatrix} \infty & 0 \\ 0 & -b_m \end{bmatrix}$	∞	$-\infty$	Saddle Points
$e_4(1, 1)$	$\begin{bmatrix} 2b_d - g \cdot \Pi & 0 \\ 0 & 2b_m - (1 - g) \cdot \Pi \end{bmatrix}$	$2(b_d + b_m) - \Pi$	$(2b_d - g \cdot \Pi) \cdot (2b_m - (1 - g) \cdot \Pi)$	Undetermined

The fourth equilibrium point can be interpreted as the situation that all the A^D and A^M apply bidding. Based on the stability analysis criteria, the constraints conditions for each stability situation is summarized in the Table 5.3.

Table 5.3 The stability constraints conditions of the fourth equilibrium point

Constraints Conditions	Sign		Stability Situation
	$\tau = \text{tr}(J)$	$\Delta_J = \det(J)$	
$\begin{cases} 0 < b_d < \frac{g \cdot \Pi}{2} \\ 0 < b_m < \frac{(1-g)}{2} \Pi \end{cases}$	-	+	ESS
$\begin{cases} 0 < b_d < \frac{g \cdot \Pi}{2} \\ b_m > \frac{(1-g)}{2} \Pi \end{cases} \text{ or } \begin{cases} b_d > \frac{g \cdot \Pi}{2} \\ 0 < b_m < \frac{(1-g)}{2} \Pi \end{cases}$	\pm	-	Saddle Points
$\begin{cases} b_d > \frac{g \cdot \Pi}{2} \\ b_m > \frac{(1-g)}{2} \Pi \end{cases}$	+	+	Unstable

From Table 5.3, it can be observed that the e_4 's stability depends on the relationship between the bidding cost, b_d and b_m , and the extra income distribution, which is determined by g and Π . When the bidding cost is smaller than the half of the received extra income, the e_4 is a ESS. In that case, most of the agents in population will bid, and thus, the prosperous of the open enterprise can be realized. However, in the case that the extra income distribution is unbalanced, the e_4 is a saddle point. It will show different trajectory directions on this point. In the last case, if the bidding cost is too high or the extra income is not enough, e_4 will be unstable. And based on the Eq. (5.12), the fifth equilibrium point will not exist. This case should be avoided, because in such case, the only ESS is e_1 , and the operation of the open enterprise will not consist.

In the case of the fifth equilibrium point, where $(X(t), Y(t)) = (X^*, Y^*)$, the Jacobian matrix is shown in Eq. (5.14).

To simplify the Eq. 5.14, three variables ρ_1 , ρ_2 , and ρ_3 is introduced in Eq. 5.15.

$$\begin{cases} \rho_1 = \sqrt{b_d(g-1)^2\Pi} \\ \rho_2 = \sqrt{b_m \cdot g(1-g)\Pi} \\ \rho_3 = \sqrt{b_m(b_d(1-g) + b_m \cdot g)} \end{cases} \quad (5.15)$$

Thus, the (X^*, Y^*) can be simplified to,

$$\begin{cases} X^* = \frac{\rho_3}{\rho_1} \\ Y^* = \frac{\rho_3 \cdot \rho_1}{\rho_2^2} \end{cases} \quad (5.16)$$

Substitute Eq. 5.16 to 5.14, the Jacobian matrix can be simplified to Eq. 5.17, its trace and determinant are calculated in Eq. 5.18 and 5.19, respectively.

$$J|_{(X^*, Y^*)} = \begin{bmatrix} \frac{-b_m^2 \cdot g \cdot \rho_1 + b_d \cdot (g-1)[(g-1) \cdot \rho_3 \cdot \Pi + b_m \cdot \rho_1]}{(g-1)^2 \cdot \rho_3 \cdot \Pi} & -\frac{g \cdot \Pi(\rho_2 + b_m^2 \cdot g) \cdot (\rho_3 - \rho_1)}{\rho_1^3} \\ \frac{b_d[2b_d(g-1) - b_m \cdot g] \cdot [b_m \cdot g(g-1)\Pi + \rho_1 \cdot \rho_3]}{b_m^2 \cdot g^3 \cdot \Pi} & b_m + \frac{b_d(g-1)\rho_3}{g\rho_1} \end{bmatrix} \quad (5.17)$$

$$\tau|_{(X^*, Y^*)} = b_d + b_m - \frac{b_d \cdot \rho_3}{g \cdot \rho_1} \quad (5.18)$$

$$\Delta_J|_{(X^*, Y^*)} = \frac{2b_d \cdot \rho_3^4(\rho_1 - \rho_3)(-\rho_2^2 + \rho_1 \cdot \rho_3)}{b_m \cdot g^2 \cdot \rho_1^3} \quad (5.19)$$

Based on the Eq. 5.17, 5.18 and 5.19, and the existence conditions for the fifth equilibrium point e_5 , the stability of e_5 is processed. The e_5 cannot be an ESS or an unstable point when $(X^*, Y^*) \in [0,1] \times [0,1]$. The e_5 is a saddle points when:

$$\begin{cases} 0 < b_d < \frac{g \cdot \Pi}{2} \\ \frac{b_d^2}{b_d - g \cdot \Pi} \cdot \frac{g-1}{g} < b_m < \frac{b_d(g-1) + \sqrt{b_d(g-1)^2(b_d + 4g \cdot \Pi)}}{2g} \end{cases} \quad (5.20)$$

Therefore, the operation of the open enterprise can consist in two scenarios: 1) the e_4 is an ESS while the e_5 is a saddle point; 2) the e_4 is an ESS while the e_5 is not exist.

The first scenario is the case that the only the e_1 and e_4 are the ESS, and the e_5 is existed as a saddle point, the constraint condition is as same as Eq. 5.20. To demonstrate this scenario, an illustrative phase diagram is shown in the Figure 5.1. In such case, the population can reach the e_4 , but a low value of e_5 is the key to enhance the probability of reaching e_4 .

The second scenario is the case that the e_1 and e_4 are ESS, the e_5 is not existed due to the unbalance income between A^D and A^M . The constraint condition is shown in Eq. 5.21. In such case, the open enterprise can reach the e_4 . The illustrative phase diagram is shown in Figure 5.2.

$$\left\{ \begin{array}{l} 0 < b_d < \frac{g \cdot \Pi}{2} \\ 0 < b_m < \frac{b_d^2}{b_d - g \cdot \Pi} \cdot \frac{g - 1}{g} \text{ or } \frac{b_d(g - 1) + \sqrt{b_d(g - 1)^2(b_d + 4g \cdot \Pi)}}{2g} < b_m < \frac{(1 - g) \cdot \Pi}{2} \end{array} \right. \quad (5.21)$$

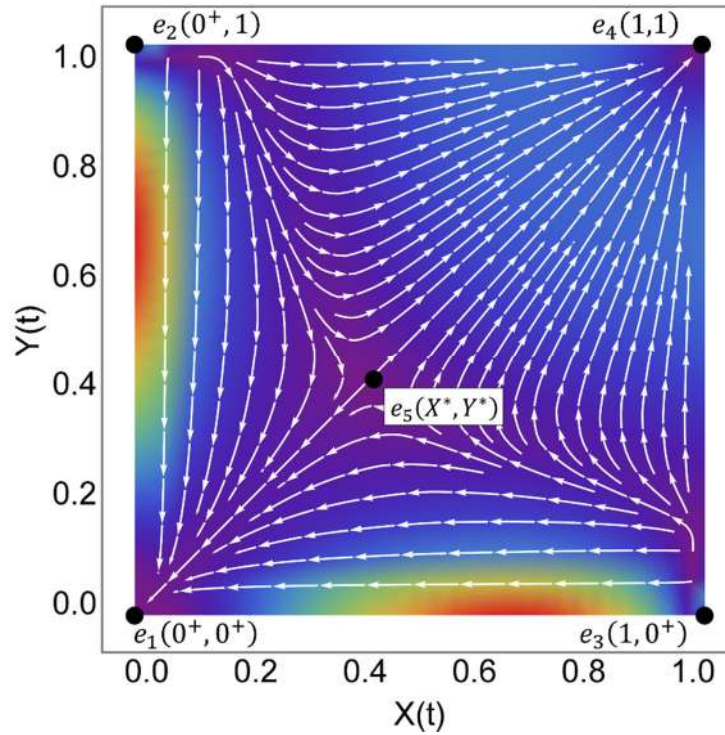


Figure 5.1 Phase diagram of scenario 1

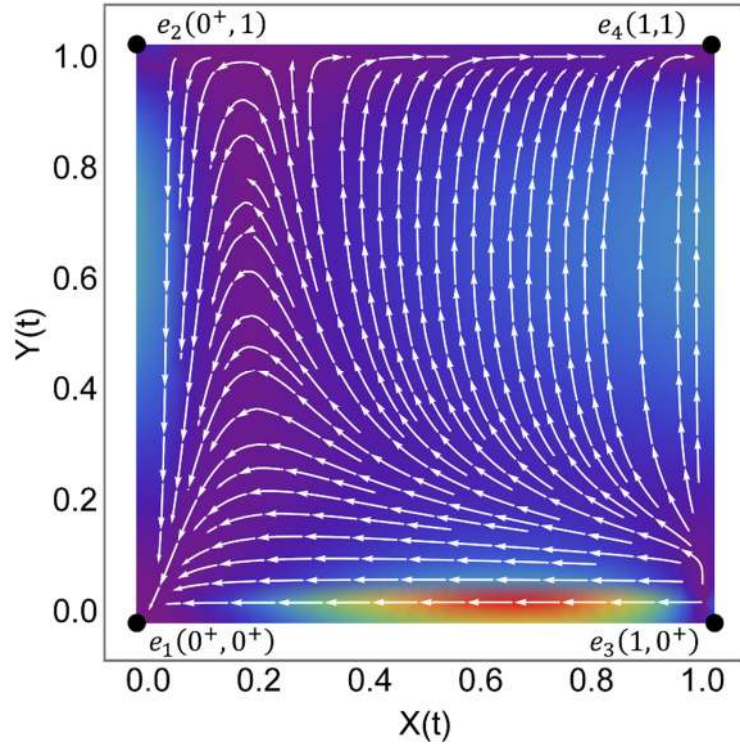


Figure 5.2 Phase diagram of scenario 2

5.3.3 Managerial Implications

From the stability analysis of the equilibrium points, the revision protocol of the ECC game model shows a strong influence on the dynamics of the agents' population. Because the equity of distribution among the populations, the scenario 1 shows a superiority. In scenarios 1, e_5 can be viewed as a peak in a landscape, and the link between e_5 to e_1 , e_2 , and e_3 consist three ridges, while the area from e_5 to e_4 can be viewed as a valley. If the states' space of the agents' population falls into the valley area, a long-time prosperity can be predicted. Thus, manipulate the e_5 can be identified as a critical method in open enterprise management. By using the proposing rules and equations, the revision protocol of the current conditions can be derived, and a judgement of the long-time prosperity can be concluded.

5.4 Chapter Summary

In this chapter, the game theoretic population dynamic model for the open enterprise has been established. Different from the traditional enterprise, open enterprises open the boundaries and expand the all-in-one decision making to group behavior. This model offers a way of describing the adoption and reversion of the ODM, considering the competition-cooperation relationship through the ODM process. From a management views, it is essential to have a dynamics model of the agents' population to serve the predicting and management of the agents' behavior.

As a conclusion, a higher income and balanced distribution among the domains will encourage the participation of the agent. Therefore, the long-time prosperity of open enterprise can be pursued. However, the relationship of the income, distribution balance and the growth rates are changing with the participation fraction. In a high participation and fraction situation, the requirement of the income and distribution balance is loosed. On the other hand, a high income shows a significant influence on the growth rates in the low participation fraction. The open enterprise can manage the agents' behavior by taking the proposing model as a guideline.

CHAPTER 6. SUPPLY CONTRACTING EVALUATION BASED ON INFORMATION CONTENT MEASURE

Recognize the significance of the evaluation of the bids, the challenges of evaluating a bid lies in three aspects. Firstly, because of the inherent characteristic of collaborative of C²PF, the bids are sets of DPs or PVs at the early stage, a stream of uncertainty is inevitable along the C²PF, such as the contextual misunderstanding in the design stage and tolerance of manufacturing process (Jiao and Tseng, 1998, Siskos et al. , 1984). Secondly, the evaluation of the bids has multi-criteria, the decision-making for suppliers have to consider various trade-offs from different disciplines, and some of these criteria may be conflicting (Ho et al. , 2010). Thirdly, since some of the RFQs are subjective, several bids may be feasible on a functional view, some of the bids may show the superiority due to its robustness (Suh, 2001).

A stream of researches has explored the handling of these challenges. The multi-criteria utility analysis is a mathematical model for evaluating a set of criteria in the engineering fields (Von Neumann and Morgenstern, 1945). This method enhances the algorithm-rigorous of the modeling, and thus, the inconvenience of applying it in the evaluation of early stage of design has been pointed out (Thurston, 1991). In contrast, the fuzzy analysis is capable of representing and manipulating the imprecise inputs based on the fuzzy set theory (Ragin et al. , 2006). Besides, fuzzy sets analysis excels in dealing with the vague description in the early stage of product development and the uncertainty of the development process (Thurston and Carnahan, 1992). Based on the previous work, Jiao and Tseng (Jiao and Tseng, 1998) proposed fuzzy ranking methods to evaluate the conceptual design under the MC paradigm. Because of the inherent uncertainty, the efforts

of the bids is minimizing the deviation of the performance and maximizing the overlap with the expectation of the RFQ (Jiao and Tseng, 2004). The multi-attribute utility theory offers the aggregation of a bundle of criteria under uncertain conditions to handle the multi-criteria evaluation problem (Keeney and Raiffa, 1993).

The uncertainty of the design bid p_i^D and manufacturing bid p_j^M is modeled in a different way. The major concern of p_i^D is the flexibility of the DPs to fulfill of the F_i . Suh formulate the information axiom, which enable the description of the F_i and p_i^D into the design fulfillment range F_{fr} and system performance range F_{pr} in the form of probability distribution function (PDF) (Suh, 2001). The evaluation of p_i^D can be processed based on calculating the overlap area of the PDF of the F_{dr} and F_{sr} .

The p_j^M is the bid of the A^M with a manufacturing planning to fulfill the P_j . Since the selected A^M will configure a production system, and the P_j will be fulfilled along the routing, evaluation of the p_j^M can be based on the performance of the configured production system. Discrete-Event Simulation (DES) can be used to imitate the operations of a real-world agent-based production system by modeling the changes of state variables at a discrete set of points in time (Borshchev and Filippov, 2004). The stochastic model of the manufacturing system can be established based on the output analysis of the DES (Alexopoulos and Seila, 1998). Similar to the evaluation of the p_i^D , the overlap of the PDF of suppling fulfillment range D_{fr} and production performance range D_{pr} can be the reference of the evaluation.

6.1 Bids Selection Methodology

This research views the evaluation and ranking of the bids as a series of multi-criteria decision-making problems in the context of C²PF. The problems can be defined as evaluating and ranking a set of alternatives with a bunch of criteria, thus, ensure the fulfillment of the requirement, regarding FR, DP and with a coordinated quantity and lead time.

As formulated in Chapter 4, the design and manufacturing bids are collected in the finite set $p_i^D = \{p_{i_1}^D, p_{i_2}^D, \dots, p_{i_{m_i}}^D\}$ and $p_j^M = \{p_{j_1}^M, p_{j_2}^M, \dots, p_{j_{n_j}}^M\}$, respectively. All of these bids will be evaluated by the design evaluation criteria set $\{c^{Fi}\}_{r_i} = \{c_1^{Fi}, c_2^{Fi}, \dots, c_{r_i}^{Fi}\}$ and manufacturing RFQ $\{c^{Pj}\}_{s_j} = \{c_1^{Pj}, c_2^{Pj}, \dots, c_{s_j}^{Pj}\}$, where $c_{r_i}^{Fi}$ and $c_{s_j}^{Pj}$ are the design and manufacturing evaluation criteria, respectively. Besides, the r_i and s_j are the number of criteria in every c^{Fi} and c^{Pj} , $r_i, s_j \in \mathbb{N}$. The performance of bids are measured by the criteria and noted as the $DoS_{c_{r_i}^{Fi}}(p_{i_{m_i}}^D)$, where $p_{i_{m_i}}^D \in p_i^D$, $p_{j_{n_j}}^M \in p_j^M$, $c_{r_i}^{Fi} \in F_i$, $c_{s_j}^{Pj} \in P_j$. In a multi-criteria evaluation condition, the evaluation result of a bid $p_{i_{m_i}}^D$ can be represented by a r_i -dimensional vector $DoS(p_{i_{m_i}}^D) = \left[DoS_{c_1^{Fi}}(p_{i_{m_i}}^D), DoS_{c_2^{Fi}}(p_{i_{m_i}}^D), \dots, DoS_{c_{r_i}^{Fi}}(p_{i_{m_i}}^D) \right]$. To model the relative importance among the vector, a weighting factor is introduced and noted as w , for a r_i -dimensional vector, $\sum_{a=1}^{r_i} w_a \equiv 1$. The evaluation result of a bid can be aggregated to total DoS, which is denoted as $TDoS(p_{i_{m_i}}^D)$ and defined as:

$$TDoS(p_{i_{m_i}}^D) = \sum_{a=1}^{r_i} w_a \cdot DoS_{c_a^{Fi}}(p_{i_{m_i}}^D). \quad (6.1)$$

However, in practice, the DoSs are heterogeneous and correlated per se, and the multi-attribute utility theory has been proposed to handle the underlying correlation (Ji et al. , 2013):

$$UDoS(p_{i m_i}^D) = \frac{1}{K} \left[\left[\prod_{a=1}^{r_i} (K \cdot w_a \cdot DoS_{c_a^{F_i}}(p_{i m_i}^D) + 1) \right] - 1 \right], \quad (6.2)$$

where the $UDoS(p_{i m_i}^D)$ is normalized DoS $p_{i m_i}^D$ with F_i , and K is a normalizing constant which scale $UDoS$ from 0 to 1. K can be derived from the equation:

$$1 + K = \prod_{a=1}^{r_i} (1 + K \cdot w_a). \quad (6.3)$$

If the K is 0, it indicates there is no preference of the attributes, and the Eq. 6.2 is equivalent to the Eq. 6.1 (Krishnamurty, 2006). After the evaluation, the results can be collected in a finite set with m_i elements, and the most preferable bid can be selected by finding the minimum or the maximum value in the set:

$$\max/\min (\{TDoS(p_i^D)\}_{m_i}) \rightarrow p_i^{D*} \in p_i^D. \quad (6.4)$$

6.2 Formulation of Degree of Satisfaction

In Suh's original formulation of the information contents (Suh, 2001), the PDF of the design range is assumed as uniform. However, because of the preference of the requirements, a triangular distribution shows the superiority of modeling F_{fr} and F_{pr} (Jiao and Tseng, 2004). The PDF of the fulfillment preference can be represented as $u(F_{fr})$ and $u(D_{fr})$, moreover, the upper and lower limit of these requirement is defined as: $\forall F_{fr} \in [F_{fr}^L, F_{fr}^U]$, $\forall D_{fr} \in [D_{fr}^L, D_{fr}^U]$. The PDF of the performance of the bids are represented by $p(F_{pr})$ and $p(D_{pr})$. The information content I , measures the probability of success of the bid, $P(F_{pr})$ and $P(D_{pr})$ can be defined as:

$$I = \log_2 P(F_{pr}). \quad (6.5)$$

As shown in Figure 6.1, the probability of success for a bid can be defined as expected preference function value of the achieved system performance over the range of the fulfillment, i.e.,

$$P(F_{pr}) = E[u(F_{pr})] = \int_{F_{fr}^L}^{F_{fr}^U} u(F_{fr}) \cdot p(F_{pr}) dF_{pr}. \quad (6.6)$$

Thus, the degree of the satisfaction of a bid is formulated as:

$$DoS = \frac{1}{1 - I} = \frac{1}{1 - \log_2 \int_{F_{fr}^L}^{F_{fr}^U} u(F_{fr}) \cdot p(F_{pr}) dF_{pr}}. \quad (6.7)$$

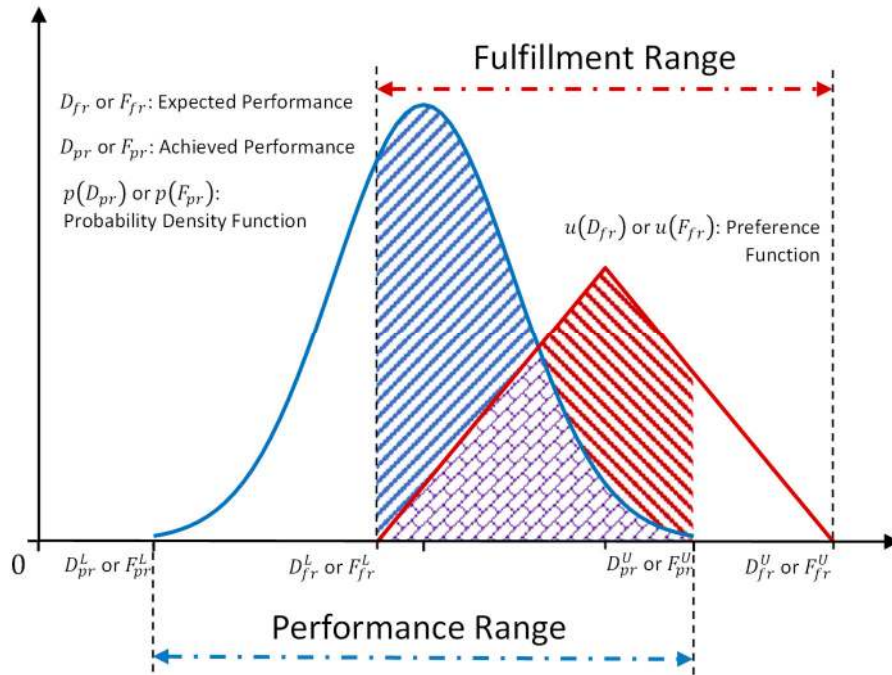


Figure 6.1 Preference function and performance distribution

6.3 Evaluation of Design Bids

The instantiation of the proposing evaluation and selection methods through open design includes design fulfillment range specification, bids collection, performance range specification and degree of stratification calculation.

In the OD segment, the RFQ to fulfill F_i is the decomposed function structure, with a set of specific FRs, with an amount of r_i of criteria as the elements, and the utility function $u_{r_i}^{F_i}(F_{fr})$ will be specified by the invitation broker I_i^D at the open call stage. $u_{r_i}^{F_i}(F_{fr})$ depicts the preference of the corresponding FR, a higher value implies the most preferred DP, while the upper bound F_{fr}^L and a lower bound F_{fr}^U implies the acceptable range of the system preference.

The m_i number of ψ^i from A^D the response this specific call with their bids $p_{i\ m_i}^D$, and the corresponding design evaluation broker E_i^D collects these bids in a set $p_i^D = \{p_{i\ 1}^D, p_{i\ 2}^D, \dots, p_{i\ m_i}^D\}$. Based on the understanding of these DPs, the performance of the system can be estimated by E_i^D and specified as $p_{r_i}^{F_i}(F_{pr})$. Substitute the corresponding function into Eqn. 6.7, the DoS for a bid on a single criterion can be derived as $DOS_{r_i\ m_i}^{F_i}$. After that, the DoS will be aggregated by using Eqn. 6.2, and Eqn. 6.3, since then, a total DoS of a bid has been generated as an evaluation result: $UDoS(p_{i\ m_i}^D)$. The selection of the bids is based on the comparison among the peers, a bid with a maximum $UDoS(p_{i\ m_i}^D)$ will be selected as the optimal $p_{i\ m_i}^{D*}$. This bid has the biggest overlap to increase the possibility of fulfilling the corresponding CNs. Based on this evaluation results, the agents who proposed the $p_{i\ m_i}^{D*}$ can be selected as a preferred agent ψ^{i*} , and the broker will form the contract with him as an award.

6.4 Evaluation of Manufacturing Bids

Different from the instantiation of the proposing evaluation and selection methods through OD, the A^M cooperate to fulfill the manufacturing tasks via an internal material flow in the reconfigured open enterprise. Thus, the evaluation of the bids can be dichotomized into process feasibility assessment and production performance evaluation. The feasibility is a binary assessment, ensure the basic fulfillment of the manufacturing RFQ Δ_j . However, since the fulfillment process of physical products is based on the material flow across a variety of manufacturers, the performance of a μ^j will propagate to downstream agents, and finally, influence the holistic performance of the open enterprise. Despite of the manufacturing feasibility assessment, a set of general performance evaluation criteria must be established to select the preferred bids. Such criteria include the price, due dates for a specific volume. Besides the lower price is always pursued by manufacturing practitioners, the volume and due dates evaluation should consider the upstream and downstream manufacturers to achieve a better performance.

Similar to the instantiation of OD process, n_j of μ^j bids with their bids $p_{j\ n_j}^M$, as a response of the open call Δ_j from I_j^M . All of these bids are collected in a set $p_j^M = \{p_{j\ 1}^M, p_{j\ 2}^M, \dots, p_{j\ n_j}^M\}$. These bids are evaluated with an amount of s_j evaluation criteria and their corresponding utility function $u_{s_j}^{\Delta_j}(D_{fr})$. This utility function depicts the basic expectation of the performance of μ^j . The evaluation job is processed by E_j^M by applying Eqn. 6.7, they estimate the bids' performance $p_{s_j}^{\Delta_j}(D_{pr})$ based on their engineering understanding, thus, the DoS for a bid on a single criterion can be derived as $DoS_{s_j\ n_j}^{\Delta_j}$. The DoS describes the probability of achieving high performance of the configured production

systems. Similar to the aggregation method in OD, $UDoS(p_j^M, n_j)$ can be derived, thus, an optimal p_i^{M*} and its corresponding proposer will be evaluated as preferred. As the result of the evaluation process, the contracts can be formed as an award.

6.5 Chapter Summary

This chapter provides a systematical design and manufacturing bid evaluation process which support the supply contracting in the open enterprise. The evaluation of bids is executed based on the overlap of their performance and corresponding fulfillment expectation from multi-criteria. The DoS has introduced to formulate this overlap with the considering of the uncertainty, and the multi-attribute utility theory has been introduced to aggregate the DoS considering the correlations between the criteria. At last, the proposed theory has been implemented through ODM. This bid evaluation mechanism evaluates the collected bids from the open call and provides the decision support of the awarding of the A^D and A^M with supply contracting.

CHAPTER 7. CASE STUDY

A case study of dental braces through ODM is used to illustrate the proposed theory. Through the developing of the fulfillment flow, an evolutionary game theoretic dynamic analysis of the partners and the evaluation process, it demonstrates the C²PF through the ODM.

7.1 Problem Context

The dental braces are the appliance used in orthodontics to align and straighten teeth and help position them to improve the patient's dental health, which involves the application of forces to teeth through the appliance. Due to the variety of the patients' intraoral profile, the dental braces are highly individualized. Thanks to the recent advancement of ICT, the workflow of the orthodontics has been highly digitized, and a typical digital orthodontics workflow can be decomposed to:

- 1) Using the intraoral laser scanner to establish the patients' digital impression model, then analyzing and planning the treatment via animation-based software and archiving the digitized profile and prescription;
- 2) Based on the treatment plan, involving the digital dental labs as the external partners to design the customized appliance via CAx software and archiving the digitized design files;
- 3) Cloud-based connecting to the orthodontic solution providers as the external partners to manufacture the appliance;
- 4) Fitting the appliance as the delivery to the customer and monitoring the treatment plan.

Several intraoral scanning systems provide the CAx and cloud integration through the product fulfillment, and a community is established (Vandeweghe et al. , 2017). By applying ODM, the dentist can act as an A^I . A^I open its boundary to crowdsource the jobs to the collaborative crowds and insource the knowledge and capacity from digital dental labs as A^D and orthodontic solution provider as A^M . Thus, A^I can focus on its core competitiveness which is case analysis and treatment planning. These three stakeholders consist a typical open enterprise. This perspective paves the way for the implementation of the ODM, and the fulfillment jobs can be crowdsourced to the external partners. Thus, the C²PF can be achieved.

7.2 Numerical Analysis of Agents Population Dynamics

An ECC game model is implemented to explore the agents' population dynamics in the braces fulfillment C²PF processes. From the formulation in Chapter 5, a numerical analysis of the dynamics model is executed to demonstrate the proposing theory. The Π of the C²PF is set at 50, which can be interpreted as the profits of the highest profits that a C²PF can reach in product fulfillment. The design bidding cost b_d and manufacturing bidding cost b_m are set to 2 and 3, respectively. This cost can be interpreted as the cost of generating the bidding cost. The distribution coefficient g is set to 0.4. This number entails the distribution among the designer and manufacturer domains. Substitute these numbers into Eq. 5.10, the replicator equations are derived in Eq. 7.1.

$$\begin{cases} \frac{dX(t)}{dt} = X(t) \cdot (1 - X(t)) \cdot \left[-2 - \frac{2X(t)}{Y(t)} + 20X(t) \cdot Y(t) \right] \\ \frac{dY(t)}{dt} = Y(t) \cdot (1 - Y(t)) \cdot \left[-3 - \frac{3Y(t)}{X(t)} + 30X(t) \cdot Y(t) \right] \end{cases} \quad (7.1)$$

From the stability analysis methods formulated in Section 5.3, the fifth equilibrium points e_5 is existed as a saddle points at $(0.447, 0.447)$. The phase diagram of this case is shown in Figure 7.1.

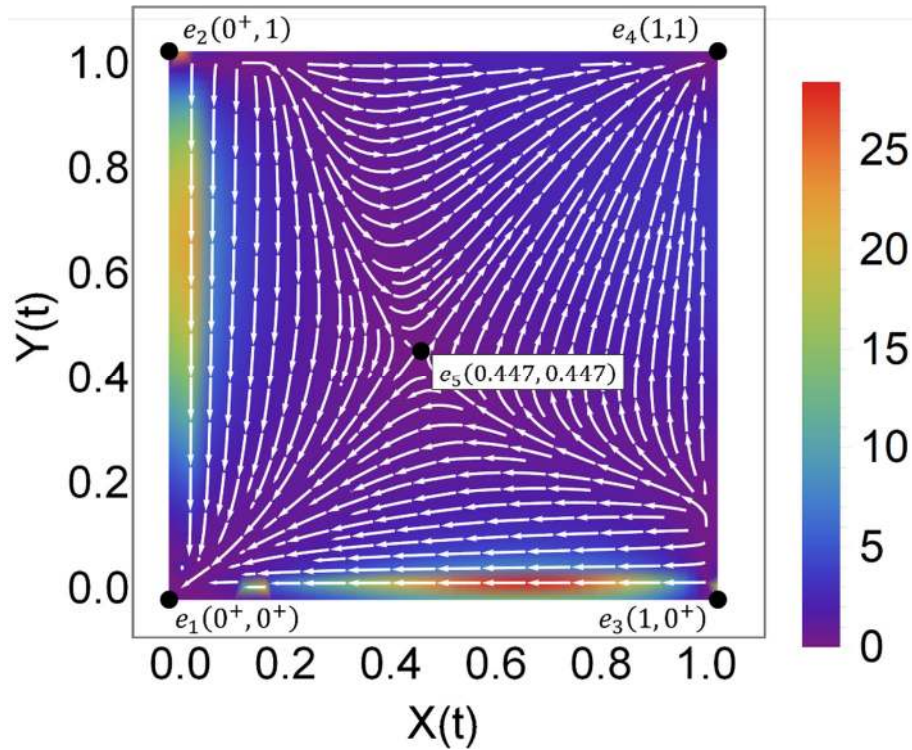


Figure 7.1 Phase diagram of dental braces fulfillment agents' population

From Figure 7.1 and the replicator equations in Eq. 7.1, some managerial implications can be identified. Firstly, there are three ridges connected from $e_5(0.447, 0.447)$ to $e_1(0^+, 0^+)$, $e_2(0^+, 1)$, and $e_3(1, 0^+)$. The valley area is in the right and upper corner. If the state falls into that area, the population will converge to e_4 as an ESS. This division implicates if the agents' participation proportion is at the right upper area, the corresponding open enterprise will show a long-time prosperity. In contrast, if the agents' participation proportion falls in the left lower area, it shows a convergence to the $e_1(0^+, 0^+)$, which is also an ESS. This trend will lead the open enterprise to an end.

Thus, to seek the long-time prosperity, the manipulation of the e_5 's position is critical in the management of open enterprise. When the participation of the agents is low, a low and left e_5 shows its essentiality. It will lead the agents population to e_4 , to achieve the long-time prosperity. Such manipulation involves a higher extra income and lower bidding costs. However, when the agents show a higher participation, a low and left e_5 is less preferred, because a high extra income to the open designer and manufacturer implies a lower income to the innovator. Thus, the open enterprise can move the e_5 in a reasonable distance.

Thirdly, from the Figure 7.1, the changing rates of participation states shows low values around the equilibrium points and higher value in the middle and the edge area. It implies the participation fraction will have higher stability near the equilibrium points. From a management perspective, a deviation of the participation paces and e_5 will result in a quicker reforming, and an approximation of the e_5 and participation states will lead to a stable circumstance.

7.3 Design Supply Contracting

As the product fulfillment process depicted in Figure 3.1 and the design supply contracting mechanism in Figure 3.2, the orthodontist is the E , who takes in charge of the collection of C^0 and F^0 generation. In the case of dental braces, the orthodontic treatment of a patient is the C^0 . E collects them by the intraoral scanner as a digital impression model and based on C^0 , E proposes the treatment plan as a F^0 . This F^0 is a series of the FRs, specified the expectations for an appliance to fulfill the orthodontic treatment. These FRs are sent to virtual domain of C²PF management and saved as the product specs.





The FRs has internal hierarchical and precedence relationship, and the functions are structured to $F = f_1 \times f_2 \dots$, and sent to the contracting brokers B^D . Inside of the B^D , the Γ^D decomposes the F to F_i , where $F_i \in F$ and send it to the I_i^D , who send the RFQ to the crowd as an open call and specify the evaluation criteria to guide the evaluation process. In this illustrate case, there is one RFQ F_1 about the braces design bids. The basic FRs for the bids is the ensuring of the correction effects and the comfortability. Besides, the bids should achieve a low price. The FRs and evaluation criteria for the F_1 , the corresponding description and the units is specified in the Table 7.1.

Table 7.1 Request for quotation of design bids for dental braces

Design Request for Quotation		Design Evaluation Criteria		Description	Units
f_1	Correction Effectiveness	$c_1^{F_1}$	Maxillary Incisor Torque	The dental braces align and straighten the teeth by applying the correctional torque to the teeth root. Usually, a higher torque value implies a better high correctional effect. Moreover, a high torque control for the orthodontic treatment, particularly in the maxillary incisors.	°
f_2	Comfortability	$c_2^{F_1}$	Thickness	The dental braces are implemented in the mouth; thus, it contacts the skin directly. The thickness describes the maximum distance from the braces to the teeth braces. A lower thickness implies a higher comfortability.	mm
		$c_3^{F_1}$	Corner Radius	Hard materials usually make the braces, and a low fillet radius implies a high tingle feeling. Thus a high corner radius is preferred.	μm
f_3	Reliability	$c_4^{F_1}$	Mean Time to Failure (MTTF)	The dental braces should provide a high-reliability performance, and a long MTTF should be provided.	month
f_4	Cost	$c_5^{F_1}$	Estimated Sales Price	The dental braces should be competitive on the market, a low sales price to the customer should be detected.	k\$

After the open RFQ F_1 has been sent to the crowds, 4 ψ^1 decide to bid, which are noted as $\{\psi_1^1, \psi_2^1, \psi_3^1, \psi_4^1\}$, and 4 design bids are collected by the E_1^D in a finite set p_1^D , where $p_1^D = \{p_{1_1}^D, p_{1_2}^D, p_{1_3}^D, p_{1_4}^D\}$. In this case, the bids are described in the Table 7.2.

Table 7.2 Dental braces design bids collection

Bids	Description	Remarks
$p_{1_1}^D$	The metal brace is the traditional dental braces, which is made of metal. It has four essential elements, which includes the brackets, bonding material, arch wire and ligature elastic. The brackets are typically made of the stainless steel and attach to the teeth via bonding materials. The archwire is a thin metal wire to ensure the correction values. The linguistic elastic holds the bracket to the wire.	
$p_{1_2}^D$	The ceramic brace has a similar shape and structure to the traditional braces, instead of using the ceramic material to replace the metal to make the brackets. The tooth-colored ceramic brackets blend into the tooth. Due to the material change, the geometric profile is different to the traditional brace.	
$p_{1_3}^D$	The lingual brace has the same structure to the traditional brace. However, it is placed inside of the teeth. This brace provides a better appearance for the patient.	
$p_{1_4}^D$	The clear aligner is a clear plastic-made brace, which looks familiar to a mouth-guard. The geometric profile of this brace is close to the patients' digital impression model. Different from other braces, the clear aligner is a set of removable braces, and the patients replace it periodically.	

E_1^D evaluates these bids based on their DoS. Based on the mechanism established in the Chapter 6, the evaluation methods can be decomposed into following steps. Firstly, E_1^D specifies the corresponding range parameters of F_{fr} and F_{pr} for every criterion and bid, thus the preference function of expected performance and the PDF of achieved performance is established. Secondly, using Eq. 6.5 and 6.6, the information contents I can be derived. Thirdly, calculating the DoS using Eq. 6.7 and aggregate these DoS using Eq. 6.2 and 6.3. At last, the preferred bid can be selected by the rule which is depicted in the

Eq. 6.4. The evaluation process for the illustrative example is demonstrated in the Table 7.3. After the evaluation, the $p_{1_4}^D$ shows superiority and it is selected to be p_1^{D*} . Thus, the corresponding bidding design agent ψ_4^1 will be evaluated as ψ^{1*} and awarded by the supply contract C^D . This evaluation and contracting results will be sent to the open product innovation domain and saved as design specs D^0 .

Table 7.3 Evaluation of design bids



		Design Evaluation Criteria														
		Comfortability														
Performance Evaluation		$c_1^{F_1}$		$c_2^{F_1}$						$c_3^{F_1}$		$c_4^{F_1}$		$c_5^{F_1}$		
		Maxillary Incisor Torque (°)		Thickness (mm)						Corner Radius (μm)		MTTF (month)		Estimated Sales Price (k\$)		
		F_{pr}^L	$p(F_{pr})$	F_{pr}^U	F_{pr}^L	$p(F_{pr})$	F_{pr}^U	F_{pr}^L	$p(F_{pr})$	F_{pr}^U	F_{pr}^L	$p(F_{pr})$	F_{pr}^U	F_{pr}^L	$p(F_{pr})$	F_{pr}^U
	$p_{1_1}^D$	7	$U(7,22)$	22	1.5	$N(1.9, 0.2)$	2.3	20	$N(30, 5)$	40	23	$N(29, 3)$	35	3	$N(5, 1)$	7
Performance	$p_{1_2}^D$	7	$U(7,22)$	22	1.7	$N(2.2, 0.25)$	2.6	40	$N(50, 5)$	60	20	$N(23, 1.5)$	26	4	$N(6, 1)$	8
Range	$p_{1_3}^D$	7	$U(7,22)$	22	1.5	$N(1.9, 0.2)$	2.3	20	$N(30, 5)$	40	22	$N(26, 2)$	30	8	$N(8.8, 0.4)$	9.6
	$p_{1_4}^D$	7	$U(0,20)$	20	0.3	$N(0.5, 0.1)$	0.7	30	$N(90, 30)$	150	10	$N(12, 1)$	18	4	$N(5.8, 0.9)$	7.6
Fulfillment Range		$u(F_{fr})$		$u(F_{fr})$						$u(F_{fr})$		$u(F_{fr})$		$u(F_{fr})$		
		$U(7.5, 14.5)$		$Tri(0.2, 0.2, 2)$						$Tri(30, 200, 200)$		$Tri(10, 30, 30)$		$Tri(3, 3, 9)$		
Degree of Satisfaction	$p_{1_1}^D$	0.204		0.213						0.0713		0.191		0.309		
	$p_{1_2}^D$	0.204		0.143						0.0947		0.200		0.274		
	$p_{1_3}^D$	0.204		0.213						0.0712		0.212		0.140		
	$p_{1_4}^D$	0.188		0.849						0.111		0.149		0.281		
Weighting Factor	w	0.3		0.15						0.05		0.2		0.3		
Normalized Degree of Satisfaction		$UDoS(p_{1_1}^D)$														0.0457
		$UDoS(p_{1_2}^D)$														0.0457
		$UDoS(p_{1_3}^D)$														0.0460
		$UDoS(p_{1_4}^D)$														0.0472

7.4 Manufacturing Supply Contracting

Based on the demonstrated product fulfillment process in Figure 3.1 and the design supply contracting mechanism in Figure 3.3, the Γ^M receives the Δ at first and delivers \mathbf{M}^* at last. Δ contains the DPs of the product and depicts the product structure. In this case, Γ^M receives the design of the braces, and it decompose the manufacturing jobs based on the





understanding of the products. In the current industrial practice, the thermoforming process is widely applied in the manufacturing of a clear aligner, which can be decomposed into 1) Δ_1 physical model construction; 2) Δ_2 thermoforming process (Martorelli et al. , 2013). The thermoforming is a way of forming clear aligners by heating up the polyurethane resin sheet to a pliable state, then pressing the sheet to a cool mold and holding it until rigidification (Throne, 2003). A 3D physical model is a part of a mold, contains the details of the treatment plan. Thus, two agent innovation brokers I_1^M and I_2^M is involved to invite the A^M bidding for the manufacturing jobs. The whole treatment requires a series of braces for a gradual adjustment. Based on the understanding of the Δ_1 and Δ_2 , E_1^M and E_2^M proposed the evaluation criteria for the corresponding RFQs. The RFQs are described in the Table 7.4.

Table 7.4 Request for quotation of manufacturing bids for dental braces

Manufacturing Request for Quotation	Manufacturing Evaluation Criteria	Description	Remarks
Δ_1 Physical Model Construction	$c_1^{\Delta_1}$ Estimated Cost (\$)	After the design of the braces, a physical 3D model needs to be constructed to be a part of the mold in the thermoforming process. It is a mimic of the patient's intraoral profile. The clear aligner requires a series of appliance for a progressive alignment. The manufacturing of the process requires rapidly forming of the geometric.	
	$c_2^{\Delta_1}$ Throughput Time (hr)		
Δ_2 Thermoforming Process	$c_1^{\Delta_2}$ Estimated Cost (\$)	The thermoforming of the clear aligner requires pressing the heated sheet again the cold 3D physical mold and trimming the formed part the after it is rigidified. The delivered braces should be polished to ensure the surface quality.	
	$c_2^{\Delta_2}$ Throughput Time (min)		

After I_1^M and I_2^M broadcast the RFQs to the crowds, $2 \mu^1$ and $2 \mu^2$ decide to bid, which are noted as $\{\mu_1^1, \mu_2^1\}$ and $\{\mu_1^2, \mu_2^2\}$, respectively. 4 bids are collected by E_1^M and E_2^M in two sets: $\{\{p_{1_1}^M, p_{1_2}^M\}, \{p_{2_1}^M, p_{2_2}^M\}\}$. The bids in this case is shown in the Table 7.5.

Table 7.5 Dental braces manufacturing bids collection

Bids	Description	Remarks
$p_{1_1}^M$	Computer numerical control (CNC) system is the prevailing technology of obtaining the final shape by subtracting material. 5-axis CNC milling machine requires the relatively higher involvement of human involvement and programming. However, it offers a quicker model generating process. CNC based milling process has the relatively proper handling of the complex shape and higher accuracy.	
$p_{1_2}^M$	The 3D printing system is an emerging technology, which obtains the final shape by adding layer-upon-layer of material. 3D printing is a highly automated production process thus a relatively less human is required in the process. However, the layer by layer building process introduces stair-case effects on the surface profile and dimensionally accuracy (Mohan Pandey et al. , 2003).	
$p_{2_1}^M$	Vacuum forming presses a heated pliable against the 3D physical mold by vacuuming out the air between the mold and sheet. Vacuum forming process offers a low cost and sharper details.	
$p_{2_2}^M$	Press forming presses a heated pliable against the 3D physical mold by vacuuming out the air between the mold and sheet and applying air pressure above the sheet. Press forming process can provide complex shapes and quicker forming process.	

Based on the manufacturing bids, the E_1^M and E_2^M builds the DES model to evaluate them by analyzing the system performance of the reconfigured production system's digital twins. The evaluation process can be decomposed into the following steps. The E_1^M and E_2^M firstly specify the corresponding range parameters of D_{fr} , and the corresponding preference function of the supplying fulfillment preference $u(D_{fr})$. Subsequently, E_1^M and E_2^M implement the DES and predict the range parameter of D_{pr} and PDF of the probability

of the success of the system performance $p(D_{pr})$. Based on these functions, the DoS of these bids are calculated by using Eq. 6.5 – 6.7. Because the evaluation is a multi-criteria problem, the evaluation results are aggregated by Eq. 6.2 and 6.3 to get rid of the correlation. At last the preferable bid is selected by rule depicted in Eq. 6.4. The evaluation processes of the manufacturing bids are demonstrated in the Table 7.6. After the evaluation, the p_1^M and p_2^M shows superiority in Δ_1 and Δ_2 , respectively, and will be selected to be the p_1^{M*} and p_2^{M*} . Thus, their manufacturing agents μ_2^1 and μ_1^2 will be selected as preferred manufacturing agents μ^{1*} and μ^{2*} and awarded by supply contract C^M . This evaluation and contracting results will be sent to the open product innovation domain and saved as the p^0 .

Table 7.6 Evaluation of manufacturing bids

		Manufacturing Evaluation Criteria											
		Δ_1						Δ_2					
		$c_1^{\Delta_1}$			$c_2^{\Delta_1}$			$c_1^{\Delta_2}$			$c_2^{\Delta_2}$		
		Estimated Cost (\$)			Throughput Time (hr)			Estimated Cost (\$)			Throughput Time (min)		
Performance Evaluation	D_{pr}^L	$p(D_{pr})$	D_{pr}^U	D_{pr}^L	$p(D_{pr})$	D_{pr}^U	D_{pr}^L	$p(D_{pr})$	D_{pr}^U	D_{pr}^L	$p(D_{pr})$	D_{pr}^U	
Performance	p_j^M	9	$N(13,3)$	17	2	$N(3.5,1)$	5	12	$N(12.7,0.5)$	13.5	15.8	$N(17,1)$	18.5
Range	p_j^M	12	$N(16,4)$	19	1.7	$N(2.2,0.3)$	3	12.4	$N(13.2,0.4)$	14	15.2	$N(16.5,0.8)$	18
Fulfillment		$u(F_{fr})$			$u(F_{fr})$			$u(F_{fr})$			$u(F_{fr})$		
Range		$Tri(9,9,15)$			$Tri(1.5,1.5,4)$			$Tri(12,12,13.5)$			$Tri(15,15,18)$		
Degree of Satisfaction	p_j^M	0.230			0.282			0.574			0.283		
	p_j^M	0.148			0.528			0.358			0.365		
Weighting Factor	w	0.4			0.6			0.8			0.2		
Normalized Degree of Satisfaction		$UDoS(p_1^M)$						0.261					
		$UDoS(p_1^M)$						0.376					
		$UDoS(p_2^M)$						0.516					
		$UDoS(p_2^M)$						0.359					

7.5 Chapter Summary

This case study of dental braces fulfillment process shows an example of the implementation of C²PF through ODM. It has proofed the proposed workflow can handle

the C²PF of tangible products. The clear aligner requires individualized treatment plan and mold. With the involving the external partners, the orthodontist can fulfill the customer needs without developing the design and manufacturing capabilities. The proposing evaluation mechanism provides an approach to constructing the collaborative-crowdsourcing team.

By applying ODM, the orthodontist can focus more on his core competitiveness, includes servicing the customers, treatment planning, and appliance implementation. Meanwhile, the digital dental labs and orthodontic solution provider can design and manufacture the braces without direct contact with the customers. The C²PF offers a bridge to link them to fulfill the customer needs complimentarily and ease the application of the emerging technologies like clear aligners. Throughout the C²PF, the SME can achieve the scale economy and catch up the opportunities easier.

CHAPTER 8. CONCLUSIONS AND FUTURE WORK

8.1 Discussions and Conclusions

The paradigm of ODM implies the opening of the boundary of the traditional manufacturing practitioners and the involving of the external partners into the value creation and capture process. This paradigm shift challenges the traditional product fulfillment flow because of the decentralized and open structure has replaced the all-in-one organization. This work focuses on the physical product fulfillment through the ODM. A product fulfillment flow named C²PF has been proposed to entail the crowdsourcing process and the collaboration in this paradigm. C²PF reengineers the conventional product fulfillment process to allow the negotiation and collaboration with external partners.

From the platform-based view, the open enterprise can be identified as a platform to serve the product fulfillment process. The open innovator, open designers, and open manufacturers can be identified as the modules. The open contracting mechanism and C²PF management offer an interface for the modules. The C²PF provides an embodiment architecture for organizing the modules to an enterprise. Various innovators and partners can be rapidly reconfigured thanks to the C²PF platform. This research provides the opportunities for the companies to utilize external resources while focus on their core competitiveness. Specifically, this work paves the way for the SME's fulfillment of the various customer needs.

For revealing the dynamics of the partners' population and seeking the open enterprise's long-time prosperity, the ECC game theoretic models has been proposed as a guideline of the management of open enterprise and the group decision-making in C²PF. The essential of negotiation and collaboration with the external partners have been

highlighted in the management of the knowledge and material flow. The supply contracting mechanism has been identified as the key to achieve the collaborative-negotiation. The contracting mechanism has been proposed, and the generalized evaluation of the preferable bids has been developed. Such mechanism shows the effectiveness of handling the complexity of the evaluation problems through ODM and reveals the collaborative-negotiation inside the open enterprise.

8.2 Limitations

However, there are several limitations in this work. Firstly, this work only focuses on the contracting stage in the collaborative-negotiation process. After, the contracting, the coordination of the design and manufacturing in the execution of C²PF need more research. Secondly, since the collaborative crowdsourcing use open calls to invite the bidding, the intellectual properties protection can be identified as the difficulties in the ODM. The decentralized C²PF must protect the intellectual properties not only during the open calls but also the operation of the reconfigured production. Thirdly, the current ECC model assumes the homogeneous inner the design and manufacturing agents' populations, respectively. It can be applied to model the behaviors of the similar partners. However, heterogeneous partners are high-likely to be involved in the C²PF. The current ECC model should be developed to handle a higher agent variety. Fourthly, the robustness of the generalized evaluation method needs further exploration.

8.3 Future Work

Several ideas are elaborated for the potential endeavors in the future. Firstly, set-based engineering techniques and predictive best matching protocol should be applied to

coordinate the design and manufacturing supply chain in the executive phase of C²PF. Secondly, the emerging blockchain technologies shed lights on the security of the decentralized networks. Applying blockchain to ensure the intellectual property protection will be an applicable method through ODM. Thirdly, a general model of income and cost formulation should be developed to support the refinement of the current ECC model. Lastly, a sensitivity analysis of the evaluation method should be implemented.

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