

Knowledge Management in Collaborative Product Design-An Activity Theory Perspective

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Abstract—Collaborative product design is nowadays a trend of advanced manufacturing technology. Collaborative product design is a knowledge-intensive activity; knowledge management in collaborative product design has been focused. Existing literatures mainly focus on knowledge management systems in collaborative design, other aspects of design activity is rarely paid attention to. The framework of activity system interaction is applied to design business scenario analysis. Furthermore, knowledge management in collaborative product design is analyzed from six perspectives, which are subject, object, community, tools, rules and division of labor, of Activity Theory. And suggestions for promoting knowledge sharing and transformation are proposed to improve knowledge management in collaborative product design.

Index Terms—knowledge management; collaborative product design ;collaborative design; Activity Theory

I. INTRODUCTION

Network manufacturing is product of economic globalization and information revolution age; it's an important strategy in reforming traditional manufacturing industry. Network manufacturing requires partners in industrial chain upstream and downstream to collaborate in fields of design and manufacturing etc, which are usually called collaborative engineering. Collaborative engineering is a new concept of optimizing engineering process with objectives of better product quality, shorter lead-time, more competitive cost and higher customer satisfaction. Based on the rapid advancement of information technology, collaborative engineering has progressed dramatically. It has been widely applied to product design, manufacturing, construction, enterprise collaboration and supply chain management [1]. In design field, in order to improve product quality, reduce the cost of whole life cycle and shorten time to market of new products, applying collaborative engineering and collaborative design is pressing. It is benefit for breaking the bounds of departments and enterprises, establishing the mode of collaborative work. Collaborative product design is a collective activity whereby a product is created through individual actions on a shared object. These actions are brought together to form processes. Processes can be fashioned into tasks that are then

described as sequences of steps. Processes, individual actions, and tasks can merge into collaborative design activity through application of communication and coordination instruments [2]. Collaborative design enhances intercourse and cooperation between departments and enterprises, utilizes advantages of group work and competitive resources, and improves the efficiency of design. Collaboration partners in the lifecycle of a new product, such as supplier of components and customer, would all be involved in the process of product design. Collaborative product design plays an important role in agile manufacturing [3].

With the arrival of knowledge economy era, economic development mainly relies on knowledge inputs. New technology and new product are created based on knowledge. And sustained competitive advantage of an enterprise relies on product innovation and knowledge innovation. Design is a knowledge-intensive activity; each task involves various areas of knowledge and experience. Successful collaborative design depends on the ability to manage and share engineering knowledge and experience throughout the entire development process effectively. Stated this way, collaborative product design is called knowledge-intensive collaborative design. Consequently, the realization of distributed engineering knowledge management, which not only supports collaborative product design but also accumulates and utilizes corporate memory situated at various locations, has become one of a key task managed by industries. Iansiti and MacCorwack [4] suggest that as firms shift from a product centric form to a knowledge centric form, support that enables continuous flow of information about stakeholder needs and evolving technologies can reduce both cost and time required for product development. Providing effective decision support by making knowledge about past and current development efforts readily available can make a significant contribution towards ameliorating the process of product design and development.

Activity Theory is a framework, which is systematically used to study practical activity of humankind, extensively used to study innovations in many disciplines and settings [5]. Nowadays, there is a common application for graphic design, information

management of changes required for the transformation of collective practices in institutions, businesses, and other activity systems [6-9]. For the purpose of solving the predicaments which is confronted by collaborative design, Activity Theory is applied to study knowledge management in collaborative product design. In the following sections, Engestrom Activity Theory Model is applied to analyze scenarios in collaborative product design. Basing on this, knowledge management in collaborative product design is analyzed from six perspectives, namely, object, community, tools, rules and division of labor, of Activity Theory. And suggestions for promoting knowledge sharing and knowledge innovation are proposed to enhance knowledge management in collaborative product design.

II. RELATED WORK

A. Collaborative Product Design

Design of complex engineering system is increasingly becoming a collaborative task among designers or design

teams that are physically, geographically, and temporally distributed. Collaborative product design task involves decision-making processes that require evaluation, comparison and selection of design alternatives as well as eventual optimization from a systematic perspective [10]. Due to its significance in commercial value and application perspective in the era of knowledge economy, collaborative product design is attached great importance to. Many research institutes and information organizations made large investments to develop collaborative product design technology, and have made significant achievement [8, 11-14]. Shared3Dviewer is a distributed collaborative design system which could be used to design geometric figure and product structure. And CoConut is a design system of distributed data sharing, which is based on STEP concurrent engineering [15]. Table 1 gives an overview of some typical collaborative design systems [16].

TABLE I. OVERVIEW OF SOME TYPICAL DESIGN SYSTEMS

System	Architecture	Platform	Communication	Collaboration granularity	Network burden	Modeling technique
DICE	Centralized	Motif Compatible Unix Workstation	Specialized Messaging & Collaboration (OODMS)	Fine	Heavy	2D/3D parametric surface/solid modeling
Alibre	Centralized	PC Windows	TCP/IP, DirectX DSL, Cable Modem, TI or faster	Coarse	Light	2D/3D, parametric solid modeling
Windchill (PTC)	Centralized	PC Windows NT, Unix Workstation	Java RMI, XML	Coarse	Light	Feature-based modeling, etc.
Cooperative ARCADE	Decentralized	SGI, HP, SUN Workstation	Specialized Workstation Network	Coarse	Light	Solid modeling
CSCW-FeatureM	Decentralized	Motif Compatible Unix Workstation	CORBA Communication Service	Fine	Light	Feature-based modeling

Collaborative design is studied from different perspectives by academicians, which gave it rich connotation and characteristics. The features of collaborative design include [17]: (i) multi-agent;(ii) collaboration;(iii) flexibility;(iv)distribution;(v) timeliness;(vi) heterogeneity;(vii) complementarity;(viii) independence

B. Knowledge Management in Collaborative Product Design

With the development of research on collaborative product design, it was found that collaborative product design was essentially knowledge-intensive work, and knowledge management was of significance to collaborative product design. Knowledge management [18], which utilizes collective intelligence to enhance the adaptability and innovation capability of an enterprise, is a method for sharing explicit knowledge and tacit knowledge. Knowledge management includes several aspects: building knowledgebase; promoting knowledge sharing between employees; constructing cultural climate in internal environment; managing knowledge as enterprise assets. Many big companies, e.g. IBM and HP, have been implementing knowledge management strategy. And knowledge management in internal

management plays an important role in developing core competence of the company.

Many researches of knowledge management in collaborative product design was done. Balasubramaniam Ramesh and Amrit Tiwana [19] focused on providing support for a collaborative task with emphasis on capturing process knowledge in collaborative systems which include functions for representing context with informal components, accessing to process knowledge, reviewing past knowledge, and managing the dependencies of tasks. Vincent Robin, Bertrand Rose and Philippe Girard [20] are particularly interested in knowledge exchanged and shared during collaborations of product design. They proposed a model of design context to support design process and knowledge exchanges, and further studied the particular case of conflict resolution during collaborative design by using a software which formalise designers' exchanges in a real industrial conflict. Xuan F.Zha and H.Du [16,21] developed knowledge-intensive distributed design models and a framework for collaborative design modeling, and presented the implementation of a web-based knowledge-intensive collaborative design support system called WebKIDSS. However, distributivity and subjectivity are essential features of knowledge, which is reflected in the

contradiction between subject autonomy of knowledge activity and from top to bottom mode of knowledge management. For the centralized multi-user system, multiple users have access to a centralized main system, which stores and manages information such as product design models, design information and design history. Although it powerful, a central system is less suited for loose and flexible collaborations as it is not an open environment and does not allow for true knowledge encapsulation [22]. That's why most conventional knowledge management systems can only be used to help in document management, engineering data management or workflow management. No effective and practical system exists for capturing and sharing design knowledge and experience in collaborative product design [23]. This is a bottleneck in managing and sharing valuable product information, design knowledge and experience in collaborative and distributed design environment. Many researches were done to improve the functions of collaborative. However, the community of collaborative designers and the mechanism of collaboration are rarely paid attention to.

C. Activity Theory

Activity Theory, which is used to analyze humankind activity through model construction of the activity, was first proposed by psychologist Vygotsky. The modeling idea is that activity is taken as a research unit and performed with some tools assisted. They modeled the activity by a ternary relation "Subject-Tool-Object". Engestrom improved the model by taking social factors into account. Illustrated in Fig.1, three core elements in activity system are: Subject, Object and Community; and secondary elements are Tools, Rules, and Division of Labor. Secondary elements make up the relationships of the core elements. Subject is someone who performs activity based on motives; Object is the object of the activity, which will turn into outcome; Community is comprised of all Subjects who share Objects and the relationship between the Subjects; Tools are the tools used in the activity, they could be material or mental; Rules, which are used to coordinate the Subject and Object, are constraints of the activity; Division of Labor, which appears as roles, is that every Subject has his special task. Activity in Activity Theory is decomposed into three levels [22]: Activity, Action and Operation (see Fig.2). Activity based-on motive is accomplished through

a serial actions based-on goal, and action is performed by operation under some conditions.

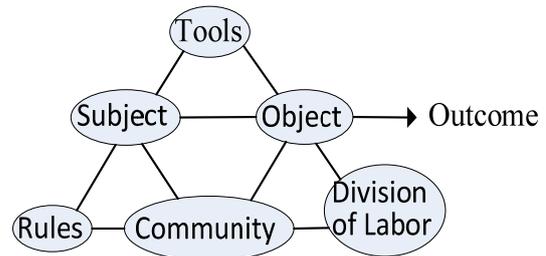


Figure 1. Framework of Activity Theory



Figure 2. Hierarchical Structure of Activity

Activity Theory provides a new perspective for knowledge management research, which focuses on knowledge activity, tools, relationships between subjects, context and object of the activity, rather than the state of knowledge. It is not a methodology, but a useful framework.

III. INTERACTIVE SCENARIOS IN DESIGN ACTIVITY

A. Framework of Activity System Interaction

The framework of Activity Theory is a revolutionized theory, but still there is some deficiency. After analyzing the malpractice of single activity framework, Engestrom proposed "super activity network" to eliminate the confine of activity framework. By interrelating activities, a higher activity system which called Engestrom Activity Theory Model (see Fig.3) is formed [24]. In contrast to Framework of Activity Theory, Engestrom Activity Theory Model emphasizes the opening and interactivity of activity, which corresponds to Social Network Theory. Engestrom Activity Theory Model is the most sophisticated Activity Theory model at present.

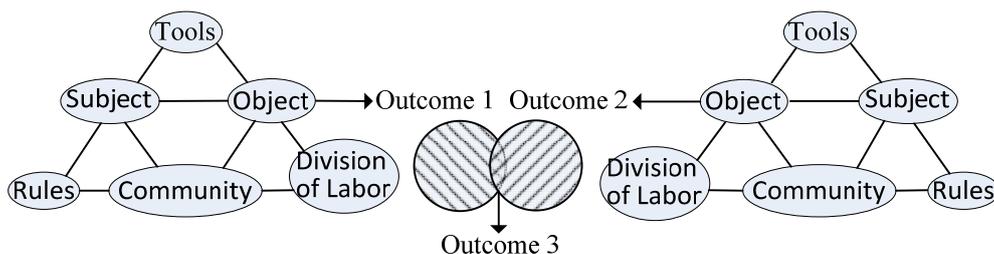


Figure 3. Engestrom Activity Theory Model

Based on the Framework of Activity Theory, Engestrom Activity Theory Model takes the social impact factors into consideration and highlight the interaction between subject and community. Interaction between activities is analazed according to elaboration of labor division and the complexity of engineering system. The model also takes relevance between activities into account, and analyzes the dynamics of activity evolution. This is in accordance with System Engineering Theroy.

Engestrom Activity Theory Model provides a framework for analyzing activity in social context, taking the impact of subject, object, community, tools, rules, division of labor on activity into consideration, emphasizing evolution unitarity between activity and subject. Activity should be performed in goal-directed behaviors. These thinking is of significance to the knowledge management in activity of collaborative product design.

B. Scenarios of Collaborative Product Design

The organization structure of collaborative product design is projectized organization, whose features are compressed and dynamic, generally. In such an organization structure, a designer may belong to several projects, and a project is composed of designers from several departments even several enterprises usually.

Gero and McNeill [25] argued that collaborative design was in fact a process that consists of a series of distinct events that occupy discrete and measurable periods. That's, collaborative design can be seen as a series of discrete activities and that the level of expertise affects the way work is done, being discernible in the temporal pattern of their work of time. Kvan and Vera [26,27] suggested that designers act as individual experts addressing design issues from their perspectives. Their expertise may change during a design session as their understanding is supplemented and they earn from their involvement, illustrated in Fig.4.

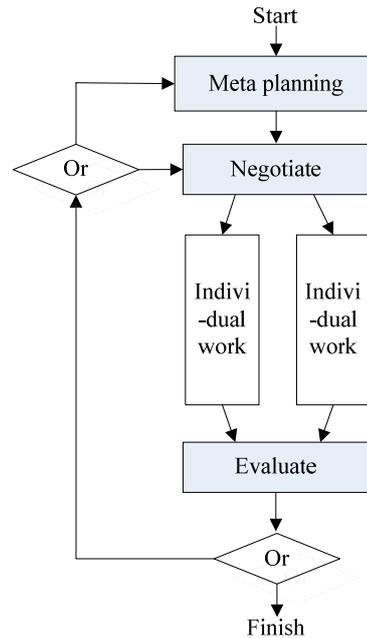


Figure 4. A Model of Design Collaboration

In the process of collaborative product design, task is accomplished through serial interactive activities which are performed by collaborative designers. Designers working on a same project often appear to be temporally and spatially distributed. Thus, quite a lot of time is spent on planning, tracking, and coordinating in the process of collaborative product design [28]. As illustrated in Fig.5, *designer A* and *designer B* perform activities concurrently, and accomplish their tasks through serial actions. In the processes, they should communicate and share knowledge with each other on collaborative product design system, and share modification of the product. Based on the outcomes of activities accomplished by *A* and *B*, *designer C* performs serial actions to achieve the goal of task. In similarly, *C* should communicate and share knowledge with *A* and *B*. With the increase of task complexity and the number of collaborative designers, efforts concentrated on commutation and knowledge sharing would build up and the scenarios of interacion would become much more sophisticated. This reflects the urgency of knowledge management in collaborative product design.

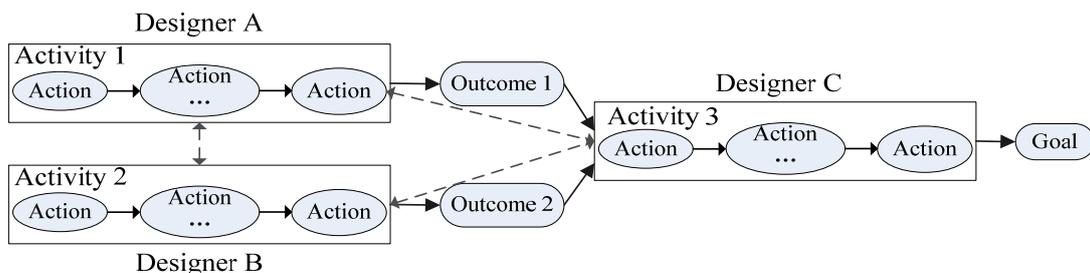


Figure 5. Activity Model of Collaborative Product Design

IV. KNOWLEDGE MANAGEMENT IN COLLABORATIVE PRODUCT DESIGN

Case-Based Design (CBD) is an important method of design. The process of CBD is: search similar cases from database; modify the cases to coincide with present case,

if it's pleased with the outcome then end, else refine the cases further until it is eligible. CBD is helpful for taking advantage of existing knowledge in database and improving the efficiency of product design.

A. Subject

In the process of collaborative product design, Subject is the collaborative designer. Design can be viewed as the process of converting information that characterizes the requirements for a product into knowledge about it. Based on the principle of decision-based design, the design equation can be expressed as follows [29]:

$$\{K\}= T\{I\} \quad (1)$$

where K is a knowledge output, I is an information input, and T is a transformation relationship, respectively. Hence, knowledge-intensive support becomes more critical in design process and has been recognized as a key enabling technology for retaining competitive advantages in product development [30]. One feature of design is that the process of design is a decision-making process. Designers choose actions in each refinement step of the design object. The final design is certainly definite and unambiguous. However, when designers choose an initial design solution or formulate the initial model, it always involves considerable uncertainties [10]. Formulated design goals and constraints are often subjectively estimated by designers, designers with rich knowledge and experience tend to make a best choice. Designed product is the syntheses of knowledge and skill. The knowledge level of designers determines the quality of product to a great extent. If a designer is rich in knowledge and experience, he would be willing to promote knowledge sharing and collaboration, offer others with knowledge demanded, and enhance the controllability of knowledge sharing. In addition, knowledge absorptive capacity of recipient would also impact on knowledge sharing. Knowledge absorptive capacity is the capacity of distinguishing valuable knowledge, comprehending, and applying the knowledge in product design. The higher their knowledge absorbing capacity is, the higher their ability to promote knowledge sharing [31].

For the principles above, several suggestions could be drawn to improve the knowledge management in collaborative product design. (i) Strengthen training and encourage life-long learning, which is benefit for enhancing the ability of knowledge sharing and knowledge absorbing and bridging the knowledge gap between designers. In this way, the designers with a wealth of knowledge would know how to solve problems, or else they would know whom they could consult to. It is important to encourage innovation spirit of designers, advocate exploring new knowledge in the process of design and strengthen knowledge absorbing ability of designers. (ii) Integrate collaborative product design system with knowledge management system; promote knowledge sharing and knowledge innovation in the process of collaborative product design. Many existing knowledge management systems are independent of collaborative product design system. When the designer confronts a problem and demands related knowledge for

guide, he has to turn to another system, this leads to decreased working efficiency. The integrated collaborative product design system could provide designers with knowledge needed, and this is convenient for capturing knowledge during the communication between the designers.

B. Object

Activity should be performed in goal-directed behaviors. That is, design activity is geared by the goal of turning object into outcome [32]. In collaborative design, Object is the business object in design process, such as design document, CAD model and so on. Object is turned into the outcome of design activity, and it is also the medium of knowledge sharing. When the number of collaborative designers is large, and interaction process is complicated, object management is especially important. For instance, the word *acquirer* may express a same meaning with the word *customer*. However, if they were not made consistent throughout the process of collaborative design, confusion would be caused frequently.

In software engineering, the procedure of software development and its context have been paid much attention to, software developers have to record the evolution of project everyday. This has been proved to be an effective approach in engineering management. In collaborative product design, design activities are completed in sequence. Recording the procedure of design, the reason for modification and its context, could contribute to comprehending design intent of product. The possibility of redesigning some parts or the whole product could be eliminated by knowledge accumulation in the process. And the knowledge is of significance to write technical specification of product. Understanding practical and theoretical knowledge of the product, production experts know how to assemble, and packaging specialists know how to pack the product. Knowledge accumulation speeds up the process of product development and reduces the time-to-market.

Therefore, efforts could be made to enforce knowledge management in collaborative product design. (i) Strengthen standard management of the object, ensure the objects, e.g. design document, technical specification, maintain consistent in terminology and form. This should be done prior to getting down to design work. (ii) Record the procedure of design and its relevant knowledge, and improve the understandability of design case. This is also benefit to maintain the schedule of project program and meet critical milestones, avoiding impacting overall progress of the project adversely due to some personal work delay. This would be conducive to enforce knowledge management of collaborative product design.

C. Community

One important feature of collaborative product design is multi-agent. Community is composed all the collaborative designers and the relationship between them. Distributed designers collaborate with others on collaborative design system, the "soft environment" community influences designers' behaviors. As studies of

collaborative design have continually identified numerous technical and soft characteristics; however, collaboration failure frequently occurs not because of explicit factors but rather because of implicit issues, such as project attitude, mutual exclusion relationships among collaborative designers. Knowledge base [33] is defined as common environment of knowledge innovation and knowledge sharing. Community in collaborative product design is the knowledge base where the designers collaborate in. Product design is a knowledge discovery process, in which information and knowledge of diverse sources are shared and processed simultaneously by a team of designers involved in the life phases of a product [34]. Yongchang Liang[35] studied the impact factors of knowledge communication in community of practice from group dynamics in sociology and McClelland Need of Achievement Theory, and drew a conclusion: a member who has a strong identification with community would be much more willing to share his knowledge with other members in the community. XU Xiao-long and WANG Fang-hua [36] hold that knowledge sharing in community of practice is impacted by community culture. The community culture impacts community member's values and behavioral patterns. Altruism is conducive to knowledge sharing in community. Egoism leads to only at the non-return and the "free-riding" would hamper knowledge sharing. Thus, in the community of collaborative product design, designers should trust each other, share knowledge and experience freely, explore new knowledge energetically. However, in practice, designers being from different enterprises and lacking trust often lead to miscommunication. Collaborative enterprises do not care enough about Community, that's one reason of low efficiency in collaborative design.

The collaborative enterprises should attach importance to community, the best that a meeting is held face to face to set up trust mechanism and stratagem alliance. Especially for the collaboration alliance allied by some small and medium enterprises, it is pressing down the boundaries of enterprises and taking advantages of talent and resource. In the process of design, climate of good communication and knowledge sharing encourages designers to explore new knowledge and new method. So that community is propitious to knowledge management and high efficiency in collaborative product design.

D. Tools

Tool is one of the important features of knowledge, it is indispensable to the practice of knowledge more often than not. Tools in collaborative product design include collaborative design system, collaborative design theory, and CAD software etc. In this paper, collaborative design system is focused. Developing collaborative design system to assist in managing knowledge in the process of design has been a topic of considerable interest. Nonaka and Konno suggest information systems can assist knowledge activists (proponents and champions of KM systems) in serving as catalysts of knowledge creation and as connectors of present initiatives with those in the future [19]. There exist two categories of collaborative

design systems, namely, web-based collaborative design system (WCDS), and agent-based collaborative design system (ACDS). WCDS is developed by adopting World Wide Web as a collaboration platform that can be accessed through a web browser over network. WCDS is convenient for designers to take on activities including product design share and review, design discussion, etc. However, WCDS isn't applicable to complex design in 3D, and has its deficiency in security. ACDS is concerned with how human designers to collectively manipulate design information and knowledge and solve design problems. The reasons given for adopting an agent-based approach to develop distributed software system are linked to its being proactive object and its simplification in architecture [37]. However, it relies much on experiential knowledge and it is complex in operation.

Task-Technology fit Theory [38] argues that, for an information system to have a positive impact on performance, the technology must be a good fit with the task it supports. Hence, ACDS should be adapted in the case of being complex in decomposing task and collaborating. And system based-on flexible workflow is applicable to the versatile process. In different application situations, the system can adopt different knowledge management approaches, e.g. knowledge map, community of practice, and expert system.

E. Rules

Rules are criteria of conduct, beliefs and patterns of design in the process, which depict how the community works [39]. Rules could be treated as existing in a recorded form (explicit rules) or unrecorded form (tacit rules). Explicit rules are that part of operation limits, resource constraints, completion time of task, reward and punishment mechanism etc. Tacit rules, on the other hand, are that aspects of rules which cannot be expressed in explicit form; for instance, design concept and knowledge sharing climate. Here, tacit rules are discussed. A shared contribution is the starting point for negotiation of common ground. Common ground is a shared cognitive frame of reference. It is through the process of internalising others contributions, and subsequently providing feedback based on one's own perspective by word or action, that common ground can be negotiated [40]. Common ground is the tacit rules. In the existing literature of knowledge management in collaborative design, explicit rules are mainly focused. The issue on knowledge sharing climate has rarely been discussed and has been paid little attention to. This theory provides a conceptual basis for explaining why performance of a group could be different in the same technology conditions.

Objective to improve work efficiency and product quality, tacit rules should be paid attention to. (i) Designers in collaboration come from different enterprises, and they are accustomed to different design concept. It is necessary to enhance communication on design concept and keep consistency. Enterprises and designers in collaborative product design should maintain stability, which could decrease the cost of communication. (ii) Institutionalize incentive scheme, and

grant rewards to those who are outstanding in performance, which make designers devote to knowledge sharing willingly. An incentive and guarantee mechanism across the collaborative enterprises is the foundation of knowledge sharing. The incentive institutions based on strategic alliance with risk-benefit balanced principle can cultivate the initiative of knowledge sharing. For instance, a connection between knowledge contribution and the promotion could be institutionalized.

F. Division of labor

Division of labor is the specialization of cooperative labor in specific, circumscribed tasks and roles. Division of labor is implemented by means of roles. The role is a subject in charge of specific tasks. Appropriate team composition is crucial to the success of ad-hoc teamwork, yet optimizing team composition is challenging [41]. Configurational and task-oriented approaches to project teaming require the composition of a team to depend on tasks of the project work. Collaborative product design, in another word, is a project of related activities completed by multidisciplinary collaborative designers, taking advantages of collective intelligence. Teaming appropriate members is an important factor for collaborative product design. Appropriate members here generally indicates two dimensions, including qualified and quality factors. Qualified members ought to fulfill concrete characteristics such as years of experience and skills. Meanwhile, quality members are expected to fulfill human-centered needs of project such as personality and interpersonal relationships [42]. Experience tells us that collaborative product design is in fact with each designer contributing what they can in different domains of expertise at moments when they have the knowledge appropriate to the situation. The designers are engaged to work together because each of them has a particular expertise that can be contributed to solution process. In this situation, it could be seen that two or more experts operating in their own domains on a shared problem [43].

Collaborative product design emphasizes intellectual distribution, encourage designers to explore new knowledge of different domains, thus increasing the heterogeneity of design knowledge. When facing up with a puzzle in design process, designers would consider the issue from different perspectives, which could lead to knowledge innovation. Hence, designers of different knowledge and experience should be selected according to the requirements of design. Collaborative designers can optimize their unique abilities and compensate for one another's weaknesses, achieving optimal allocation of knowledge resources. In addition, new designers should be recruited according to the lack of knowledge in a collaborative design team, this is conducive to the abundance of knowledge scope.

V. CONCLUSION

Collaborative product design is adaptive to economic globalization and globalization manufacturing, in support of supply chain management and customer relationship management. It brings about enterprise of being

knowledge centered. Knowledge management is indispensable to the development of collaborative product design. For now, low efficiency in collaborative product design is concerned with lacking effective knowledge management. Former researches mainly focus on improving knowledge management in collaborative design by perfecting design system, other aspects of the design activity is rarely paid attention to. In the light of Activity Theory, knowledge management in collaborative product design is analyzed from six perspectives, namely, subject, object, community, tools, rules, and division of labor. From every perspective of activity, collaborative product design has its unique features. And suggestions for promoting knowledge management in collaborative are given according to the features. It is the first attempt to research knowledge management in collaborative product design from perspective of Activity Theory. It is hoped that following researchers will continue this idea to proceed the deeper research.

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