Constructing a Sustainable Collaborative Innovation Network for Global Manufacturing Firms: A Product Modularity View and a Case Study From China

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ABSTRACT An enduring challenge of soaring market complexity has significant impact on global manufacturing firms. The purpose of this paper is to explore a product modularity-based routine that enables global manufacturing firms to leverage product innovation, particularly in an open challenging environment through the collaborative innovation network. Based on an analysis of the effects of product modularity on collaborative innovation, this paper develops a collaborative innovation network model featuring customer-driven, module as innovation carrier and sustainability, in which the modular product architecture (MPA) plays a role in linking customers, the core firm, and heterogeneous external partners. Next, two kinds of generic partnership management mechanisms are designed. Results in conjunction with an explorative case study show that the positive impact of product modularity on collaborative innovation is verified, which not only facilitates interactions among participants in the collaborative innovation network, but also provides an effective way for the global manufacturing firm to manage external partners.

INDEX TERMS Collaborative innovation network, global manufacturing firms, product modularity, partnership management mechanism.

I. INTRODUCTION

During the last decades, an enduring challenge of soaring market complexity has drawn much attention [1]. As a result of such complexity, product structures are becoming increasingly complicated, which in turn leads to decreased efficiency within companies [2]. Under such circumstances, innovation is popularly regarded as the key driving force of the global economy, especially in the manufacturing sector [3], [4]. Innovations in products and services have become a necessity for the survival of global manufacturing firms in a more challenging environment [5]. Fortunately, these firms are gradually realizing the importance of utilizing heterogeneous knowledge and technology from beyond their corporate network of subsidiaries [6]. To innovate, they must make greater efforts to effectively respond to local customers’ demands by flexibly integrating external partners [7], [8].

More specially, one solution to the above dilemma is to increase a firm’s capabilities through collaborative or open innovation [9]. To acquire knowledge and improve technological innovation, firms can incorporate partners such as universities, research institutions, and suppliers into their collaborative innovation networks [10]. Studies have suggested that such collaborative innovation can be desirable in terms of competitive advantage, especially where the integration of external knowledge is a critical determinant of a firm’s technological innovation [11]. Various findings regarding the modes [12], [13], influencing factors [14], [15], and management mechanisms [16], [17] of collaborative innovation have deepened both practical and scholarly awareness of such innovation.

However, questions remain regarding how to construct a customer-driven collaborative innovation network featuring sustainability, especially for global manufacturing firms. Research questions of this study include the following: (1) By what means can customers’ voices be effectively reflected...
in collaborative innovation processes? (2) Is there a better way to fuel the interactions between global manufacturing firms and their external partners in collaborative innovation networks? Lastly, (3) how can we design applicable mechanisms for managing external partners? This study contributes to the literature by combining the theories of collaborative innovation and product modularity. With that, we propose a product-modularity-based collaborative innovation network model. We also discuss generic partnership management mechanisms to coordinate diverse demands of global customers and heterogeneous external partners participating in product innovation. The remainder of this paper is organized as follows. Section 2 reviews the literature. Section 3 presents the theoretical basis of the study, and then proposes a collaborative innovation model, along with generic partnership management mechanisms. Section 4 conducts a case study, and Section 5 concludes the paper and outlines directions for future research.

II. LITERATURE REVIEW
A. OVERVIEW OF COLLABORATIVE INNOVATION
According to Haken [18], collaboration can generate a “1+1>2” effect in terms of the coordination and cooperation of all elements in a system. Building on this, subsequent studies have found that collaborative innovation is not only a key source of firm innovation [19], [20], but also a focus of government attention [21]. According to a survey of 236 firms in China, Wang et al. pointed out that there are significant positive relationships between collaborative innovation activities, knowledge sharing, collaborative innovation capability, and innovation performance of a firm [22]. Despite the recognized importance of collaborative innovation, barriers have emerged in terms of collaboration modes because of cultural differences [12] and conflicting goals [17], [23]. Consequently, it can be difficult to achieve the expected results of collaboration. In particular, firms and universities often have different perspectives on collaboration. For example, academia pays more attention to scientific results while firms pay more attention to economic benefits.

Collaborative innovation networks are considered effective frameworks for facilitating knowledge transfer [24], [25], acquiring funds, equipment, and raw materials, and training students [26]. Regarding the construction of collaborative innovation networks, Veilen et al. [27] tested different ways of composing collaborative action networks in food innovation. Xiao et al. [28] built an evolutionary game model for collaborative innovation networks related to environmentally friendly technologies that included governments, firms, financial institutions, and research institutes. Also, it has been indicated that the level of collaboration with different partners can enhance a firm’s innovation capabilities only if the focal firm’s managers have developed the capacity to scan and acquire external knowledge [29]. Customers’ roles in collaborative innovation have also drawn attention. For example, by classifying customer motives for participating in online co-creation processes, Lorenzo-Romero and Constantines [30] found that online crowdsourcing and co-creation with customers are becoming attractive alternatives to traditional forms of innovation management.

Implementing management mechanisms for coordinating relationships between firms and external partners is important for achieving multilateral collaboration [19], [31], [32]. Importantly, Hurwicz [33] introduced the concept of incentive compatibility to capture the forces of individual self-interested behavior, which has proven to be a powerful organizing principle. Based on this principle, Laffont and Tirole [34] proposed contract incentive theory, noting that firms need to stress the constraints of suppliers by establishing quality guarantee deposits. Liu and Yan [35] suggested that self-organized collaborative innovation networks must meet two conditions: the innovation network must be open, and the innovation subjects must mutually cooperate. Hemmert et al. [17] proposed that fostering trust is key to overcoming barriers between firms and other parties; the mechanisms for fostering such trust include strengthening joint responsibility, improving partners’ reputations, and enhancing contract security. Han and Qin [36] proposed a game method based on revenues, aiming to achieve a more reasonable intermediary mechanism in collaborative innovation in production and research. To promote collaborative innovation in equipment manufacturing, Si [37] proposed the four factors of driving-force mechanisms, resource-supply mechanisms, dual mechanisms, and incentives.

B. MODULARITY AND COLLABORATIVE INNOVATION
The concept of product modularity emerged in the 1960s, when it was viewed as a complex system comprising many interacting parts [38]. In Baldwin and Clark [39] widely accepted definition, modularity involves “building up a complex product or process from smaller subsystems that can be designed independently yet function together as a whole.” This emphasizes the attribute of modules as “exhibiting relatively weak interdependencies between each other and relatively strong interdependencies within them” [40]–[42].

Product modularity refers to the degree of technical independence between the constituents of a product [43]. This means modules with standardized interfaces can be independently designed, procured, or produced [2]. Then, those modules can be used in different systems to drive multiple functionalities. At the same time, increased supplier involvement is positively associated with the technological novelty of modular designs [44], [46]. Overall, modularity is most often discussed in the literature of product and service design [47], [48], production [49], [50], and organizations [51], [52]. From a practical perspective, modularity can deal with product complexity by enabling manufacturing firms to configure variants of products [53]. This can influence new product development processes [46], [54], [55] and reduce the costs associated with acquiring components and managing tacit knowledge [56].

Shibata [57] suggested that product innovation is achieved through module dynamics in a two-stage process of...
partitioning and integrating modules. Modularity also plays a positive role in the design and management of vertical and horizontal interorganizational relationships [49], [50], [58]. Baldwin and Clark [39] suggested that the industrial division of labor based on modularity is an effective way for organizations to innovate. Furthermore, in terms of firm architecture, by standardizing the interfaces between decision making agents, firms can improve their learning and innovation capabilities [59]. Although many linked performance benefits have been proposed in the modularity literature [47], [60]–[62], such benefits have rarely been linked with collaboration and tested empirically. Moreover, the relationship between product modularity and collaborative innovation is not well understood. As such, a systematic framework that clarifies the relationships between customers’ demands, product innovation, and collaboration with external partners has yet to be developed.

III. CONSTRUCTION OF A COLLABORATIVE INNOVATION NETWORK MODEL

A. EFFECTS OF PRODUCT MODULARITY ON COLLABORATIVE INNOVATION

1) LEVERAGING A FIRM’S PRODUCT INNOVATION

Global manufacturing firms are likely to face situations where new-product research and development (R&D) becomes inefficient and complex following the increasing expansion of product offerings [63]. Product modularity aims to reflect customer demands in product properties and to configure products based on modular product architecture, which consists of modules linked by functional or structural relationships (Figure 1). By virtue of MPA, considerable product variants can be realized by configuring modules and components. A modular product is characterized by the following: (1) the functional partitioning of a product or service into smaller manageable and configurable modules to better react to changing customer demands; (2) well-defined interfaces between modules with “plug-and-play” functionality, which helps engineers to understand and predict the interactions among modules; and (3) technology transparency featuring the adoption of industry standards for key interfaces [2], [64].

2) SPECIALIZED DIVISION OF LABOR IN COLLABORATIVE INNOVATION NETWORKS

Modularity helps promote division of labor and collaboration among network members. Modularity has been found to be an effective method for analyzing complex social networks [60]. Complex social networks are composed of several communities connected by nodes. Modularity can distinguish such communities, which is conducive to understanding the dynamic changes and information transmission in a network. This is also complementary to the nature of modular production networks [49]. Moreover, a global manufacturing firm in a collaborative innovation network must balance its interests with its partners’ expectations, and shift from a “face-to-face” competitive orientation to a “side-by-side” win-win pattern of balanced interests. Modularity can help firms to combine external partners in line with the nature of modular product architecture (MPA), which can form a more reasonable division of labor in collaborative innovation networks. Correspondingly, conflicts of interest between firms and their partners can be reduced.

3) ELIMINATING ASYMMETRIC INFORMATION AMONG PARTICIPANTS OF INNOVATION

Asymmetric information is likely to occur when a global manufacturing firm interacts with external partners. Asymmetric information refers to situations where two parties start...
a potential transaction and do not have the same information [65]. The presence of asymmetric information often leads to an adverse selection of qualified partners in a collaborative innovation activity, which in turn has negative effects for making well-informed decisions. Fortunately, standardized interfaces of modules provide symmetric information according to “transparent design rules” [39], and there is no need for external partners to study the internals of the “black box” (module). This allows participants in innovation to effectively interact with each other. Taking Apple’s MacBook Pro (ME665CH/A) for example, any supplier can design external devices (e.g. scanners, flash disks) for the connection of the above personal computer on the condition that those devices comply with HDMI or USB interface specifications.

4) FLEXIBLY COORDINATING FIRMS AND EXTERNAL PARTNERS

Loose coupling is an approach that interconnects the elements in a system or network so that those elements depend on each other to the least extent possible [40]. A collaborative innovation network is a system in which the loose coupling effect is widely found at all levels of innovation [58]. Collaborative innovation is known to be driven by customer demands, which is consistent with the design philosophy of modularity. In a collaborative innovation network affected by product modularity, supply and demand can align their innovative solutions and requirements through the “transparent design rules” of modules [39] and eliminate barriers resulting from information asymmetries and other factors. In module-focused cooperative innovation, multidisciplinary knowledge flow is integrated, and the external partners associated with modules experience a dynamic exchange of knowledge. Moreover, with modularity, firms can sort out the technological innovation requirements of modules and decide which modules can be independently developed and which need to integrate external partners.

Given the functional independence of modules, external partners are loosely related when providing innovation services for firms, and the entry or exit of one partner will not affect other external partners. Conversely, under tight coupling design situations, there are complex relationships among the various components of the product [40], and dependency among the external partners is strong. In this scenario, a manufacturing firm must expend a lot of time and energy on coordinating external partners. Therefore, the import and exclusion of a certain partner will affect other partners. Similarly, in the context of firms, external partners can be organized to achieve a common goal when faced with specific technological innovation requirements originating from a single module or interrelated modules.

5) GENERATING BUSINESS ECOSYSTEM EFFECTS IN A NETWORK

Successful businesses tend to evolve rapidly and effectively, and they must attract all types of partners, drawing in capital, partners, suppliers, and customers to create collaborative networks. In a business ecosystem, firms and their partners work cooperatively to support new product R&D, fulfill customer needs, and eventually incorporate new innovations [66], [67]. Hyperloop Transportation Technologies, Inc. (HTT) launched in 2013 by Dirk Ahlborn and co-founder Bibop Gresta, for example, has a loosely coupled structure featuring a business ecosystem in which the contributors are generally part-time; they learn from each other and ensure that maximum value is created with minimal time expenditure [68]. A collaborative innovation network can meet the following three key criteria of business ecosystems: (1) the global firm is the core; (2) win-win results are advocated rather than a winner-takes-all logic; and (3) the dynamic optimization and coevolution of the network are based on loose coupling and a “suitable is survival” philosophy (i.e., only qualified partners have access to the ecosystem while unqualified ones do not participate).

B. COLLABORATIVE INNOVATION NETWORK MODEL

1) CONSTRUCTING STEPS OF COLLABORATIVE INNOVATION NETWORK

Based on above analysis on the effects of product modularity on collaborative innovation, this study constructs a product-modularity-based collaborative innovation model (Figure 2), mainly including the following steps:

- Mapping customers’ demands into product properties. To classify customers’ demands in global market, the quality function deployment (QFD) tool is adopted to create a link between the voice of customers and a firm’s product properties. Next, product property priorities are identified in terms of weighting relations between customers’ demands and product properties. Accordingly, the construction of the collaborative innovation network is premised on “customer orientation”.
- Defining the modular product architecture. Based on the analysis on customers’ demands analysis, we adopt the modular function deployment (MFD) methodology to define the MPA consisting of modules, module interfaces and modules’ configuration rules. Next, whether a module is designed in-house or jointly developed with external partners is decided, which leads to innovation targets of the MPA and efforts in search of external partners.
- Integrating external partners to match modules. In a collaborative innovation environment, external partners are classified into research institute, university, design house, testing lab, supplier, and other types [69]. In view of innovation requirements of modules, a global manufacturing firm needs to cross its own organizational border, and take effective measures to search for external partners through corporate IT platform, trade show, third-party agency, etc.
- Managing the network in a sustainable manner. To inspire external partners to work actively and effectively in a dynamic network, a global manufacturing firm (the core firm of the network) should play a dominant role in designing and implementing relevant
management mechanisms. Through such efforts, the goals and behaviors of participants of the network can be aligned, and only qualified external partners should be allowed to stay in the collaborative innovation loop. Conversely, optimization of external partners may push the MPA to evolve and stay competitive in the global market.

2) FEATURES OF THE COLLABORATIVE INNOVATION NETWORK

Customer-driven. Under a product modularity scenario, a module is the interaction carrier between the global manufacturing firm and external partners. Generally, the demands of end customers can be broken down into different categories, each of which can be satisfied by a corresponding module with a specific function. With household refrigerators, for example, customers’ demands for “food quality preservation,” “variable temperature storage,” and “ice making” can be realized by a “fresh-keeping module,” “refrigerating module,” and “icemaker module,” respectively. The MFD tool [2] is adopted to conceptualize functional modules. Regarding the composition of MPA, a global manufacturing firm needs to distinguish whether modules are jointly developed with external partners or developed independently. For the former, the firm mainly relies on in-house R&D; for the latter, the firm combines qualified external partners for collaborative innovation design and strives to ensure the technological competitiveness of the modules.

Module as an innovation carrier. In the collaborative innovation network shown in Figure 3, the global manufacturing firm occupies the top of the pyramid, providing instructions, guidance on customers’ demands, and product specifications. The external partners mainly include research institutes, universities, design houses, testing laboratories, suppliers [21], innovation media and venture capital agents. Under this circumstance, the global manufacturing firm plays a dominant role in absorbing and mapping customers’ demands (C1, C2, …, Cn) into product properties (P1, P2, …, Pm) and modules via QFD and MFD. Hence, the global manufacturing firm can cooperate with external partners via specific modules. Due to the commonality among the modules, the global manufacturing firm can further cluster relevant modules into the module system to produce more benefits from the technological innovation platform and integrate external partners. A product can be fully functional when it is composed of modules that are connected by internal interfaces. Interfaces accommodate connection, transformation, and interaction functions [70]. Module interfaces represent an agreement or contract between modules in a product architecture [71], [72]. Considering the nature of heterogeneous external partners as well as the technological interaction requirements of diversified knowledge flows, this study follows the definition of six types of technological interfaces to conceptualize interactions between modules [2], [72]: (1) attachment interface (A) – physical attachment between modules; (2) transfer interface (T) – material or energy exchange between modules; (3) communication interface (C) – command and control between modules, such as USB and WIFI; (4) field interface (F) – transmission of field force between modules, such as electromagnetic field force; (5) environment interface (E) – impact on environment via interface; and (6) spatial interface (S) – spatial interaction among two or more modules, where geometry and space may be used to describe the interface. Broadly, technological interactions among modules offer indispensable learning opportunities for global manufacturing firms, provide the ability to adapt to the changing globalized economy, and underpin long-term competitive advantages [73].

FIGURE 2. The proposed product-modularity-based collaborative innovation network model.
**Sustainability.** Management mechanisms are needed to keep qualified external partners within the innovation circle while excluding unqualified partners. These external partners can also share information dynamically via real-time interaction. The sharing of risks and benefits in manufacturing is comparable to the “survival of the fittest” phenomenon in natural selection. Consequently, a collaborative innovation network featuring sustainability is constructed, in which qualified external partners proactively collaborate with the global manufacturing firm to match customers’ demands. Moreover, as modular product technology evolves over time, the typology and nature of innovation network relationships must also evolve. That is, once technical interactions are better understood, codified, modularized, and shared, more exploitative networks may be better suited to exploit the current technology of modular products [10]. Furthermore, increased globalization combined with constant learning provided by technological interaction among modules could be linked to the proliferation of self-organizing innovation networks [74]. This can lead to adaptation and new organizational structures or processes that solve technological problems.

**C. GENERIC PARTNERSHIP MANAGEMENT MECHANISMS**

Management mechanisms are essential for solving the problems of innovation organization [64]. The following two generic partnership management mechanisms are proposed to ensure the quality of external partners and strengthen their interactions with global manufacturing firms.

*Dynamic optimization and sustainable operation.* From an ecological perspective [75], an organization’s adaptation to environmental changes includes variation, selection, and retention. Accordingly, the global manufacturing firm needs to develop evaluation, acceptance, and rejection criteria for external partners to enhance the operation of a collaborative innovation network. Under a product modularity scenario, the functional modules originating from customers’ demands are treated as the interaction carriers in the collaborative innovation network, which makes the participants in the network closely interrelated. External partners should also have fair opportunities to access the network. Here, technical innovation requirements can be satisfied by qualified partners.

Participation constraint and incentive compatibility. To regulate the collaborative innovation actions of firms and external partners, and to avoid the effects of random exits, the global manufacturing firm should develop mechanisms to ensure the introduction of qualified external partners. Furthermore, to effectively promote the input of external partners’ competitive innovation schemes into firms, the global manufacturing firm should implement appropriate incentives to stimulate external partners [33], [34]. For example, if external partners pass innovation ability tests, and their performance outputs meet or exceed expectations, they can enjoy corresponding profit sharing or chances to participate in more innovative cooperation projects.

**IV. CASE STUDY**

**A. CASE SELECTION**

This study explores the influence of product modularity on the collaborative innovation network, which belongs to the problem of “How” and “Why”. Therefore, the method of an exploratory case study was adopted [76]. This study followed the principle of theoretical sampling, using analysis and selection of case materials, and completed an in-depth longitudinal single-case study focusing on the Haier Group (referred Haier). At present, Haier has established the layout and global operation in about 160 countries and regions, which is in line features of global manufacturing firm.

Despite its rapid development in recent decades, Haier realizes that it has become impossible to address soaring product design complexity and satisfy customer demands relying only on its own R&D. Consequently, Haier has adopted the innovation strategy of “taking the world as our R&D center” to explore innovation potentials via external partners. In 2011, Haier switched from traditional component design to product modularity for its large home appliances lines. Modularity has thus become a key pillar for the firm to leverage product innovation and even business-model transformations.

This study focused on Haier’s air conditioning product line. In recent years, China’s air conditioning industry has become highly competitive. First, tasks related to energy conservation and emission reduction have increased while real estate regulation has had an inhibitory effect on the industry. Second, with the cessation of energy-saving-product subsidies in China, the production costs of air conditioners have been rising. In addition, many homogeneous Chinese air conditioning products lacking technological innovation have pushed market competition to a high level. As a consequence, Haier realized it needed to cooperate with research institutes, universities, design houses, testing laboratories and even upstream suppliers to implement the collaborative innovation strategy and improve its technical and product competitiveness.

**B. DATA COLLECTION**

To ensure a high response rate for valid and reliable analysis, data were collected as follows: (1) One of the authors previously worked for Haier, largely engaged in technological innovation system management and product modularity design; this was helpful for acquiring firsthand materials. (2) Semi-structured interviews were conducted with the CTO of Haier and executives from its air conditioning division. (3) Questionnaires were completed by each member of the above executives at the air conditioning division. Lastly, (4) data were collected from secondary sources.

**C. DATA ANALYSIS**

1) **OVERVIEW OF HAIER’S PRODUCT MODULARITY PRACTICE**

The internal unit of the second generation of the T-series air conditioner (T-AC-II), featuring a modular design, was chosen as the product case. Originally, the concept design
of the T-AC-II derived from a demand analysis covering 673,372 consumers in the world. Different from the first generation of T-series air conditioners (T-AC-I), which are rooted in component design, this innovative product mainly focused on providing solutions for air conditioning sickness, excessive cold air, and intelligent control issues. The QFD tool is adopted to map customers’ demands into product properties (abbreviated as PPs) and then identify product-property priorities for the T-AC-II. The ranking results helped the design engineers understand the market situation and the R&D focus and adopt corresponding collaborative innovation activities.

Figure 3 shows the relations between customer demands and properties. Four kinds of fuzzy intensity expressions of relationships are defined as strong (●, 9), medium (○, 3), weak (△, 1), and none (□, 0). Accordingly, we can identify which PP is more vital by comparing the calculation results of the fuzzy values (the top three are P1-air volume, P2-panel style, and P3-compressor type). Then, more innovative inputs can be capitalized to strengthen PPs’ competitiveness. The MPA of the T-AC-II was then created based on the MFD tool [2], which is composed of 20 functional modules (Table 1). To further strengthen the product competitiveness of the T-AC-II and optimize the number of external partners, module systems can be constructed based on the functional and structural correlations among the modules. Consequently, MPA can be expressed as a four-module system plus other seven other modules. Given the rapid technological evolution of home appliances, the MPA of the T-AC-II is not fixed and will be updated in the future according to consumer demands.

The case firm aims to obtain a delicate balance between in-house and collaborative strategies to guarantee product competitiveness and cost-effectiveness. Hence, the above modules (systems) were classified according to whether they were self-developed (in-house) or developed in collaboration with external partners. On this basis, the relationship matrix between modules and product properties could be built. In this way, the priorities of modules under collaboration innovation could be ranked. The computer board module (639), evaporator module (534), and skeleton module (501) were found to be the top three. Thus, attention should be paid to integrating external partners to fulfill their innovation requirements. In addition, Haier released module interface specifications in the bidding stage, including technical specifications, drawings, and inspection standards. Hence, technical secrets and intellectual property can be protected in this regard. External partners can also flexibly interact and independently cooperate with Haier via the modules according to their own aspirations and innovation abilities. The scope of the module interface standards mainly consists of 1) module interface style, such as the attachment interface, transfer interface, and communication interface; 2) specifications for the modules at both ends of the module interface, such as module functionality, performance, and price; and 3) purchasing quantity, delivery date, and other information related to modules or module systems.

2) CONSTRUCTION OF A COLLABORATIVE INNOVATION NETWORK

Based on the MPA of the T-AC-II, Haier initiated a collaborative innovation network in which the core firm interacts with external partners via specific MPA modules. Figure 4 visualizes the concrete collaborative innovation relationship between Haier and its external partners. In this network, modules act as innovation carriers between Haier and its external partners from mainland China (CN), Taiwan (TW), Japan (JP), Korea (KR), Germany (GE), and the United States (US). Module interfaces\(^1\) bridge the knowledge flows among modules, combining their linked partners. With the effects of product modularity, external partners can be clustered into six groups (marked by dotted lines in Figure 4) composed of two module-system-based partner circles and four module-based partner circles. To avoid excessive dependence on specific partners, Haier built the network with secondary candidates or backup partners candidates, making it a self-sufficient network that was controllable and filled with benign interdependence relationships among multiple stakeholders, which helped to reduce risks [77].

As shown in Figure 4, Haier classified external partners into: (1) **Strategic Partners (SP)**. Strategic partners not only have technological innovation capacity, but also sourcing, testing, and even production capacities. A strategic supplier is not restricted to the supply of a specific module; it could also contribute to collaborative innovation in terms of early supplier involvement (ESI) in the module R&D stage. Generally, a strategic supplier that engages in ESI may have a good chance for supplying modules after completing collaborative innovation on the module. As far as this kind of partner is concerned, Haier signed cooperative agreements in terms of a joint R&D entity, long-term roadmap sharing, and other agreements, in order to achieve strategic goals or core technologies. (2) **Ordinary Partners (OP)**. Ordinary partners have inputs to non-core modules attributing to their cost effectiveness, advantages on design for customer intimacy, and geographical proximity to Haier. Here both parties carry out R&D consignment or joint R&D to develop noncore technologies. This can help shorten the time to market, reduce R&D costs, and dilute uncertainties or risks.

In response to the priority ranking results for the modules (Table 1), the connection nodes of the collaborative innovation network were distributed more intensively around the computer board module and skeleton module. It can also be observed that universities and research institutes played important roles in the collaborative innovation processes. Meanwhile, suppliers with innovation abilities also engaged in early product R&D and conducted interactive docking and collaborative innovation around customer demands with firms and other partners. Furthermore, some innovation media (e.g., 9-Sigma, InnoCentive) were integrated into the

\(^{1}\) In Figure 4, A, C, and S indicate attachment interface, communication interface, and spatial interface, respectively. A combination of interfaces (e.g. AC) means there exist at least two interfaces in effect between modules.
network, introducing potential candidates to refresh healthy competition among external partners. In this sense, existing external partners strive to strengthen their innovative capacities and remain competitive in the ecosystem network.

Considering the standardized interface features and the functional independence of modules, external partners of the T-AC-II are independent of each other when they communicate with specific modules. However, they can also cooperate with others associated with certain modules under the coordination of the core firm. This means that traditional unilateral cooperation (external partners ↔ core firm) under collaborative innovation evolves into multilateral cooperation (external partners ↔ core firm; external partners ↔ external partners). For instance, Haier consigned the China National Institute of Standardization (CNIS) to calculate the heat transfer efficiency of its evaporator modules in conjunction with

**Figure 3.** QFD matrix mapping consumer demands into the product properties of the T-AC-II.

**Table 1.** Product modularity design and external partners’ configuration for the T-AC-II.

| No. | Module name               | Module system            | In-house/collaboration | Collaboration module’s related PPs | Subtotal value |
|-----|---------------------------|--------------------------|------------------------|-----------------------------------|----------------|
| 1   | Evaporator module         | Evaporating module system| Collaboration          | P3(○), P4(○), P7(●), P9(●), P10(○), P17(●) | 534            |
| 2   | Electrical heating module |                         | Collaboration          | P15(○)                           | 27             |
| 3   | Motor module              | Air supplying module system| Collaboration | P1(●), P9(○), P10(○), P17(○), P20(●) | 432            |
| 4   | Fan module                |                          | Collaboration          | P1(○), P5(○), P8(●), P9(○), P10(●) | 407            |
| 5   | Skeleton module           |                          | Collaboration          | P1(○), P2(●), P4(○), P5(○), P10(●) | 501            |
| 6   | Air induction module      |                          | Collaboration          | P4(●), P10(○)                    | 279            |
| 7   | Stepping motor module     |                          | In-house               | /                                 | /              |
| 8   | Self-cleaning module      |                          | In-house               | /                                 | /              |
| 9   | Fan curtain module        |                          | In-house               | /                                 | /              |
| 10  | Display module            | Casing module system     | Collaboration          | P4(●), P6(●), P19(○)             | 198            |
| 11  | Panel module              |                          | In-house               | /                                 | /              |
| 12  | Anion generator module    |                          | In-house               | /                                 | /              |
| 13  | Electrical control box module |                      | In-house               | /                                 | /              |
| 14  | Computer board            |                          | Collaboration          | P1(○), P3(●), P6(○), P9(○), P11(○), P14(○), P18(○), P19(○) | 639            |
| 15  | PM2.5 scavenger module    |                          | Collaboration          | P12(●)                           | 108            |
| 16  | Formaldehyde scavenger module |                      | Collaboration          | P1(●), P13(●)                    | 225            |
| 17  | Exhaust module            |                          | In-house               | /                                 | /              |
| 18  | Fixed frequency control module |                      | In-house               | /                                 | /              |
| 19  | Electrical parts box module |                     | In-house               | /                                 | /              |
| 20  | Intelligent sensing module|                          | In-house               | /                                 | /              |
Xi’an Jiaotong University to perform the structural design of the evaporators. Since these two external organizations were consigned different tasks associated with the evaporator module, they worked together with Haier to build a collaborative innovation circle intended to ensure that the evaporator module was appropriately designed.

3) IMPLEMENTATION OF THE GENERIC PARTNERSHIP MANAGEMENT MECHANISMS

General conflicts can be resolved by signing formal contracts with heterogeneous external partners during the collaborative innovation process. However, due to the limitations of contracts, it can be difficult to deal with a lack of motivation, conflicting interests, and many other potential obstacles and risks. Therefore, Haier implemented diversified partnership management mechanisms to deal with such issues.

*Dynamic optimization and sustainable operation.* Based on Haier’s technology requirements, several global partners were absorbed into the collaborative innovation and were evaluated under conditions of equal competition and access. During the collaborative innovation project, any qualified external partners with the right innovative solution could present a proposal complying with the requirements of the module. Previously, most partners or suppliers in Haier’s air-conditioner division came from China. Now, however, external partners outside of China can use networking tools to participate in the bidding procedures. Due to the function of partners filtering mechanism, external partners still must continuously enhance their capabilities and adjust their service strategies based on the dynamic needs of Haier’s T-AC-II. Only partners who meet customers’ demands can stay in the collaborative innovation network.

*Participation constraint and incentive compatibility.* To manage external partners within a controllable scope (i.e., to restrict their behaviors to avoid risks during collaborative innovation), strict clauses related to participation constraints were included in the contracts between Haier and its external partners. In short, uncontrolled behaviors by partners are not allowed once they sign a contract with Haier. The use of incentive compatibility measures can be effective for driving external partners to gain more profit depending on more innovative contributions. For example, the Chinese manufacturer *Sunwill* had previously only supplied the T-AC-II’s fan module.

However, driven by Haier’s incentive compatibility mechanism, *Sunwill* became the designer and supplier for the whole air-supply module system, responsible for more than 100,000 units per quarter under a two-year contract. With that, *Sunwill* came to manage the suppliers of other modules, including motors and wind deflectors.

D. RESULTS

Following the Haier Group’s R&D transformation from a component-based mode to a module-based mode, this study further compared the partnership management efficiencies corresponding to their total life cycles of the case products (T-AC-I, T-AC-II) under different R&D modes (Table 2). As shown in Table 2, the normalized value of each evaluation index was calculated according to the formula $(W_i-W)/S$, where $W_i$ is the original value relating to evaluation index $i$, and $W$ and $S$ are the mean value and standard deviation of each group of data, respectively. Regarding the T-AC-I designed under Scenario I, the case firm cooperated with many external partners pertaining to components. Although this offered many choices for the firm, the com-

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2The full name of Sunwill is Guangdong Sunwill Precising Plastic Co., Ltd. Sunwill is a Sino-foreign joint-venture company established in 1992, and it was listed on the Shenzhen Stock Exchange in 2012. Sunwill is the earliest professional company in China that is primarily engaged in the design and manufacturing of air conditioner fans.
TABLE 2. Comparison of partnership management efficiencies under various R&D modes.

| Evaluation criteria                  | Description of criteria                              | Component-based R&D (Scenario I) | Product modularity |
|-------------------------------------|------------------------------------------------------|---------------------------------|--------------------|
| Valid registered external partners (E1) | Number of external partners actively responding to innovative requirements of core firm | 0.412                           | −0.903            |
| Interaction activity of external partners (E2) | Received proposals/number of valid registered partners | −0.859                          | 0.415              |
| Innovative contribution per external partner (E3) | Accepted proposals/received proposals from external partners | −0.928                          | 0.356              |
| Configuration cycle per external partners (E4) | Average lead time from partners sourcing to partners importing to collaborative innovation projects | 1.027                           | −0.741            |
| Ratio of strategic partners (E5) | Sustainable and strategic partners/number of valid registered partners | −1.036                          | 0.402              |
| Adoption flexibility of external partners (E6) | Number of innovation requirements released by core firm/number of external partners | −0.925                          | 0.694              |
| Product properties benchmarking (E7) | Number of leading product properties/total product properties | −1.019                          | 0.748              |

(*) In Table 2, only E4 is the negative correlation index, which means the smaller it is, the more efficiency it will contribute.

V. CONCLUSION AND FUTURE WORK

A. CONCLUSION

1) THEORETICAL CONTRIBUTION

China has grown into the world’s leading manufacturing power since 2010, and has become one of the major producers of products and services for global markets. However, with the gradual disappearance of the “low-cost advantage,” China must transform and upgrade manufacturing from low-end to high-end industries as much as possible. Consequently, global manufacturing firms must explore effective innovation strategies and robust measures to achieve technological catch-up strategies.

Product modularity is one of the key strategies for increasing responsiveness to global customers. In light of global manufacturing firms facing intense competition in the globalized economy, this study explored a new method to manage the construction, as well as partnerships, in a collaborative innovation network in which the theories of product modularity and collaborative innovation are bridged. First, the effects of product modularity on collaborative innovation were analyzed. Then, a collaborative innovation network model featuring customer-driven, module as innovation carrier and sustainability was advanced. To illustrate how global manufacturing firms can better interact with external partners, modules within modular product architecture were treated as the innovation carrier, and a modularity-based collaborative innovation network model was constructed, in which the QFD tool and the MFD tool were adopted to map customers’ demands into concrete product properties and build the modular product architecture. Hence, this study enriches the collaborative innovation literature. To promote sustainable operation and the win-win development of collaborative innovation, this study offers two kinds of generic partnership management mechanisms: (1) a dynamic optimization and sustainable operation mechanism, and (2) a participation constraint and incentive compatibility mechanism.

2) EMPIRICAL CONCLUSIONS

One of the key motivations for this study was the appeal, “We must do a better job of connecting our research to the world around us” [78]. In view of this, this study explored theoretical issues from a microscopic perspective in conjunction with a case study. In this way, we were able to obtain meaningful results applicable to global manufacturing firms in terms of collaborative innovation management.
Based on the case study of the Haier Group, three conclusions can be drawn. First, product modularity positively affects the interaction between the large manufacturing firm and external partners during collaborative innovation. The “transparent design rules” provided by modularity help shift the participants in collaborative innovation from a face-to-face to a side-by-side orientation. Due to the commonalities among modules, the global manufacturing firm can further cluster relevant modules into the module system to produce more benefits from collaborative innovation, facilitate a common technological platform, and integrate external partners. Second, the proposed collaborative innovation network model can map customers’ demands into the collaborative innovation network, where external partners can be effectively linked with the core firm’s innovation requirements via modules. At the same time, product property priorities can be identified, which is vital for strategizing during collaborative innovation. Third, with the help of the above partnership management mechanisms, the global manufacturing firm can manage external partners dynamically and effectively; thus, qualified external partners remain in the collaborative innovation cycle while unqualified ones are eliminated. Meanwhile, the case study of Haier’s collaborative innovation management practice based on product modularity can provide helpful references for other global manufacturing firms for benchmarking and strategizing purposes.

In summary, the proposed collaborative innovation network is conducive to the core firm in its design of a modular product. First, the embeddedness of the QFD tool and the MFD tool in the network model helps prioritize customers’ demands, product properties, and modules, and consequently facilitates the core firm’s understanding on how to leverage its innovation strategy. Second, the core firm can use the network model to build a flexible modular product architecture (a skeleton for configuration design), which not only connects customers’ demands but also links inputs of external partners. Third, the core firm can release innovation requirements through its corporate IT platform or other channels, especially when searching for external partners to carry out collaborative innovation via relevant modules. In that regard, every external partner is supposed to have opportunity to share their expertise on corresponding modules. For instance, suppliers may participate in joint module design with the core firm by means of early supplier involvement (ESI), which is beneficial for forthcoming module supply. Finally, the proposed network model offers practical management mechanisms for effectively coordinating external partners, with which the core firm is able to operate the network in a sustainable manner.

Product modularity requires upstream and downstream linkages in the industrial chain, giving full play to large-scale economic benefits. The whole industrial chain should be mobilized to ensure sustainable R&D investment and jointly develop common technologies and standard systems of product modularity. Moreover, global manufacturing firms need to pioneer the trend toward product modularity and promote transformations in product R&D and collaborative innovation modes. Meanwhile, small and medium-sized firms, innovation providers (universities, research institutes), and service providers (such as designing houses and testing laboratories) also have a responsibility to share know-how to drive the upgrading of manufacturing industry in the global value chain.

**B. LIMITATIONS AND FUTURE WORK**

This study has some limitations that can be addressed in future research. First, although a detailed case study was conducted, the number of research objects was relatively limited. In addition, the home appliance industry is a representative manufacturing industry in China with strong competitiveness. Therefore, future research should increase the sample size of specific industries and conduct multiple case analyses in terms of comparative study or large-sample study. Future research should also conduct cross-industry studies to test the external validity of this study’s conclusions for various industries. Moreover, modularity is a long-term, complex, and systematic project that not only exists at the product level, but also involves production and organizational modularity. The structure of collaborative innovation networks under integrated scenarios of product, production, and organizational modularity should also be considered. Some concrete questions are also worthy of further exploration, such as: (1) influences of modular product architecture on the structure of the collaborative innovation network; and (2) what are the evolution dynamics of the collaborative innovation network, and how does it evolve? Final, it would be worthwhile to design specific partnership management mechanisms corresponding to heterogeneous external partners based on the generic management mechanisms proposed in this study.

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Please refer to the webpage link (http://hope.haier.com/hope_web/en/), for more details of Haier’s collaborative innovation platform (Haier Open Partnership Ecosystem, HOPE), which acts as an innovation community for distributed interaction and collaboration between Haier and its global partners.
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