Feasibility investigation of crowdsourcing-based product design and development for manufacturing

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Feasibility investigation of crowdsourcing-based product design and development for manufacturing

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ABSTRACT

In the era of Industry 4.0, to help manufacturers make quick response to rapidly changing market and customer needs, this research explores the feasibility of realizing benefits of crowdsourcing in product design and development from a lifecycle point of view through investigations on product design quality control and crowdsourcing technology theories, product design lifecycle information modelling, and simulation platform prototyping. It intends to help manufacturers create a product-service ecosystem to deliver values to all involved stakeholders of a PDD process.

This study started with building up the theoretical foundation of product design quality control in crowdsourcing design environment. Then, key crowdsourcing technologies for realizing a lifecycle PDD process on a crowdsourcing platform while enabling the design quality were explored. Thirdly, a multi-layer product design lifecycle information model was developed to accommodate all design related information in a PDD process and the identified information at each design phase and the relationships and interactions among information entities were evaluated by case studies and ORM modelling method, respectively. Finally, two crowdsourcing platform prototypes based on the PDLIM were developed to test their effectiveness in communicating design information among stakeholders and delivering value to them.

The proposed research made contributions to knowledge through the following improvements/advancements: (1) understanding of key factors affecting product design quality in crowdsourcing design environments, (2) a technical foundation of crowdsourcing technologies for PDD process, (3) a novel product design lifecycle information model accommodating design information in crowdsourcing environments, and (4) guidelines on developing intermediary and integrated crowdsourcing platforms for PDD.

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NOMENCLATURE

List of Abbreviations

Abbreviations	Full name
PDD	Product Design and Development
ORM	Object-Role Modelling
PDLIM	Product Design Lifecycle Information Model
IP	Intellectual Property
SMEs	Small and Medium Enterprises
PS2/PSS	Product Service Systems
EAUC	Environmental Association for Universities and Colleges
PDS	Product Design Specification
PFD	Product Family Design
C-PDD	Crowdsourcing Product Design and Development
DT	Digital Twin
DT-PDD	Digital Twin supported Product Design and Development
UX	User Experience
R&D	Research and Development
CAD	Computer-Aided Design
PLM	Product Lifecycle Management
CAx	Computer-Aided design, manufacturing, analysis, engineering, etc.
UML	Unified Modeling Language
ERM	Entity-Relationship Modelling
STEP	STandards for the Exchange of Product model data
MVC	Model-View-Controller
CRUD	Create, Read, Update, and Delete
2D/3D	Two/three dimensional
XML	Extensive Markup Language
QFD	Quality Function Deployment
HOQ	House Of Quality
APIs	Application Programming Interfaces
TIM	Tencent Instant Messenger
Design for X	X means manufacturability, reusability, safety, etc.

Abbreviations	**Full name**
PDM	Product Data Management
ERP	Enterprise Resource Planning
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CPM	Core Product Model
OAM	Open Assembly Model
DAIM	Design-Analysis Integration Model
PFEM	Product Family Evolution Model
BOM	Bill of Materials
IoT	Internet of Things
CJ	Critical Justification
IT	Information Technology
ID	Identity/identification
CPS	Cyber-Physical System
IoU	Internet of Users
IoS	Internet of Service providers
AI	Artificial Intelligence
IoB	Internet of Beings
XaaS	Everything as a Service
UM	User Management
TM	Task Management
PM	Product Management
SM	Service Management
NORMA	Natural ORM Architect, an extension for Visual Studio
SIM	Subscriber Identity Module
UPC	User Profile Contract
PPC	Product Profile Contract
SPC	Service Profile Contract
TPC	Task Profile Contract
RWRC	Requester-Worker Relationship Contract
SC	Service Concept

List of Symbols

Symbol	Explanation
M	A set of machines on the crowdsourcing platform
M_N	The total number of machines
C	The set of end users
O	The set of machine owners
O_N	The total number of machine owners, satisfying $O_N \leq M_N$
W	A set of service providers
W_N	The total number of service providers
S	A set of service packages around machines
S_N	The total number of service packages
T_i	A service task related to M_i and R_i
R_i	Service request initiated and authorized by O_i
f	Service analysis tool
P	complexity
K	Required skills
SC	Estimated service cost
SL	Urgency level
$\$$	Detailed service request description
$dis1$	The constraint for service providers' skills
$dis2$	The constraint for estimated service cost
$dis3$	The constraint for the distance to destination
$dis4$	The constraint for accepted performance of service providers
AR	Acceptance Rate
CS	Customer Satisfaction
SQ	Service Quality
$Q(w_j)$	The real quote of service provider w_j
$L(w_j)$	The current location of service provider w_j
$Rank(w_j)$	The rank of w_j under a selected service recommendation principle

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DECLARATION

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. Approval has been sought and granted by the Faculty Ethics Committee on November 2017.

I declare that the Word Count of this Thesis is 46, 844 words.

Name: Xiaojing Niu

Signature:

Date: February 4, 2021

Chapter 1 Introduction

Industry 4.0 is changing everything, and it is widely heralded as the key for manufacturers to unlock cost reductions and facilitate new efficiencies (Minturn, 2017). In the manufacturing sector, it has led to better transparency and agility, responsiveness to customer needs and cost savings through intelligent connectivity between machines and technology (Pearce, 2017). However, concentrating on product cost, quality and time to market is no longer sufficient to maintain the competitive advantage of an enterprise (Evans *et al.*, 2016). The focuses of enterprises are progressively turning towards open business innovation with clearly differentiated product and service offerings being the anticipated outcome through a closer collaboration with customers (Yuen, King and Leung, 2011a; Markman, 2016). Crowdsourcing is a key paradigm of this open business movement.

1.1 What is Crowdsourcing

Crowdsourcing is initially proposed to solve tasks that cannot be processed by sophisticated computer programs but trivial for humans, such as image labelling and basic data collections (Yuen, King and Leung, 2011a). Since then, it is widely adopted by enterprises as an effective tool to get crowds involved in their business practices for open innovation, problem solving, collective intelligence and marketing (Sammie, 2014). For manufacturers, it is expected to help reduce the production costs and make more efficient use of labour and resources (Yuen, King and Leung, 2011a). From the perspective of manufacturers, crowdsourcing is an innovative business model which helps them obtain needed services, ideas, or contents by soliciting contributions from a large group of people (the crowd).

Crowdsourcing has also been leveraged in many areas, such as health care, smart business solutions, social innovation, software/web development, multimedia data annotation, social innovation, etc. To make crowdsourcing appliable to specific application area, diverse crowdsourcing definitions have emerged. In Table 1-1, some crowdsourcing definitions are listed. More additional definitions of crowdsourcing can be found in 'Towards an integrated crowdsouricng definition' (Estellés-Arolas and González-Ladrón-De-Guevara, 2012) and 'Crowdsourcing Definitions and Its Features: An Academic Technical Report' (Hosseini, 2014). Correspondingly, various crowdsourcing models have been proposed, such as intermediary model, citizen media production model, collaborative software development model, digital goods sales model, product design model, consumer report model, knowledge base building model, and collaborative science project model (Saxton, Oh and Kishore, 2013).

Table 1-1 The definitions of crowdsourcing

Reference	**Crowdsourcing definition**
(Howe, 2006)	The act of taking a job traditionally performed by a designated agent (individual, institution, non-profit organization or enterprise) and outsourcing it to an undefined, generally large group of people in the form of an open call.
(Alonso and Lease, 2011)	The outsourcing of tasks to a large group of people instead of assigning such tasks to an in-house employee or contractor.
(Brabham, 2009)	A legitimate, complex problem-solving model.
(Pedersen *et al.*, 2013)	A collaboration model enabled by people-centric web technologies to solve individual, organizational, and societal problems by using a dynamically formed crowd of interested people who respond to an open call for participation.

Table 1-1 The definitions of crowdsourcing (Continued)

Reference	Crowdsourcing definition
(Brabham, 2008)	An online, distributed problem-solving and production model already in use by for profit organizations such as Threadless, iStock etc.
(La Vecchia and Cisternino, 2010)	A tool for addressing problems in organizations and business.
(Estellés-Arolas and González-Ladrón-De-Guevara, 2012)	A type of participative online activity in which an individual, an institution, a non-profit organization, or company proposes to a group of individuals of varying knowledge, heterogeneity, and number, via a flexible open call, the voluntary undertaking of a task.
(Saxton, Oh and Kishore, 2013)	A sourcing model in which organizations use predominantly advanced Internet technologies to harness the efforts of a virtual crowd to perform specific organizational tasks.
(Bhatti, Gao and Chen, 2020)	An online distributed problem-solving paradigm, in which an individual, company, or organization publishes defined task(s) to the dynamic crowd through a flexible open call to leverage human intelligence, knowledge, skill, work and experience

Regardless of the application area of crowdsourcing, the identified key elements of a crowdsourcing process include the crowd, the task, the crowdsourcer/requester, and the process based on a platform (Saxton, Oh and Kishore, 2013; Hosseini, 2014).

The crowd

In Howe's definition to crowdsourcing, the crowd is an undefined online community that is expected to play the role of service providers as producers, innovators, and problem solvers. In practice, to ensure the output quality, the crowdsourcer/requester usually selects the crowd with specific skills and qualifications to participate in the crowdsourced task.

The crowdsourcer/requester

In the process, the crowdsourcer refers to the person or institution seeking knowledge, creativity, innovative ideas and solutions for their business problems from the crowd. Generally, crowdsourcer also acts as solution evaluators who are responsible for evaluating and selecting winner solutions to the crowdsourced task.

The task

There is a broad array of activities that can be crowdsourced. It can be products, services, or parts of products. And the complexity varies from task to task. And according to the complexity of the task, different crowdsourcing platforms will be utilized (Saxton, Oh and Kishore, 2013). During a crowdsourcing process, only when the crowdsourcing task is well-defined, the proper crowds with specific knowledge and skills will be selected. The crowdsourcing task proposed by the requester needs to be mapped from the high-level goal to specific subtasks to be completed by the crowd.

The process

The crowdsourcing process is controlled by the platform. It provides a virtual space where the initiator can crowdsource his/her task to the crowd. Both social media platforms such as Twitter and Facebook and purposely developed platforms, such as 99designs and Amazon MTurk can be used in this process. The platform provides the crowdsourcer a way to get access to tons of crowds conveniently and involve them into their production process and decision-making process, and the platform organizes the crowd structure and manages workflows to enable the crowdsourcing process.

Crowdsourcing forms

The crowdsourcing form depends on the nature of crowdsourcing tasks. Before crowdsourcing of the task, an open call including the specific task and its evaluation criteria need to be defined first. The evaluation criteria can be provided by the requester directly or be collected from the cloud. According to the board of innovation and the guidelines to effective crowdsourcing (Simperl, 2015), there are a lot of ways to crowdsource a task, which are shown in Table 1-2. The crowdsourcing forms could be used for classifying crowdsourcing platforms.

Table 1-2 Ways of crowdsourcing a task

Form	Description	Platform examples
Micro tasks	The Crowdsourced routine work is broken down into smaller and independent units	Amazon MTurk, microtask.com, Clickworker
Macro tasks	Close to classical outsourcing	Quirky, InnoCentive
Challenges	Competitions targeting grand scientific, technology, business, or social questions	OpenIDEO, InnoCentive
Volunteer campaigns	Initiatives seeking ideas and contributions for the public good	Crowd4U
Contests	Asking crowds to work and only providing compensation to the winner	99designs, crowdspring

In these crowdsourcing forms, micro tasks and macro tasks are classified by the granularity of tasks. Compared to macro tasks, micro tasks are highly parallelisable and can be divided into smaller pieces, which can be completed by taking seconds to minutes. Micro tasks are always the tasks that are simple and easy to be accomplished by humans but are challenging for computers, such as recognising things in images. Macro tasks are difficult to be decomposed straightforward and the resolutions for macro tasks require a great share of contextual information or dependencies to intermediary results.

In addition to micro tasks and macro tasks, other crowdsourcing forms could be classified into the same category as neither can they be divided into micro tasks, nor did they depend on the context information and intermediary results. How the task will be crowdsourced depends on the task nature.

1.2 Benefits of using crowdsourcing

Crowdsourcing is firstly adopted mainly because of the way it provides to access to a large pool of community to address business problems with potentially reduced time and monetary cost. With the extensive application of crowdsourcing, more benefits have been brought and crowdsourcing is being used in many situations as a powerful and flexible tool. The benefits brought by crowdsourcing can be divided into process-based and results-based (Wazny, 2017), as shown in Table 1-3.

Table 1-3 Benefits of using crowdsourcing (Wazny, 2017)

Process-based crowdsourcing benefits	Results-based crowdsourcing benefits
- Large potential scale of participants involved - Large scale of coverage of potential intervention - Raising public awareness - Transcending borders and boundaries - High social robustness - High mobility - Ability to 'tap into' untapped expertise - Ability to cover unpredictable events - Widespread software available to enable feasibility	- Increased accuracy over or when results combined with machine learning tasks - Enabling high speed of research progression - Novel discoveries - Data produced previously unattainable - Ability to complete tasks otherwise not possible, including digitizes medical artefacts or notes - Rewards may accrue more directly - Possibility to detect and respond to disease outbreaks earlier - Result accuracy has been shown to be equal to or more accurate than traditional research

Despite considerable benefits brought by crowdsourcing, there are concerns with the output quality, security and data protection issues of sensitive data, trust between crowdsourcer (problem owner) and the crowd, IP issues, and copyright ownership of submitted solutions (Pedersen *et al.*, 2013; Sonnleitner *et al.*, 2013).

1.3 Crowdsourcing and manufacturing success

In manufacturing sector, crowdsourcing is defined as ‘the process by which manufacturers complement and expand their manufacturing processes with manufacturing capabilities, tools, equipment, processes and ideas from outside their organizational boundaries tapping into a larger mass of people, typically by means of internet-enabled solutions’ (Diederik *et al.*, 2014). It not only actively involves a diverse crowd of users but also involves the management of them via web-based collaborative technologies to elicit their knowledge and skill sets and thus fulfil the pre-identified business goal (Saxton, Oh and Kishore, 2013). Within the manufacturing industry, the categories of crowdsourcing applications (Table 1-4) include product development, innovation, provision of data and information for manufacturing, fine tune design and concepts (Diederik *et al.*, 2014; Vianna, Graeml and Peinado, 2020).

Table 1-4 Typologies of crowdsourcing in manufacturing industry

Category of crowdsourcing application	**Sources**
Product development	(Qin *et al.*, 2016); (Yao and Lin, 2016); (Yang, Shen and Wang, 2018); (Yao *et al.*, 2019); (Caruso, 2018)
Innovation	(Qin *et al.*, 2016); (Yao *et al.*, 2019)
Provision of data and information for manufacturing	(Yao *et al.*, 2019); (Caruso, 2018); (Jiang, Ding and Leng, 2016)
Fine tune design and concepts	(Tao, Sui, *et al.*, 2019)

Crowdsourcing is developing rapidly and has disruptive consequences. In 2014, Gartner Consulting predicted that enterprises using crowdsourcing solutions in product development will add 1% more to their revenue by 2015 than non-crowdsourcing ones.

And it can be used for various scenarios, such as building predictive models, designing adverts, and solving technical problems, etc. Regardless of types of crowdsourcing platforms, they connect people and use collective intelligence to go through new innovation challenges and shape the practical interactions between users and products (Kittur *et al.*, 2013). The board of innovation (https://www.boardofinnovation.com/staff_picks/open-innovation-crowdsourcing-resources/) gives 6 categories of existing intermediary platforms according to their purpose. The general work process of these platforms consists of ideas, review, refinement, final review, top ideas, awards and impact. They also have capabilities to support some design activities. For example, Quirky is a crowdsourcing invention platform where great ideas from general people could come into reality and an e-commerce platform as well. Through this platform, the produced products would be sold. OpenIDEO and Innocentive are examples of crowdsourcing platforms for making ideas grow, while crowdspring, 99designs and DesignCrowd provide design options for selection from the requester. Other crowdsourcing platforms, like Figure Eight, are used for data processing and analysis. Regardless of application scenarios of the crowdsourcing platforms, the tasks performed on them are simple and independent. Intermediary crowdsourcing platform is an optimal choice for SMEs to get ideas faster (Jim, 2014). By using certain technologies like cloud and collaborative software, designers and manufacturers can view and edit designs straight from a web browser, eliminating largely the need for specialist software and opening the process to a large group of people. In order to support the crowdsourcing process of complex tasks, the platform needs to be improved in some aspect, e.g., solution evaluation, the communication and cooperation among crowds. In addition, due to the uncertainty of involved crowds, there are also some risks in terms of IP and the outcome quality of crowdsourcing. Furthermore, the existing platforms are mostly only generating ideas rather than implementing them collaboratively (Solverboard, 2016).

Different from SMEs, large enterprises usually develop their own innovation platforms with crowdsourcing function to make themselves closer to their customers and shape their business, which is regarded as a necessary skill to enable them to realize digital transformation of their business. The examples of crowdsourcing platforms adopted by large enterprises are presented in Table 1-5.

Table 1-5 The examples of crowdsourcing platforms adopted by large enterprises

Enterprise	Platform	Benefits
Dell	Idea Storm	The platform, which was created in 2007, is used to filter customer proposals about Dell products and services. To 2018, it has already generated more than 20,000 ideas, 100,000 votes and 740,000 comments. And 550 of those ideas have been put into practice.
Lego	Lego Ideas	The platform is a win-win solution, created in 2014, which was moved from Lego Cuusoo. Lego Ideas is to propose, share and support proposals for new Lego games created by other fans. With this strategy, Lego does not run the risk of investing money into designing products that are never launched for sale, and the process of voting for and reviewing projects works like a free promotion campaign among fans.
IBM	InnovationJam	The platform helps businesses and organizations to generate and evolve ideas around business-critical issues. It engages thousands of participants and uses powerful analytics function.
BMW	Innovation Lab	The platform is mainly used to test solutions in a live customer environment. It helps improve customer offering.
Starbucks	My Starbucks Idea	The platform was launched in 2008 to increase the focus on customers and what they want. The combination of the most popular and innovative ideas will be considered and put to work.

The innovation platforms integrated with crowdsourcing functions indeed enable better understanding of customers by creating better connections with them. These platforms mainly involve customers in collecting customers' feedback on existing product and service offerings and new ideas on new products. However, how the collected ideas and feedback change product and service offerings is undisclosed to the idea proposer for the purpose of protecting IPs. This is also the key obstacle stopping large enterprise from adopting crowdsourcing in their business practice (Solverboard, 2016). Furthermore, the future of manufacturing is crowdsourced innovation and the emphasis of crowdsourcing is moving from content creation towards content curation (Sammie, 2014).

1.4 Research background: The need of crowdsourcing in PDD

The need of crowdsourcing in PDD is embedded in three PDD perspectives: product design quality, product design process, and product design trends.

1.4.1 Product design quality

Products with high quality will not only meet the needs of manufacturing enterprises and various users along the product lifecycle but also bring good user experience and better social and environmental benefits to our society, thus helping the enterprises remain globally competitive in the fierce competition. Therefore, the control of product quality through the whole lifecycle is a vital activity to enterprises. The aim of product quality control is to make a compromise between cost and product quality. However, product quality is a nebulous concept and it may be viewed in different perspectives (Belyh, 2017). And the existing literature usually pays too much attention to quality control of manufacturing and activities after the product is manufactured. For example, literature (Belyh, 2017) shows that quality control of product quality is controlling production, carrying out repairs and warranty costs through defect discovery and maintenance, which ignores the importance of product design quality. From the incline of product quality through the whole lifecycle (see Figure 1-1) in literature (Chu *et al.*, 2010; Zhu *et al.*, 2011), it is clear that product design quality is the key factor determining product quality.

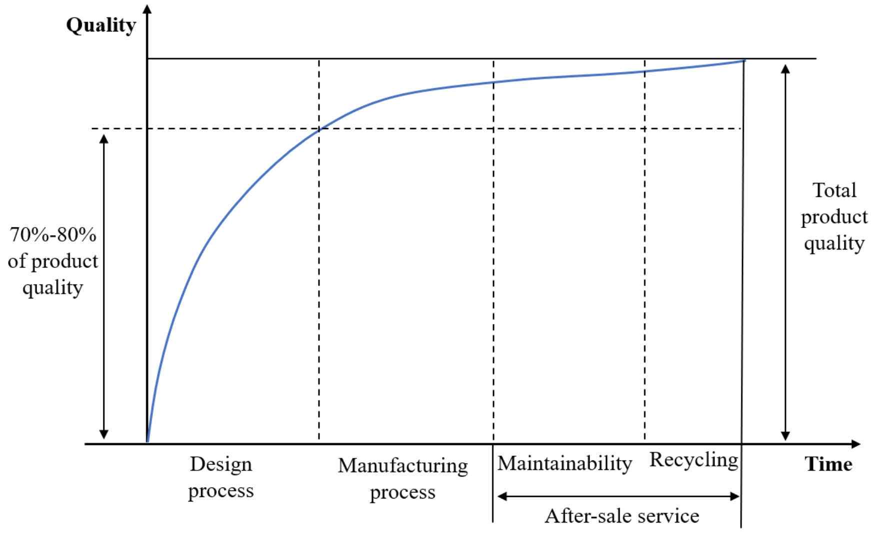


Figure 1-1 Incline of product quality through the whole lifecycle (Chu *et al.*, 2010; Zhu *et al.*, 2011)

As a stand-alone product is not sufficient to fulfil customer requirements, product service systems (PS2 or PSS) are usually combined with the product to provide product-related services, such as maintainability, repair, update and quality warranty throughout the whole lifecycle to better fulfil user requirements (Mert, Waltemode and Aurich, 2014; Pasch, Rybski and Jochem, 2016). Therefore, product quality is the sum of product design quality, manufacturing quality, maintainability, and recycling. Correspondingly, the product lifecycle is considered to consist of four stages, i.e. design, manufacturing, maintenance, and recycling (Niu *et al.*, 2018). The relationship among these terms is shown in Figure 1-2.

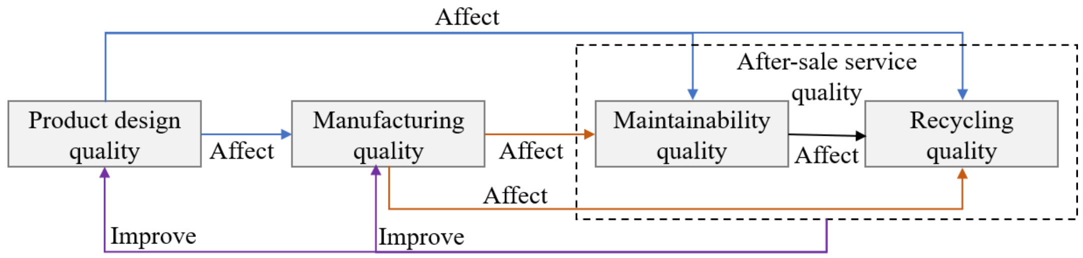


Figure 1-2 The relationship among quality-related terms through product whole lifecycle (Niu *et al.*, 2018)

In manufacturing aspect, many studies have been conducted to ensure the product quality from various perspectives, such as manufacturing methods and modelling approaches (Bikas, Stavropoulos and Chryssolouris, 2016), the influence of human factors (Neumann, Kolus and Wells, 2016), key technologies of intelligent design for customised products (Zhang *et al.*, 2017), challenges and future of manufacturing in engineering (Gao *et al.*, 2015), etc. Key factors affecting manufacturing quality can be classified into two categories: hard and soft factors (Lombard, Waveren and Chan, 2014). After the product is manufactured and sold out, after-sale service, such as maintenance and recycling, plays a critical role in the successful marketing of many products as it enables customers to get the full value from its products (Szwejczewski, Goffin and Anagnostopoulos, 2015).

After-sale services attempt to resolve problems met by a customer, e.g. product failure restoration and problem with using the product, which will cause dissatisfaction if the problem is not well resolved (Markeset and Kumar, 2003). Due to the increasing importance of after-sale service, various aspects of after-sale services with regards to business model, service-delivering methodology, performance metrics, service portfolio and product planning and control have been discussed (Rolstadaas, Hvolby and Falster, 2008), while measures for ensuring the quality of after-sale services are summarized (Takeuchi and Quelch, 1983). Markeset and Kumar (2003) maintain that the key factors affecting maintainability includes cost consideration, technological consideration, human factors, statutory requirements and accidents, etc. While Environmental Association for Universities and Colleges (EAUC) argues that product collection method, local authority facilities, charging structure and support, geographical location are considered to influence recycling quality. Compared to manufacturing, at maintenance and recycling stages, there are relative fewer studies focusing on how to integrate product design quality into product after-service qualities despite the fact that design for manufacturing, design for assembly and design for disassembly are proposed as design guidelines.

In conventional in-house design environments, product design activities are usually performed by an in-house design team consisting of individuals with different expertise and experience while systematic and mature quality control measures are adopted.

As the advancement of information technology, especially crowdsourcing, brings more flexible manufacturing possibilities and further involvement of customers in the manufacturing process, more and more manufacturers are moving part of their product design processes on to a crowdsourcing platform, benefiting from the participation of a large number of crowds, including their potential customers, to the fast speed and cost-effectiveness of the solutions generated. However, product design research over a crowdsourcing platform is still in its early stage, and few studies have been conducted on how to control the product design quality over a crowdsourcing-based platform.

1.4.2 Product design process

To ensure product design quality, a structured product design process is usually adopted by manufacturers. It transforms ideas or needs from consumers or marketplace into a product that satisfies these needs (Aquino, 2017). Product design process includes sequential and concurrent ones. Concurrent design process is used widely than sequential one as concurrent design process could respond to the changing design requirements and customer demands in a timely manner. The concurrent design process involves a series of stages that designers follow to come up with a solution to a problem. The exact division in stages is determined by the complexity of the product and the management structure of the organization. It is hard to give a specific definition to design process as each designer or company interprets it differently (Design Council, 2007; Aquino, 2017), and sometimes it needs to be modified in order to suit the local projects environment (Aw, 2005; Azlan, Ismail and Hasnanywati, 2008). To date, there is no a standard product design process universally that is accepted by all designers (Azlan, Ismail and Hasnanywati, 2008). An iterative product design process as shown in Figure 1-3 involves product concepts generation, concept evaluation, selection and feedback in an iterative manner. This design process starts from a market research to identify the customer needs and then establishes a design brief or a PDS. Based on the PDS, a wide range of product concepts can be generated and then evaluated with reference back to the PDS and even the customer needs. After that, design decision is made to select good concepts for developing further in the next stage, or discarding bad ones, or providing feedback based on the evaluation to improve the good concepts. The feedback can be provided to guide the concept improvement, or even to guide the PDS update. This is a typical iterative concept development process. The process does not stop until one or several concepts are accepted.

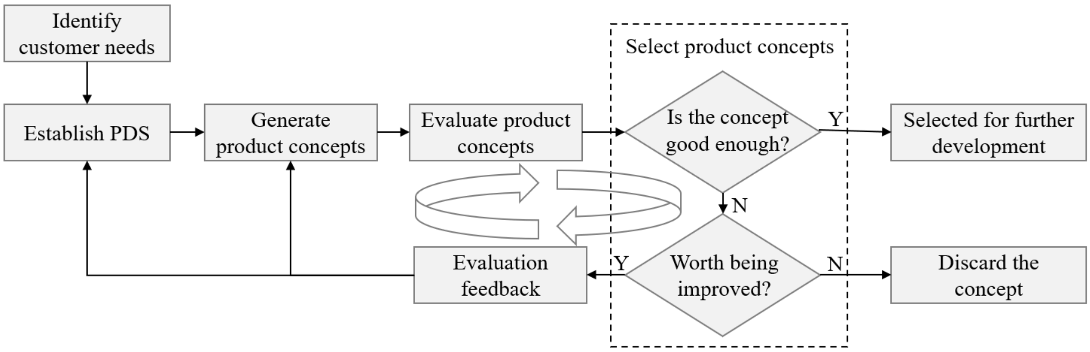


Figure 1-3 An iterative product design process

In a detailed level of product design phases, many product design studies have highlighted the design process differently. However, most of the studies have indicated that the design process should include stages of marketing research, specification and planning, idea generation and development, concept design, process planning, detail design, production (manufacturing), product launch and in use, and product maintenance & recycling (Table 1-6).

Table 1-6 Process of product design and development

Source	Marketing research	Specification and planning	Idea generation & development	Concept design	Process planning	Detail design	Production	Product launch and in use	Product maintenance & recycling
(Aw, 2005)		✓	✓	✓		✓	✓		
(Hermans and Liu, 2013)		✓	✓	✓		✓			
(Zhang *et al.*, 2016)		✓	✓	✓		✓			
(Portioli-Staudacher *et al.*, 2003)		✓	✓	✓		✓	✓	✓	
(Lundgren, Hedlind and Kjellberg, 2016)					✓		✓		
(Wright, 1998)	✓	✓	✓	✓		✓	✓	✓	✓

The introduction to these stages is as follows:

Marketing research: This stage is the start of a PDD process which focuses on identifying market needs and customer expects for developing new products or making improvements on current product offerings.

Specification and planning: This stage focuses on exploring the shortcomings of existing similar products in the market, the needs and expectation of customer and the market trends, in order to generate design specification.

Idea generation & development: Based on design specification, approaches like brainstorming and focus group are adopted to inspire the designer to generate new ideas of product design and development.

Concept design: In this stage, the ideas from previous stage are appraised and production capability, technology availability, costs are taken into account to analyse the feasibility of making the ideas into reality, then the designers visualise their ideas by sketching and prototypes.

Process planning: It includes design planning and manufacturing planning. Before the design of a concept or the manufacturing of a product, a project plan should be put into place to clarify objectives, allocate resources, and establish timescales and budgets.

Detail design: In this stage, the agreed concepts will be further development. The designers will work closely with the manufacturer to ensure that the product will be made successfully.

Production: Once the concept is realized and pass the test, it will be forward to manufacturing.

Product Launch and in use: At this stage, product will be advertised to users through media and be consumed by users.

Product maintenance & recycling: Product maintenance is to ensure the product performance, thus to ensure user experience, while product recycling is to determine how to deal with the product and corresponding components. According to the component nature, it may be reused, recycled, or disposed.

As different companies or design teams have diverse design strategies and focuses, the sequence and stages of the above product design process may vary. Currently, the two basic strategies for customer engagement in a PDD process include (1) customer data capture via large forums and surveys, and (2) target, ongoing customer advisory groups (Chinn, 2015). The traditional strategies for engaging customers are time and labour consuming. Crowdsourcing has been utilized to get customers involved in the PDD process, especially at the market research stage for collecting market information and design concept generation stage for collecting design ideas and evaluating them. However, how to engage customers and other stakeholders at the later stages along a product lifecycle is less studied. Engaging customers and stakeholders in the whole PDD process helps manufacturers build sustainable relationships with them in the competitive and challenging environments.

1.4.3 Product design trends

To satisfy the changing user needs to products, three main trends of PDD emerged. The first trend is Product Family Design (PFD), which increases a product's variants by sharing assets such as components, processes, and knowledge across the products, not only satisfying a variety of market segments but also helping SMEs gain an edge in fierce market competition by reducing product development time. The PFD is a holistic product design approach requiring strong support of data and information along the product lifecycle (Zhang *et al.*, 2020). The lack of recorded key product design data and information especially at the early stage is a big barrier for next generation product design. This in turn requires a robust product design information model to guide the collection and recording of the product design data and information in the design process when the design proceeds. Currently, the information captured in PFD is often incomplete, unstructured, and is mostly proprietary in nature, prohibiting SMEs from exploiting the potential of shared assets in a product family by effective information representations and communication among the product design participants (Nanda *et al.*, 2007).

The second trend is crowdsourcing product design and development (C-PDD), through which SMEs directly take crowds into their PDD processes to transform product design from 'design for customers' to 'design by customers' and 'design with customers'. Currently, design activities such as idea generation and concept evaluation (mainly voting and rating) are usually crowdsourced. In practice, the product design is conducted typically in a combined environment of traditional in-house design and platform-based crowdsourcing design. In order to have a good design quality assurance (Niu *et al.*, 2018), effective design information communication and data-informed decision making within the combined design environments are key influential factors. Again, this requires a proper product design information model that is able to describe product design in the combined design environment.

The third one is digital twin supported product design and development (DT-PDD) (Schleich *et al.*, 2017; Tao *et al.*, 2018), in which all physical components in a product lifecycle are mapped to their virtual twins which analyse the received data in real-time and adjust the physical twins automatically and timely. It provides a new way of information collection for accelerating data driven PDD and a new way of information communication especially at product use and maintenance stages. Thus, digital twins can achieve automatic collection of product design related information during these later-life stages and promote data driven through-life product design and development. Many recent researchers (see details in next section) are investigating DT paradigm into PDD process, aiming to build a closed loop of a PDD process where the needed information of through-life product design is obtained and shared by both the physical and virtual twins. Currently, digital twin is mainly implemented at a sole PDD stage, especially product manufacturing (35%) (Roy *et al.*, 2020), product health management (38%) at product in use and maintenance stages (Tao *et al.*, 2019). However, such developments still provide insufficient support to earlier PDD process although the significant value of applying DT at early design stages are explored (Jones *et al.*, 2019) in terms of the opportunities for new product development and innovation. Thus, research on implementing a design (process) DT at the early design stage for effective information gathering and communication is just at its infant stage, requiring a consistent product design information model to underpin a design DT framework.

As effective ways to ensure the competitivity of enterprises, in particular the SMEs, these three main design trends are fusing with each other to aid SMEs in their PDD practice.

Although the research on crowdsourcing PDD is still at the early stage, it has been regarded as one of key enabling technologies for realizing the goal of Industry 4.0. Currently, crowdsourcing is mainly used for engaging crowds for great ideas on new products or existing product offerings. In 2012, the market for crowdsourced professional services had racked up over $1 billion and continues to grow more than 60% year over year (Sammie, 2014). On the Industry 4.0 journey, crowdsourcing plays an important role in helping manufacturers move product ideas into development, identifying new sources for and types of design solutions, increasing available resources for PDD in an iterative and collaborative manner (Diederik *et al.*, 2014; Allen, Chandrasekaran and Basuroy, 2018).

1.5 Research challenges when applying crowdsourcing into through-life PDD

Currently, crowdsourcing is mainly utilised to solve simple and independent tasks such as image labelling and data collections (Yuen, King and Leung, 2011a). It is expected to help manufacturers reduce the production costs and make more efficient use of labour and resources (Yuen, King and Leung, 2011a). As an innovative business model of obtaining needed services, ideas, or contents by soliciting contributions from a large group of people (the crowd), crowdsourcing has been explored to support complex tasks like PDD from the perspective of structuring crowds (Valentine *et al.*, 2017), task decomposition (Kittur *et al.*, 2011; Jiang, Zuo and Matsubara, 2020), task assignment (Ho and Vaughan, 2012; To, 2016), task matching (Yuen, King and Leung, 2011b), and crowdsourcing framework (Kittur *et al.*, 2011, 2013), etc. Although crowdsourcing opens up opportunities for flexibly coordinating external participants or even experts/professionals for data and knowledge intensive activities such as product design and development, complex system modelling and simulation, and real-time decision-makings (Cheng and Bateman, 2008), it also brings some research challenges. The first one is how to ensure the data and final design output quality caused by more external participants, complicated processes, and dynamic semantic information.

With manufacturers adopting crowdsourcing in their business practice, the PDD process has become progressively more complex in the last decades. This can be explained by three key reasons. Firstly, to better meet the needs of customers and market, the product is usually co-created by a team of participants with different knowledge and experience, such as product designers, marketing professionals, UX designers, manufacturing engineers, targeted customers and end users, and other stakeholders on the supply chain (Jauregui-becker and Wits, 2013). Secondly, to spur productivity, manufacturers usually crowdsource part of their design work to business partners on their supply chain or online communities (Diederik *et al.*, 2014). By 2017, manufactures are expected to receive 75% of their new product development inputs from crowdsourced solutions rather than in-house R&D capabilities (Diederik *et al.*, 2014). Thirdly, the PDD process is extremely dynamic because of the dynamics of design participants and their diverse skills, the unpredictable outcomes at each design stage, which leads to high level of uncertainty in the whole PDD process. According to the aforementioned reasons, it is getting more and more difficult to share information during the PDD process among various participants/teams.

So far, a great deal of research has been carried out on connecting products with smart sensors embedded, team management, product lifecycle management, and data collection and idea seeking enabled by crowdsourcing. However, little research has investigated ensuring iterative product design in a crowdsourcing environment by creating a product-service ecosystem.

In this research, the through-life product-service ecosystem can be treated as an extension of product-service systems which focuses on delivering product and service integrated value offerings to customers. So far, many design methods like Service CAD, Service Explorer, integrated product and service design process model, and fast-track design process model (Vasantha *et al.*, 2012; Marques *et al.*, 2016) for developing product-service systems with different emphases have been proposed. However, the relative maturity of considered issues in product-service system domain varies largely and the research of roles and capabilities of the stakeholders involved in designing the system, co-creation process, and dynamics involved in the system characteristics both for requirements and solutions (Vasantha *et al.*, 2012) is at the very early stages. When product-service systems are developed with crowdsourcing for supporting product lifecycle design and development, higher requirements for the ecosystem are proposed to support the co-creation process. The ecosystem makes it technically feasible for the network of stakeholders including end users, customers, and service providers on the supply chain to work together using common product data models. However, due to the diversity of stakeholders' backgrounds and expertise involved in the product-service ecosystem, stakeholders may interpret the same information like a product design word or concept in different ways without the support of a unified semantic model for through-life product design information (Lee *et al.*, 2012). Thus, the second research challenge is how to develop a product design information model for supporting effective design communication and helping ensure the product lifecycle design and development quality with crowdsourcing.

1.6 Research motivation

Although numerous studies have focused on utilizing crowdsourcing for various design and manufacturing purposes, there are still some research gaps in this area. Firstly, the existing intermediary crowdsourcing-based platforms can only partly support PDD activities (Qin *et al.*, 2016) and the related crowdsourced PDD research is mainly based on existing crowdsourcing platforms. Therefore, there is a need to develop a crowdsourcing-based platform prototype supported with a new product design information model to fully support the iterative PDD process and test its feasibility to support product lifecycle design and development.

Secondly, with the crowdsourcing platform for PDD process, it is very important to develop a new product lifecycle design information model that not only supports design communication among various stakeholders and crowds, but also enables the crowdsourcing in a product development ecosystem. To ensure product design quality, the core problem should be addressed is the communication and information sharing among the manufacturers and their stakeholders/partners in the product design process (Cheng and Bateman, 2008), which can enhance product design agility and manufacturing responsiveness. The explicit product design information and knowledge communication requires a product design ontology to provide open semantics in which design information and knowledge from multiple sources can be easily combined and checked for consistency (Lee *et al.*, 2012). However, currently there is no such product information model with explicit, logical semantics of the product design concepts and relationships involved in the crowdsourcing PDD process yet.

Therefore, this PhD research focuses on investigating the research question of *How to feasibly realize benefits of crowdsourcing in product design and development from a lifecycle viewpoint.* More specifically, this research is keen to investigate and develop a product design lifecycle information model to provide explicit and logical semantics of product design concepts and relationships to all stakeholders in the crowdsourcing PDD process, thus, to create a product-service ecosystem to deliver value to involved stakeholders/actors. The development of the platform prototype is to evaluate its feasibility of supporting the design team members to conduct their PDD activities through the whole lifecycle with product design information communicated and shared among them and in turn to drive their designs closer to the design requirements with expected quality.

1.7 Research aim and objectives

The aim of this exploratory study is to investigate how the product lifecycle design and development context and semantics affect the feasibility of using crowdsourcing in the PDD process given the concern of product design quality. In this process, not only the participants quality, but also the process quality and information quality affect the final design output quality. Therefore, to achieve the research aim, the following three objectives were identified:

- O1: Can product design quality be controlled when introducing crowdsourcing into the product design process?

The first objective is to understand the factors affecting product design quality and key quality control methods and quality assurance policies in both traditional in-house and crowdsourcing environments. The quality concern is the biggest problem that stops enterprises from applying crowdsourcing into their manufacturing practice. The investigation of the key factors affecting product design quality could provide a theoretical basis for modelling the product design information throughout the whole PDD process.

- O2: Are there proper technologies to enable crowdsourcing PDD process in order to have guaranteed product design quality?

The second objective is to understand the key crowdsourcing enabling technologies in terms of the key components of a crowdsourcing process such as open call generation, incentive mechanism, quality control, workflow management, crowd's qualification, and crowd's structure, etc. and how they affect product design process and quality. The investigation of the key enabling technologies for crowdsourcing PDD can provide technical guidelines for developing a crowdsourcing platform for PDD process.

- O3: How to develop a product design lifecycle information model and test its utility in the crowdsourcing platforms for two types of businesses?

The third objective is to identify, construct, and collect information through the whole lifecycle of the product design process, and then to model it and its relationships semantically using ORM approach into a PDLIM to enhance design information communication and sharing among stakeholders/participants during the crowdsourcing PDD process. Based on the PDLIM, two crowdsourcing platform prototypes (the intermediary one for SMEs and the integrated one for large enterprises) are developed to illustrate the control of the crowdsourcing PDD process and utility of the PDLIM with two case studies. The first case study is to evaluate if the intermediary platform prototype can support the iterative PDD process through design information representation and interaction model. And the second one is to evaluate if the integrated platform can support the ‘crowdsourcing as a service’ concept by simulating the co-evolution of smart heating products and their virtual models.

1.8 Contributions of this study

This study investigated the theoretical foundation in quality control methods of product designs in crowdsourcing environments and key crowdsourcing enabling technologies for PDD, developed a product design lifecycle information model and finally achieved two crowdsourcing platforms (the intermediary one is developed purposely for SMEs and the integrated one is for large enterprises) that can support the iterative product design process and the coevolution of physical products and virtual models. The research outcomes make contributions to a wide knowledge field regarding design information representation and communication in crowdsourcing environments, product design lifecycle information model, crowdsourcing system developments for both SMEs and large enterprises.

- The outcome of crowdsourcing PDD investigations could result in better understanding of product design quality and its attributes and the quality control measures when their PDD activities are crowdsourced.
- Better understanding of key crowdsourcing enabling technologies for PDD process is generated from this study as well.
- A novel product design lifecycle information model consisting of the overall model structure, the information representation model, and the ORM interaction model has been developed for PDD in in-house and crowdsourcing combined design environments. The model can enrich the theory of design information representation and communication in virtual environments and can support effective design communication and information sharing during the product lifecycle and can be integrated into the current PLM systems for supporting the emerging data-driven product development paradigm in a closed loop of PDD process.
- This study filled some knowledge gaps in crowdsourcing PDD system developments. The newly developed system establishes an ecosystem which enhances the information acquisition and communication of design information in the whole PDD process. It connects not only the network of smart products but also the network of stakeholders on the supply chain, enabling it to support the coevolution of physical products and their corresponding virtual models.

The contributions of this study are supported by following publications and journal submissions. Full copies of them are attached in Appendix E.

- Niu, Xiaojing, Qin, Shengfeng, Vines, John, Wong, Rose and Lu, Hui Lu (2019) Key crowdsourcing technologies for product design and development. International Journal of Automation and Computing, 16(1). pp. 1-15.

- Niu, Xiaojing, Qin, Shengfeng, Zhang, Haizhu, Wang, Meili and Wong Rose (2018) Exploring product design quality control and assurance under both traditional and crowdsourcing-based design environments. Advances in Mechanical Engineering, 10(12). pp. 1-23.
- Mountney, Sara, Tracy, Ross, May, Andrew, Qin, Shengfeng, Niu, Xiaojing, King, Melanie, Kapoor, Kawaljeet, Story, Vicky and Burton, Jamie (2020) Digitally supporting the co-creation of future advanced services for 'Heat as a Service'. In Proceedings of the Spring Servitization Conference (SSC), pp. 64-71.

- Niu, Xiaojing and Qin, Shengfeng (2017) A review of crowdsourcing technology for product design and development. In Proceedings of the 23rd International Conference on Automation and Computing (ICAC), pp. 1-6.

- Niu, Xiaojing, Wang, Meili and Qin, Shengfeng (2021) Product design lifecycle information model with crowdsourcing product design and development. International Journal of Advanced Manufacturing Technology. (Under review)
- Niu, Xiaojing and Qin, Shengfeng (2021) Integrating Crowd-/Service-sourcing into Service-oriented Digital Twin for Enabling Advanced Manufacturing Services. IEEE Transactions on Industrial Informatics. (Under review)

1.9 Structure of the thesis

This thesis is to investigate whether it is feasible to introduce crowdsourcing into the product design and development process with expected quality for manufacturing.

The study is structured by answering the investigation questions listed in Figure 1-4.

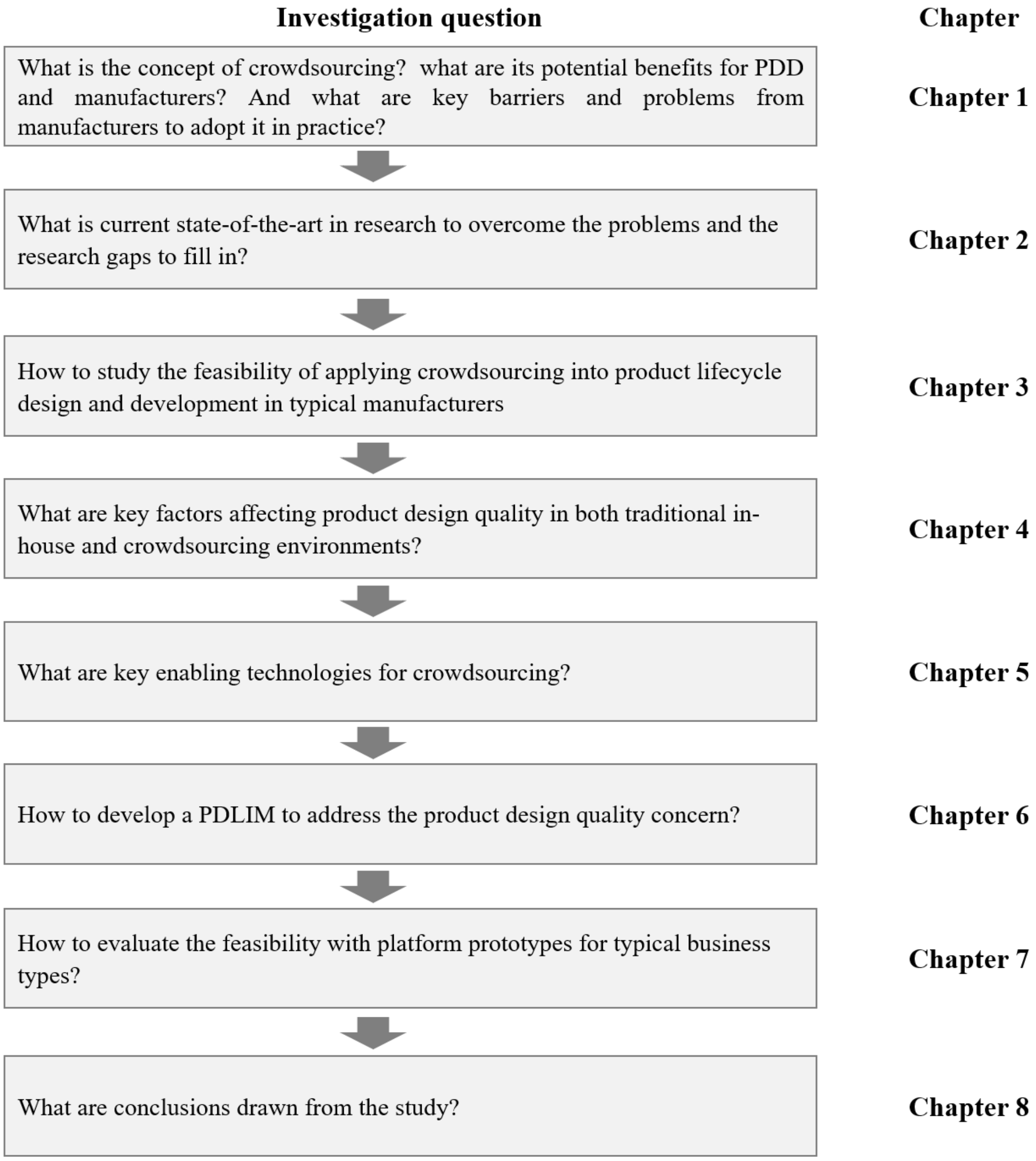


Figure 1-4 The structure of this study.

The brief summary of each chapter is as follows:

Chapter 1: Introduction. This chapter describes the research background, motivations, and contributions of this research. In addition, it states the research aim and outlines the specific research objectives.

Chapter 2: Literature review. This chapter mainly contains a comprehensive literature review of academic research around the application of crowdsourcing in PDD process and the development of PDD process models. This chapter also identifies the research gaps in crowdsourcing PDD and proposes new solutions to fill the gaps.

Chapter 3: Methodology. This chapter introduces the overall research methodology. According to research timeline, the applied methods for analysing the factors affecting product design quality in crowdsourcing environments and crowdsourcing technologies for PDD process, data collection and information extraction, the construction of design information model, and the development of crowdsourcing platform prototypes are discussed.

Chapter 4: Exploration of factors affecting product design quality under in-house and crowdsourcing environments. This chapter defines product design quality and identifies its key attributes and sub-attributes. Then the key factors affecting product design quality in in-house and crowdsourcing environments are analysed.

Chapter 5: Crowdsourcing technologies for PDD. This chapter explores crowdsourcing technologies for PDD in terms of framework, platform, techniques, and tools. The challenges in crowdsourcing PDD have been identified as well.

Chapter 6: Development of product design lifecycle information model. This chapter explores the information affecting product design quality at each phase of a PDD process and describes the development of a lifecycle PDD information model, which consists of the overall structure of the model, design interaction model and design information representation model.

Chapter 7: Development of crowdsourcing platform prototypes for PDD process and feasibility study. This chapter describes the configurations of the intermediary and integrated crowdsourcing platform and presents evaluation studies with case studies.

Chapter 8: Conclusions and future work. The research applications are discussed and summarized in this final chapter. In addition, the chapter also includes a summary of contributions and the limitation of this research, as well as recommendations for potential future work.

Chapter 2 Literature review

2.1 Introduction

This section mainly reviews existing crowdsourcing research in crowdsourcing systems and crowdsourcing PDD studies, aiming to understand the research status, confirm the research gaps, and eventually propose new research solutions for crowdsourcing PDD. Section 2.2 presents the scope of literature review. Crowdsourcing system research in terms of crowdsourcing models and components of a crowdsourcing platform is described in Section 2.3. Section 2.4 summarized crowdsourcing PDD research in terms of the analysis of existing crowdsourcing platforms for PDD and the classification of crowdsourcing PDD studies at different design phases. Then the research gaps are identified in Section 2.5 and a new solution is proposed in Section 2.6.

2.2 Scope of literature review

A structured literature review has been conducted. The academic database Web of Science was consulted to locate papers which include the expected keywords. The keywords used to search articles are organized in three descriptor groups with rules listed below. In this review, Boolean operators ‘AND’ and ‘OR’ are adopted to make logical searches. R_1, and R_2 use the rule of ‘OR’ to represent the descriptor groups, respectively. R_3 is the sum of R_1 and R_2 with the rule ‘AND’. For example, several keywords combinations, such as ‘crowdsourcing’ with ‘product design’, ‘co-creation’ with ‘manufacturing’ have been examined.

$$R_1 = keywords \in (crowdsourcing\ OR\ crowd - sourcing\ OR$$
$$co\ creation\ OR\ co - creation\ OR\ peer\ production)$$

$$R_2 = keywords \in (product\ design\ OR\ product\ development\ OR\ Manufacturing)$$

$$R_3 = keywords\ \in (R_1\ AND\ R_2)$$

As a final retrieval result, a total number of 123 papers published after 2009 were found (78 journal articles, 42 conference papers, and 3 review papers).

In academic publications, Figure 2-1 illustrates the research distributions by year. It is found that 111 out of 123 paper relating to crowdsourcing product design and development have been published between 2014 to 2020. The highest number of publications was reached in 2018, when 22 papers were published (13 journal articles, 7 conference papers and 2 review papers).

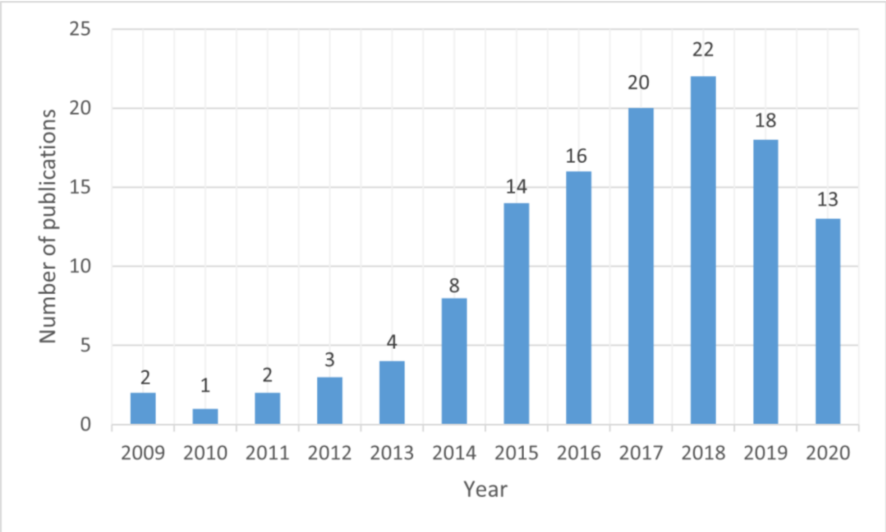


Figure 2-1 Distribution of literature by year

After a review of the content of each article individually, it was found that most papers (42 out of 123 papers) focus on using crowdsourcing to generate and evaluate ideas and solve problems in PDD process, including models, frameworks and processes or the development of new system to enable crowdsourcing in PDD process. Based on the initial data analysis, the research findings from the analysis are detailed in the following sections.

2.3 Crowdsourcing system research

Due to the advantages of crowdsourcing, many organizations are developing their own crowdsourcing systems. However, the development of a crowdsourcing platform and its integration into the existing enterprise innovation platforms are risky and hard undertaken without theoretical foundation (Hetmank, 2013). Furthermore, the design of any crowdsourcing system is deeply related to the answer to three questions: what the required data are, how to obtain it through crowdsourcing, and how to use it in the specific application scenario. The features of the required data usually determine the complexity of the whole system. Next section will introduce the research development in crowdsourcing process models and the components of crowdsourcing systems.

2.3.1 Crowdsourcing process models

Since existing crowdsourcing platforms have their own logic of how to crowdsource tasks, e.g., marketplace, contest, or bid, the activities conducted in a crowdsourcing process vary from project to project (Tranquillini *et al.*, 2015; Amrollahi, 2016). Tranquillini et al. (2015) considered that the typical steps involved in crowdsourcing a task is task publication, worker preselection, task execution, validation and rewarding, while Amrollahi (2016) regarded the preparation stage before crowdsourcing and post stage after crowdsourcing as necessary parts of a crowdsourcing process. To generally describe a crowdsourcing process (Tranquillini *et al.*, 2015), Amrollahi (2016) extracted common crowdsourcing phases and identified key activities at each phase. Table 2-1 shows the key phases and corresponding activities in a crowdsourcing model from the perspective of the crowdsourcer.

Table 2-1 Key phases and corresponding activities in a crowdsourcing model

Crowdsourcing phase	**Definition**	**Phase activities identified from the literature**
Technical design	Design and development of the crowdsourcing platform	Platform selection, platform design and development
Conceptual design	Activities which should be performed before start of the technical development of the project	Definition of tasks, qualification requirements of participants, timeline
Participant selection	Selection of the crowd who will participate in the crowdsourcing task	User selection, team formation
Communication	Communication with the selected crowd	Contact the crowd, crowdsourcer broadcasting, communication
Idea generation	The crowd start their interactions with the system to submit their ideas	Task choice, idea generation, collection of ideas from crowd, job execution
Idea evaluation	Checking the appropriateness of the crowd’s inputs/ideas, then ranking, filtering, and commenting on the crowd’s inputs/ideas	Crowd’s inputs evaluation, result analysis, competitive and judging process
Monitor	Organization of the team during the implementation	Coordination, manage concurrency/input and output/ time, workflow management
Grant award	Identification of the best entry and awarding related incentive	Prize for winning ideas, reward

Table 2-1 Key phases and corresponding activities in a crowdsourcing model (Continued)

Crowdsourcing phase	**Definition**	**Possible activities in the literature**
Process evaluation and documentation	Reviewing the project and documenting the lesson learned for future improvements	Knowledge retrieval and capture, Knowledge evaluation, deciding on future crowdsourcing arrangements, project evaluation, train models
Implementation	Implementation of the results of the crowdsourcing	Collaborative discussion, presentation of result, collective action, results and analysis, implementation actions

2.3.2 Components of a crowdsourcing system

Because of the diversity of crowdsourcing models, it is difficult to define crowdsourcing systems and to derive a unified crowdsourcing process that should be implemented in a crowdsourcing system. However, crowdsourcing systems have the same key components, namely, the requester, the crowd (workers), the task, and the platform (Hetmank, 2013; Bhatti, Gao and Chen, 2020). After analyzing the diverse definitions of crowdsourcing systems, Bhatti, Gao and Chen (2020) proposed the components and processes in crowdsourcing systems (*Figure 2-2*) that should be implemented. In addition to the proposed key components of a crowdsourcing system, Hetmank (2013) classified the crowdsourcer and the crowd into the user category and considered that contribution/solution submitted by the crowd was also an important part because it connected the crowdsourcer and the crowd.

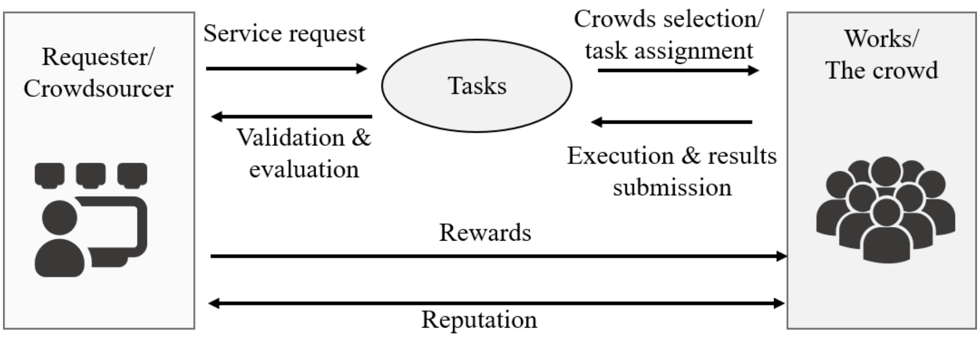


Figure 2-2 Components and processes in crowdsourcing systems (Bhatti, Gao and Chen, 2020)

Around the key components of a crowdsourcing system, key functions that should be implemented in each component have been identified (Hetmank, 2013). In addition to the basic functions, such as user registration and task broadcasting, additional functions to support the activities listed in Table 2-2 should be implemented as well.

Table 2-2 Functions in each component of a crowdsourcing platform (Hetmank, 2013)

Crowdsourcing system component	**Functions**
User (including the crowdsourcer and the crowd)	Register user, evaluate user, form user group, and enable coordination
The task	Design task, and assign task
Contribution/Outputs from the crowd	Represent contribution, evaluate contribution, and select contribution
The platform	Define workflow, manage workflow, and organize the structure of the crowd

With the identified system components, the system entities can be extracted as they refer to the individual or organization interacting with the platform to generate and process data. To ensure the management and effective sharing of information and the output quality during a crowdsourcing process, the system entities must be well defined (Evans *et al.*, 2016).

According to the crowdsourcing quality model (Florian *et al.*, 2018), the output (data/product) quality is determined by people quality, process quality and software/crowdsourcing platform quality (as shown in Figure 2-3).

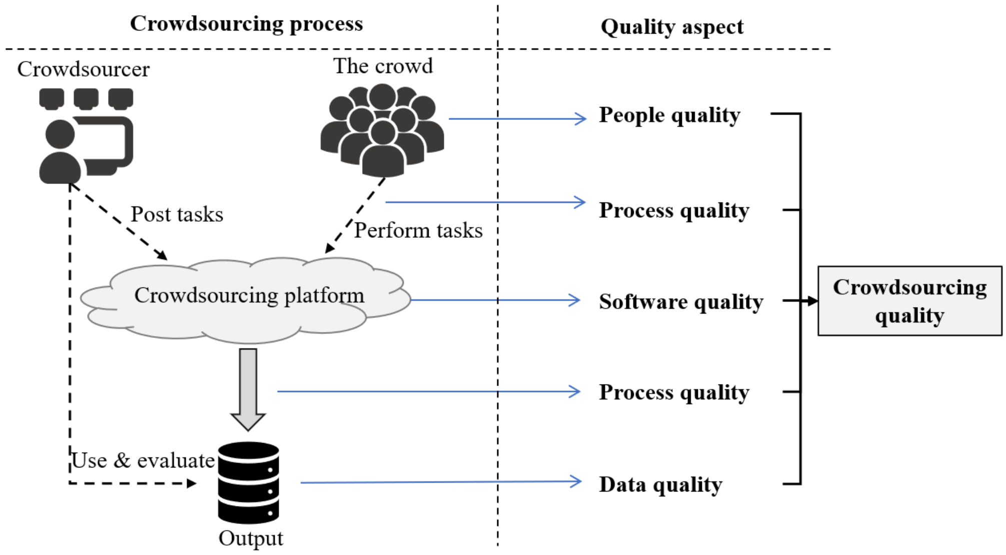


Figure 2-3 The basic crowdsourcing scenario with its quality aspects (Florian *et al.*, 2018)

The existing crowdsourcing platforms mainly defined the user and the task as follows:

The representation of user

The user profile records both the user identity of the crowd and that of the crowdsourcer. The user identity may be associated with their corresponding public profiles on the social network sites to improve the trust between the crowdsourcer and the crowd (Klinger and Lease, 2011).

The representation of task

The task must be defined and formulated appropriately. Its formulation should cover the type (e.g., straightforward, novel), the size, the reward or incentive scheme (Von Ahn and Dabbish, 2008; Mason and Watts, 2009), the submission time, the latency (e.g., immediate, waitable) (Liu et al., 2010), the degree of confidentiality, and the qualification of participants. Additionally, the contextual information such as location and time and the crowdsourcer's profile is assigned to the task specification automatically (Hetmank, 2013).

2.4 Crowdsourcing PDD research

2.4.1 Research background

It has been found that the crowd can solve certain problems faster, better and cheaper than in-house only working mode (Blohm *et al.*, 2018). Crowdsourcing can be used to find solutions to many kinds of tasks, especially problem-solving and data-gatherings (Jonathan, 2019). For example, crowdsourcing has been used for collecting data in various domains of geophysics including weather, air pollution, geography, and ecology, etc. to address the lack of sufficient data in geophysical system research (Zheng *et al.*, 2018). Companies like DHL (Blohm *et al.*, 2018) and Dell (Bayus, 2013) also seek ideas from crowds for their product designs and improvements. For the purpose of solving specific technical problems, a specific group with highly developed skills and experience should be targeted.

With the increased successful application of crowdsourcing in diverse fields (Saxton, Oh and Kishore, 2013), many enterprises have begun to use the crowd as part of the PDD process. Generally, depending on the nature of crowdsourced problems/tasks, crowdsourcing can take a lot of different forms, such as dedicated crowdsourcing sites, social media platforms and apps, etc. However, the application of crowdsourcing in this field seems to be stagnating since crowdsourcing was coined in 2006. From the benefits that crowdsourcing platforms bring to large enterprises shown in *Table 1-5*, crowdsourcing is still mainly used for collecting ideas from users, testing solutions with users, and collecting user needs and expects. It has been found that crowdsourcing-based product design and development is interesting to many SMEs but there are some barriers preventing them from adopting crowdsourcing into their new product development practice (Qin *et al.*, 2016). For example, how to achieve good quality of product design over a crowdsourcing platform is one of main concerns from many SMEs. In addition, there is industry-wide scepticism towards crowdsourcing and the value of crowd (Burnap *et al.*, 2017). This is largely because crowdsourcing brings larger risks from open design process, unknown participants to their PDD activities, unpredictable output quality and the limited guidance on applying crowdsourcing in PDD (Forbes and Schaefer, 2018). To enable the output quality when crowdsourcing PDD activities, every aspects should be seriously considered (Qin *et al.*, 2016; Forbes and Schaefer, 2018).

2.4.2 The analysis of existing crowdsourcing platforms for designs

This part mainly focuses on analysing crowdsourcing platforms for designs. According to the type of the crowdsourced task, crowdsourcing platforms for designs could be classified into two categories: graphic design supported and product design supported. The typical crowdsourcing platforms for graphic designs are 99designs and crowdspring. Taking 99designs as an example, it works as follows: a. Build a design brief; b. Pick a design package; c. Launch the design contest; d. Receive dozens of designs; e. Give feedback; f. Pick the favourite and get the full design copyright. On this platform, any internet users who registered on it can participate in the contest and contribute their thoughts and ideas. crowdspring has a similar work process as 99designs.

Threadless, Jovoto, Spreadshirt, and Quirky are open innovation platforms supporting creative co-creation among online community. They have similar work process.

Taking Threadless as an example, it crowdsources T-shirt design to the online community on threadless platform (https://www.threadless.com/) to request submissions from online users through an open call. Once a T-shirt design is submitted, online community begins voting, scoring, and commenting about the design. And based on the voting scores and comments, the design with more votes will be manufactured and the selected designers will be rewarded with credit points that can be used to buy T-shirts or exchange for cash. Different from Threadless, graphic design platforms like 99designs and crowdspring usually launch a design contest for a design task, only the winner designer will get the reward. Regardless of the design types of the crowdsourced task, the evaluation method on these platforms is mainly voting, and it does not support the iterative design process.

The existing crowdsourcing platforms typically support simple and independent tasks, such as labelling an image or collecting information in a specific field. As for complex tasks, the crowd may need to build his/her own team as in conventional setting. When they finish the task, they can submit their results to the platform for later evaluation. The output evaluation on existing platforms is relatively simple, as the selection of winner solution is achieved by the voting of the crowd. For some tasks, the solution is assessed by a group of experts as in traditional way, such as the innovation process of Jovoto. Some research work has proposed the idea of coordinating many individuals to complete more complex tasks (Kittur *et al.*, 2011). In this context, crowdsourcing becomes a way to provide solutions to complex problems by automatically coordinating potential machines and human beings to work together (Muntés-Mulero *et al.*, 2013). For crowdsourcing of a complex task like PDD activities, incentive mechanisms, crowd qualification, organization structure of the crowd, workflow and quality control, etc. should be seriously considered (Hetmank, 2013; Evans *et al.*, 2016; Wazny, 2017; Florian *et al.*, 2018; Forbes and Schaefer, 2018).

2.4.3 Classification of existing crowdsourcing PDD studies

The majority of current literature considers crowdsourcing to be an effective way for the ideation and concept evaluation stages of a PDD process. For example, a crowdsourcing design framework for exploiting online customer reviews to aid concept generation at concept design phase (Liu and Lu, 2016) and a framework for acquiring quality critiques in a timely manner and evaluating crowdsourced designs (Xu and Bailey, 2011; Wu, Corney and Grant, 2015) have been explored.

A PDD process is typically structured into five lifecycle design stages (Wright, 1998): pre-design stage (S1), design stage (S2), manufacturing stage (S3), launch & in use stage (S4), and maintenance & recycling stage (S5). At each stage, several key design phases (shown in Figure 2-4) are identified (Cheng, 2018). The design phases at pre-design & PDS stage, design stage, and manufacturing stage are iterative processes. The distribution of studies at each product development phase is shown in Table 2-3.

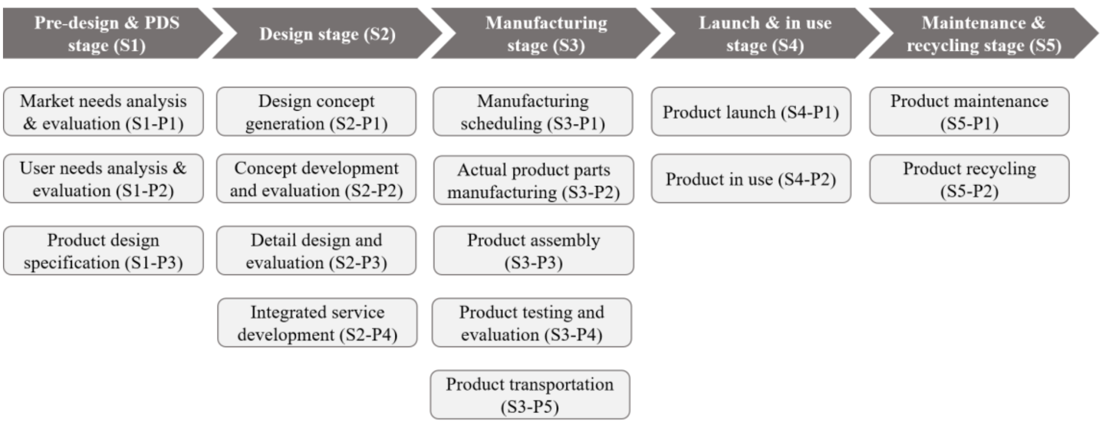


Figure 2-4 Key phases at each design stage of a PDD process

Table 2-3 The distribution of crowdsourcing studies at each product development phase

Design phase	References
Market needs analysis (S1-P1)	(Nishikawa *et al.*, 2017); (Pacauskas *et al.*, 2018); (Lang, Bharadwaj and Di Benedetto, 2016)
Design concept generation (S2-P1)	(Liu and Lu, 2016); (Sun *et al.*, 2015); (Goucher-Lambert and Cagan, 2019); (He *et al.*, 2019)
Concept development and evaluation (S2-P2)	(Xu and Bailey, 2011); (Wu, Corney and Grant, 2015)
Detail design and evaluation (S2-P3)	(Forbes and Schaefer, 2018)

From Table 2-3, crowdsourcing is mainly applied to marketing research, concept generation and evaluation stages, while the potential of applying it in other stages of a PDD process beyond ideation and evaluation have been recognised (Panchal, 2015; Qin *et al.*, 2016). Furthermore, none of these papers offer detailed guidance on using crowdsourcing throughout the product development process.

2.5 Research gaps analysis

Research gap in crowdsourcing platforms for PDD

To date, there is no one crowdsourcing platform that fully supports a PDD process (Qin *et al.*, 2016). Instead of developing a purposed crowdsourcing platform for PDD, the existing research focuses on algorithms of accomplishing complex and interdependent tasks using existing platforms for micro-tasks, such as Amazon MTurk (Kittur *et al.*, 2011). In this way, the design process is out of the requester's control and the process information is invisible to the requester, while these aspects are important for manufacturers to ensure the output quality.

Although some enterprises have integrated crowdsourcing into their existing innovation platforms to evaluate ideas and collect user feedback, the platform cannot be appliable to other phases of a PDD process as there is no guideline on how to realize this.

Research gap in crowd representation

The existing crowdsourcing platforms like 99designs and crowdspring describe the crowd profile with attributes: joining date to the platform, nationality, language, specializations, customer ratings, experience (described by the summary of previous participated crowdsourcing projects in terms of the number of winners, runners up, and the 1-to-1 projects, and the possibility of responses within 24 hours), and certifications defined by the platform (e.g., intermediate level and top level, calculated based on the crowd's experience). A crowd usually have more than one skill and their proficiency varies from skill to skill. Such a crowd profile representation cannot tell how the crowd is qualified in a specific area.

Research gap in staged output/product design representation

Since crowdsourcing has not been applied into the whole PDD process, there is no work focused on how to represent a product design that changes over time at early design stages. But many studies have already focused on feature-based representation of engineering product design. Feature-based design representation is the basis for data exchange and communication among different CAx systems. According to the high-level UML model for engineering product design as shown in Figure 2-5, an industrial product consists of many assemblies and one assembly has many components and one component has many features (Sanya and Shehab, 2015). Feature is treated as the smallest unit in modelling product design. The four main fields for representing a generic feature include attributes, parameters, constraints, and topological entity pointers. Attributes refer to the self-describing properties like material and surface finish, and non-geometric entities such as functions, rules, and machining operations. Parameters are the key for describing the shape, dimensions, orientation, and position of entities, topological entities are those that can be shown to the user such as a point, line, cylinder, or cube. However, feature-based design models only concern design geometry, constraints, parameters, and dimensions, but fail to pay attention to other related information, such as information driving design feature changes and the feature changes process (Tang, Chen and Ma, 2013). Therefore, the proposed PDLIM should consider the driving information and the feature change process to ensure the integration of the proposed PDLIM to existing CAx systems.

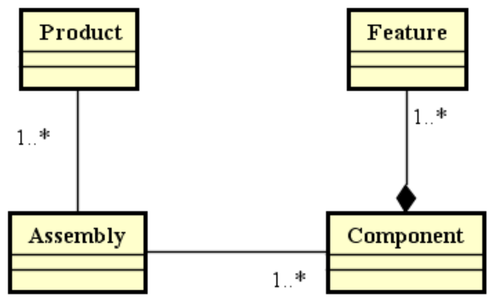


Figure 2-5 High-level UML model for engineering product design (Sanya and Shehab, 2015)

To reduce the disambiguation of the feature meanings in different design and manufacturing ontologies, Sanfilippo and Borgo (2016) identified I-feature and P-feature for modelling product features in CAx systems. I-features are properties used to define product types while P-features are physical entities in space and time that satisfy I-features. Therefore, I-features can be treated as a list of requirements/constraints the product design should meet. In practice, P-features may correspond to several I-features since the physical product may satisfy slightly different models depending on the range of parameters, granularity, and tolerance. The features in design ontologies can be further classified into assembly feature, component feature, form feature, functional feature, geometric feature, and material feature, etc. and their uses have been identified (Sanfilippo and Borgo, 2016). Therefore, a product design can be represented as a group of features.

With the increasing needs for customised products and services, enterprises are transforming to service-lead business to offer flexible and rapid services around their existing core products. The business transformation requires enterprises to make changes to their products, so service is also regarded as a feature in product design representation (shown in Figure 2-6).

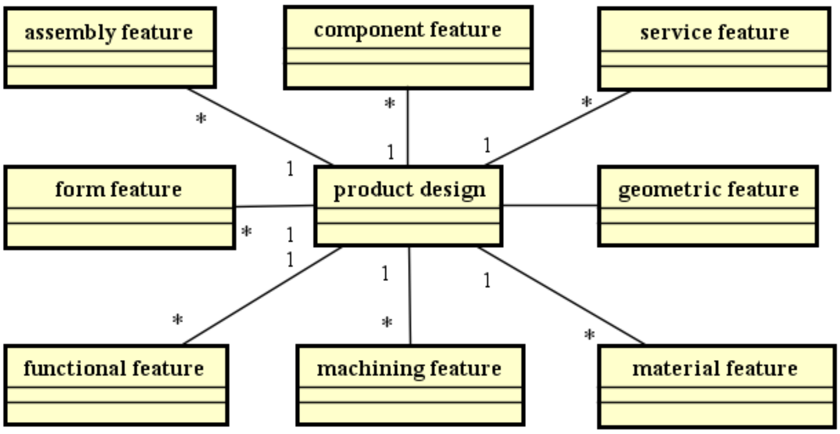


Figure 2-6 Product design representation

Although no work has focused on representing staged product design at early design stages, the feature-based design representation method should be adopted when modelling the staged output using CAx systems.

2.6 Proposed new solution for crowdsourcing PDD

The development of information acquisition and analysis technologies brings new opportunities to enhance the production efficiency and product competitiveness by utilizing the valuable data generated in the entire product lifecycle. In this context, data-driven product design is an inevitable trend. Therefore, the information representation and modelling are critical on crowdsourcing platforms for PDD.

The components and process of the proposed crowdsourcing platform for PDD is shown in Figure 2-7.

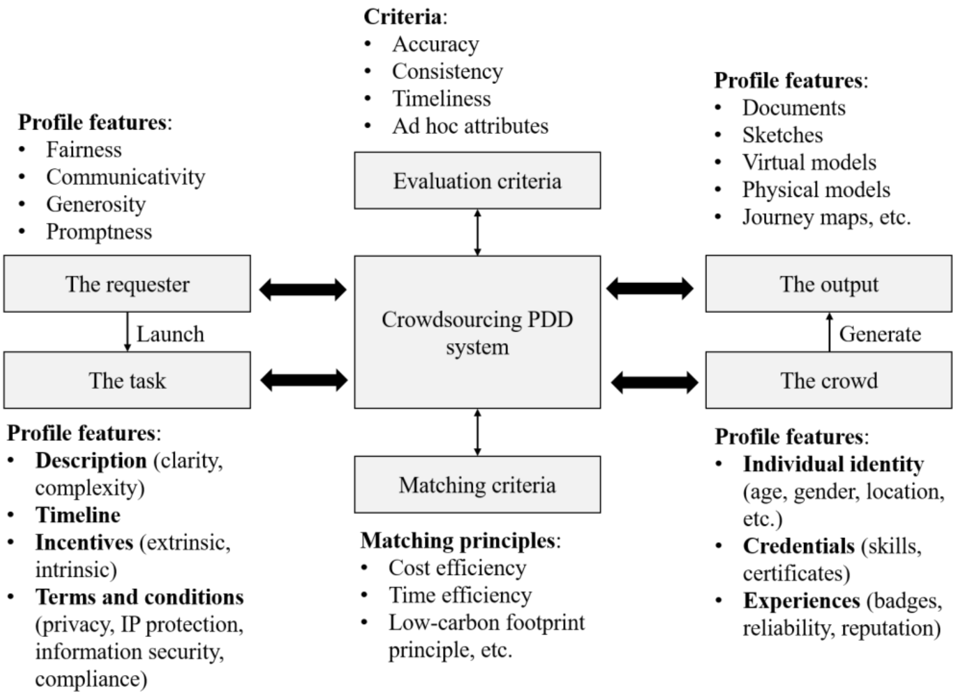


Figure 2-7 Components and process of the proposed crowdsourcing platform for PDD

The simple working process on the platform is:

Step1: The requester inputs the task and launches the crowdsourcing process.

Step2: Based on the matching criteria, the task is broadcasted to the qualified crowd.

Step3: The crowd perform the task and submit their design solutions to the platform.

Step4: The requester evaluates the submitted design solutions with reference to evaluation criteria, and then submits the comments to the platform.

Step5: The crowd revise the design solution according to the comments. Then step4 and step5 iterate until the design solution is satisfactory.

This thesis focuses on modelling the key entities/actors and staged product designs to support the iterative PDD process on a crowdsourcing platform.

2.7 Summary

This chapter conducts a comprehensive review of academic publications in the field of crowdsourcing PDD activities to understand the state-of-the-art in crowdsourcing PDD and highlight the research gaps. The main review body is on the research development of crowdsourcing systems in terms of crowdsourcing models and the components of crowdsourcing systems and the crowdsourcing PDD research in terms of the analysis of existing crowdsourcing platforms for PDD and the classification of crowdsourcing studies in different PDD phases. Based on the literature review, the research gaps are analyzed and a new solution for crowdsourcing PDD is proposed.

From next chapter, the research is moved forward to evaluate the feasibility of the proposed solution for crowdsourcing PDD.

Chapter 3 Methodology

3.1 Overview of research methodology

This section provides an overview of research methodology in this study. Figure 3-1 illustrates applied research methods based on the research timeline. The main research structure of this study is phased by research aim and objectives. After reaching the research aim from the research gaps identified through literature review, three objectives have been identified, i.e., improved product design quality control theory in crowdsourcing design environments, technical foundation of key crowdsourcing enabling technologies for the PDD process, and the investigation of the product design lifecycle information model and the evaluation of the crowdsourcing PDD process in two different application contexts. In accordance with the context of research structure, a fourth-staged research methodology is adopted for addressing the research objectives. For research objective O1 and O2, systematic literature review is chosen for theory explorations in the first and second stage. The research objective O3 is answered by the third and fourth stage with some primary research. In the third stage, a number of research methods such as entity data identification, data collection, data evaluation by questionnaire and case studies, and ORM modelling are adopted, and object-oriented modelling, platform development and case study evaluation are used in the fourth stage.

3.2 Exploration of improved product design quality control theory in crowdsourcing environments

The first research issue is regarding key factors affecting product design quality, the quality control methods and quality assurance policies in both traditional in-house and crowdsourcing design environments. These will be the fundamental knowledge encoded in the crowdsourcing platform for PDD to ensure the design output quality. Therefore, a systematic literature review is conducted to analyse quality control and assurance studies in both traditional in-house and crowdsourcing environments.

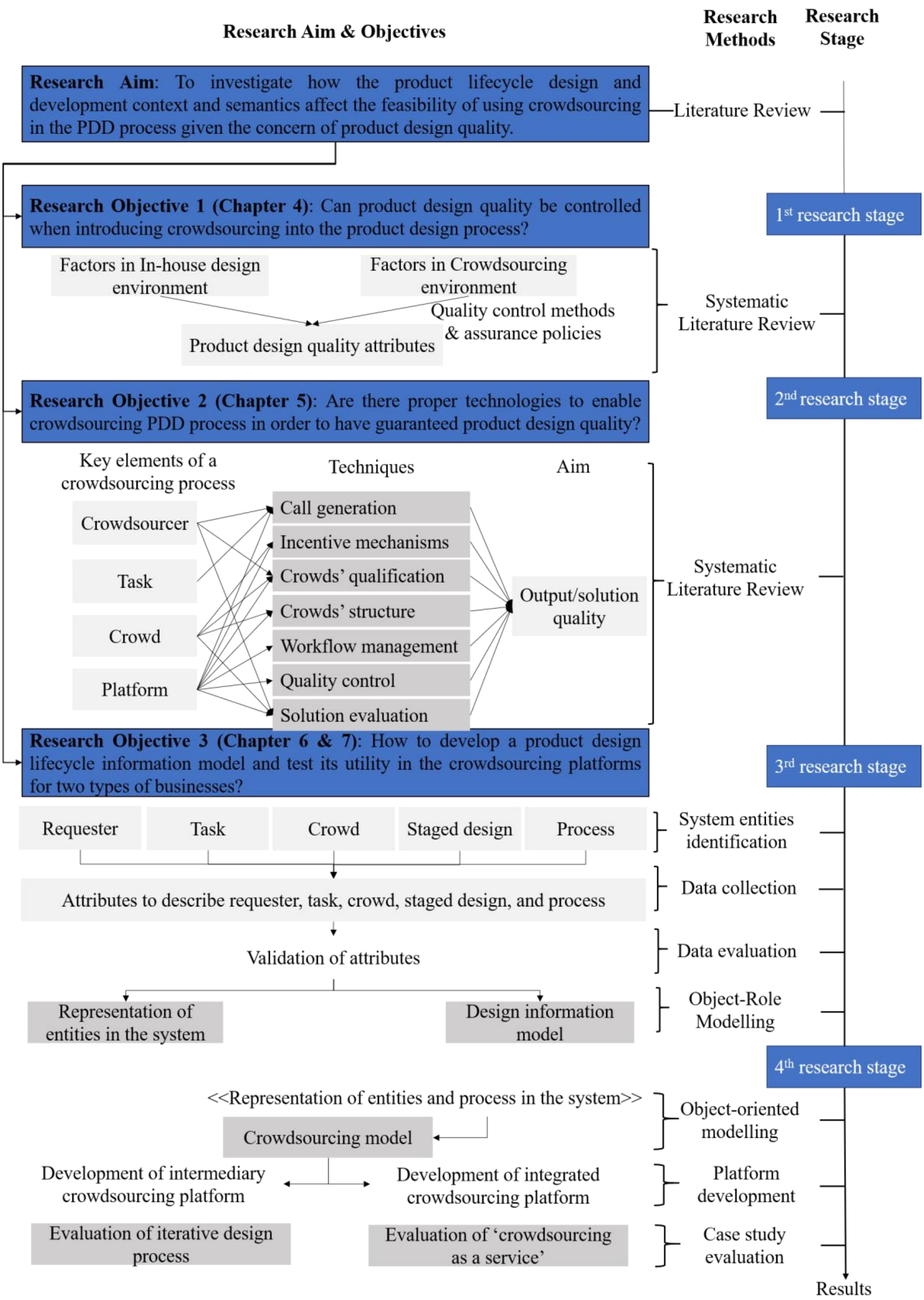


Figure 3-1 Framework of research methods

3.3 Exploration of key enabling crowdsourcing technologies for PDD

The second research issue is regarding the crowdsourcing technologies for PDD. These provide a guideline on how to implement a crowdsourcing platform for PDD and which aspects should be emphasised on. Similar to the research method used in the first research issue, a systematic literature review is also conducted.

3.4 Product design information extraction and modelling methods

The third research issue is to model product design information through the whole lifecycle. The top-down design approach was adopted. The model investigation includes the definition of the scope of the model's applicability, data requirements collection and analysis, data evaluation, and object-oriented modelling stages.

3.4.1 Definition of the scope of the model's applicability

The PDLIM is to support the exchange of design information among system users at early design stages. Therefore, the identification and definition of system entities should be explored first. From previous literature review, the identified entities include key platform users (i.e., the requester, the crowd, and the evaluator), the task, staged design, and the process. These entity classes are either the objects interacting with the platform or outputs at a specific design phase. With the identified system entities, the crowdsourcing process for PDD will be analysed to extract the process information representing interactions between entities and the platform. On the platform, to ensure the crowdsourcing process, all entity classes and their relationships will be described by certain descriptors.

However, the existing crowdsourcing platforms mainly focus on defining the crowd on the platform to ensure the selection of them for a requested task and relying on the crowd (acting as the evaluator) to evaluate the output to a requested task, few emphases have put on representing the requester and the evaluators. The attributes to represent platform user and the task are shown in Table 3-1. the representation of staged design and the process will be explored in Chapter 6.

Table 3-1 Attributes for representing platform user and the task

Entity	Platform user	The task
Attributes	- Personal information (such as name, age, gender, location, nationality, email, language, joining date to the platform) - Specializations - Customer ratings - Experience (the number of winners, runners up, and the 1-to-1 projects, repeat clients, and the possibility of responses within 24h) - Certification defined by the platform, etc.	- Call description - Timeline - Submission requirements - Judging and prizes - Criteria and disqualifications - Crowd qualification requirements - Rules and regulations - About the sponsor, etc

3.4.2 Data requirements collection and analysis

This stage aims to find out what information is required for representing the identified entity classes and what about their relationships. Literature survey was conducted to capture data requirements. Specifically, secondary resources including existing literature in modelling product design information and case studies recording detailed design process and staged outputs are collected and entity descriptors are extracted manually. The description of the requester, the crowd, and the task are mainly extracted from existing literatures and crowdsourcing platforms, while the descriptors for staged design/output are extracted from literatures and case studies.

3.4.3 Data evaluation

The identified descriptors for entity classes especially those for the staged design are evaluated in two steps. First, the necessity/usefulness of the identified descriptors is qualitatively evaluated via various information representation examples in three case studies (illustrating product concept design, product family design, and product lifecycle design, respectively). Second, the comprehensiveness of the identified descriptors for representing entity classes and the feasibility of applying them to support iterative product design and development process is quantitively evaluated by a questionnaire survey. The respondents of the survey are design researchers, practitioners, and students whose degree is above master.

3.4.4 Object-Role Modelling (ORM)

The development of crowdsourcing PDD platform requires a well-designed information database which involves the development of a formal model. Currently, entity-relationship (ER) modelling, object-oriented modelling and ORM are valuable information modelling approaches. By far, although ER modelling and UML-based object-oriented modelling are the most popular approaches for database design and modelling software systems, they are arguably less suitable than fact-oriented approach, i.e., ORM, for formulating, transforming, or evolving a conceptual information model (Halpin and Bloesch, 1999; Halpin and Morgan, 2008). ORM models has several advantages: semantic stability, natural verbalization, populatability, and null avoidance. The graphical language of ORM is far more expressive for data modelling purposes than that of UML and ER (Halpin, 2009). ER models and UML class diagrams are further removed from natural language, lacking the expressibility and simplicity of a role-based constraint notation. Furthermore, they may hide information about the semantic domains that glue the model together because they are less stable in the face of domain evolution and are harder to populate with fact instances (Halpin and Morgan, 2008). ER and

UML models better highlight the major features of the domain, so they will be developed as views of ORM models at the platform implementation stage.

Therefore, ORM approach (Halpin and Bloesch, 1999; Halpin and Morgan, 2008) is adopted to simplify the analysis and design process by using natural language, intuitive diagrams, and examples.

3.5 Platform realization and evaluation methods

3.5.1 Object-oriented modelling

Due to the advantages of easier modelling of complex objects, better extensibility, and easier integration with object-oriented database and programming code, objected-oriented modelling approach was adopted. To formally represent an information model, quite a few information modelling languages have been developed. In general, the modelling languages are presented in either graphical form or textual form. Two frequently object-oriented modelling languages used in the manufacturing areas are EXPRESS and UML. EXPRESS was created to formally specifying information requirements of product data model, which is the core part of STEP (STandards for the Exchange of Product model data). However, it cannot support the modelling of product design and development process. Differently, UML consisting of an integrated set of diagrams that are developed for specifying, visualizing, constructing and documenting the artifacts of software systems, has proven successful in modelling large and complex systems. As the primary form of system requirements, UML is an effective technique for communicating system behaviour in the user's terms by specifying all externally visible system behaviour. Therefore, it is adopted to describe the functions and interactions the platform should fulfil at the system level (Nielsen, 1995), which can accurately capture, interpret, and represent the voice of users. In addition, UML can model implementation details as well as behaviours and deployment aspects not covered by the ORM models (Halpin and Bloesch, 1999; Lee, 1999) when developing the crowdsourcing platform for PDD. Therefore, UML was adopted to build up a product design lifecycle information structure and describe the interactive information.

3.5.2 Platform prototyping and evaluation

The research issue in the fourth stage is to prototype the intermediary and integrated crowdsourcing platforms. There are many different programming languages that can be used to develop a software for the crowdsourcing PDD simulation platform prototype, such as C, C++, Java, C#, JavaScript, and Python. Due to the simple syntax, a large library of standards and toolkits, and integration with other popular programming languages, python ranked number 1 among the top 10 most popular programming languages in 2020 (Eastwood, 2020). Python is an interpreted, object-oriented programming language with dynamic semantics. Its high-level built-in data structures allowing rapid application development.

The developed platform prototype is a web application consisting of frontend and backend/server-side. The frontend is supported by JavaScript, Bootstrap, html, whereas the backend is mainly based on a python-based free and open-source web framework Django which follows the model-template-views architectural pattern. Django is a free, open-source, and full-stack web application framework written in Python language, providing a toolkit of all ready-made components for any web application development (Nesmiyanova, 2019). Its technical features such as simple syntax, MVC (Model-View-Controller) core architecture, Object Relational Mapper allows the developers to mainly focus on new application components instead of already developed ones. Additionally, it provides a dynamic CRUD (create, read, update, and delete) interface to describe the basic database commands, facilitating viewing, changing, and searching for information.

These feasibility of the developed crowdsourcing platforms on supporting iterative design process and ‘crowdsourcing as a service’ concept was evaluated by case studies.

3.6 Summary

This chapter focuses on selecting the most suitable methods for each research issue in this research. The following chapters describe three feasibility studies addressing Objective 1 – 3 in this research:

- Key factors affecting product design quality and quality control measures.
- Key crowdsourcing enabling technologies for PDD.
- The application of crowdsourcing in PDD through data-enabled crowdsourcing platform, process and information model.

The first two feasibility studies are answered in Chapter 4 and Chapter 5, respectively. And Chapter 6 and Chapter 7 are to address the third feasibility study.

Chapter 4 Exploration of product design quality control approaches and assurance policies

4.1 Introduction

The previous chapter outlined the overall research methodology. This chapter focuses on the Objective 1 which aims to investigate '*Can product design quality be controlled when introducing crowdsourcing into the product design process?*' More specifically, this chapter describes the exploration of key factors affecting product design quality, quality control methods and assurance policies in both an in-house and a crowdsourcing design environment.

From the manufacturer's point of view, quality control of consumer products is one of the most important activities in an iterative PDD process to enable the achievement of the design goal by checking the key aspects of design quality against a set of standards or specifications. With the design environment gets open and complex, manufacturers are getting part of their PDD activities, especially idea generation and evaluation conducted in a crowdsourcing environment (Boess, 2009; Qin *et al.*, 2016; Yao and Lin, 2016; Caruso, 2018; Yang, Shen and Wang, 2018; Yao *et al.*, 2019). However, due to the quality concerns to crowdsourced PDD, crowdsourcing has not been applied to benefit the whole PDD process (Qin *et al.*, 2016). With the intention to develop a crowdsourcing platform for PDD, this chapter focuses on defining product design quality, exploring the key factors affecting product design quality and corresponding quality control methods and assurance policies.

This chapter is structured as follows. Section 4.2 defines product design quality, and the research methodology used in this chapter is illustrated in Section 4.3. Section 4.4

presents the research findings under both in-house and crowdsourcing design environments, and at the end of the chapter, the conclusion is drawn.

4.2 Definitions of product design quality

PDD is an iterative process which helps designers discover unknown variables and their interrelationships through evaluating design prototypes with different fidelities ranging from 2D sketches, 3D CAD models, 2D/3D mock-ups to printed 3D models (Dow, 2011). Design prototypes offer a way to explore the opportunities and constraints of the design contexts and elicit feedback from the physical world through simulations or from colleagues and potential users for improving current design concepts (Dow, 2011). However, the interpretation of product design quality varies from person to person, so it is hard to define it precisely. Nevertheless, many studies have tried to define it. The various definition of product design quality can be found in Table 4-1.

Table 4-1 Product design quality definitions

Source	Definition or arguments of product design quality
(Zhu *et al.*, 2011)	Design specification should conform to the requirement of customers.
(Zhu, Alard and Schoensleben, 2007) ; BBC	Design requirements reflect the voice of the customer or the demands of the market
(Aas, 2000); (Mrugalska and Tytyk, 2015)	Design object satisfies its specification.
(Salimun, Janom and Arshad, 2015); ISO 9000: 2005	The degree to which a set of inherent characteristics fulfils requirements.
ISO 9001: 2015	The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs
(Spacey, 2017)	The value of a design to customers.

Table 4-1 Product design quality definitions (Continued)

Source	Definition or arguments of product design quality
Business Dictionary	Level of effectiveness of the design function in determining a product's operational requirements (and their incorporation into design requirements) that can be converted into a finished product in a production process.
IBM; (Hermans and Liu, 2013)	The degree in which customer requirements are met.
(Montgomery, 2020)	The appropriate technical term is the quality of design.

The perceived product quality is linked to five levels of Maslow's hierarchy of needs, i.e., functionality, reliability, usability, proficiency, and creativity (Bradley, 2010). Most of the existing product design quality control approaches are used to ensure the lower levels of user needs, i.e., functionality, reliability and usability. Nevertheless, in the domain of industrial design, the maintenance of product is an important aspect affecting quality as well. Therefore, the maintainability should be taken into consideration when designing the product and it is treated as a key quality attribute in our product design quality hierarchy. In addition, the research regards proficiency as a sub-attribute of functionality. Figure 4-1 shows the product design quality hierarchy of this research.

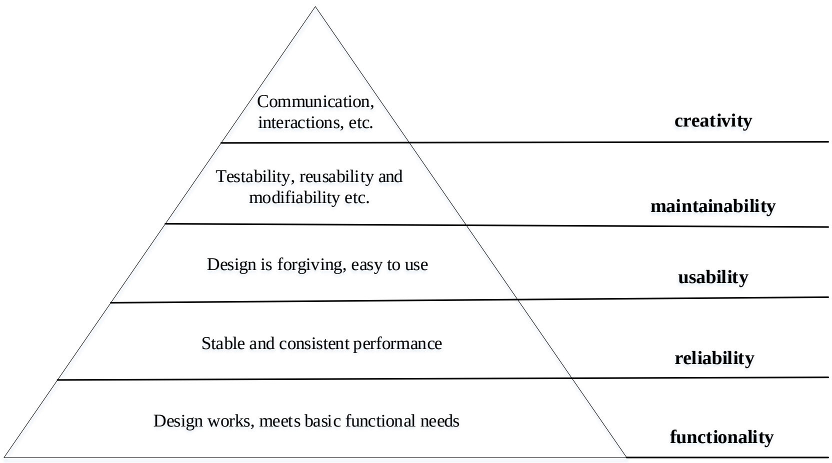


Figure 4-1 Product design quality hierarchy

Therefore, this research defines product design quality as: *the degree in which a set of inherent design characteristics of a product meet requirements of hierarchical design quality of functionality, reliability, usability, maintainability and creativity, commercial requirements and the required standards*. With adoption of the five levels of design quality hierarchy as design quality attributes, the sub-attributes to each quality category were identified into Table 4-2 with reference to product quality characteristics defined by ISO 25010 standards in Software Engineering.

Table 4-2 Definitions of sub-attributes to product design quality attributes

Design quality attributes	**Quality sub-attributes**	**Definition**
Functionality (Boess, 2009; Chu *et al.*, 2010; Lutters *et al.*, 2014; Mrugalska and Tytyk, 2015)	Functional completeness	The extent to which the functions cover all specified tasks and objectives.
	Functional correctness	The extent to which the product provides correct results with the needed degree of precision.
	Functional appropriateness	The extent to which the functions facilitate the accomplishment of specified tasks and objectives.
	Time behaviour	The extent to which the response and processing times meet requirements.
	Resource utilization	The extent to which the amounts and types of resources used by a product meet requirements.
	Capacity	The extent to which the maximum limits of a product meet requirements.
	Sustainability/ environment friendly	It is a requirement to the designer. The product must be friendly to environment.
	Safety & Security	The extent to which a product is safe for its users.

Table 4-2 Definitions of sub-attributes to product design quality attributes (Continued)

Design quality attributes	**Quality sub-attributes**	**Definition**
Reliability (Mamtani, Green and McDonald, 2006; Cheng, Zhang and Wang, 2015; Mrugalska and Tytyk, 2015; Shao *et al.*, 2016; Sanchez, Inc and Pan, 2017)	Maturity	The extent to which a product meets needs for reliability under normal operation.
	Fault tolerance	The extent to which a product continues in a reasonable way when errors occur.
	Availability	The extent to which a product is operational and accessible when required for use.
Usability (Han *et al.*, 2000; Zaharias and Poylymenakou, 2009; Jovanovic, Starcevic and Jovanovic, 2012; Van Eijk *et al.*, 2012; Haug and Münster, 2013)	Appropriateness recognisability	The extent to which users can recognise whether a product is appropriate for their needs.
	Learnability	The extent to which a product can be used by specified users after learning.
	Operability	The extent to which a product has attributes that make it easy to operate and control.
	User interface aesthetics	The extent to which a user interface enables pleasing and satisfying interaction for the user.
	Accessibility	The extent to which a product is useful for everyone in the context of use.
Maintainability (Camba, Contero and Company, 2016; González-Lluch et al., 2017)	Analysability	The extent to which the product behaviours and performances are diagnosable and predictable.
	Testability	The extent to which a product facilitates the establishment of acceptance criteria and supports evaluation of its performance.
	Modularity	The extent to which a product is composed of discrete components.

Table 4-2 Definitions of sub-attributes to product design quality attributes (Continued)

Design quality attributes	Quality sub-attributes	Definition
	Reusability	The extent to which a product or its components can be reused after disposal.
	Modifiability	The extent to which a product can be modified without introducing defects or degrading existing product quality.
Creativity (Asawa, Goto and Kanazawa, 2009; Gkantouna, Tsakalidis and Tzimas, 2016; Özcan, Cupchik and Schifferstein, 2017)	User interaction/ experience	Intangible elements of quality.
	Emotional durability	A design that people value at an emotional level such that they do not easily throw it out.

In the product design quality hierarchy, functionality provides a basis for reliability, usability, maintainability, and creativity. Although the design process is always controlled to ensure the product design quality in practice, what factors affect design quality at different quality levels and how to control them in a crowdsourcing environment have not been explored.

4.3 Research methodology

In order to identify key factors affecting product design quality and explore approaches of quality control and assurance policies, a systematic literature review was conducted.

Academic database Web of Science, ScienceDirect, ACM Digital Library, and IEEE Xplore Digital Library are used to search literature in this field. The keywords used to search articles are organized in three descriptor groups with rules listed below. Boolean operators 'AND' and 'OR' are adopted to make logical searches. R_1, R_2 and R_3 use the rule of 'OR' to represent the three descriptor groups, respectively. R_0 is the sum of R_1 and R_2 or R_1 and R_2 and R_3 with the rule 'AND'. For example, several keywords combinations, such as 'industrial product design' with 'quality control', 'conceptual design' with 'design for functionality' and 'crowdsourcing' have been examined.

- $R_1 = keywords \in (product\ design\ OR\ conceptual\ design\ OR\ detail\ design\ OR\ idea\ development\ OR\ idea\ generation\ OR\ process\ design\ OR\ idea\ prototyping\ OR\ idea\ evaluation)$
- $R_2 = keywords \in (quality\ control\ OR\ design\ for\ functionality\ OR\ design\ for\ usability\ OR\ design\ for\ reliability\ OR\ design\ for\ maintainability\ OR\ design\ for\ creativity)$
- $R_3 = keywords \in (crowdsourcing\ OR\ cloud\ OR\ cloud-based)$
- $R_0 = keywords\ \in ((R_1\ AND\ R_2)\ OR\ (R_1\ AND\ R_2\ AND\ R_3))$

As a final retrieval result, studies from six categories of resources, i.e. journal articles, conference proceedings, book sections, related webpages, standard and thesis, were found and classified. With the literature searching rules, the found studies could be classified into two categories according to the design context: the traditional design environment and the crowdsourcing context. After getting the data set, all found literature is screened manually to select out studies that are conducted at product design stages. As a result, 125 papers were selected as materials most closely related to our research objective, with 105 studies in traditional design environment and 20 in the crowdsourcing context. Since key crowdsourcing technologies for PDD regarding to organization structure, incentive mechanism, solution evaluation, workflow management and quality control have been studied (Niu and Qin, 2017; Niu *et al.*, 2019), here 20 papers (11 journal papers, 8 conference papers and 1 book section) were mentioned to analyse factors affecting product design quality in crowdsourcing context. Table 4-3 shows distribution of studies in the traditional design environment.

Table 4-3 Distribution of studies in the traditional design environment

Reference type	The number of references
Journal articles	66
Conference proceedings	17
Book sections	6
Related webpages	14
thesis	1
Standard	1
total	105

For these research papers appearing in journals and conference proceedings at product design stages in traditional environments, the TagCrowd (a data visualization tool) was applied to extract keywords distributions to find out the research focuses. During this process, the searching keywords were excluded. Figure 4-2 illustrates the top 50 words with the highest frequency. The result shows that the top-ranking keywords are management, collaborative, process, information, model, data, sharing, communication, knowledge, lifecycle, systems and conflict. Based on this result, the extracted key research focuses of controlling product design quality in traditional design environments includes the management and communication of relevant information and quality control approaches. After reading through these studies, another research focus, quality assurance policies, is found. The detailed analysis against each term is presented in the following sections.

Figure 4-2 Distribution of keywords from product design quality control studies in the traditional design environment

The keywords analysis result from the 20 papers related to crowdsourcing context is shown in Figure 4-3. The top-ranking keywords are communication, collaborative, co-creation, incentive, participation, motivation, feedback, and assessment. It is clear that the research focuses in crowdsourcing environments are crowd participation, incentive mechanisms, communication, feedback and assessment. Since the studies about these research focuses have been analysed by Niu and Qin (2017) and Niu *et al.*(2019), here we no longer describe them.

Figure 4-3 Distribution of keywords from product design quality control studies in the crowdsourcing context

4.4 Research findings

This section outlines research results of quality control studies in in-house and crowdsourcing environments, respectively.

4.4.1 Research findings of quality control studies in in-house design environments

In traditional in-house design environments, a product design task is performed by a well-designated team which consists of employees from different functional departments, such as marketing, finance and technical department (González and Palacios, 2002). During a PDD process, in addition to the design budget, the capability of employees and the tools used, many other factors, e.g., product development strategies, market orientation, technology, top management support, affect at least one attribute of product design quality (González and Palacios, 2002). For a product design team, the support of design process, team environment and other assistance like collaboration tools is to aid team members to access the required knowledge and to utilize the knowledge for product design (Qiu, Chui and Helander, 2006). The identified factors affecting product design quality are mainly from three perspectives, as shown in Figure 4-4.

In terms of the design process, the identified factors include problem scoping (Cross, 2004; Sobek and Jain, 2007), problem setting (Sobek and Jain, 2007), idea management (Sobek and Jain, 2007; Kim, 2017), engineering analysis (Sobek and Jain, 2007), design refinement (Sobek and Jain, 2007), information gathering (Atman *et al.*, 1999; Adams, Turns and Atman, 2003; Sobek and Jain, 2007), and analysis of design goal (Badke-Schaub and Frankenberger, 1999; Gerhard, Badke-Schaub and Frankenberger, 1999), etc. In terms of team management, factors like communication (Holladay, 2010), cooperation (Holladay, 2010), coordination (Holladay, 2010), work environment (Holladay, 2010), company culture (Holladay, 2010), team structure (Barczak and Wilemon, 2001; Holladay, 2010), team member satisfaction (Barczak and Wilemon, 2001), and effective leadership (Barczak and Wilemon, 2001) are identified. In the aspect of information management, factors affecting product design quality include organization culture (Holladay, 2010; Pimchangthong and Tinprapa, 2012), human resource (Pimchangthong and Tinprapa, 2012), information sharing (Pimchangthong and Tinprapa, 2012), technological infrastructure (Pimchangthong and Tinprapa, 2012), information context (Cummings and Teng, 2003), information transfer (Cummings and Teng, 2003), and information strategy (Cummings and Teng, 2003).

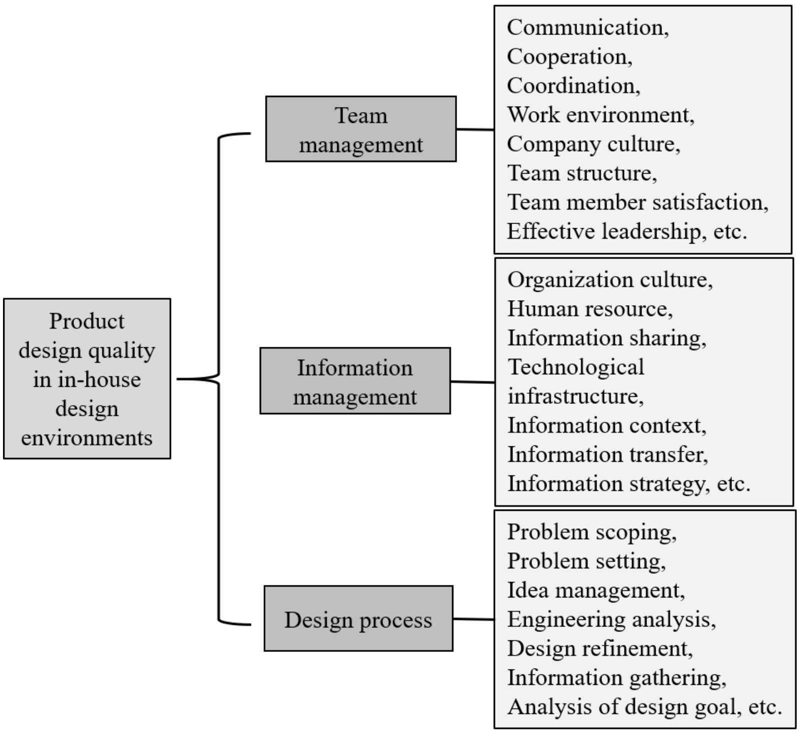


Figure 4-4 Key factors affecting product design quality in in-house design environments

Furthermore, this research explores factors affecting product design quality at different quality levels, key quality control theories/principles/methods/tools, and key quality assurance policies, which are shown in Figure 4-5. The identified factors (Esaki *et al.*, 2002; Ding, 2009; Chu *et al.*, 2010; Wallace *et al.*, 2013; Teh, Adebanjo and Ahmed, 2014; Van Der Bijl-Brouwer and Van Der Voort, 2014; Yana, Rusdhi and Wibowo, 2015; Özcan, Cupchik and Schifferstein, 2017) may affect more than one attribute of product design quality.

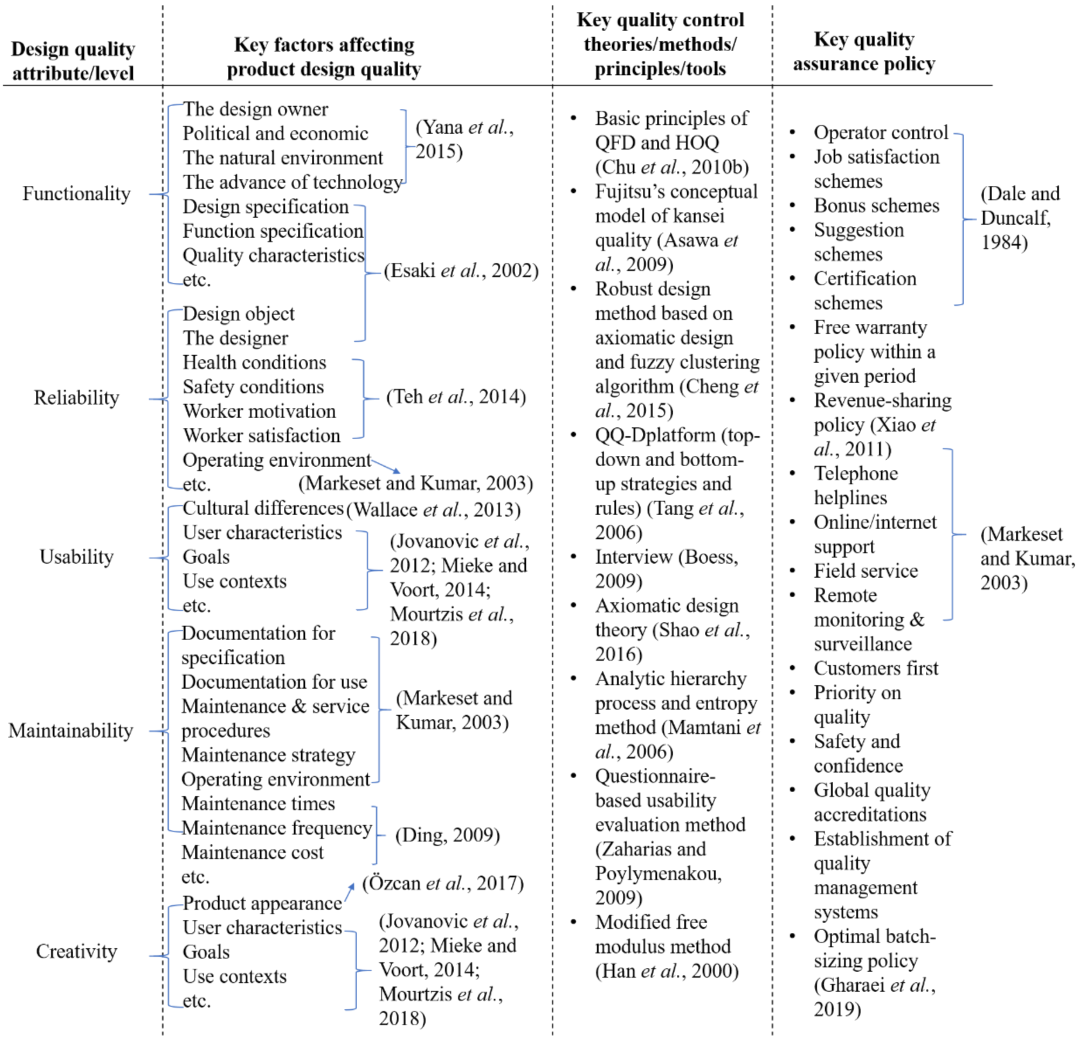


Figure 4-5 Factors affecting product design quality attributes, quality control methods, and quality assurance policies

In order to better understand how to ensure the product design quality, this research explored product design quality control theories (Shao *et al.*, 2016), approaches (Han *et al.*, 2000; Mamtani, Green and McDonald, 2006; Asawa, Goto and Kanazawa, 2009; Boess, 2009; Zaharias and Poylymenakou, 2009; Cheng, Zhang and Wang, 2015), principles (Chu *et al.*, 2010) and tools (Tang, Wang and Wang, 2007). Quality assurance is a set of policies through product lifecycle to make sure the product can systematically meet the quality standards and thus leave an impression to the customers that the provided products are reliable, durable, and dependable (Markeset and Kumar, 2003). The quality assurance policies on both supply chain (Xiao, Yang and Shen, 2011) and after-sale service (Markeset and Kumar, 2003) have an influence on final product quality. They enable the quality of products according to Plan-Do-Check-Act ethos. It is found that nearly all companies have quality assurance policies that usually exist in the form of written documents or verbal communications (Dale and Duncalf, 1984).

Based on the research focuses identified from the analysis of keywords in product design quality control studies conducted in the traditional in-house design environment, the classification of related studies according to the research focuses is shown in Figure 4-6.

Research focus	References	
• Information management • The representation of information • The quality control of gathered information • The management of conflict information	(Gao and Bernard, 2018) (Giannini *et al.,* 2002) (González-Lluch *et al.,* 2017) (Buskermolen *et al.,* 2015) (van der Lelie, 2006) (van den Hende *et al.,* 2007) (Culley *et al.,* 2005) (Awasa *et al.,* 2009) (Boess, 2009)	(Answer *et al.,* 2010) (Yagci and Das, 2018) (Ouertani, 2008) (Ouertani *et al.*, 2007) (Barclay, 1991) (Bertrand *et al.*, 2004) (Lu *et al.*, 2000) (Lara and Nof, 2003) (Ouertani and Gzara, 2008)
• Information sharing	(Zhu *et al.,* 2011) (Gao and Bernard, 2018) (Zhang *et al.,* 2004) (Yam and Chan, 2015) (Gao and Bernard, 2018) (Giannini *et al.* 2002)	(Sudarsan *et al.* 2005) (Ouertani *et al.*, 2011) (Mun *et al.*, 2009) (Lin *et al.*, 2010) (Hasby and Roller, 2016)
• Quality control approaches • Quality control models/tools • Product design optimization	(Zhang *et al.*, 2017) (Tang *et al.,* 2007) (Zhang *et al.*, 2016) (Chu *et al.,* 2010) (Awasa *et al.,* 2009) (Cheng *et al.,* 2015) (Papalambros, 2002) (Montgomery, 2020)	(Mrugalska and Tytyk, 2015) (Chen and Li, 2002) (Taguchi, 1993) (Cheng and Lin, 2014) (Liu *et al.*, 2014) (Andersson, 1997) (Wang *et al.*, 2018)
• Quality assurance policies	(Markeset and Kumar, 2003) (Xiao *et al.,* 2011) (Dale and Duncalf, 1984) (Gharaei *et al.*, 2019)	

Figure 4-6 Classification of literature in terms of research focuses

4.4.1.1 Information management

Information management is to identify, capture, evaluate, retrieve, maintain and share all of the information assets in an enterprise (Gao and Bernard, 2018). Effective information management can help the enterprise find out valuable information, thus earning more economic benefits. With the global collaboration tendency, the management of information from geographically distributed collaborative partners is particularly crucial in achieving specific market objectives (Giannini *et al.*, 2002).

In an in-house PDD process, the designers always need to communicate a subset of the design information they are working on with co-designers (Giannini *et al.*, 2002). Therefore, it is necessary to effectively and securely track, control, manage and share the rich information (González-Lluch *et al.*, 2017). Currently, the management of product design information is often achieved by PLM systems which manage cross departments information throughout the product lifecycle. However, the design information at early design stages has not been covered by PLM systems. To make the information at product design stages managed, the most important work is to identify it firstly from existing studies. after reviewing the existing literature, it is found that there are some information modelling frameworks (see Table 4-4) that have been proposed to identify and manage design information and knowledge at product design stages.

In a PDD process, the product design quality is controlled in terms of the representation of information, quality of gathered information and the management of conflict information.

Table 4-4 Product design information frameworks/models from existing literature

Framework/model	**Information managed at design stages**	**reference**
Based on CPM and its extensions (OAM, DAIM and PFEM)	Product information, design rationale, assembly and tolerance information, the evolution of products and product families.	(Sudarsan *et al.*, 2005)
Product manager	Product specific knowledge, concepts pertaining to the description of the product whose design is in charge of the node and its lower-level co-designers.	(Giannini *et al.*, 2002)
Process manager	The description of the processes: needed activities, dependencies between them, rules to follow, time schedules and constraints, planning of work, participant organization and synchronisation of all of them.	(Giannini *et al.*, 2002)
Satisfaction importance evaluation model	Personal information, product feedback, feedback on service, feedback on product modules, extra comments.	(Mourtzis *et al.*, 2018)
Cloud-based design	Product data, customer feedback, market information	(Wu *et al.*, 2015)
Product data master model	Design data, material properties, geometric and topology models, dimension information, finite element analysis and optimisation, process planning, scheduling.	(Zhang, Shen and Ghenniwa, 2004)
Quality function knowledge deployment model	Domain knowledge, design standards, design specifications, comprehensive knowledge, material, mechanical assembly, CAD technology and related design experience, the social background, technology development, production resources, schedule.	(K. Zhang *et al.*, 2016)

The representation of information

A large amount of structured and unstructured information is usually generated during a PDD process and it is often stored at designated servers for easy handling and monitoring. To help designers collaboratively work on a product design project and help users judge whether the design concept satisfies their needs and interests, a unified information representation is needed (Buskermolen *et al.*, 2015). The dimensions of product design information are: Formal vs. Tacit, Product vs. Process, and Compiled vs. Dynamic (Table 4-5).

Table 4-5 The dimensions of product design information

Dimension	**Explanation**
Formal	Embedded in product documents, repositories, product function and structure description, problem solving routines, technical and management systems, computer algorithms, expert knowledge systems, etc.
Tacit	Tied to experiences, intuition, unarticulated models or implicit rules of thumb.
Product	Includes requirements, various kinds of relationships between parts and assemblies, geometry, functions, behaviour, various constraints associated with products, and design rationale.
Process	Design process knowledge refers to design methods in representing designs, providing mechanisms for realizing design details.
Compiled	Gained from experience that can be compiled onto rules, plans or scripts, cases of previously solved problems, etc.
Dynamic	Qualitative and quantitative knowledge. Qualitative knowledge consists of common-sense reasoning, approximate theories, causal models of processes, general problem-solving knowledge, etc. Quantitative knowledge consists of constitutive, compatibility, equilibrium equations, numerical techniques, closed form equations, etc.

The most common and classical representation of design concept is storyboard. Such a representation usually consists of a sequence of sketchy pictures with captions (Van Der Lelie, 2006). Storyboard is effective in communicating the role that the design would have in the lives of people. Another typical representation of design concept is prototype, which helps minimise design errors that may occur in the design process. Prototypes often help designers identify design issues and learn from failures and they support both design concepts evaluation and design exploration (Lim, Stolterman and Tenenberg, 2008; Deininger *et al.*, 2017). Feedback elicited from prototypes often frames subsequent actions around the existing design solution (Dow, 2011). However, new technologies, such as virtual reality, make it possible for designers to create more advanced representations through utilizing animations and videos, even early in the design process. These media integrate sounds, motion and light effects into the representation to enable an immersive feeling that is an important element of good interaction design (Buskermolen *et al.*, 2015).

In the exploration of different representations on users' responses to early design concepts, the representation format of design concepts does not have significant effects on perception and comprehension of concept, but it has distinctive effects on absorbing the participants in the narrative world (Van Den Hende *et al.*, 2007). After analysing the effects of visual quality and animation of concept representation on users' responses to early design concepts, Buskermolen *et al*. (2015) suggested that sketchy representations provided more elaborate feedback and suggestions grounded on past experience while visually refined representations were more helpful in eliciting definite judgements.

Quality control of gathered information

In a PDD process, the gathered information has many formats, like document, dialog, audio and video. To quantify the quality of a document, a comprehensive list of 94 information assessment criteria has been proposed (Culley *et al.*, 2005). In addition to document format, information in other formats, such as web reviews and user feedback, also needs to be measured. User feedback is an important part in a PDD process for promoting the improvement of product design concepts. Therefore, this part mainly concerns the measures to enable feedback quality.

User feedback can be gathered through on-site observations, questionnaires and interviews (Asawa, Goto and Kanazawa, 2009) and its quality relies on the gathering criteria and process, the reliability of participants, and information quality checks, etc.

Boess *et al.* (2009) found that how people use products is quite different from the expectations of designers, so the users need to be involved into the design process. Their feedback is potentially valuable for designers. Additionally, user review is an important part of information at product design stages. Both the designers and manufacturers should pay attention to these reviews as they contain information about product and service experience, and they have an influence on making buyers' purchase decisions (Anwer, Rashid and Hassan, 2010). The potentially valuable reviews help designers identify customer likes, dislikes and desires. To evaluate the content, complexity and relevancy of the product-related reviews, a design-level information quality measure was introduced which regarded the number of reviews, sentences, words, noun words and feature matching noun words in a review database as key determinants in measuring information quality (Yagci and Das, 2018).

The management of conflict information

A final product design is a compromised result of various constraints such as functional requirements and geometrical, behavioural and structural features (Ouertani, 2008). The common types of conflict identified in product design are a) imagined or perceived conflict; b) latent or substantive conflict; c) affective conflict (Barclay, 1991). All these conflict types are accompanied by process-related conflicts. With better understanding of the conflict types and causes that lead to conflicts, the management of them can make the outcomes of conflicts constructive.

The conflicts can be controlled by the five-phase process: conflict detection, forming the conflict resolution team, negotiation management, solution generation, and solution impact evaluation (Ouertani, Gzara and Ris, 2007; Ouertani, 2008). The proposed methods for conflicts management are mainly around conflict detection (Lu *et al.*, 2000; Bertrand, Gzara and Lombard, 2004), the conflict resolution (Lara and Nof, 2003), the conflict negotiation process (Ouertani, Gzara and Ris, 2007; Ouertani and Gzara, 2008). To assess the impact of a selected solution on the product as well as on the design process organization, Quertani (2008) proposed a process organization framework based on data dependencies network.

4.4.1.2 Information sharing

In a PDD process, the collaboration among participants with different professional knowledge backgrounds is a key to enhance competitiveness (Yam and Chan, 2015) and to improve product quality (Zhu *et al.*, 2011). The foundation for product design collaboration is information communication and sharing which disseminate information within a community (Zhang, Shen and Ghenniwa, 2004; Gao and Bernard, 2018). Effective information sharing drives organizational and individual learning, which in turn speeds up and improves the quality of product.

Information sharing is effective in helping individuals, teams and organizations improve their work performance (Cummings, 2004) and shorten the time to market (Gao and Bernard, 2018), giving the enterprise an edge in the fierce competition. In order to help designers work together effectively, certain measures must be adopted to enable the exchange of design information. ISO 10303 has provided an ISO standard for the computer-interpretable representation and exchange of product manufacturing information. However, there is still no similar standard for the exchange of product information at product design stages.

The design-related and process-related information in a PDD process can be classified into two categories: public and exchanged information (Giannini *et al.*, 2002). Public information describes and indicates the main characteristics of the product and can be treated as a set of technical requirements, to which all participants involved in the process can get access. While the exchanged information can only be seen by certain participants and their versions depending on the sender, e.g., customer, co-designer or supplier, and the states of the project development. In information sharing, only exchanged information is considered.

Based on collected product and process information, proper information sharing and communication mechanisms enable designers and their partners to collaborate effectively, which is a critical determinant of collaboration (Sudarsan *et al.*, 2005; Ouertani *et al.*, 2011). The main contents of communications are the product data and the process data (Giannini *et al.*, 2002). In traditional collaborative design scenarios, the designers usually have to spend much time on communicating with their partners through emails or phones. As for the design-related data stored at designated servers, they have to be authorised to have access to them. Data access mechanisms from the perspective of functional views, personal workspace, worktable, and personal storage space have been proposed by Zhang *et al.* (2006) and access to data is authorised according to the user role. However, the proposed product model can only support static product information, which cannot satisfy the needs of real-time collaborative design. As for the systems where all design information is public, the protection of IP is threatened (Mun, Hwang and Han, 2009). A suggested solution for this is sharing the essential data with collaboration partners only (Mun, Hwang and Han, 2009).

In practice, information sharing is usually achieved through various design representations with different formats like 3D models, images, videos, and extensible markup language (XML) files (Lin, Chen and Lai, 2010). One problem that needs to be considered in this process is that the users should exchange their ideas as instantly as possible. Therefore, a CAD system facilitating the conceptual embodiment design stage in a collaborative manager is proposed (Hasby and Roller, 2016), where designers can communicate their opinions and ideas freely. To avoid the possibility of losing information, the system should create a list of changes that the user has made and notify relevant users to update information in their sides automatically.

4.4.1.3 Quality control approaches

Quality control models/tools

Quality control is an activity throughout the whole product design and development process, aiming to satisfy the customer needs as well as to decrease the design and development cost in terms of time and money (Zhang *et al.*, 2017). In this process, customer requirements and PDS are benchmarks of the controlled quality of product design (Tang, Wang and Wang, 2007). To control the quality of product design, many researchers linked customer requirements with quality characteristics. For example, Tang *et al.* (2007) have argued that quality characteristics are the key control factors in the whole PDD process and the focus of quality control is on how to translate customer requirements into product quality characteristics. Similarly, a vector-based mapping tool that can provide reasonable mapping among PDS, behaviour parameters and structure parameters has been proposed by Zhang *et al.* (2016). Chu *et al.* (2010) converted user requirements into the relevant technical requirements of design using Quality Function Deployment (QFD) and House of Quality (HOQ).

Although customer requirements provide benchmarks for the designated product, one problem that cannot be neglected is that customer requirements change over time. In order to understand how requirement changes propagate in the design of complex product systems thus to help select best options to guide design, Zhang *et al.* (2017) proposed a PDS-Behaviour-Structure-based design change model that can systematically analyse and search change propagation paths.

The quality control models can be classified into computer-oriented and human-oriented. Among computer-oriented quality control models, Tang *et al.* (2007) translated customer requirements into product quality characteristics and achieved their quality control aim by controlling these quality characteristics. Wang *et al.* (2018) proposed a deep convolutional neural network to detect defects by visual means, thus to ensure the product quality. As for human-oriented quality control models, a typical one is Fujitsu’s conceptual model of kansei quality (Asawa, Goto and Kanazawa, 2009). The model has six elements: product/service usage situations, stimuli produced in usage situation, somatic sensations (perception/cognition), personality and past experience, impressions/emotions, and behaviour (Asawa, Goto and Kanazawa, 2009). The somatic sensations are the contact point between the user and the outside world. These elements are controlled in the Plan-Do-Check-Act cycle.

Product design optimisation

During a PDD process, the initial design may be functional, but it may be far from optimal in terms of quality and cost (Cheng, Zhang and Wang, 2015). Hence, it is necessary to optimise the initial product design to make it better meet the design requirements. The aim of design optimisation is to make the product design as robust as possible. To achieve this goal, different sources of uncertainties and variations in design and manufacturing process, such as model uncertainty, parameters uncertainty and noise, should be taken into consideration (Mrugalska and Tytyk, 2015).

Design optimisation is effective in improving the product quality through minimising the effect of the causes of variation (Cheng, Zhang and Wang, 2015). The optimisation involves product design optimisation and design process optimisation. Product design optimisation means improving the design in terms of one or more performance aspects of a specific type of products (Papalambros, 2002), while design process optimisation could benefit nearly all corresponding product designs produced by adopting the optimised design process.

When a product design is finished, it is expected to maximise performance as well as be less sensitive to variation such as environmental changes in practical situations (Cheng, Zhang and Wang, 2015; Mrugalska and Tytyk, 2015). Design optimisation is usually achieved by mathematical optimisation techniques (Papalambros, 2002). The mathematical model allows to choose the optimal values of parameters of the model that accurately reflect customers' expectations (Mrugalska and Tytyk, 2015). In the mathematical model, experiments based on fractional factorial designs and orthogonal arrays can be applied to improve it. However, there are still some challenges in design optimisation, such as mathematical challenges, topologies and configurations, systems design, controlled artefacts, and enterprise-wide design (Papalambros, 2002).

To optimise design process, a computerized team approach was proposed where design teams were treated as game players in a multi-player game and different types of team interactions were classified from the perspective of game theory (Chen and Li, 2002). Differently, the product design process was divided into three stages: system design, parameter design and tolerance design and the design focuses are basic functional prototype design, the control of parameters to make the design insensitive to variations, and the upper limit of the number of variation or noise factors allowed in the design, respectively (Taguchi, 1993). Compared to research work in system design, more work is conducted in parameter design and tolerance design (Cheng, Zhang and Wang, 2015). the deviations of design parameters were considered in sensitivity analysis and robust optimisation design of suspension system so that the system would have better performance (Cheng and Lin, 2014). In product redesign process, goal programming approach was utilized to incorporate analytic network process and cost budget limitation to determine the variant components (Liu, Hsiao and Hsiao, 2014). However, system design determines the attainable level of product robustness in the parameter stage (Andersson, 1997). Due to the importance of system design, a frame on the basis of system modelling, cluster analysis and design of experiments for the development of robust system is proposed (Cheng, Zhang and Wang, 2015).

4.4.1.4 Quality assurance policies

To enhance customer satisfaction, enterprises/organizations usually strategically adopt quality management systems through the product lifecycle to offer customers with products and services that fully comply with customer, statutory and regulatory requirements. The quality management system establishes a list of quality policies that provide frameworks for establishing and reviewing quality objectives, making offered products/services comply with customer requirements and continually improving the effectiveness of the quality management system. There are usually national quality standards for quality management systems for organizations in a particular industry. For example, AS/EN 9100 is the core international standard in the aerospace and defence industries for standardizing process-based quality management system requirements, which can be used at all levels of the supply chain by organizations. The international standard can be used to assess the organization's ability to meet customer, statutory and regulatory requirements applicable to the product.

According to AS/EN 9100, the design and implementation of an enterprise's quality management system is influenced by many factors, such as its organizational environment, changes and risks in that environment, its varying needs, its particular objectives, and the products it offers, etc. Most of the existing enterprises have their quality assurance departments to ensure the quality of their products and they have their own product or service quality rules, such as customer first, priority on quality, safety and confidence and global quality accreditations. These quality rules/policies are usually in the form of written documents and statements that are communicated and understood within the enterprise and are reviewed for continuing suitability.

In addition, some enterprises utilize verbal communications via the management structure to communicate quality policy information as well. The attainment level of quality objectives relies on constant examination, improvement and effective communications and the way of quality assurance policies affects the communications and decision-making processes (Dale and Duncalf, 1984). In order to obtain the correct quality products, all participants in the production process should be well controlled and should be motivated into the process. Therefore, operator control method can be combined with job satisfaction schemes, bonus schemes, suggestion schemes and certification schemes in production (Dale and Duncalf, 1984).

The attainment of the desired quality level also relies on its suppliers (Dale and Duncalf, 1984; Xiao, Yang and Shen, 2011). How an enterprise coordinates the supply chain with a quality assurance policy via a revenue-sharing contract was investigated in the game theoretic model and it was found that the optimal service quality first decreased and then increased as the defective rate of the final product increased (Xiao, Yang and Shen, 2011). Additional, optimal batch-sizing policy (Gharaei, Karimi and Shekarabi, 2019) in an integrated multiproduct constrained supply chain was also proposed. After the product is launched on the market, the enterprise will have telephone helplines, online/Internet support or field service for helping customers solve problems in place (Markeset and Kumar, 2003). In addition, many databases and information systems will be utilized to manage customer feedback, complaints, and product problem resolution for future improvement of corresponding products.

4.4.2 Research findings of quality control studies in crowdsourcing environments

To overcome the shortcomings of enterprises especially SMEs in employees and resources, sometimes in budget in traditional in-house design environments, enterprises tend to apply crowdsourcing into their PDD practice. During this process, the additional factors affecting product design quality have been identified. Although there are many factors affecting product design quality along key elements of a crowdsourcing process, they can be classified into the three factor categories identified in Figure 4-4. Figure 4-7 shows key factors affecting product design quality in each dimension along the traditional in-house design environment and the crowdsourcing design environment.

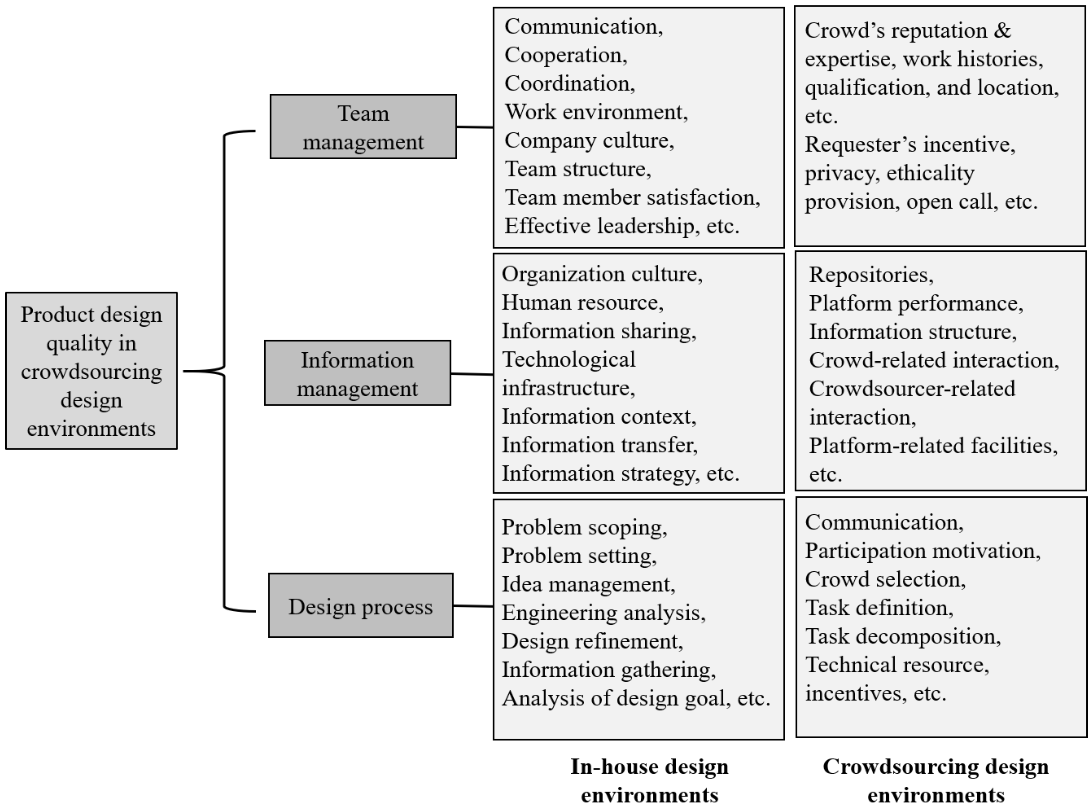


Figure 4-7 Key factors affecting product design quality in crowdsourcing design environments

The factors along the key elements of a crowdsourcing process can be explained as:

- Crowds. One of the key elements of a crowdsourcing process. It is extended from the traditional design team, so it can be treated as a virtual team. In traditional design environments, the capability of their employees is well mastered by the team leader. Thus, the team leader can assign a task to the most right individual/design team. While in crowdsourcing contexts, the truthfulness and reliability of the information provided by the crowds are usually doubtful. Before assigning the task to right crowds, the information must be verified.

- Requester. Another key element of a crowdsourcing process. The requester is responsible for proposing task requirements, incentives, timelines, etc.
- Task. The task is proposed by the requester and crowds perform it to achieve expected outcomes. In order to better assign the task to crowds, it usually needs to be decomposed either by the requester or by the crowdsourcing platform runner.
- Platform. The crowdsourcing platform is a workplace which provides interfaces for its users including the crowds and the requester to interact with it. All information related to design process, information management, task, the requester and the crowds are controlled by the crowdsourcing platform.
- Design process. In the crowdsourcing context, the product design process is controlled by the crowdsourcing platform. The process consists of many sub-processes, such as task decomposition, task assignment, the selection of crowds, and the synthesis of task results, etc. In order to ensure the collaboration of crowds, the process should have the capability to involve enough qualitied crowds by participation motivations and proper selection rules and support the communication among them (Florian *et al.*, 2018).

More factors affecting product design quality in terms of key elements of crowdsourcing process are shown in Table 4-6.

Table 4-6 Key factors affecting product design quality in terms of key elements of a crowdsourcing process

Key elements of crowdsourcing process	**Factors affecting design quality**
Requester (Hosseini *et al.*, 2014)	Incentive provisions, open call, ethicality provision, privacy provision.
Platform (Hosseini *et al.*, 2014)	Crowd-related interaction, crowdsourcer-related interaction, task-related facilities, platform-related facilities.
Crowds (Allahbakhsh *et al.*, 2013; Finnerty *et al.*, 2013; Hosseini *et al.*, 2014; Yu *et al.*, 2014)	Reputation and expertise, instruction and user interface, user identity, nationality, qualification, job title, entry date, department, location, accomplishment, diversity, unknown-ness, largeness, undefined-ness, suitability, social, learning, financial.
Task (Allahbakhsh *et al.*, 2013; Finnerty *et al.*, 2013; Hosseini *et al.*, 2014)	Task definition, user interface, granularity, and incentives and compensation policy, instruction, task description, target audience, complexity, type of action, modularization, nature of the reward, type of the reward, latency, submission time, closure time, duration, visibility, confidentiality, human requirement, technical resource.

Quality control studies in terms of crowds, platform, task, and workflow, will be explored in Chapter 5. Here, this research mainly compares in-house and crowdsourcing design environments in terms of the key aspects affecting product design quality, which is shown in Table 4-7.

Table 4-7 Comparison of in-house and crowdsourcing design environments

Comparison item	**Traditional design environment**	**Crowdsourcing context**
Design process	Controlled by team leader	Controlled by the requester and platform
Team management	Controlled by team leader	Controlled by the platform
Information management	Documents, videos, etc.	Database
The number of participants	Limited	Unlimited
The qualification of participants	Known	Unknown
Incentive mechanism	Bonus, team building activities, etc.	Reward, enjoyment, reputation, etc.
Organization structure of participants	Hierarchical structure and cross-functional organization structure	Hierarchical structure
Task description	Team members can discuss to better understand it	The crowd can interpret it by himself/herself or discuss it with other crowds through communication tools
Task decomposition	Performed by team leader	Performed by the requester or the platform
Task assignment	Assigned by the team leader	Calculated by the platform
Communication	Regular meeting, workshop	Forum, social medium, and related tools provided by the platform

In crowdsourcing environment, the design process, team management, and information management are controlled by the crowdsourcing platform. Currently, the crowdsourcing platform can only partly support PDD process, and the existing studies on product design quality control is relatively less. Daniel *et al*. (2018) analysed the quality attributes, assessment techniques, and assurance policies, and controlled the design quality from the view of individual, group and computation. And a technical survey on statistical modelling and design methods for crowdsourcing quality control has been conducted Jin *et al.* (2020), providing systematic technical insights to a wide variety of quality control methods. Differently from treating quality control as an additional procedure in crowdsourcing, Hu *et al.* (2020) tried to embed sequential zero-determinant strategies into the crowdsourcing process, thus to achieve the aim of quality control. Although there are already many studies focusing on controlling quality in crowdsourcing design environments, the factors affecting quality in such an environment have not been modelled semantically by existing information models.

As for the crowdsourcing quality assurance policies, Daniel *et al.* (2018) identified 6 strategies: (1) improve data quality; (2) select people; (3) incentivize people using extrinsic and intrinsic motivations; (4) train people; (5) improve task design; (6) control execution. In addition, some assessment measures have positive side effects on quality, especially when the assessment objects are people. For example, reviews have can improve the performance of both crowds and reviewers (Zhu *et al.*, 2014). And rating the performance of crowds has similar positive side effects (Dow *et al.*, 2012). To ensure the product design quality in crowdsourcing environments, the quality control approaches and assurance policies in both in-house and crowdsourcing environments should be considered when crowdsourcing PDD activities. The existing quality control approaches and assurance policies in crowdsourcing environments are summarized in Table 4-8.

Table 4-8 Quality control approaches and quality assurance policies in crowdsourcing environments

Assessment perspective	Quality control approaches	Quality assurance policies
Individual	Rating, qualification test, self-assessment, personality test, referrals, expert review, usability check, etc.	Improve data quality, select people, incentivize people, train people, improve task design, control execution, etc.
Group	Voting, group consensus, output agreement, peer review, feedback aggregation, user study, etc.	
Computation	Ground truth, outlier analysis, finger printing, achievements, implicit feedback, association analysis, content analysis, transfer learning, collusion detection, etc.	

4.5 The quality control challenges on a crowdsourcing platform for PDD

Although crowdsourcing has widely been applied to achieve specific goals, such as to increase customer engagement and to choose better design ideas, there are still some challenges on ensuring the quality of generated ideas and solutions on a crowdsourcing platform. From the perspective of quality control, the possible challenges include:

- The management of information. On a crowdsourcing platform, there are more participants in the product design project than in conventional settings. The participants are globally distributed and have various cultural background and different levels of expertise, which may lead to more product design conflicts.
- The representation of product design. On the crowdsourcing platform, the participants have various levels of design capabilities and they may not know how to present their designs as expected.

- The communication among designers. Effective communication plays an important role on improving product design quality, which can help designers have a better understanding of design requirements and work done by their colleagues.
- The protection of intellectual property. To support the collaboration of crowds, the platform has to support information sharing and communication. Since crowdsourcing process is open to the crowds registered on the platform, the intellectual property protection faces more risks than in traditional environment.

Targeting at the identified challenges, the requirements for developing a crowdsourcing platform for PDD were indicated:

- The platform should be cloud-based. With the support of cloud technology, the distributed participants of product design process can easily get access to product and process related information to effectively perform design activities.
- The platform should provide a presentation tool to guide designers to present their designs and other users can pose queries about the design such as rationale and purpose, or the causality between physical and functional elements.
- The platform should provide APIs to common social media to make users easier access to the platform with their social media account and it may provide a way to evaluate the reliability and work quality of a user by analysing his/her previous behaviours. This feature may not be implemented currently, but it needs to be supported in the near future.

- The platform should be integrated with blockchain technology to support the encrypted transmission of information.

4.6 Conclusion

This chapter conducts a systematic literature review of quality control studies in both in-house and crowdsourcing design environments. In order to better understand key factors affecting product design quality, this research first gives a definition of product design quality and identifies its key attributes and sub-attributes. Then TagCrowd is adopted to analyse the keywords to find out the research focused in these two design environments. In the in-house design environment, the research focuses include information management, information sharing, quality control approaches and quality assurance policies. In crowdsourcing design environments, this research mainly analyses the key factors affecting product design quality, compares these two design environments and discusses quality control and assurance policies. Finally, four product design quality control challenges on a crowdsourcing platform were identified, indicating the development requirements for a crowdsourcing PDD platform. This chapter lays the foundation for developing crowdsourcing PDD platforms in terms of the definition of product design quality, key factors affecting product design quality, and measures for controlling and ensuring product design quality. The identified factors should be modelled by the information model that forms the basis for a crowdsourcing platform.

The development of such a crowdsourcing platform for PDD requires the support of crowdsourcing technologies. Therefore, next chapter will focus on key crowdsourcing technologies which are closely related to the quality control of crowdsourcing PDD.

The research in this chapter has led to the following peer-reviewed publication:

Niu, Xiaojing, Qin, Shengfeng, Zhang, Haizhu, Wang, Meili and Wong, Rose (2018) Exploring product design quality control and assurance under both traditional and crowdsourcing-based design environments. Advances in Mechanical Engineering, 10(12). pp. 1-23.

Chapter 5 Crowdsourcing technologies for PDD

5.1 Introduction

The previous chapter investigates product design quality control mechanism in terms of key factors affecting product design quality, quality control approaches and assurance policies, which lays the theoretical foundation for the feasibility investigation of crowdsourcing PDD for manufacturing. This chapter focuses on the Objective 2 exploring the technical foundation for crowdsourcing PDD. Specifically, it aims to investigate '*Are there proper technologies to enable crowdsourcing PDD process in order to have guaranteed product design quality?*'

With the wide application of crowdsourcing, it has been studied from various perspectives, such as crowdsourcing models (Zhao and Zhu, 2014; Evans *et al.*, 2016), human resource management (Buettner, 2015), components and functions (Hetmank, 2013), barriers and opportunities for new product development (Qin *et al.*, 2016), etc. However, little has focused on implementing a crowdsourcing platform for PDD from the technical perspective. To explore crowdsourcing technologies for PDD, this research defined it from four aspects, i.e., techniques, frameworks, platforms, and tools that are used to accomplish a crowdsourcing task (Figure 5-1). Since existing crowdsourcing platforms have been analysed in Section 2.4.2, here this research mainly focuses on techniques, frameworks, and tools.

This chapter is structured as follows. Section 5.2 presents the research methodology used in this chapter. The crowdsourcing technologies for general tasks and PDD activities are summarized in Section 5.3 and 5.4, respectively. Section 5.5 concludes this chapter.

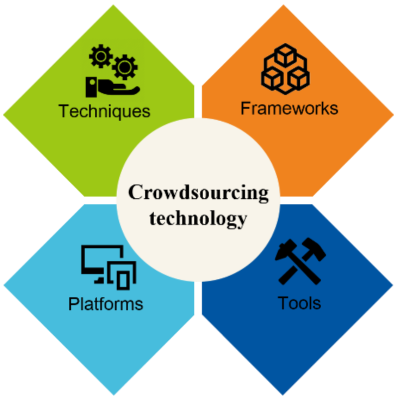


Figure 5-1 Crowdsourcing technology structure

5.2 Research methodology

Similar to Chapter 4, a systematic literature review was conducted to search literature related to crowdsourcing technology.

The literatures are from conference proceedings, journal articles, posters, design magazines and crowdsourcing websites. The online database of ScienceDirect, ACM Digital Library, IEEE Xplore Digital Library are used as database sources. In this chapter, boolean operator 'OR' and 'AND' are adopted to manage searching rules. R and S represent the two descriptor groups respectively with the rule of 'OR'. Q is the sum of R and S with rule 'AND'.

- $R = keywords \in (crowdsourcing\ OR\ crowdwork\ OR\ crowd\ work\ OR\ the\ crowd)$
- $S = keywords \in (task\ assiganment\ OR\ incentive\ OR\ motivation\ OR\ communication\ OR\ Collaboration\ OR\ workflow\ OR\ quality\ control)$
- $P = keywords \in (product\ design\ OR\ product\ development)$
- $Q = keywords \in ((R\ AND\ S) OR (R\ AND\ S\ AND\ P))$

After retrieval, more than 100 papers were found. Then their abstracts were read and those that were believed to be more related to the research content were filtered out. As a result, a number of 59 literatures are considered as the most valuable sources.

5.3 Crowdsourcing technologies for general tasks

5.3.1 General crowdsourcing framework

Crowdsourcing framework is linked to the utilization form (e.g., micro task, contest, and macro task) of crowdsourcing. Inspired by the crowdsourcing framework proposed by Kittur *et al.* (2013) for micro tasks, this research proposed a general crowdsourcing framework (Figure 5-2) regardless of the crowdsourcing forms.

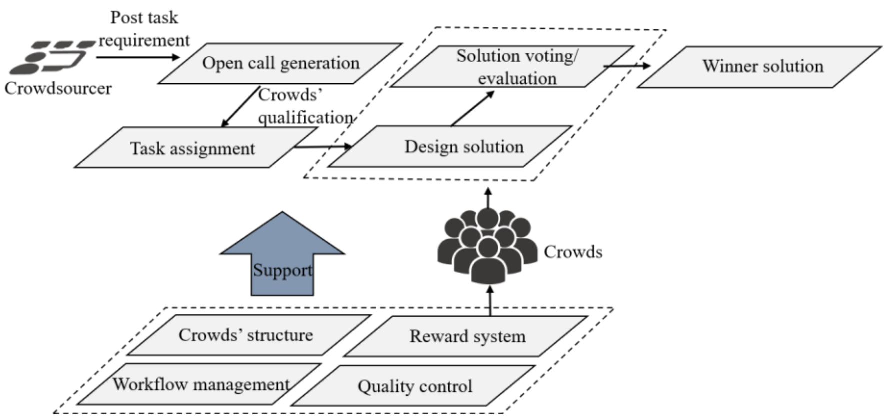


Figure 5-2 Crowdsourcing framework for general tasks

In the crowdsourcing process, the general task is usually performed by individual crowd as the task is simple enough for individuals to tackle. As for complex task, the crowds may need to build his/her own team as in conventional setting. When they finish the task, they can submit their results/contributions to the platform for later evaluation. The output evaluation here is relatively simple, as the selection of winner solution is achieved by the voting of crowds. For some tasks, the solution is assessed by a group of experts as in traditional way, for example, the innovation process of Jovoto.

In Figure 5-2, the techniques mentioned are call generation, rewarding, crowd qualification for working, the organization structure of crowds, solution evaluation, workflow and quality control, which will be explained in the next section.

5.3.2 Crowdsourcing techniques

In crowdsourcing scenarios, decomposing a task into subtasks is a key to enable the task to be completed in a timely manner by parallelly performing subtasks. However, how to decompose a task into subtasks and manage those subtasks is a challenging problem, especially for complex and interdependent tasks (Kittur *et al.*, 2011; Jiang, Zuo and Matsubara, 2020). Here, this research assumes that the tasks to be crowdsourced have been decomposed into subtasks and each subtask is the smallest unit for crowdsourcing. The following analysis of crowdsourcing techniques is based on this assumption.

5.3.2.1 Call/brief generation techniques

Call generation is the first step of a crowdsourcing process. Clear instructions in the call will provide larger possibility of receiving high-quality responses from the crowds (Kittur *et al.*, 2013). Currently, there is no related research focusing on the generation of a good open crowdsourcing call. But how to prioritise engineering characteristics for quality function development (Jin, Ji and Liu, 2014) and a quantitative method for requirements development using quality loss function (Pedersen, Christensen and Howard, 2016) have been investigated.

To fill in this gap, this research analysed 14 open call documents collected from OpenIDEO, herox, challenge.gov, devpost.com, and 5 from Northumbria Design School. As a result, 8 key elements of an open call were extracted. The open call structure is shown in Table 5-1.

Table 5-1 Key elements of an open task call (Niu et al., 2019)

Element	Explanation
Call description	Explains the task background and the goals of the task. When the task is related to a specific product or component, it should explain the features and functionality and how they affect the task goals.
Timeline	Lists the duration of each phase and incorporates with the crowdsourcing process.
Submission requirements	Tells the crowds which format of submission is acceptable. It may include prototype or demonstration video, related text description, image and video requirements, language requirements, intellectual property, financial or preferential support, etc.
Judging and prizes	Eligible submissions will be evaluated by a panel of selected judges. The judging criteria may not apply to every prize. Each prize has its own judging criteria that are more specific and concrete.
Criteria and disqualifications	The description of criteria could be derived from goals for the challenge and the target customer group. It may include three parts: what type of ideas are they looking for, what stage of ideas are they looking for and evaluation criteria. For a specific product or component, the criteria may be in terms of the following aspects: 1) UX and design appeal, including the degree to which the design reinvents the user experience – focusing on utility, usability, intuitiveness, and design appeal; 2) Effectiveness and efficiency; 3) Functional properties, emotional and experiential qualities; 4) Aesthetics, and practicality, etc.
Crowd qualification requirement	Tells the crowds who can participate in the task (participation eligibility) and how to get involved.
Rules and regulations	Includes goals for the task, resources to spur ideas and other additional information, such as reference.
About the sponsor	Tells if the crowdsourced task is sponsored and who is the sponsor.

On existing crowdsourcing platforms, the open call is generated in an interactive way of answering pre-set questions. When generating a call, not all the 8 elements are required. For instance, when the task is open to all crowds, the crowd qualification requirements are not necessary.

5.3.2.2 Incentive mechanism techniques

Incentive mechanism motivates crowds to get involved in performing the crowdsourced task. Since the existing crowdsourcing platforms are typically open to the public and do not rely on contracts, certain measures must be adopted to compel crowds to participate in the task; otherwise, they cannot be performed. The ways to attract crowds could be categorised into two distinct categories: extrinsic (e.g. reward, building of their personal reputation, etc.) and intrinsic (e.g. enjoyment, being part of the common good, etc.) (Simula and Ahola, 2014).

Reward, enjoyment, and reputation are three main incentives adopted by a crowdsourcing platform. According to the type of a crowdsourced task, the platform can adopt more than one incentive.

5.3.2.3 Crowds' qualification techniques

Different crowdsourced tasks have different skill and qualification requirements to their participants, such as open to all, reputation-based and credential-based. Therefore, the evaluation of crowds' qualification is vital for a crowdsourcing platform to ensure the crowds' quality. To assess a crowd's quality, gold data were integrated seamlessly to learn the quality of crowds when the crowds are asked to answer a multiple choice question to complete a task (Ipeirotis, Provost and Wang, 2010).

Existing crowdsourcing platforms rely on the crowds to fill in their profiles, leading to a possibility of mismatching to their actual qualifications. To avoid such cheating behaviours, the most often adopted measure is verification questions (gold questions)

(Chang and Chen, 2015; Bragg, Mausam and Weld, 2016) that are inserted to test the performance of crowds, especially when crowdsourcing micro tasks.

Besides cheating behaviours, some crowds do not perform the task carefully as a result of poor platform control on the submissions. To ensure the quality of work submitted by crowds, worker agreement is usually signed before participating in the task. This measure is adopted by most of the crowdsourcing platforms, but it works little on the final output. A promising approach for ensuring the reliability of submissions is to recommend crowds which have strong points in desired skills and capabilities. Although this method is powerful, the cold-start question (Sedhain *et al.*, 2014) that is common in recommender system cannot be neglected.

5.3.2.4 Task assignment techniques

The aim of task assignment is to assign the requested tasks to suitable crowds on the platform to get tasks finished within a fixed time and budget. In a formalised task assignment problem, the requester owns a fixed set of tasks of different types and a budget that specifies how many crowds are required and how soon the requester would like the task to be accomplished. Before assigning the task, many matches about reputations and interests will be carried out to guarantee that all employed crowd workers have the potential to accomplish the tasks with high quality.

There are two different assignment types: worker-selected and server-assigned. In worker selected-task mode, the server publishes tasks and it is totally the crowd's call to choose any tasks they are interested in. One drawback of this mode is that the server does not have control over the allocation of tasks, which may cause some tasks not to be assigned while others do. Differently, in server assigned task mode, the task is totally assigned by the server according to certain rules. This mode has a global picture of the tasks. Here are three basic algorithms that are used to assign tasks in the server assigned task mode: Greedy algorithm (Gao *et al.*, 2020), online primal dual framework (Ho and Vaughan, 2012) and least popular priority (To, Shahabi and Kazemi, 2015). More studies about task assignment can be found in Niu and Qin (2017).

5.3.2.5 Crowds' structure techniques

In crowdsourcing environments, hierarchy structure is the most popular organization structure. Since the crowds have various professional skills and experience, they are good at in one or some specific domains, but not in others. As a result, they play different roles in different crowdsourcing tasks. In a hierarchy structure with many layers, the position of a crowd depends on his/her capability. The hierarchy structure is more suitable for performing micro tasks. The crowds at the lowest level perform subtasks with the smallest granularity, while those at higher level integrate the results submitted by the crowds at the lower layer.

As for tasks that are not easy to be decomposed, the hierarchy structure is useless as all employees work collaboratively targeted at the same goal and their work may have dependency to others. Taking software design and development consisting of various functional modules as an example, the task of software design and development is a micro task on the whole, but when focusing on the lowest level of decomposition (module), it is a macro task, as each module is still complex and cannot be decomposed anymore, which will be realized by the collaboration of a group of individuals with various specialities. In this occasion, a team structure with different expertise should be more effective and efficient. Thus, the traditional team structure can be applied in the virtual environment if it can be well organized and controlled.

5.3.2.6 Solution evaluation techniques

Solution evaluation reduces the volume of the alternative solutions effectively (Pedersen *et al.*, 2013). The evaluation methods on existing crowdsourcing platforms include crowd voting and assessment of a group of experts or the combination of these two methods. However, these methods are insufficient when the volume and complexity of submitted solutions increase rapidly. In this case, text mining approaches (Wang, Liu and Fan, 2011; Walter and Back, 2013) are usually adopted.

5.3.2.7 Workflow management techniques

Enabling more complex workflows on a crowdsourcing platform can result in large differences in output quality even with small differences in rewards and task order (Kittur, Chi and Suh, 2008; Shaw, Horton and Chen, 2011). Workflow management involves where the data come from and where they go, as well as the integration of data steams coming from various sources. It is affected by many factors, such as the organization structure of crowds, the volume of submitted solutions and task integration mechanism (Pedersen *et al.*, 2013).

Generally, the structured workflow (Xu *et al.*, 2015) is usually used to provide interpretative and diverse feedback. Additionally, decision theory was used to model the iterative workflows and define equations that govern the various steps of the crowdsourcing process (Dai and Weld, 2010). Kittur *et al.* (2013) indicated that existing workflows should be improved on a large space of parameters, instructions, incentives, and decompositions so that they can be able to support the execution of complex tasks.

5.3.2.8 Quality control techniques

The quality control approaches could be classified into two categories (Allahbakhsh *et al.*, 2013): design-time and runtime. The design-time approaches include the open call generation and crowds' qualification, as described previously. There are a lot of runtime quality control approaches. For example, workflow management, expert review, output agreement, ground truth and majority voting (Allahbakhsh *et al.*, 2013). These approaches can be adopted together for better quality as using one approach alone may contribute to cheating behaviours.

5.3.3 Crowdsourcing tools

Crowdsourcing platform integrates tools to help requesters to realize specific purpose, such as new inventions, innovations and products. Since the crowdsourcing process varies from task to task, so specific tools in various crowdsourcing phases are needed. As the general crowdsourcing process (Figure 1-3) is iterative, this research holds that review and final review phase can be realized by the same tool. With reference to various crowdsourcing phases, the classification of crowdsourcing tools is shown in Table 5-2.

Table 5-2 Classification of crowdsourcing tools according to various crowdsourcing phases

Crowdsourcing phases	**Functions**	**Example of platforms including the tool that realizes the associative function**
Idea	Idea or solution generation	Quora, IdeaScale, social media like WeChat, Facebook, email, etc.
Review	Idea evaluation	Comment function realized by social media like WeChat, Facebook, microblog.
Final review		
Refinement	Idea selection	Vote function realized by most of the crowdsourcing platforms.
Top ideas		

As social media can only realize relatively simple and independent purpose like ideation and comment, crowdsourcing platforms that integrate various tools are easier for requesters to use. In addition, crowdsourcing platforms provide better service for managing mass data collected from crowds and the requester can achieve his/her aim with just a few clicks of the mouse. In addition to the mentioned tools, other tools like an assistive tool that help the requester to input their needs and evaluation criteria to generate an open crowdsourcing call and providing rewards to the winner designer are needed as well. On a crowdsourcing platform, all these tools work in sequence to ensure the execution of crowdsourcing process rather than work in isolation.

5.4 Crowdsourcing technologies for PDD

Before the crowdsourcing technologies for PDD are explored, a crowdsourcing process for PDD and corresponding challenges are first presented.

5.4.1 Crowdsourcing PDD process and challenges

When PDD activities are executed on a crowdsourcing platform, the crowdsourcing process is summarized in Figure 5-3. It indicates the main activities/steps during the process.

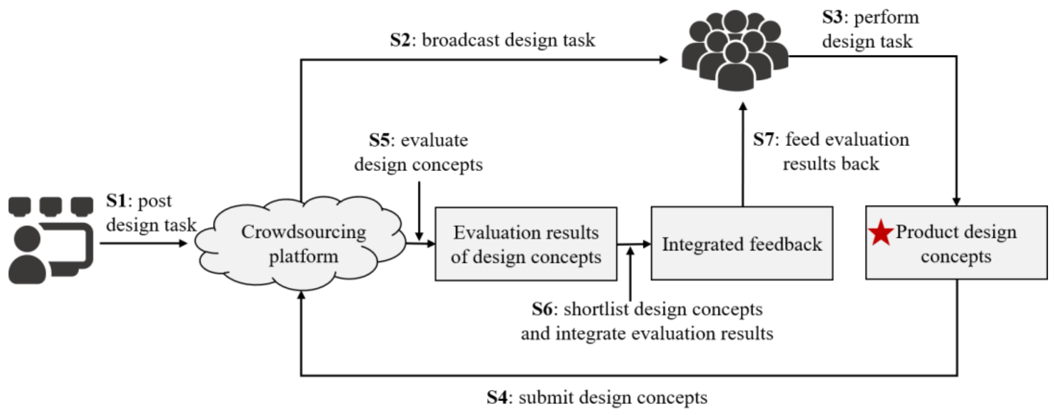


Figure 5-3 The PDD process and challenges on a crowdsourcing platform

The steps of the crowdsourcing PDD process are shown as follows:

- **S1**. The requester (e.g., a design project manager), defines product design tasks (challenges) through a form of product design brief (e.g., PDS) or a design challenge brief and sets the evaluation criteria and crowdsourcing conditions/terms.

- **S2**. The design challenge is broadcast online via a crowdsourcing platform and crowds registered on the platform are invited to perform the product design task.

- **S3**. Once a crowd agrees to take on the product design task, he/she can work on product concepts individually or in a group ongoing formed on the platform. They can also work either online on the platform or offline.

- **S4**. At some point, product concept design results will be submitted by an individual crowd or a group of crowds to the platform for evaluation. The concept design results can be submitted with a concept presentation or design pitch document to better communicate or explain the designers´ ideas or rationales.

- **S5**. Submitted product design concepts will be evaluated via suitable approaches such as automatic evaluation based on machine intelligence or crowdsourcing-based methods.

- **S6**. After concepts have been evaluated, better design concepts will be shortlisted based on the evaluation results and the corresponding evaluation results will be summarized to generate constructive feedback that will be communicated back to the related designers, thus guiding them to improve their designs and entering the next loop of the product concept design process.

Different from general crowdsourcing tasks, crowdsourcing PDD is risky and challenging for enterprises because their quality concerns need to be addressed properly. In a crowdsourcing PDD process, the output quality and cost for crowdsourcing PDD cannot be ignored. This feasibility study mainly concerns the output quality of a crowdsourcing PDD process. In order to ensure the output quality in a crowdsourcing PDD process, many aspects should be improved, such as the representation of design concepts, the evaluation of design concepts, and the integration of evaluation results, and so on (Niu *et al.*, 2019). Among these aspects, the representation of design concepts (or results) is the basis for later evaluation and further design improvement. Therefore, this research mainly focuses on how to represent product design concepts in terms of what information is needed for representing design concepts, how to collect the needed information and how to use the information on crowdsourcing-based platforms to support PDD activities.

5.4.2 Framework of crowdsourcing PDD process

The framework for crowdsourcing PDD shown in Figure 5-4 is derived from Figure 5-2. Compared to the general crowdsourcing process, the one for PDD pays more attention to design evaluation and feedback to enable the iterative process on a crowdsourcing platform. Thus, the techniques for information communication and sharing, product design evaluation, and the integration of evaluation results need to be investigated.

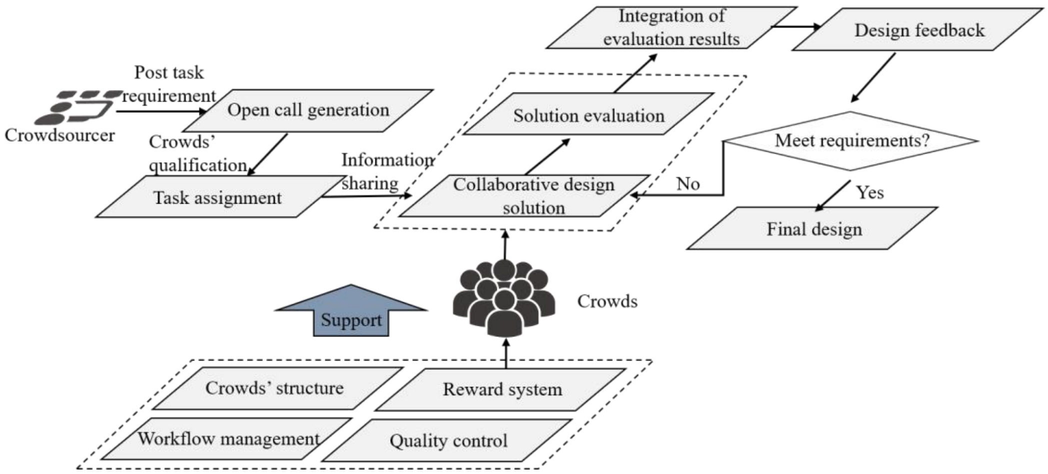


Figure 5-4 Framework of crowdsourcing PDD process

5.4.3 Techniques for crowdsourcing PDD

5.4.3.1 Techniques for information communication and sharing

In the crowdsourcing PDD process, all participated crowd workers must be teamed structurally such as hierarchical structure and team structure in traditional in-house design environments so that they could collaborate effectively. Effective communication approaches could enable crowds to spend less time on understanding their tasks and improve the work efficiency.

Currently, discussion forums, blogs and microblogs (e.g., SinaWeibo (Zhang *et al.*, 2014)) are commonly used by crowds as their communication medium, which is not real-time and may lead to some delays. Also, such kind of communication is not suitable in a large scale (Zhai, Khoo and Zhong, 2009; Girotto, 2016). Social media, like Facebook, Twitter, and WeChat, are real-time, but they only support the sharing of information and asynchronous edition of documents. In order to satisfy the increasing need of synchronous collaboration, Tencent Instant Messenger (TIM) is developed as a free cloud-based and platform independent office software. It not only supports instant messaging and the synchronous edition of simple documents, such as

Word and Excel, but also integrates social interaction functions. However, when it is applied to product design and development, the platform can only support the sharing of documents in various formats, but it is inconvenient for users to view and edit them unless corresponding software or tool is installed.

To improve communication and work output in expert crowdsourcing, a structured handoff method (Embiricos *et al.*, 2014) where participants were asked in live (live conference and screen share are used) and recorded scenarios (short screen capture video with voiceover) respectively. Their experiments indicated that higher work quality could be resulted in by the structured handoff approach. Since crowds are located at various places and they are not available to participant in the task at any time, the structured handoff may be useful for them to know the working process.

5.4.3.2 Techniques for product design evaluation

Until now, little research has focused on design concepts evaluation in the context of crowdsourcing. Chang and Chen (2014, 2015) were the first to address this problem. However, their research only focused on the data-mining based approach. In their research, domain ontology is adopted to hierarchically represent the types, properties and interrelationships of design concepts in order to better support the selection of promising design concepts (Chang and Chen, 2015). Differently, XML is also used for presenting product design information to enable the data integration, sharing and exchange in later design stages (Wang, Ren and Guo, 2010). The XML representation of product design information is easily understood by computers but not ordinary designers and evaluators. When crowdsourcing a product design, a structured format/representation of design concepts can effectively decrease the time used on understanding and evaluating the design concepts.

5.4.3.3 Techniques for integrating evaluation results

Design feedback motivates designers to improve design quality and productivity. It consists of descriptive, effective, evaluative, and motivational four categories. In traditional in-house design environments, Sticky notes method (Jackson, 2009) and MS Excel are usually adopted to categorize comments.

In crowdsourcing environments, there is a lot of research about how to produce high-quality feedback. For instance, techniques including anonymity and communal efforts have been adopted to improve the quality of feedback from crowds (Hui *et al.*, 2015). To address superficial and disorganized feedback (Xu and Bailey, 2012; Dow, Gerber and Wong, 2013) from unknown members, tools to support structured feedback online have been created (Luther *et al.*, 2014; Xu, Huang and Bailey, 2014).

5.4.4 Tools needed in a crowdsourcing PDD process

To address the identified challenges, the following enabling tools are needed.

Collaborative design tool

In PDD, design is generally performed by a team of professional designers located in different places, thus a collaborative design tool needs to be provided to help them work together and monitor the design process and progression. The tool provides a virtual workspace for the crowds in a team.

Design presentation tool

When the design is finished, it needs to be submitted to the platform for later evaluation. The evaluation results will be provided back to designers for further refinement and improvement. To describe the product design briefly and clearly, the tool should generate a presentation file by integrating together the common file formats, such as jpg, txt, audio, and flash.

Design evaluation tool

After submission of the design presentation file, it is ready for later evaluation. The file will be sent together with the evaluation criteria to proper crowds for assessment. The tool will generate an evaluation template with reference to product design specifications and even user needs, crowds only need to fill their evaluation results in the evaluation template, and then submit their evaluation results.

Integration tool of evaluation results

The integration tool can extract and classify evaluation results into various categories, thus reducing the heavy burdens of the designers from reviewing large numbers of evaluation results from the crowds.

5.5 Conclusion

This chapter analyses the framework, platform, tools, and techniques used in crowdsourcing processes in terms of open call generation, rewards, crowd qualification for working, team structure of crowds, solution evaluation, workflow, and quality control. Then this research proposes a framework for applying crowdsourcing in the PDD process and investigates what techniques and tools are needed in the process while indicating the main challenges. Mainly, collaborative product design process on a crowdsourcing platform, information communication and sharing, design evaluation and feedback generation by integrating evaluation results are four key challenges in the PDD process.

In response to the crowdsourcing quality, this chapter analyses the crowdsourcing frameworks for general tasks and PDD activities and then analyses key enabling techniques for implementing the key components of a crowdsourcing process, providing guidelines on how to implement a crowdsourcing PDD process from the technical perspective.

Next chapter will study product design lifecycle information model, which can facilitate product design information gathering, storage, retrieval, management and sharing for effectively working with the key crowdsourcing technologies towards a better crowdsourcing-based product design approach.

The research in this chapter has led to the following peer-reviewed publications:

Niu, Xiaojing, Qin, Shengfeng, Vines, John, Wong, Rose and Lu, Hui Lu (2019) Key crowdsourcing technologies for product design and development. International Journal of Automation and Computing, 16(1). pp. 1-15.

Niu, Xiaojing and Qin, Shengfeng (2017) A review of crowdsourcing technology for product design and development. In Proceedings of the 23rd International Conference on Automation and Computing (ICAC), pp. 1-6.

Chapter 6 Development of product design lifecycle information model

6.1 Introduction

The previous chapter discussed key enabling crowdsourcing technologies, which are to some extent depending on product design lifecycle information in terms of what information are available and the quality of information. Thus, this chapter focuses on the first question in Objective 3 investigating '*How to develop a product design lifecycle information model?*' Specifically, this chapter describes the development of the PDLIM which identifies the key entities involved in the PDLIM and their interactions in a crowdsourcing PDD process. The developed PDLIM provides information support for the crowdsourcing platforms that will be developed in next chapter.

An information model is a representation of concepts, relationships, constraints, rules, and operations to specify data semantics for a chosen domain of discourse (Lee, 1999), providing sharable, stable, and organized structure of information requirements for the domain context. In the domain of crowdsourcing PDD, an information model plays an important role in minimising knowledge gap between two different design stages, facilitating knowledge exchange, retrieval, and reuse during the PDD process (Li and Ramani, 2007; Li *et al.*, 2018) and accelerating data-driven PDD. The leading approach for representing product data is feature-based product modelling which focuses on modelling knowledge in a specific domain from the perspective of design ontologies (Li and Ramani, 2007; Catalano *et al.*, 2009; Sanya and Shehab, 2015) and the mapping of design and manufacturing ontologies (Li *et al.*, 2018), lacking support to the whole PDD process.

It has been found that the design stage accounts for 70%-80% of the product quality (Chu *et al.*, 2010; Zhu *et al.*, 2011) and considering constraints (Design for X) from other PDD stages at the early design stage is an effective way to optimize product designs while reducing time-consuming iterations of design changes (Li *et al.*, 2018). That is why 'Design for X' (X means manufacturability, reusability, safety, etc.) techniques are usually adopted at the design stage (Benabdellah *et al.*, 2019). Additionally, digital twin supported data-driven PDD is an inevitable development tendency in manufacturing industry (Schleich *et al.*, 2017; Tao *et al.*, 2018), requiring a consistent product design information model to underpin such a design digital twin framework. Therefore, this chapter focuses on the development of a PDLIM.

This chapter is structured as follows: Section 6.2 illustrates the research methodology used in this chapter. Section 6.3 mainly describes the development of the PDLIM in terms of the overall structure of the PDLIM, key design information exploration, and design environment associated information exploration. Section 6.4 first qualitatively evaluates the necessity of the identified information in PDLIM with three case studies and then evaluates its feasibility through a questionnaire survey in supporting the closed loop of the PDD process and providing insights on product redesign/improvement on next round PDD process. The evaluation of the PDLIM's entities' relationships and its manageability are described in Section 6.5 and the conclusion is drawn at the end of the chapter.

6.2 Research methodology

There are four phases for developing the PDLIM. Phase1 is to develop the overall structure of PDLIM enabling all necessary data/information along a product lifecycle based on the identified entities and design phases. Phase2 is to explore product design information against the main product lifecycle stages and the corresponding key phases. Phase3 is to qualitatively verify/evaluate the necessity of the identified information from Phase2 with case studies and a survey and Phase4 is to verify and evaluate the PDLIM's entities' relationships and its manageability. Correspondingly, a set of research methods are chosen to apply in this research (see Figure 6-1).

Based on the literature review conducted in Chapter 2, key entities in a crowdsourcing PDD process include the requester, the crowd, the task, staged design, and the process, and the attributes representing profiles of the requester, the crowd, and the task have been identified. Therefore, this chapter mainly focuses on exploration and evaluation of information at each design phase, and the information modelling of staged product design and design process.

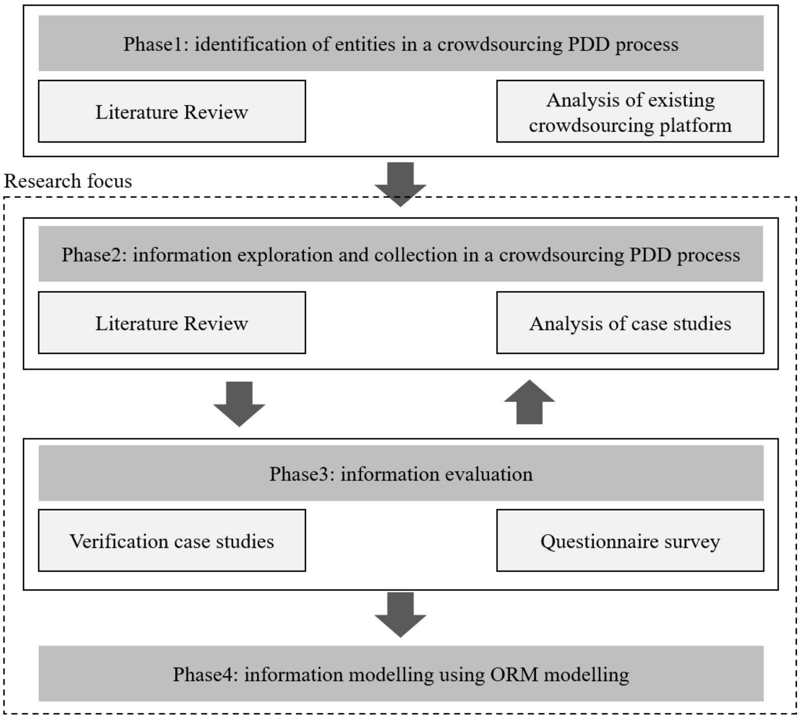


Figure 6-1 The overall research methodology in this chapter

At the exploration phase, a systematic research approach as shown in Figure 6-2 is adopted to explore the attributes of staged design and process in the PDLIM. Step1 is to identify the key information exploration guides for each design phase including what information is needed and where it is generated, how and when does the information need to be communicated for information sharing, how the information is used in design reviewing and decision-making, what is the design team structure and key players in the design process, and how is the information updated with a history tracing for up-to-date application. Design actions in each design phase may involve different design teams in different design environments in action and thus their interaction information is important. Therefore, the resultant key guides from Step1 are then used for a guide to scope key design information in each phase, together with the team structures and profiles in associated design environments and interaction information. In this way, design information involved in each phase can be identified. Finally, Step5 will synthesise all information and structurally represent it into a product design information model, followed with evaluations. The research method is partially based on secondary research from literatures and some primary research from design case studies and a questionnaire. This process could be iterative.

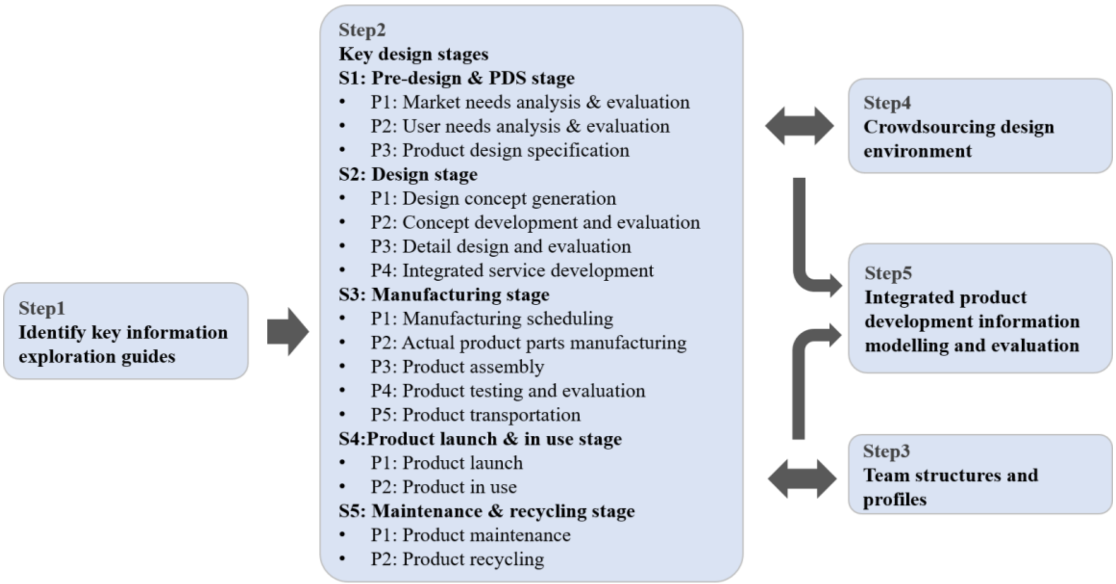


Figure 6-2 Guideline for design information exploration in phase2

6.3 Development of the PDLIM

This section will present Phase1 and Phase2 in detail, and the Phase3 and Phase4 are described in Sections 6.4 and 6.5, respectively.

6.3.1 Overall structure of the PDLIM

To develop the overall structure, this research first sets up the general requirements for it. First, it needs to support sustainable product design and development in both in-house and crowdsourcing combined environments, and second, it should be able to present what information is needed at each design stage, where it is generated, and how and when this information is shared/exchanged for use in product design. The overall structure of the PDLIM is the model representation at the system level, mainly illustrating product lifecycle design process and information structure for supporting the closed loop of a product lifecycle development.

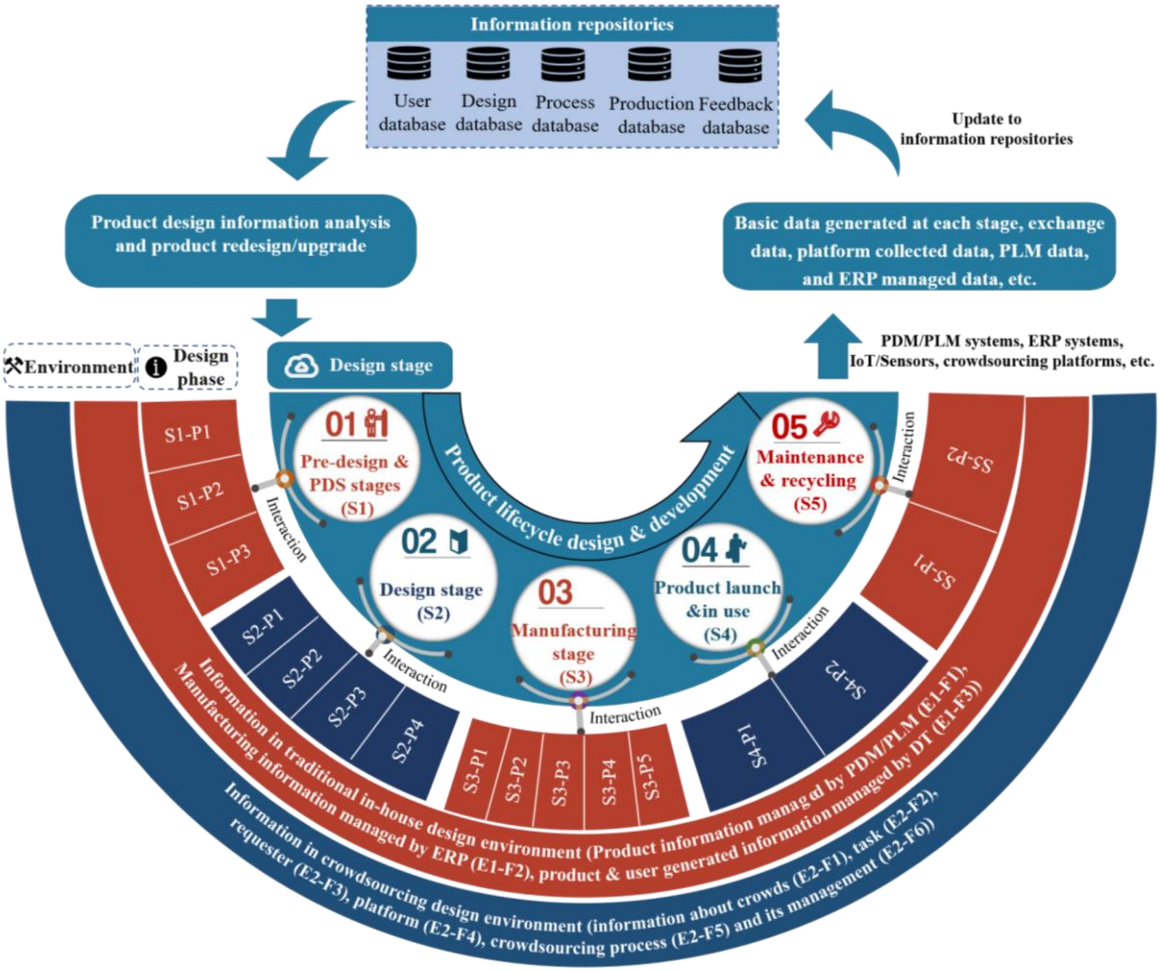


Figure 6-3 The overall structure of the PDLIM

The overall structure of the PDLIM is shown in Figure 6-3 as a multi-layered information model. Among the identified design stages in Figure 2-4, the pre-design and design stages account for 70%-80% of the product quality (Zhu *et al.*, 2011) and to reduce design iterations, 'Design for X' techniques are usually considered at the pre-design and design stages to optimize product designs (Benabdellah *et al.*, 2019). These five key design stages are presented in the inner 'Design stage" layer from the left to right indicating a product lifecycle design and development.

Next, the information at each design phase identified in Figure 2-4 is presented in the 'Design phase' layer. Finally, the product design and development environmental information is presented on the 'Environment' layer. It includes two sub-layers. One is the traditional in-house design environments consisting of the design teams, design/manufacturing management tools such as PDM/PLM/ERP systems (Liu and Xu, 2001; Lee, Leem and Hwang, 2011) and manufacturing platform such as DT. It can represent the human players, products, and tools generated data/information. The other sub-layer is to represent a crowdsourcing environment related data/information covering tasks, crowds, requesters, platforms, crowdsourcing processes, and information management.

The top part of Figure 6-3 also illustrates how the information in the PDLIM could be stored in a central information repository with integration to PDM/PLM/ERP and DT for supporting the next round of data-informed product design and development in a close-loop fashion.

Between the 'Design stage' layer and the 'Design phase' layer, it is the virtual 'Interaction' information layer. The information on this layer is secondary information captured how primary information on the three main information layers are interacted and utilized for supporting design activities and decision making. In section 6.5, this research will demonstrate examples of how information interacted with each other as secondary information along the product design and development lifecycle, which could be regarded as design activity-based information.

6.3.2 Key design information exploration

Based on Figure 6-3, for each key stage, key design information at each phase is explored to enrich the information model. Note that the identified key design information is commonly used at each design stage as input and output information. Thus, they are adaptable for a specific product design application case.

Through an analysis of the collected 51 case studies and a review of literature (Wright, 1998; Pfeifer, 2009; Johnson and Gibson, 2014), it is found that a series of design activities are conducted to collect information about the market and users, the product functions, and the interactions between users and the existing products, etc., helping shape new products or upgrade existing products. At pre-design and design stages, design research, market research, personas & reasoning, storyboarding, user journey, CAD modelling and simulation are key design activities conducted by designers to get expected information. Among these design activities, design research and market research can be conducted in parallel to gather information about market and customer needs. Storyboarding and user journey are normally conducted after personas. Storyboarding helps create user journey maps of the target personas. Personas, storyboarding, and user journey are all to analyse user behaviours to help designers understand the interactions between users and the product by visualising the user requirements and helping feed into other design activities such as sketching at design concept generation and development phases. However, user journey can also be used further down the line when scoping out pieces of functionalities in more detail.

The rich details of these design activities are usually recorded in design process related documents, such as design notebook, design reviews, and design reports, to track ideas developed and decisions made during the design process so that no information is lost and the generated information can be communicated to others (Ullman, 2017). However, it is not well structured in a way that is intuitive for other team collaborators to track the design changes when focusing on a specific aspect. When a specific format is assigned to the product design, it is easy to track the design structure changes with computer-aided design software, but the background and reasons behind the changes are only documented roughly in design process-related documents.

After analysing the design process related documents of collected case studies and reviewing literature, the key information at phases S1 and S2 is identified and presented in Figure 6-4.

Design Phase	Market needs analysis & evaluation (S1-P1)	User needs analysis & evaluation (S1-P2)	Product design specification (S1-P3)	Design concept generation (S2-P1)	Concept development & evaluation (S2-P2)	Detail design and evaluation (S2-P3)	Integrated service development (S2-P4)
Information	1. Competitor products 2. Development/market trends 3. Marketing strategies of competitors 4. Packaging 5. Market potential 6. Product positioning 7. Targeting strategy 8. Market share 9. Marketing context 10. Market sales 11. Prince point analysis 12. Innovation strategy 13. Brand audit 14. Competitive advantage 15. Unique selling point 16. Feasibility study, etc.	1. Customer segments 2. Customer motivations 3. Customer personas 4. Frustrations/pain points for each customer segment 5. Customer journey maps 6. Customer experience 7. Customer comments on the product 8. Human context 9. Stakeholders 10. Stakeholders' comments on the product 11. Customer preferences 12. Observation study 13. Emotional design 14. Expert interviews, etc.	1. Product size & weight 2. Performance requirements 3. Service environment 4. Safety requirements 5. Reliability standards & requirements 6. Ergonomic requirements 7. Product aesthetics 8. Maintenance/recycling requirements 9. Material requirements 10. Market/company constraints 11. Patents & standards 12. Prototype testing requirements 13. Schedule requirements 14. Prototype iteration 15. Cost and time requirements 16. Product interactions and experiences 17. Government regulations, 18. Enabling technology, etc.	1. Sketches with annotation 2. Low fidelity model 3. Ideas with other forms like text 4.Scenario/research boards 5. Idea selection 6. Concept feedback, etc.	1. Sketching 2. Intention map 3. CAD models with different levels of detail and quality 4. Physical models 5. Rendering 6. Materials 7. Interacting process 8. Product structure 9. Mechanisms 10. Costing 11. Prototype iterations 12. Concept prototype feedback 13. Evaluation criteria 14. Feasibility 15. Compatibility 16. Completeness 17. Cost evaluation 18. Evaluation methods 19. Selection criteria 20. Stakeholders' review etc.	1. Complete specification of the geometry, material, and tolerances of all parts 2. Detail and assembly drawings 3. Parts list with raw material sizes and specifications 4. Bill of materials (BOM) 5. Selection of materials 6. CAD models 7. Manufacturing techniques 8. Machine tools and processes 9. Analysis results of the robustness & performance of components and assemblies 10. Impact of design decisions on the performance, reliability, and cost of the product 11. Product verification tests 12. Evaluation criteria 13. Stakeholders' review, etc.	1. Company's policies & procedures 2.Company culture 3. Compliance & legal regulations 4. Tools to deliver a service 5. Service information flow 6. Interactive touchpoints 7. Service evaluation 8. Environment interactions 9. Service strategy 10. Service blueprints 11. Experience prototypes 12. Users iterations 13. Service evaluation 14. User feedback, etc.

Figure 6-4 Key information at product pre-design and design stages

In S2-P3, the CAx models refer to various CAD/ CAE/CAM models (Sanfilippo and Borgo, 2016; Eckert *et al.*, 2017). These CAx models can support different types of information (Sanfilippo and Borgo, 2016). For example, CAD models focus on geometric or form description of design, while CAE models focus on engineering analysis under different working conditions, and CAM models focus on facilitating different manufacturing processes and technologies such as additive and subtractive manufacturing. In general, CAE and CAM models are derived from CAD models with additional information. The various models in multiple formats are deliverables of a specific design stage resulted from the analysis of collected information at previous product design stages. To improve product design and development efficiency, these CAx models (Lee, 1999) are required to exchange data with each other. Therefore, many product data exchange models such as STEP and CPM (Sudarsan *et al.*, 2005) have been developed. STEP is the standard for product model data exchange while CPM, as a base-level product model, is capable of capturing the full engineering context commonly shared in product design and development process and it needs to be used together with its extension models such as OAM (Open Assembly Model), DAIM (Design-Analysis Integration Model), or PFEM (Product Family Evolution Model), which mainly focus on the exchange of product, mechanical parts and assemblies information between heterogeneous modelling systems (Sudarsan *et al.*, 2005). The information listed in Table 6-1 is embedded in CAx models and can be shared and exchanged among them (Rachuri *et al.*, 2008; Loos, Verbeeck and De Laet, 2019).

Table 6-1 Exchanged basic information in existing product data exchange models

Attribute	**STEP Application Protocol AP 203**	**CPM and its extensions**
Geometry (point, line, plane, wireframe, surface models, faceted models, manifold surfaces and solids, constructive solid geometry, hybrid models, etc.)	●	●
Function	●	●
Form	●	●
Behaviour	●	●
Material	●	●
Flow		●
Colors and layers	●	
Textual annotations associated to the geometry	●	

Table 6-1 Exchanged basic information in existing product data exchange models (Continued)

Attribute	STEP Application Protocol AP 203	CPM and its extensions
Data for configuration control	●	
Relationship (association, constraint, usage, and trace relationships)		●
Specification		●
Requirement		●
Information (a brief textual description slot, a textual documentation string, a properties slot that contains a set of attribute-value pairs stored as strings representing all domain- or object-specific attributes)		●
References to product data represented in another format than STEP	●	
Process information		●
Data related to the documentation of design change process, approval, security classification	●	
Rationale (attributes that record explanatory information on the reasons for or justifications of a particular decision in the product development process)		●
Assemblies and parts	●	●
Relative position and orientation of assembly and part		●
Connection and association relationship among assemblies and parts		●
Tolerance information including dimensional tolerance and geometric tolerance (form, profile, runout, orientation, and location tolerances)	●	●
Validation properties (global as volume, area, center; local as clouds of points)	●	
Construction history in 3D	●	
Definitions for PDM specially configuration management	●	

Table 6-1 Exchanged basic information in existing product data exchange models (Continued)

Attribute	STEP Application Protocol AP 203	CPM and its extensions
Tools used by manufacturing	●	
Information for process plan, configuration control	●	
Parametric assembly constraints		●
Relationship among assembly features		●
Kinematic pair/structures	●	●
Rules and constraints	●	●

The key information for stage S3 from the literature study (Jauregui-becker and Wits, 2013; Li *et al.*, 2015; Tao *et al.*, 2018) is identified into Figure 6-5. Similarly, the key information for stages S4 and S5 is extracted and listed in Figure 6-6.

Design Phase	Manufacturing scheduling (S3-P1)	Actual parts manufacturing(S3-P2)	Product assembly (S3-P3)	Product testing (S3-P4)	Product transportation(S3-P5)
Information	1. Raw materials availability in stock 2. Cost of raw materials 3. Material & component orders 4. Suppliers' lead times and prices 5. Availability of workstations and workers 6. Information about other works on the machine 7. Manufacturing capacity and productivity 8. Costs related to machines and workers on the workstations 9. Scheduling tool 10. Schedule of collaborators 11. Plan for conflicts 12. Implementation plan, etc.	1. Monitoring of manufacturing process 2. Manufacturing environment 3. Government manufacturing regulations 4. Changes to components/parts 5. Changes to manufacturing process 6. Changes to manufacturing technology 7. Performance indicators 8. Manufacturing flow 9. Actual material cost 10. Actual labour cost 11. Actual overhead cost 12. Interaction with collaborators 13. Checking quality and accuracy of parts against the design specifications, etc.	1. Assembly cost 2. Assembly standards 3. Assembly process 4. Functional requirements 5. Functional analysis 6. considerations/ Assumptions 7. Number of parts 8. Number of interfaces 9. Mistake proofing 10. Handling 11. Insertion 12. Secondary operations 13. Checking fit and function against parts accuracy/drawings/desig n intent, etc.	1. Testing standard 2. Product usability 3. Product safety 4. Product function test 5. Product reliability 6. Testing methods 7. Testing technology 8. Work experience and professional levels of testing personnel 9. Testing manufacturing procedure 10. Design defects 11. Manufacturing defects 12. Testing product lifespan 13. Product competition, etc.	1. Packaging 2. Transportation mode selection 3. Transportation cost 4. Transportation strategy 5. Customer requirements 6. Carrier relationships 7. carrier's performance 8. Product transportation track history 9. Transportation quality 10. Transportation efficiency 12. Sustainability carbon footprint 13. Time cost, etc.

Figure 6-5 Key information at product manufacturing stage

Design Phase	Product launch (S4-P1)	Product in use (S4-P2)	Product maintenance (S5-P1)	Product recycling (S5-P2)
Information	1. Launch date 2. Product promotion channels 3. Sales strategy and training 4. Technical data sheets 5. Technical support materials 6. Product launch cost 7. Infrastructure changes 8. Communications plan both inside and outside the organization 9. Analyst briefings 10. Product propagate 11. Technical data sheets 12. Brand development, etc.	1. Product real-time conditions 2.Product operational environment 3. Feedback from end users 4. User behavior data 5. Tools for collecting product-generated and user-generated data 6. real-time data analysis tool 7. Real life observational study 8. Forecasting future service, etc.	1. Failure data and causes 2. Product maintenance record 3. component/part status and quality 4. Maintenance service providers 5. Maintenance cost 6.Condition evaluation 7. Fault diagnosis 8. Maintenance service quality 9. Maintenance time 10. Cost measures, etc.	1.The cost of recycling and disassembly 2. The reusable state 3. Remaining service time of parts/ components 4. Recycling technology 5. Recycling process 6. Revenue from product recycling 7. Material recycling 8. Recycling service 9. Percentage of recycled products, etc.

Figure 6-6 Key information at product launch & in use and maintenance & recycling stages

The information at each design phase is required to communicate with each other so that executives make better decisions to improve design quality. However, this requires the establishment of topological relationship between information throughout the product lifecycle, which also plays an important role in helping evaluate product designs and provide design suggestions for future design projects. The modelling of the identified information will be illustrated in Section 6.5.

6.3.3 Design environment associated information

PDD is a process which usually involves various participants within different teams work collaboratively to process various information to reach a detailed design, along which design information evolves over time. Comparing to many other processes, the PDD process is especially challenging to be managed as it tends to involve significant elements of novelty, complexity, and iteration (Wynn and Clarkson, 2018). In a PDD process, design activities can be performed in a traditional in-house design environment or a combined design environment with crowdsourcing. The key information related to a traditional or combined crowdsourcing design environment can be explored from a design quality control and assurance point of view (Niu *et al.*, 2018).

6.3.3.1 Associated information in traditional in-house design environment

In traditional design in-house design environment, it has been found that higher information densities and larger information flows have been resulted from the involvement of various teams/departments with different functions (Jauregui-becker and Wits, 2013). Thus, the management of involved teams/departments and their generated information are vital for the product success (Niu *et al.*, 2018). In a traditional in-house design environment, associated information that should be covered by the PDLIM comes from the following three aspects:

- Product family or lifecycle changes-related information, which is typically managed by the PDM (Liu and Xu, 2001) tool or integrated PLM tool (Rachuri *et al.*, 2008; Lee, Leem and Hwang, 2011).
- Design team, IP and supply-chain related information, which is typically managed by ERP systems (Lee, Leem and Hwang, 2011) in manufacturing stages.
- Product and end-user generated information such as product performance data and user feedback, which can be managed by DT platform.

In practical product manufacturing, ERP systems and PDM/PLM are usually adopted by SMEs to manage this information. Specifically, PDM helps manage all information that defines a product from design to manufacture, and to end-user support (Liu and Xu, 2001). It is responsible for managing the actual digital product files such as CAD files and documents that move through a PDD process and controlling their versions. The process of version control for physical products has an impact on the cost, quality and time of the PDD process (Jones *et al.*, 2019). However, it lacks the support of the design knowledge sharing among various teams/departments and workflow management. Therefore, PDM systems are extended to PLM systems. PLM systems provide control of the product record across all development stages from concept generation to manufacturing (Rachuri *et al.*, 2008). They connect people, processes, and data to a central repository of information. Their ability to view all product data in a centralised location allows people to access right information at the right time, thus, to trace any changes to product information, communicate revisions to the supply chain, and make more evidence-based decisions regarding product cost management and resource management.

When the product design has developed to a point where resources need to be managed to produce the design, the ERP system integrated with the SME's existing PLM system will be used to organize information between financials, sales, and manufacturing departments. The integration of ERP and PLM can reduce BOM (Bill of Materials) errors, ensure consistency and save time in design changes for product design quality improvement (Lee, Leem and Hwang, 2011). Except the information extracted at product manufacturing phases, the additional information managed by ERP systems is also added in the PDLIM as part of the traditional environment information (see Figure 6-7).

With PDM/PLM and ERP systems, SMEs have the information for improving the quality of their products, but still lack product real-time performance information and user interaction information for better data-informed product design. Currently, the most suitable technology to obtain and use such data information along the product lifecycle is digital twin enabled by Internet of Things (IoT) and sensors. DT has been listed as one of the top 10 technology trends in 2018 (CeArley *et al.*, 2016). It provides a means of connecting information such as real-time status of the physical product and its behaviour in the physical world with the digital representation, enabling companies or users to have a real-time view of the product and its usage in the physical space. Meanwhile, it provides a channel for customers to provide their feedback, offering value in operational efficiency and insights into how products are used and how they can be improved in the next round of product development process. Tao *et al.* (2019) have put forward a digital twin-driven design framework to ensure that useful customer voices from online customer reviews would be considered for decision makings for redesigning the existing products.

Product information managed by PDM/PLM (E1-F1)	**Manufacturing information managed by ERP (E1-F2)**	**Product and user generated information managed by DT platforms (E1-F3)**
1. Real-time BOM information 2. Details for understanding and approving engineering change requests 3. Engineering change orders 4. real-time product development status 5. Milestone tracking during development process 6. Data version control 7. Visualization of involved stakeholders 8. Approved manufacturer lists 9.Property parameters 10. Management team, etc.	1. Team structure 2. Team members' skills 3. Company culture, rules & policies 4. risks 5. Supply chain operations 6. Team members' satisfaction 7.Team members' education background 8. Record of purchasing 9. Inventory and procurement 10. Process parameters, etc.	1. Real-time product conditions 2. Product's operating environment 3. Customers' comments 4. Historical product operation data 5. Historical interaction data between physical and virtual twins, 6. Connection to data sources, etc.

Figure 6-7 Key information related to traditional in-house design environments

The DT can collect real-time product conditions, its operating environment, and its customers' comments in a more reliable and faster manner, enabling evidence-based actions on physical asset management (CeArley *et al.*, 2016). Through real-time data analysis, the virtual twins can make the physical counterpart respond in a timely and smart way. More importantly, digital twin can store historical data of the product conditions, operations, and interactions between the physical and virtual twins, which are valuable for reducing design iterations in the next round of product design and development.

Thus, the additional information managed by PDM/PLM systems, ERP systems, and DT platforms is added in the PDLIM as part of the traditional environment information listed in Figure 6-7.

6.3.3.2 Associated information in crowdsourcing design environments

To shorten the lead time to market, SMEs are increasingly adopting concurrent design strategies to get core design tasks conducted by in-house design teams/departments while crowdsourcing less important ones to the crowds. Although diverse crowdsourcing models have been implemented by existing crowdsourcing systems, they have the same key components affecting product design quality, namely, the requester/crowdsourcer, the crowds (workers), the task, and the platform (Hetmank, 2013; Bhatti, Gao and Chen, 2020). When a design task at the early design stage is crowdsourced, the crowds could be further classified into the designer and the evaluator. Therefore, the information identified in crowdsourcing design environments is mainly extracted into the following six categories (Florian *et al.*, 2018; Niu *et al.*, 2018) (see Figure 6-8).

Crowds/service provider (E2-F1)	Task (E2-F2)	Requester (E2-F3)	Platform (E2-F4)	Crowdsourcing process (E2-F5)	Information management (E2-F6)
1. Work histories 2. Location 3. Qualification 4. Reputation/history comments 5. Expertise 6. Participation motivation 7. Time or schedule of crowds, etc.	1. Task definition 2. Task decomposition 3. Technical resources 4. Incentives mechanism 5. Task input and output 6. Task distribution process 7. Timeline, etc.	1. Open call design 2. Privacy provision repositories 3. Ethicality provision 4. Incentives provision, etc.	1. Platform performance 2. Interaction tools for crowds and requester 3. Platform facilities 4. Platform pattern and characteristics, etc.	1. Crowds selection criteria 2. Open task design requirements 3. Interaction among crowds 4. Design team establishment, etc.	1. Information structure 2. Information repositories 3. The performance of information management software 4. Service information management 5. Information reliability, etc.

Figure 6-8 Key information related to crowdsourcing design environments

6.4 Evaluation of identified information in the PDLIM

The proposed product design information model has been evaluated in two steps. First, the necessity (or usefulness) of the primary information in the three main information layers are qualitatively evaluated via three case studies (one of them involving crowdsourcing environment) and the effectiveness of the proposed information model in supporting the iterative design process, design communication and collaboration, and performance analysis and predictive maintenance is quantitatively evaluated by a questionnaire survey. Second, the secondary interaction information on the virtual 'Interaction' layer is qualitatively evaluated with an example, which are detailed in Section 6.5.

6.4.1 Evaluation by case studies

The aim of case studies is to verify if the identified design information can represent design inputs/outputs at specific design phases. In case studies, the design process related document is called Critical Justification (CJ).

The first two case studies come from design projects for Industrial Design undergraduates at Northumbria Design School, one representing the concept design of a product and the other illustrating a product family design. Their design briefs, CJs, and presentation documents are analysed to verify the identified design information by various information representation examples. The third one is from existing literature, mainly focusing on the product design lifecycle information shared during the development process of bicycles from docked IT-based generation to dockless IT-based generation.

6.4.1.1 Case study 1 – the concept design of 'Helping Hand'

This case study is set up by an undergraduate student and aims to create an inclusive product that uses modern technology to enhance the spatial awareness of hard-of-hearing individuals and cyclists to enable them to be more responsive, aware and confident on the road. Since the case is a graduation project done by a master student, it mainly concerns related design information at product pre-design and design stages. To achieve the design aim, design activities such as design research, market research, personas and reasoning, user journey, and concept design have been conducted.

Based on the poster presentation document, the corresponding information and its representation examples at each design phase are shown in Table 6-2.

Table 6-2 Design phases, corresponding information involved in case study 1 and its representation examples

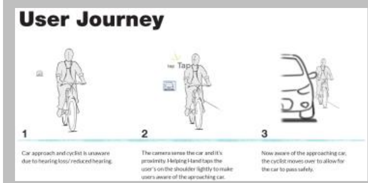
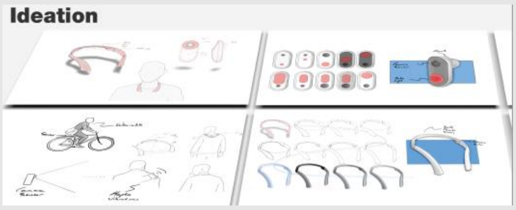
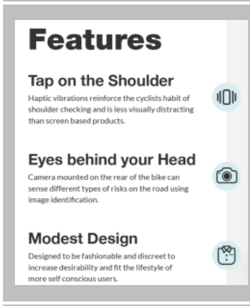
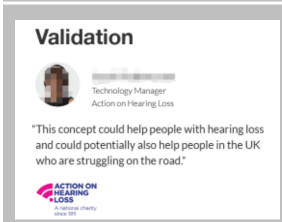
Design phase	Information	Information representation example
Market needs analysis (S1-P1)	Development/market trends (S1-P1-2)	Increasing popularity of electric vehicles, EU noise limiting regulations and wind noise experienced by cyclists means that vehicles will be less audible even for more abled cyclists.
User needs analysis (S1-P2)	Customer motivations (S1-P2-2)	
	Customer personas (S1-P2-3)	
	Frustrations/pain points for each customer segment (S1-P2-4)	
	Customer journey maps (S1-P2-5)	
Design concept generation (S2-P1)	Sketches with annotation (S2-P1-1)	
	Low fidelity model (S2-P1-2)	
	Concept feedback (S2-P1-6) Colors (S2-P2-5)	

Table 6-2 Design phases, corresponding information involved in case study 1 and its representation examples (Continued)

<table>
<tr><th>Design phase</th><th>Information</th><th>Information representation example</th></tr>
<tr><td rowspan="3">Concept development & evaluation (S2-P2)</td><td>Physical models (S2-P2-4)</td><td rowspan="2">


</td></tr>
<tr><td>Product structure (S2-P2-8)</td></tr>
<tr><td>Concept prototype feedback (S2-P2-12)</td><td>
</td></tr>
<tr><td>Detail design and evaluation (S2-P3)</td><td>CAx models (S2-P3-6)</td><td>
</td></tr>
</table>

6.4.1.2 Case study 2 - 'Redesigning the food processor' as a product family design

This case study is set up by a kitchen appliance manufacturer with a design brief. It aims to shift the trends from baking to food preparation for meals that are healthier and fit into a balanced diet. The design brief provides the information about the brand vision, the product history, the segmentation of target customers, company design language, and company insights, etc. It also specifies what project deliverables should be submitted. In this project, as the kitchen appliances for food preparation are diverse, participants have the freedom to choose any existing one they are interested in for improvement (mimic to a product family design), but their design must be in line with the current line of the project founder. In this case study, a food processor is chosen for bringing better user experience to customers.

From the presentation document, design activities including personas and reasoning, design research, market research, concept development, and storyboarding have been conducted to extract expected design information at each design phase of pre-design and design stages in this case study. The corresponding information and its representation examples at each design phase are shown in Table 6-3.

Table 6-3 Design phases, corresponding information involved in case study 2 and its representation examples

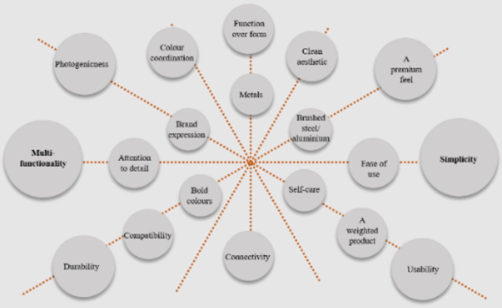
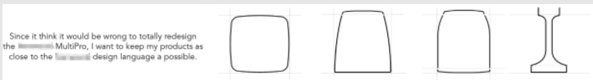
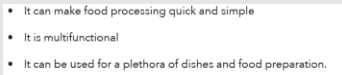
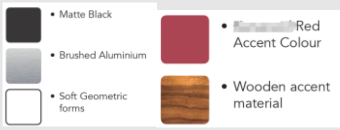
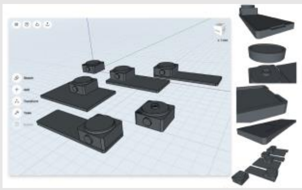
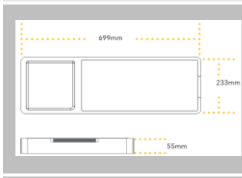
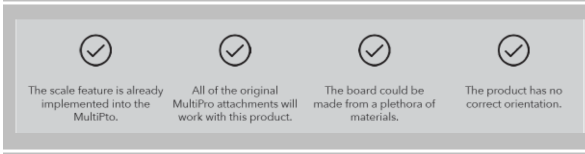
Design phase	Information	Information representation example
Market needs analysis (S1-P1)	Development/market trends (S1-P1-2)	
	Innovation strategy (S1-P1-12)	
	Brand audit (S1-P1-13)	
	Competitive advantage (S1-P1-14)	
User needs analysis (S1-P2)	Customer personas (S1-P2-3)	
	Frustrations/pain points for each customer segment (S1-P2-4)	

Table 6-3 Design phases, corresponding information involved in case study 2 and its representation examples (Continued)

Design phase	Information	Information representation example
Product design specification (S1-P3)	Material requirements (S1-P3-9)	
	Market/company constraints (S1-P3-10), constrained by S1-P1-12 and S1-P1-13	
Design concept generation (S2-P1)	Sketches with annotation (S2-P1-1)	
Concept development & evaluation (S2-P2)	CAD models with different levels of detail and quality (S2-P2-3)	
	Colours (S2-P2-5)	
Detail design and evaluation (S2-P3)	Detail and assembly drawings (S2-P3-2)	
	Selection of materials (S2-P3-5)	
	CAx models (S2-P3-6)	
	Product verification tests (S2-P3-11)	

From case studies 1 and 2, it is clear that designers are following identified design phases in practice. However, these two case studies mainly focus on pre-design and design stages, and it remains unclear how the feedback from later stages affects design. Therefore, the third case is studied next.

6.4.1.3 Case study 3 - 'the design of dockless sharing bikes' from previous generation design

This case study is to verify what information is necessary in bicycle lifecycle design and how the information in previous design generation affects that in later generation. From mid 1960s, there have been four generations of bike-sharing systems, namely, free bikes, coin-deposit system, docked IT-based system, and dockless IT-based system (Prince, 2014). The first two bike-sharing generations are free of charge and the users are anonymous for using this service, while for later generations, they do require the users with verifiable personal ID to use their payable services.

Taking the docked and dockless IT-based bicycles as an example, the information identified at bicycle in use and maintenance phases at the docked IT-based bicycle generation is shown in Table 6-4. With engineering design information in literature (Hadland and Lessing, 2014; Prince, 2014; Wu, 2017; Wang, Huang and Dunford, 2019; Yang, Li and Zhou, 2019; Chen, Van Lierop and Ettema, 2020), design information on the dockless IT-based bicycles throughout the bicycle lifecycle is extracted into Table 6-5. Table 6-4 and Table 6-5 mainly list the key information at each design phase, the information relationships are modelled in next section by ORM modelling.

Table 6-4 Design phases, corresponding information involved in docked bicycle and its representation examples

Design phase	Information	Information representation example
Product in use (S4-P2)	Product operational environment (S4-P2-2)	-Built environment characteristics such as population density, job density, bicycle and public transit infrastructure, street design, land-use mix and proximity to central areas affect the usage of docked bicycles. -Traffic congestion.
	Feedback from end users (S4-P2-3)	-More organized pickup and dropping-off experience for users. -Limited bicycles and docking spots around public transit stations influencing bicycle pickups when needed and bicycle returns.
	User behavior data (S4-P2-4)	-A substitute for walking or public transit trips. -The duration of trips generally falls between 16 and 22 mins. -Males and younger populations account for a larger percentage of docked bike-sharing users.
Product maintenance (S5-P1)	Maintenance cost (S5-P1-5)	-Substantial investment required. -Increased maintenance costs in terms of economic and human resources with higher density of docking stations.
	Maintenance time (S5-P1-9)	-Limited distribution of stations around public transit stations. -Bicycles' redistribution required. -Drop-off restriction.

Table 6-5 Design phases, corresponding information involved in dockless bicycle and its representation examples

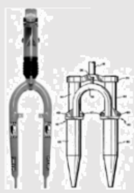
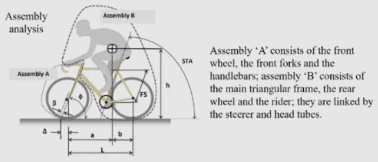
Design phase	Information	Information representation example
Market needs analysis (S1-P1)	Competitor products (S1-P1-1)	OFO, MoBike, Lime.
	Marketing strategies (S1-P1-3)	Targeted to specific areas or socio-demographical groups.
	Marketing context (S1-P1-9)	The existing large number of shared bikes has not taken into account whether these systems promote the equity of bike-sharing access to all potential users, including disadvantaged groups with limitations in approaching other transport modes.
User needs analysis (S1-P2)	Frustrations/pain points for each customer segment (S1-P2-4)	The seat too low and unable to adjust; the seat cushion too stiff; no basket; most importantly, hard to operate due to the weight.
Product design specification (S1-P3)	Government regulations (S1-P3-17)	Green lifestyle, low-carbon travel.
	Enabling technology (S1-P3-18)	Digital bicycle locks, GPS devices, 4G/5G network, the popularity of smartphones.
Concept development & evaluation (S2-P2)	Product structure (S2-P2-8)	Adjustable seat, airy basket, one sided frame, and non-inflatable tires.
	Mechanisms (S2-P2-9)	The lock system removed buttons altogether, the lock opens automatically once authenticated.
Detail design and evaluation (S2-P3)	Complete specification of the geometry, material, and tolerances of all parts (S2-P3-1) CAx models (S2-P3-6)	
	Selection of materials (S2-P3-5)	Plastic non-inflatable tires, plastic timing belt design to replace the traditional metal chains.

Table 6-5 Design phases, corresponding information involved in dockless bicycle and its representation examples (Continued)

<table>
<tr><th>Design phase</th><th>Information</th><th>Information representation example</th></tr>
<tr><td rowspan="4">Detail design and evaluation (S2-P3)</td><td>Analysis results of the robustness & performance of components and assemblies (S2-P3-9)</td><td rowspan="2">

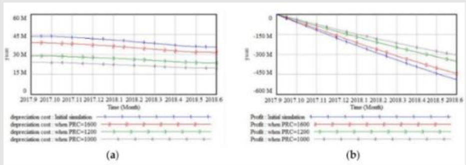
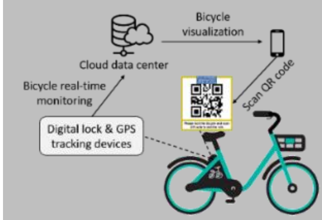
Partial analysis results
<table>
<tr><th>Relevant design chart</th><th>Symbol</th><th>Parameter definition</th><th>Benchmark value/s</th><th>Units</th><th>C % change 1</th><th>Comments 2</th></tr>
<tr><td rowspan="2">1. Steering Geometry Design Chart</td><td>Φ</td><td>head tube angle</td><td>73</td><td>degrees</td><td>5.93%</td><td>significant term</td></tr>
<tr><td>β</td><td>fork rake</td><td>0.045</td><td>m</td><td>1.41%</td><td>moderately significant</td></tr>
<tr><td rowspan="2">2. Wheel Properties Design Chart</td><td>D</td><td>diameter of the bicycle wheel</td><td>0.675</td><td>m</td><td>5.75%</td><td>significant term</td></tr>
<tr><td>Iw</td><td>MOI of wheels about X, Y and Z 3</td><td>0.10</td><td>kgm²</td><td>2.02%</td><td>moderately significant</td></tr>
</table></td></tr>
<tr><td>CAx models (S2-P3-6)</td></tr>
<tr><td>Impact of design decisions on the performance, reliability, and cost of the product (S2-P3-10)</td><td>
Simulation results of the different values of Production cost/bike (PRC): (a) depreciation cost; (b) profit.</td></tr>
<tr><td>Evaluation criteria (S2-P3-12)</td><td><table>
<tr><th>Procedural step</th><th>Comments</th></tr>
<tr><td>1. Select the bicycle frame size (FS)</td><td>• the bicycle's basic size is set by the frame size (FS), see Appendix B
• this is determined ergonomically from the rider's inseam measurement, FS = IS x 0.65 (68, 69)
• the correct FS allows the rider to pedal efficiently</td></tr>
<tr><td>2. Determine the wheelbase (L)</td><td>• the wheelbase (L) is determined empirically from Appendix F
• a longer L increases stability but reduces the speed of response (75)
• the wheelbase also influences the top tube length which has ergonomic & aerodynamic significance (69)</td></tr>
</table></td></tr>
<tr><td rowspan="3">Integrated service development (S2-P4)</td><td>Service information flow (S2-P4-5)</td><td rowspan="3">
</td></tr>
<tr><td>Interactive touchpoints (S2-P4-6)</td></tr>
<tr><td>Colors (S2-P2-5)</td></tr>
<tr><td>Actual parts manufacturing (S3-P2)</td><td>Changes to components/ parts (S3-P2-4)</td><td>Components added: Smart locks, GPS devices, SIM card, barcodes/QR codes.
Components deleted: key/card connected to payment, docking stations.</td></tr>
<tr><td rowspan="2">Product assembly (S3-P3)</td><td>Assembly cost (S3-P3-1)</td><td rowspan="2">The changes to bike structure and the materials can lead to the change of assembly cost and process.</td></tr>
<tr><td>Assembly process (S3-P3-3)</td></tr>
</table>

Table 6-5 Design phases, corresponding information involved in dockless bicycle and its representation examples (Continued)

Design phase	Information	Information representation example
Product in use (S4-P2)	Feedback from end users (S4-P2-3)	Improved users' experience at the end of their rides and flexible route and destination choices.
	Tools for collecting product-generated and user-generated data (S4-P2-5)	-The QR code is used to connect the dockless bicycle to the cloud data center. The users can provide feedback to the product as well by scanning the QR code. -Collect and display user's cycling data from GPS devices.
	Real-time data analysis tool (S4-P2-6)	The server side of the dockless bicycle system provides online services such as real-time data analysis, the management of all dockless bicycles, the monitor of bicycle status, the payment for using the bicycle, etc.
Product maintenance (S5-P1)	Maintenance cost (S5-P1-5)	-The exceeding supply of dockless bike-sharing systems and inadequate redistribution schemes led to a large amount of abandoned or damaged bikes remaining on the streets without timely maintenance or clearance. -The redistribution of shared bikes occurs on a larger geographic scale. -Controlling and regulating shared bikes becomes more difficult in regions that have dockless systems.
	Maintenance time (S5-P1-9)	

From this case, it is clear that the feedback collected at previous bicycle generations definitely has impacts on the design of later generation bicycles.

6.4.2 Evaluation by questionnaire survey

The aim of this questionnaire survey is to verify the information comprehensiveness of PDLIM and the feasibility of applying it to a closed loop of product design and development. The questionnaire survey was conducted via Wenjuanxing (www.wjx.cn), a professional online questionnaire survey tool focusing on questionnaire establishment, distribution, management, and analysis. The questionnaire is attached as Appendix A. To ensure the reliability of the survey result, the questionnaire was only emailed to design researchers and practitioners in UK and China.

6.4.2.1 Participants of the questionnaire survey

In total, 21 participants returned valid questionnaire surveys, with 19 from design researchers and 2 from design practitioners. Their expertise areas cover design strategy, design management, engineering design, graphics design, human factors design, and engineering design. Among the participants, most of them have many years product design experience. 19.05% of them have more than 10 years design experience and 33.33% of them have 5 to 9 years design experience. The percentages of those having 3 to 4 years' and 1 to 2 years' experience are the same (23.81%). The distribution of participants in terms of expertise and working experience is shown in Figure 6-9 and Figure 6-10, respectively.

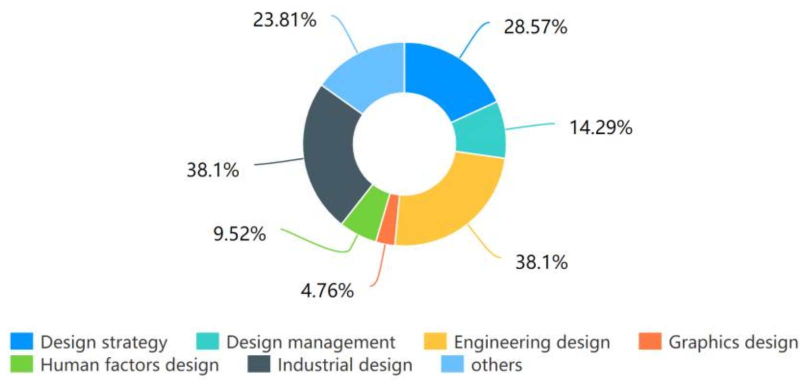


Figure 6-9 Participants distribution in terms of expertise

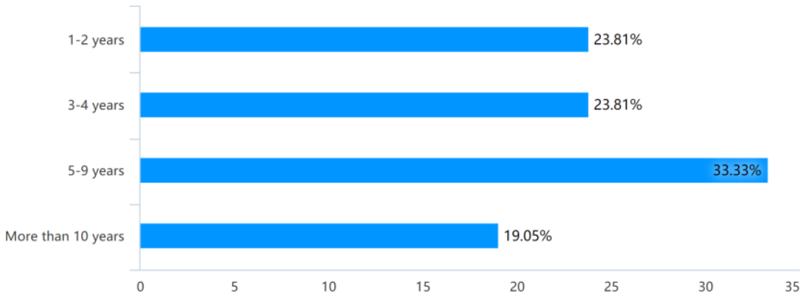


Figure 6-10 Participants distribution in terms of working experience

6.4.2.2 Results on the information comprehensiveness of the PDLIM

From the questionnaire survey, 90.48% (N=21) of the respondents considered that the overall PDLIM structure covered all information categories during a PDD process. They held that testing/evaluating/redesign stages should be added both before and after product manufacturing, as the evaluation of staged outcomes determines whether the design process enters to the next stage or goes back for further improvement. In addition, more design stages and corresponding information should be added to the PDLIM according to specific product design categories.

In the survey, this research also attempted to evaluate its effectiveness of supporting the closed loop PDD process, design collaboration and communication, and product performance analysis and predictive maintenance. The number of respondents who think that the PDLIM is effective in these three aspects are shown in Table 6-6.

Table 6-6 Feedback on applying the PDLIM to effectively support lifecycle product design

Effectiveness / Percentage	Effectiveness of supporting the closed loop PDD process	Effectiveness of supporting design collaboration and communication	Effectiveness of supporting product performance analysis and predictive maintenance
More than 90%	3	4	3
70% - 90%	4	6	5
50% - 70%	9	9	8
30% - 50%	4	1	5
Less than 30%	1	1	0

For collaboration and communication among participated design teams/departments, the PDLIM can help to provide a centralized information structure based on which the platform coordinates information flows to make information shared across different participants. The PDLIM can guide participants to present their ideas to other team members, making their collaboration and communication more effectively.

In terms of product performance analysis and predictive maintenance, suitable tools should be linked to the model to help users find the right tools to perform their tasks. Although real-time user and product generated data can be obtained by sensors and IoT infrastructures, how to model them to predict product faults and analyse product performance based on big data and make it available as a plug-in on CAD packages in conjunction with maintenance scheduling software still need to be investigated.

However, the PDLIM could have limited application in the more creative aspects of design approaches that value art/aesthetics/character etc., and some designers may be against it as it feels counterintuitive to free/creative thinking.

6.4.3 Discussions

Overall, the survey results are positively supporting the PDLIM model development, but there are some concerns due to the adoption of digital twin and crowdsourcing in the proposed PDLIM.

On the one hand, this adoption provides great potential to support product through-life design and development, especially for certain types of mass manufactured products. With valuable knowledge leant from historical data through data mining, designers can have a better understanding of the product design and application context, making it easier for the next round of product design and development.

On the other hand, since the PDLIM intends to support product through-life design and development in a combined design environment, it relies heavily on a suitable platform to integrate all data produced in a PDD process. Under such a circumstance, the collaboration and communication among participants are mainly progressed through the platform, whose effectiveness has a direct influence on the success of a PDD process. Therefore, the future work needs to address the following participants' concerns: (1) how to provide intuitive, well-structured, user friendly and integrated interfaces to make the whole PDD process easily accessible; (2) how to guide people to use the PDLIM during a PDD process, (3) how to embed PDLIM into existing online and CAD platforms in use, and (4) how to acquire real-time data throughout the whole PDD process.

6.5 Information interaction modelling in the PDLIM

This section aims to demonstrate and qualitatively evaluate the secondary interaction information on the virtual 'Interaction' layer with ORM models (Budiman *et al.*, 2017) of exemplar application scenarios. Each information item in PDLIM can be regarded as an object in object database designs. The reason for using ORM is that it can illustrate the use of object features within the design of object-relational database.

6.5.1 The evaluation of information interaction within the design representation model

At each design phase identified in Figure 6-3, to help a design team effectively communicate or 'sell' their design ideas or results at different stages to funders, partners, consumers and other stakeholders, information in the PDLIM needs to be synthesized together to produce a good design representation. Design representations can be made before, during, and after the process of designing any entity, regardless of whether the designed entity is being constructed, manufactured, and assembled as a real product (Goldschmidt, 2004).

Goldschmidt (2004) considers that design representation can be used to communicate more than design facts, conveying messages concerning a wide cultural, social, economical, and technological context in which the design has been conceived and is to be integrated. Cognition, history and culture, and technology and media are key underlying dimensions in representing designs (Goldschmidt, 2004). The cognition dimension aims to provide a design context, an ill-structured problem, and a reasonable design search process to elicite potent preliminary ideas among which a design concept that can be developed and refined into a concrete solution proposal. The history and culture dimension aims to position the design on a socio-cultural map, as “one that best fits the market niche for which the products are destined.” The technology and media dimension aims to have a great impact on representational capacities with the advent of CAx modelling, drawing, and valuable asset that is generously rewarded by employers and clients. Three explicit information aspects in terms of customer needs, market needs and feedback from participants around the three core dimensions have been highlighted for forming an abstract design representation model (Figure 6-11).

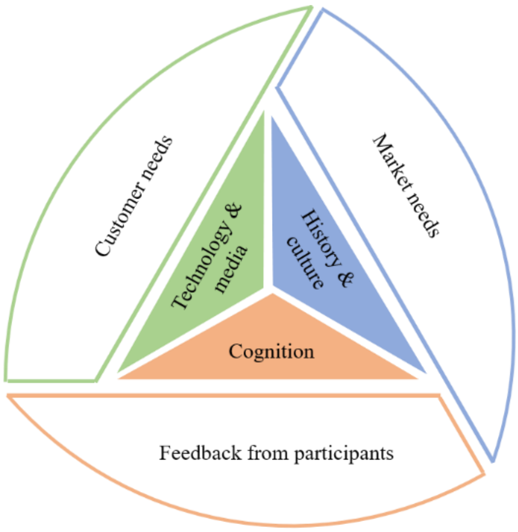


Figure 6-11 Abstract design representation model

The abstract design information representation model identifies what information dimensions affect the product design, but not list what information affects product design and how the information is used for product design over time. Therefore, how the staged information identified in Figure 6-4, Figure 6-5, and Figure 6-6 is used in other PDD phases should be modelled. Between different design phases, the later one can capture information from the previous one. And between different product design generations, the newer one can capture information from the older versions.

An ORM model in Figure 6-12 indicates the information interaction between market needs analysis (S1-P1) and product design specification (S1-P3) phases and how the identified information in S1-P1 is used in S1-P3 phase. The ORM model mainly focuses on the information communicated between these two design phases.

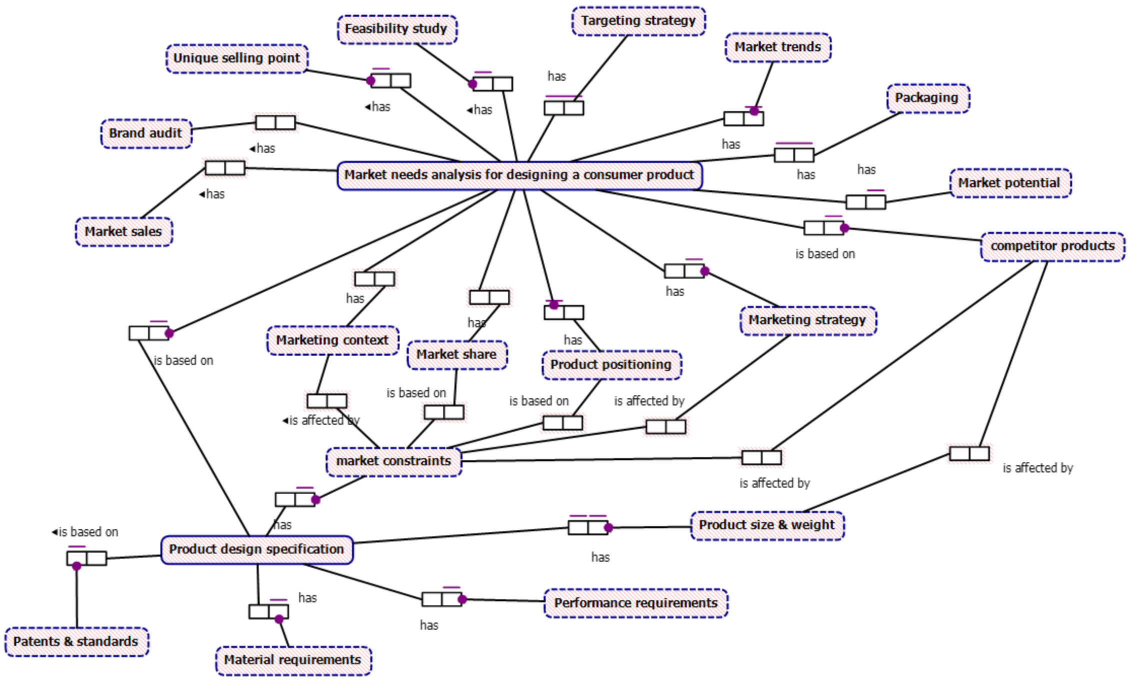


Figure 6-12 An exemplar ORM model showing information interaction among different design phase entities

6.5.2 Relationship model among identified entities within the design environment

The design environment information especially in the crowdsourcing environment is modelled in an ORM model to help evaluate and illustrate how to utilize, share and communicate the collected information among platform users throughout the crowdsourcing PDD process.

The system entities that are relevant and meaningful to the crowdsourcing PDD process, such as key role players, design task call, design staged output, and design feedback, are identified as object entities. Then an ORM model (Figure 6-13) of relationships among them in a crowdsourcing PDD process has been developed which only models entity ID as key entity identifier. Work experience and certificate are key indicators to measure the qualification of a designer or an evaluator. To record more details about the qualification instead of statistical data like most existing crowdsourcing systems, work experience and certificate are treated as entity types rather than value types.

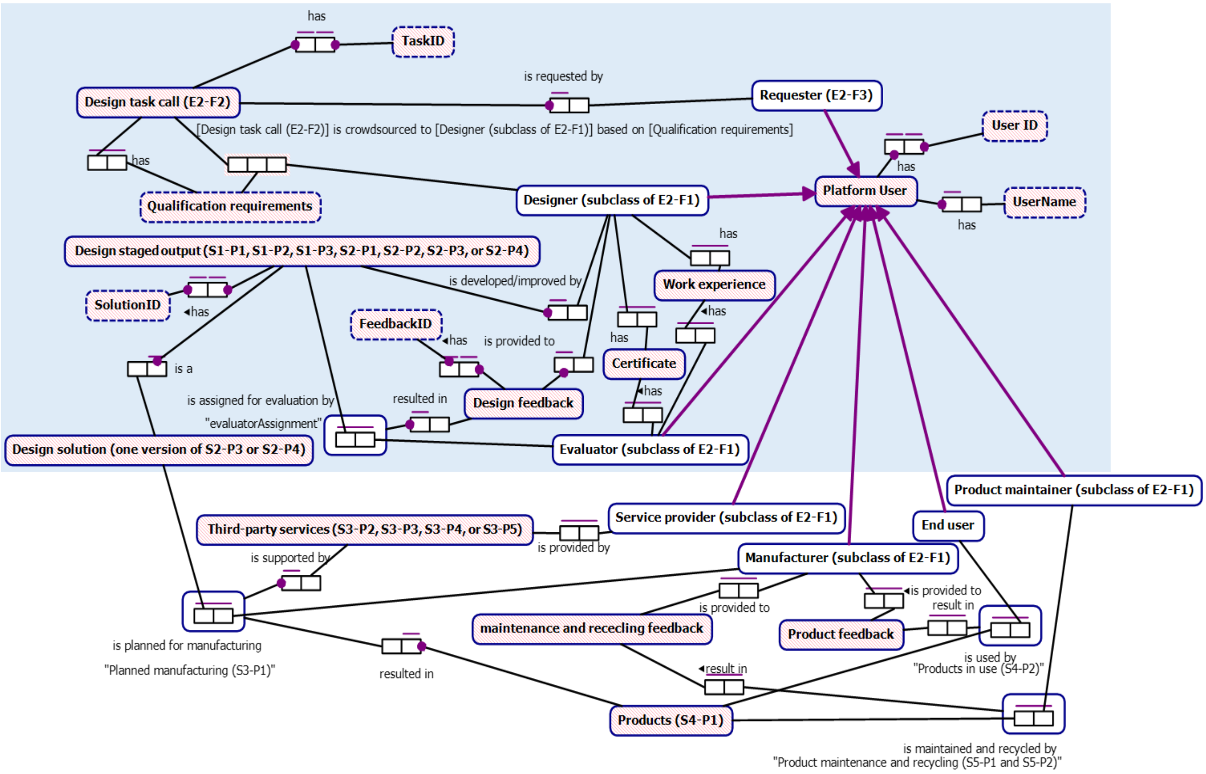


Figure 6-13 ORM model of relationships among identified entities in a crowdsourcing PDD process

In the model, all role players involved in the crowdsourcing PDD process are treated as platform users. Requester, designer, evaluator, manufacturer, service provider, and end user are key role players inherited from platform user in a crowdsourcing PDD process. At the product design stage, the key role players involved are requester, designer, and evaluator. Here, requester refers to the individual or organization that launches the product design call/task, designer refers to the crowd that can provide design ideas and solutions, and evaluator refers to the crowd that can assess design idea/solution or organizations that can provide design assessment services.

The relationship ORM model has the following features:

- It illustrates the design process and key interactions among platform users when crowdsourcing a product design task. The crowdsourcing PDD process starts from the request of a design task call, then it is crowdsourced to professional or general crowd designers by matching the participant requirements in the design task call with the designer profiles. When the design task is accepted, the designer will iteratively work on the design staged output with design feedback from evaluators until the staged output is satisfactory. In this process, all identified entities have their unique identifiers.
- It is easily extensible. Before a design solution is ready for manufacturing, the key involved role players are requester, designer, and evaluator, and their interactions are modelled as light blue area in Figure 6-13. But when it comes to the whole PDD process, more role players, such as manufacturer, service provider, and end users will be involved, and their interactions with existing identified entities can be easily modelled as shown in Figure 6-13. In this process, when the manufacturer receives product feedback from end users, it can determine when to start a new round PDD process to improve its products.

With the ORM model, the information created and owned by a role player can be shared with others, making them aware of the whole product design progress and in turn informing their decision makings. Meanwhile, with feedback from other role players, more insightful suggestions for next actions can be obtained.

6.5.3 The ‘bicycle’ case information interaction model

To demonstrate how to use the PDLIM to establish the relationship of information between different product generations, the third case study ‘the design of dockless sharing bikes’ in Section 6.4.1.3 is taken as an example as shown in Figure 6-14. The light blue area shows key information at docked bicycle in use and bicycle maintenance phases, while the remaining part shows key information at current dockless bicycle generation. Both the information at last bicycle generation and current generation has an impact on dockless bicycle design. The bicycle design process is iterative.

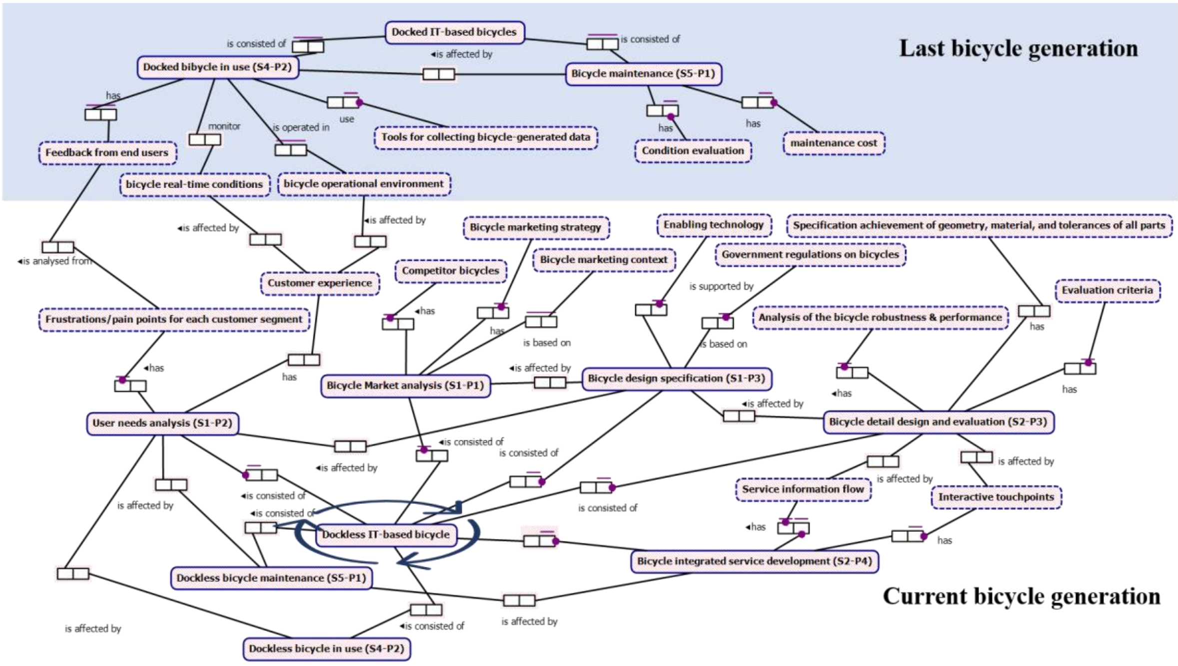


Figure 6-14 Information relationship between two bicycle generations

With the PDLIM, it is easy to record any design changes/versions in the whole product design process, making it easier for designers and their collaborators in tracing and understanding the design information changes. In addition, the PDLIM could establish a unified structure of key information in an iterative product design and development process, saving designers' time on managing design changes and design process related documents.

6.6 Conclusion

This chapter proposes a PDLIM enabling product through-life design and development trends under an in-house and crowdsourcing combined design environment. Firstly, a multi-layered product design lifecycle information modelling structure has been developed to accommodate all design related information. Secondly, the key information at each design phase and that associated with both in-house and crowdsourcing design environments are identified to enrich the information model. Next the identified information in the PDLIM is qualitatively evaluated by three case studies. Finally, ORM modelling method is adopted to evaluate the relationships and interactions of information entities in the PDLIM as well as to demonstrate the PDLIM's manageability. The PDLIM can enable designers to explore the design space and make evidence-based design decisions. Moreover, it can record the progression of design information during the design process, making it easier for participants at later design stages to track the design changes throughout the process. Also, it can enhance the communication and collaboration between collaborators, making the design process more effective. With the proposed information model, the manufacturers can have better access to information and quickly react to market and user needs changes.

Furthermore, the PDLIM is extensible. New application scenarios can be easily modelled to integrate with the existing PDLIM. Further investigations on how to implement the PDLIM for a crowdsourcing PDD process will be conducted in next chapter.

This chapter mainly models the design information items in a product design lifecycle and their relationships. The developed PDLIM can provide data support for the crowdsourcing PDD process, forming the information basis for the crowdsourcing platforms.

The research in this chapter has led to the following submission for peer-reviewed publication:

Niu, Xiaojing, Wang, Meili and Qin, Shengfeng (2021) Product design lifecycle information model with crowdsourcing product design and development. International Journal of Advanced Manufacturing Technology. (Under review)

Chapter 7 Development of crowdsourcing platform prototypes for PDD process and feasibility evaluation

7.1 Introduction

The previous chapter develops a PDLIM for supporting the crowdsourcing PDD process. Based on that, this chapter investigates the second question in Objective 3, namely '*How to test the utility of product design lifecycle information model in the crowdsourcing platforms for two types of businesses?*'. Specifically, this chapter aims to investigate the feasibility of (1) developing an intermediary crowdsourcing platform for SMEs with enabling tools, such as team up tool and design collaboration and communication tool, to fully support the iterative PDD process, (2) developing a crowdsourcing platform for large enterprises integrated with existing innovation platforms to coordinate stakeholders to co-create the desired products or services and deliver them to involved actors.

This chapter is structured as follows. Section 7.2 describes the feasibility evaluation design. Section 7.3 and 7.4 illustrate the development and evaluation of the intermediary and integrated crowdsourcing platforms in terms of platform architecture, realizing mechanisms and technologies, prototypes of key interfaces, and the evaluation with case studies. And the conclusion is drawn in Section 7.5.

7.2 Feasibility evaluation design

Two crowdsourcing platform prototypes with enabling tools are developed to examine the technical feasibility of crowdsourcing PDD. Based on the key factors affecting product design quality and quality control measures, key enabling technologies for crowdsourcing PDD, and the proposed PDLIM, a framework for the crowdsourcing platform development and evaluation is presented in Figure 7-1.

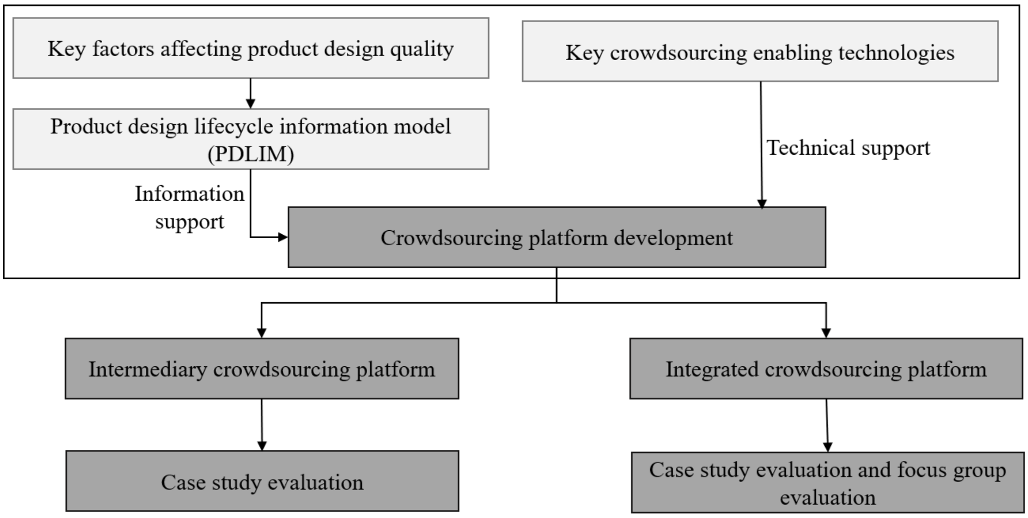


Figure 7-1 Framework for developing and evaluating crowdsourcing for manufacturers

In Figure 7-1, the research findings from previous Chapters, i.e., key factors affecting product design quality, key crowdsourcing enabling technologies for PDD, and the developed PDLIM form the basis for the design and development of the crowdsourcing platform prototypes and the evaluation.

To test crowdsourcing in different scenarios, a digital intermediary crowdsourcing platform prototype and an integrated one are developed. The intermediary crowdsourcing platform is mainly for use in SMEs while the integrated one is for use in large enterprises. In the intermediary crowdsourcing platform, crowdsourcing is utilized as a general business model, while in the integrated crowdsourcing platform, it is used as a service coordination tool.

These two platforms are qualitatively evaluated by two case studies: 'The design of dockless sharing bikes' from literature and 'Maintenance as a service' from industrial practice, respectively. The integrated crowdsourcing platform is also evaluated by four scheduled focus groups and bi-weekly zoom meetings over 12 months.

The case studies are to evaluate if the developed crowdsourcing platforms can support the product design process or service process by communicating and sharing necessary information with participating design collaborators and evaluators. So the evaluation process emphasized if the information provided by the enabling tools in the platforms is enough for design communication and evaluation. The effectiveness of the integrated crowdsourcing platform in creating a product-service ecosystem to offer value provisions to all stakeholders involved in a PDD process around 'Maintenance as a service' concept is also evaluated by the voting of 9 experts in focus groups.

7.3 Feasibility evaluation of the intermediary crowdsourcing platform

7.3.1 Development of the intermediary crowdsourcing platform prototype

The intermediary crowdsourcing platform is prototyped to support the iterative PDD process with enabling tools. This research assumes that the involved crowds on the intermediary crowdsourcing platform have equal opportunities to receive the design task call.

7.3.1.1 The functions of the intermediary crowdsourcing platform

To model the interactions between role players and the platform, UML is utilized to create structured interfaces and to accomplish the interactive information flows of the platform prototype.

Since the intermediary crowdsourcing platform is designed for through-life PDD, all stakeholders crossing product lifecycle should be involved. According to the role the user plays in the platform, the platform users could be classified into six categories: business owner/manufacturer, system administrator, requester, designer, evaluator, and service provider/supplier, which are shown in Figure 7-2. Designer and evaluator are subclasses of service provider. To better describe the design process, this research distinguishes designer and evaluator from other service providers. The common functions the intermediary crowdsourcing platform should realize can be modelled by a use case diagram shown in Figure 7-3. Every use on the platform can access the common functions. However, due to various roles they play on the platform, each role player has its unique functions. To demonstrate the interactions of different role players, here we mainly consider the requesters, designers, and evaluators at product pre-design and design stages. On the platform, crowds act as designers or evaluators. For these three role players, their unique functions were modelled in Figure 7-4.

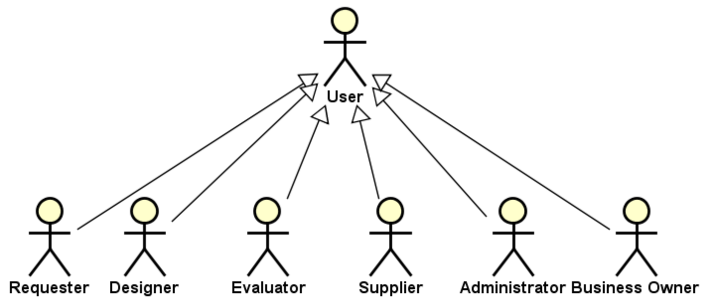


Figure 7-2 The identified role players on the intermediary crowdsourcing platform

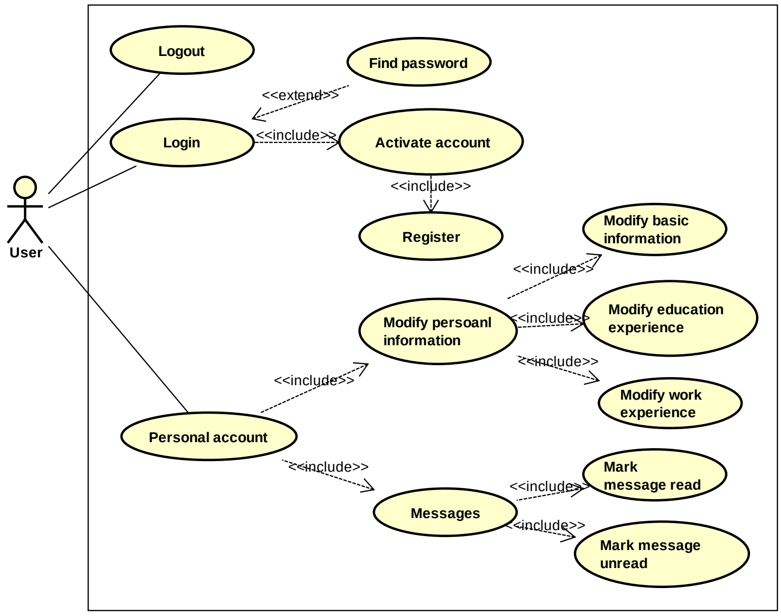


Figure 7-3 UML use case diagram of platform common functions

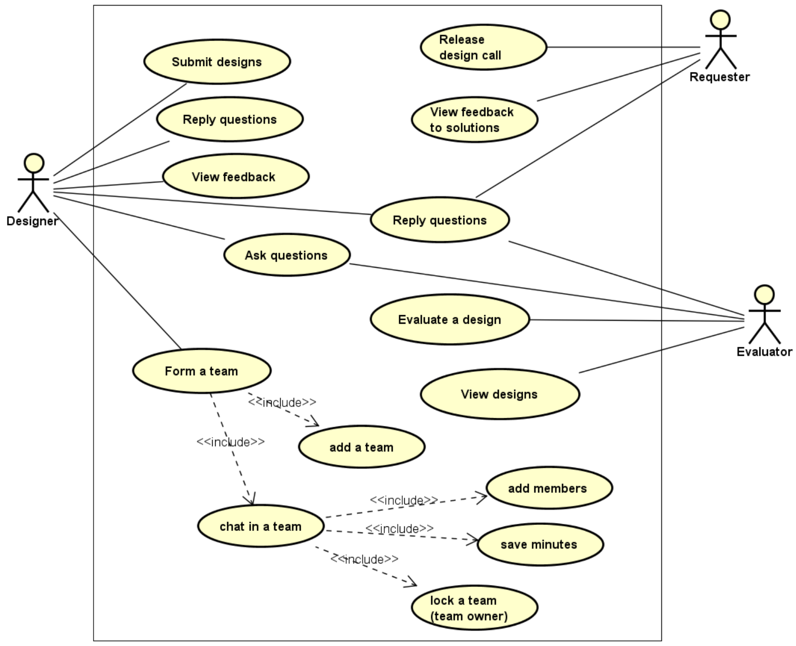


Figure 7-4 UML use case diagram of the intermediary crowdsourcing platform prototype

Based on the product design process on a crowdsourcing platform proposed in Figure 5-3 and the UML use case diagram in Figure 7-4, the intermediary crowdsourcing platform should support design communication, information sharing, interaction and collaboration among all stakeholders. The implementation mechanisms of these functions will be demonstrated in section 7.3.1.3.

7.3.1.2 The systematic architecture of the intermediary crowdsourcing platform

Based on the use case diagram in Figure 7-4, the systematic architecture of the intermediary crowdsourcing platform is proposed as shown in Figure 7-5. The identified functions can be realized by the coordination of key modules of the intermediary crowdsourcing platform: private panel, public panel (discussion board), teamwork panel (team up tool), and communication among them.

Public panel

Public panel is mainly to display the advertisements, news, and the cases performed on the platform. Considering the protection of IP, only the titles of cases are shown to platform users who do not log in.

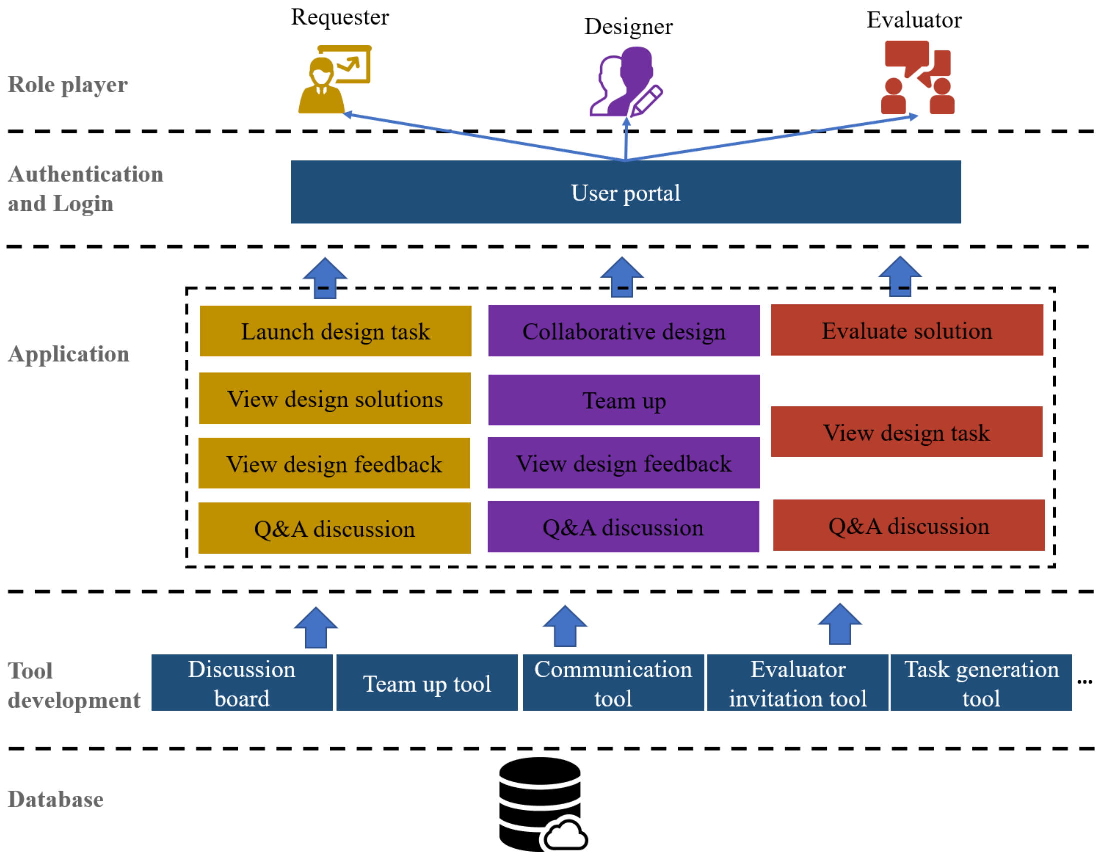


Figure 7-5 The systematic architecture of the intermediary crowdsourcing platform prototype

Private panel

Private panel is a personal workspace where a collection of all available work is presented to the login user. The collection of available work varies according to the role the user plays. Table 7-1 shows the key functions of the private panel, which are classified according to the role the user plays on the platform.

Table 7-1 Key functions of each role player at product pre-design and design stages

Role player	Key functions
Requester	Propose design requirements, answer the questions asked by platform users, and view design solutions
Crowd	View design requirements, submit design solution, ask and answer questions about the design requirement and design solution, team up to perform design tasks, and view comments to design solution
Evaluator	Evaluate design solutions, view design solutions, and ask and answer questions about evaluation criteria and evaluation results

Teamwork panel

Teamwork panel is to provide a design space for a group of designers teamed up for a specific product design task. In this panel, the team members could have real-time communication and sharing of design ideas with each other just as in a practical meeting room.

Communication among panels

The communication among panels includes two types: real-time and non-real-time. The communication between private and public panel is non-real-time while it is real-time in teamwork panel.

7.3.1.3 Implementation mechanisms

This section is mainly to demonstrate the implementation mechanisms on design communication, information sharing, interaction and collaboration.

Design communication

The communication among platform users is achieved by the communication among panels. The real-time communication in teamwork panel is similar to the existing social media, while the non-real-time communication is realized by a discussion board. Any platform user who logs in the platform can put questions on the discussion board, and then the answers from other platform users will be reposted to the questioner by notification. On the intermediary crowdsourcing platform, once the status of an activity that one user has participated in changes, the platform will notify him/her automatically so that he/she could process it timely.

Information sharing

On the intermediary crowdsourcing platform, the information on public panel and teamwork panel is shared, but the users need different permissions to get access to these resources. Permissions to different resources are controlled by the permissions and group mechanisms built-in Django.

Interaction and collaboration

All platform users interact with each other through interfaces provided by the intermediary crowdsourcing platform. When the user logs in the platform, he/she can easily find all to-do functions. The collaboration among platform users is achieved by the question board and the teamwork panel.

7.3.2 Prototyping of the intermediary crowdsourcing platform

The intermediary crowdsourcing platform consists of frontend Web App and backend web service. The frontend is implemented by Bootstrap, html, CSS, JavaScript, JQuery, and Ajax, while the backend is supported by Django framework. Data generated in the platform are stored in MySQL database.

The platform frontend includes three key components: private panel, public panel, and teamwork panel. Platform users have different access permissions to these three components. All users, no matter whether they sign up or not, can get access to the public panel, whereas teamwork panel and private panel can only be accessed by registered users. The key functions implemented in private panel vary from one user play role to another, as Table 7-1 shows. The prototyped interfaces of the private panel for the requester, the designer, and the evaluator designers are shown in Figure 7-6, Figure 7-7, and Figure 7-8, respectively. The requester can post new task request, view design solutions submitted to the requested task, view details of posted tasks, and answer questions to the requested task. The designer can view the details of his/her participated cases, submit his/her design solutions to the requested task, or work on the requested task collaboratively with other team members in Design Dashboard which is accessed via ‘View’ button. The Design Dashboard will be presented in the prototype for teaming up and collaborative design function. The evaluator can process invitations for evaluating design solutions, view solution details awaiting to be evaluated and evaluate design solutions. The interfaces for these functions will be presented in Section 7.3.3.

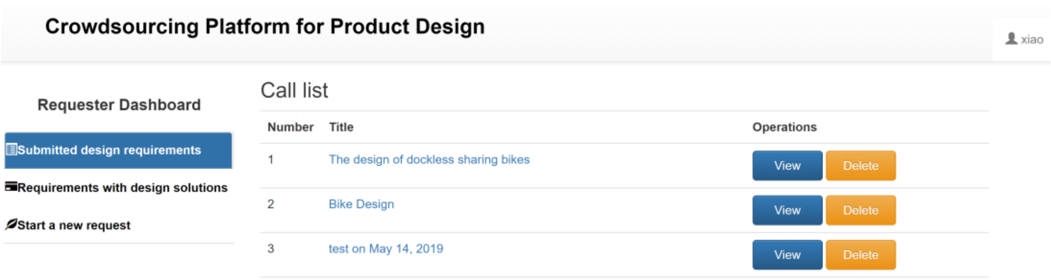


Figure 7-6 The prototyped interface for requester private panel

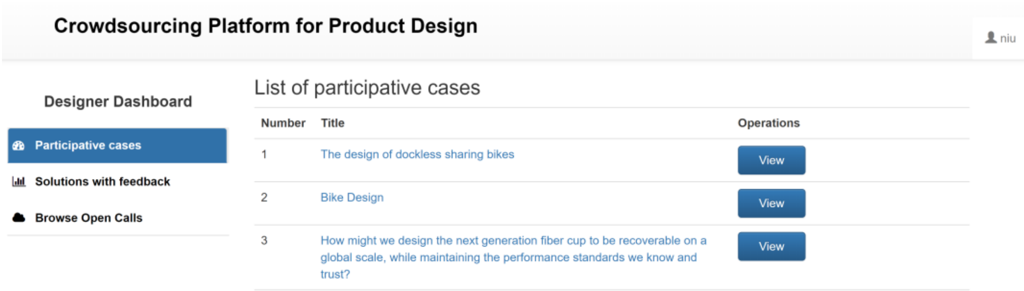


Figure 7-7 The prototyped interface for designer private panel

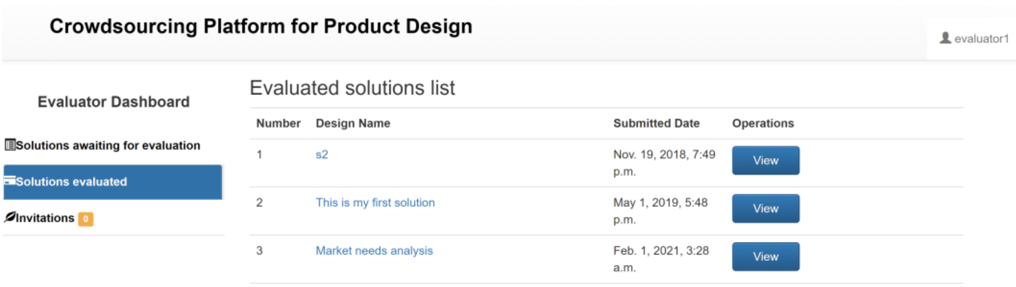


Figure 7-8 The prototyped interface for evaluator private panel

Next, we mainly present prototypes of some key functions: the release of an open design call, ask and answer questions, and the processing of platform messages.

Prototype of call release function

The release of an open design call is the basis of subsequent design work. Figure 7-9 shows the prototype of call release function. Since an open call involves many multimedia elements, such as texts, images, hyperlinks and videos, the platform utilizes a plugin named UEditor to edit these elements, which enables the display style of the open call to be consistent with the editing style. When editing the open design call, the requester can use either his/her own format or the template function to select a default format offered by the platform.

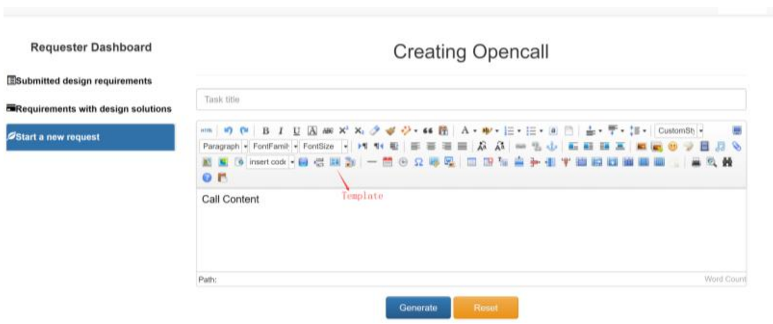


Figure 7-9 The prototype of call release function

Prototype of asking and answering questions function

The function of asking and answering questions plays an important role in performing product design tasks. In the virtual environment, it is impossible for the requester to answer all questioners one by one. When a group of platform users take part in a specific design task, many of them may have similar questions to the design requirements, and therefore, providing a discussion board is a good choice for both the requester and the participant crowds.

Figure 7-10 shows the prototype of asking and answering question function, respectively. As in call release function, the UEditor is applied to ensure questions and answers to be represented in various formats.

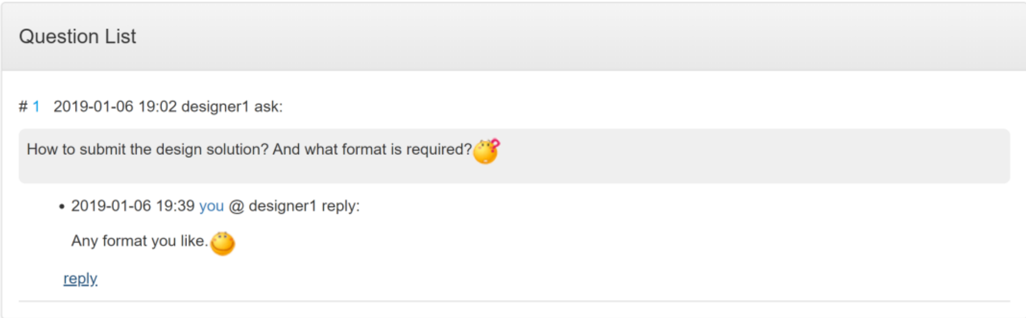


Figure 7-10 Prototype of asking and answering question function

Team up and collaborative design function

On the intermediary crowdsourcing platform, a designer can create a collaborative space to invite other designers to work on the same design. In the group, both one-to-one communication and one-to-many communication are supported. The interface for teaming up and communication is shown in Figure 7-11.

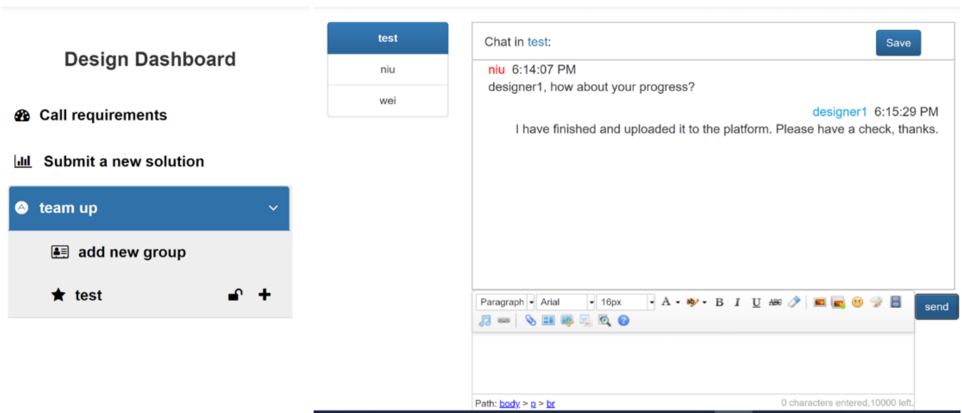


Figure 7-11 Interface for teaming up and communication

7.3.3 Evaluation of the intermediary crowdsourcing platform

Initially, the intermediary crowdsourcing platform is planned to be evaluated by comparative experiments consisting of two groups of designers on the same design project with one group in face-to-face setting and another in virtual setting. The aim of the comparative experiment is (1) to evaluate if the enabling tools in the intermediary crowdsourcing platform are effective in supporting the communication and sharing of design information by information representations supported by the developed PDLIM during an iterative product design process, and (2) to evaluate the user experience during the interaction process to further improve the platform in interaction process and interfaces. However, due to the covid-19 epidemic, it is impossible to conduct the comparative experiments in both face-to-face and virtual environment settings. So this research is limited to only use a case study 'the design of dockless sharing bikes' to simulate the iterative design process to evaluate if the enabling tools can present design information at a specific design phase and communicate it with other design collaborators. The comparative experiments for platform evaluation will be conducted in future work.

In this case study, the iterative market needs analysis phase is taken as an example to demonstrate the crowdsourcing process. In an iteration, at the end of this phase, the submitted staged results are evaluated by appointed evaluators, providing feedback for next phase iteration. The iterative crowdsourcing process of market needs analysis phase for this case study includes five steps.

- Step 1: The requester posts the design call on the platform from requester dashboard. The requester can edit the design call in an UEditor which is much like a word processor. After editing, the requester can post it to the platform. The design call in this case study is shown in Figure 7-12.

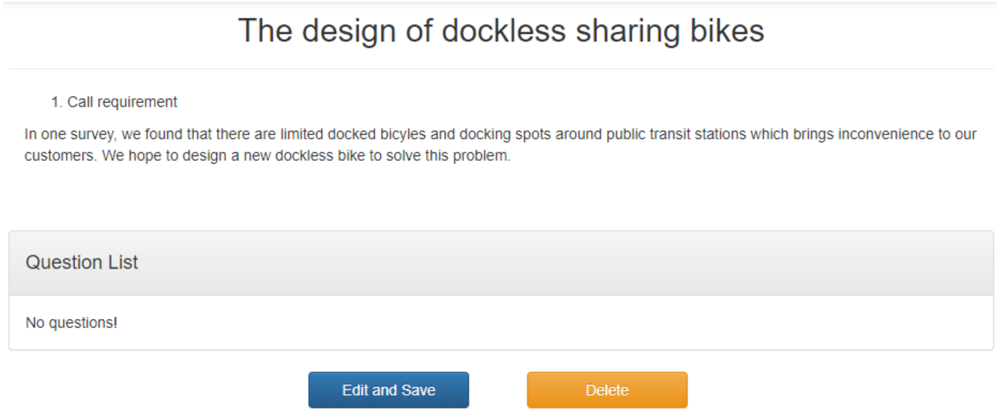


Figure 7-12 Design call posting in the case study

- Step 2: The designer browses the call list from designer dashboard and participates in the design call (see Figure 7-13). Whether the designer participates in the call or not, he/she can ask questions related to the call through provided question dialog. Additionally, he/she can view questions asked by other platform users listed on the discussion board (Question List).

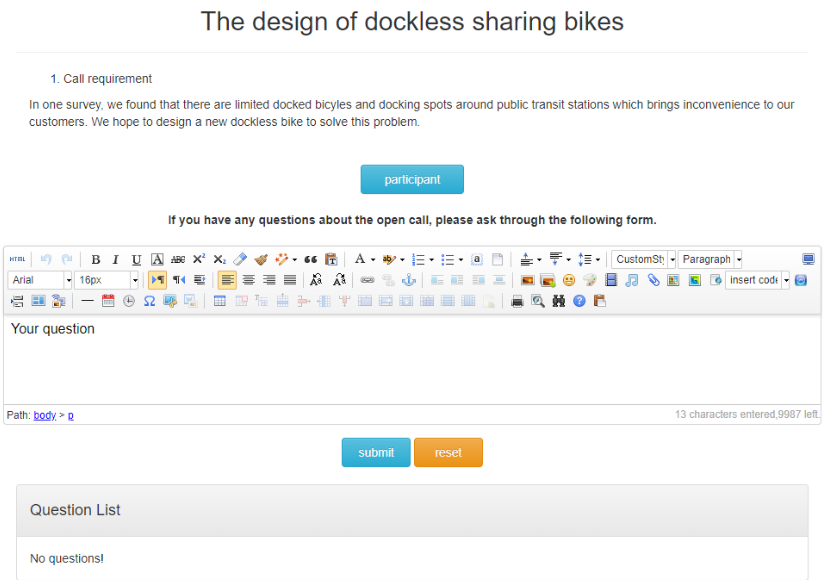


Figure 7-13 Participating in the design call

- Step 3: The designer conducts marketing research and submits the results through pre-defined ‘market needs analysis’ template. On the platform, one template represents one design phase. Before submitting the market needs, the designer can create a collaborative group where he/she can share his/her ideas with the group members.

- Step 4: After submitting market needs successfully, the requester can view the total number of submitted results and view their details (see Figure 7-14). Meanwhile, the platform will distribute the submitted results to qualified evaluators by matching key words. Once the evaluator is selected, an invitation email will be sent to him/her (see Figure 7-15).

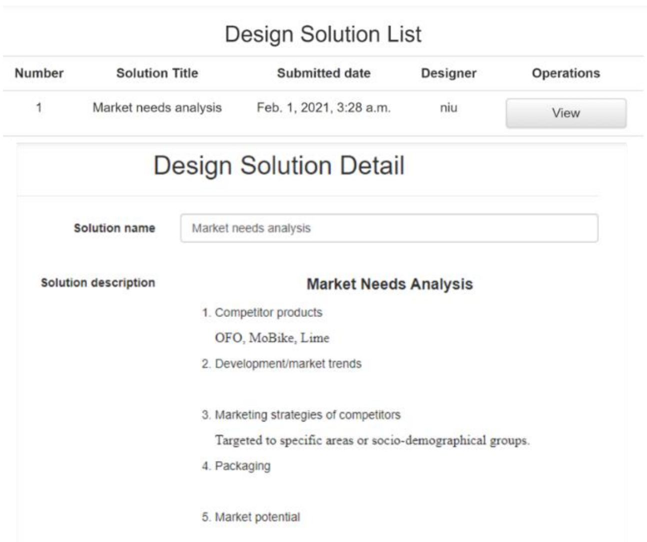


Figure 7-14 Submitted results for market needs analysis

Figure 7-15 Invitation for evaluating submitted design results

- Step 5: If the evaluator accepts the invitation, the accepted task will be shown in the to-do list of his/her dashboard. And with reference to the evaluation criteria, the evaluator can submit his/her evaluation results (Figure 7-16).

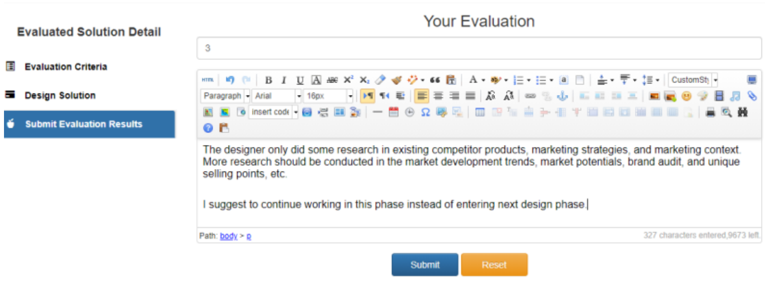


Figure 7-16 Evaluation results to the submitted stage result

- Step 6: After the evaluation results submitted successfully, both the requester and the designer can access the feedback detail as shown in Figure 7-17. Then the designer can improve his/her design accordingly and start the iteration of the design phase.

Figure 7-17 Evaluation feedback

In the evaluation process, the design information recorded in the CJ can be fully represented in the intermediary crowdsourcing platform and can be communicated to expected collaborators for co-design or assessment. Additionally, the changes to design information, such as when it is changed, how it is changed, and who changes it, can be recorded automatically, making it easier to trace how the design evolves in the product design lifecycle.

The core code of the intermediary crowdsourcing platform is provided in Appendix B.

7.4 Feasibility evaluation of the integrated crowdsourcing platform

7.4.1 Background and industrial application context

In the era of Industry 4.0, for the manufacturing industry, digital transformation from physical product-centric base services to customer-centeric intermediate and advanced services (servitization) along its product-service system lifecycle is one of the keys to business success (Lightfoot, Baines and Smart, 2013). And the DT technology underpinned by IoT, Cyber-Physical System (CPS), Big-Data analytics and other Industry 4.0 technologies provides a great potential for supporting and speeding up this digital transformation process (Van der Walt, 2018).

In customer-centric service business, manufacturing industry requires insight not only into the way how a product is manufactured, but also how it is transported, installed, used, repaired, and recycled in real world. The interaction data between the product and various human users is a must to be collected and analysed in a platform. Thus, the platform is required to collect a great deal of data from both physical smart products and human users during their interactions with products and services. Human users include human workers/service providers (such as repairers, installers, retailers, wholesalers, and transporters) and end-users along the product lifecycle. To better coordinate human workers on the platform to serve customers, it is important to make joint availability of data generated by machines and by processes involving humans. Therefore, the platform should be supported not only by IoT enabled smart products but also by Internet of Users (IoU) and Internet of service providers (IoS).

With the increasing variety of digitally enabled services and business models, the ways of delivering services to end users in collaboration with various service providers (or human/crowd workers) will be diversified via various service outsourcing/crowdsourcing (Niu *et al.*, 2018, 2019; Ishizaka *et al.*, 2019) mechanisms. To better satisfy business requirements, it is necessary to integrate crowdsourcing mechanisms into the platform. For one thing, this integration can support new business models based on service outsourcing/crowdsourcing for better product/service quality. For another, it can help model human users' behaviour and service experience and relationship from service interaction data in the platform, in addition to modelling product (machine) behaviours.

Currently, how to develop such a crowdsourcing platform for digitally supporting advanced services is still at its early stage of investigation (Catarci *et al.*, 2019; Mountney *et al.*, 2020; Napoleone, Macchi and Pozzetti, 2020), and few studies are available on how to design and implement a platform along the product-service lifecycle to support customer-centric service business models with service outsourcing/crowdsourcing.

The central problem of developing such a platform is how products, services, networks of "players" or stakeholders and supporting infrastructures can be holistically modelled, connected, and interacted in both the physical space and the mirrored cyber space and be able to collect and utilize user-generated data and product-generated data for smart products and service innovations along the product-service lifecycle. This is due to the limitations of existing DT technology proposed to support the use of virtual models of physical manufacturing asset for typical physical system monitoring, optimization, and control usages. It lacks human behaviour modelling or human DT capability (Bécue *et al.*, 2020).

Under the circumstance, our industrial research partner, a residential/domestic boiler manufacturer, is on its investigation journey of developing platform-based advanced 'Heat as a service' businesses, expecting to create a product-service ecosystem not only involving smart products and smart services, but also engaging all stakeholders (actors) along the lifecycle of smart product and service system evolution. To evaluate the feasibility of the platform-based business concept, this research prototyped the integrated crowdsourcing platform around 'Maintenance as a service' which is one concept under advanced 'Heat as a service'.

A domestic boiler, typically a gas boiler, is used widely in a huge number of homes for heating. As reported by Wendt (2019), in the UK domestic sector, around 85% percent of energy is used for heating. Typically, a boiler as a product can be owned by a householder or a landlord based on the current product-centred business model. Regardless of what the product ownerships are, a boiler itself needs a regular annual maintenance service for reasons including safety check, identifying potential faults, and energy efficiency. For example, landlords in the UK who rent out their property are legally required to have their gas appliances and flues serviced on an annual basis by a certified Gas Safe heating engineer with a visual inspection and prescribed tests. In order to make the boiler product smart, one of the top trends for boiler product development is its better connectivity at product level. It is envisaged that a boiler product enabled by IoT can well connect itself with its consumers, installers, and manufacturer to enable them to be able to remotely monitor and control the product with an intuitive and easy interface (Altun, Tavli and Yanikomeroglu, 2019). Furthermore, a smart boiler or AI-IoT can have advanced features with self-monitoring, self-adjusting and automatic commissioning. Its ability to send out service notices will enable the installing contractor and homeowner to view what is occurring within the boiler and make setting changes remotely.

When the transformation from product-centric business model to service-centric business model during servitization, the ownership of product could change to a product provider such as a manufacturer or jointly with householders or landlords, while the heating services including basic, intermediate, and advanced services (Mountney *et al.*, 2020) need to be provided to the end users such as home residents or tenants by various service providers such as installers, repairers, and annual service providers. The better connectivity is also required at the service level to connect the smart product to its owners such as landlords, end users (residents or tenants) and service providers. These greater connectivity around the product itself and associated services will enable the collection of performance data along the product lifecycle, which could be used to support the smart product and service ecosystem development.

7.4.2 Development roadmap of the integrated crowdsourcing platform

To maintain the competitiveness of a manufacturing business under such service-oriented business environment, a roadmap is proposed to develop an integrated crowdsourcing platform integrating both the 'sales' and 'purchase' sides (see Figure 7-18) while engaging customers and business stakeholders, including manufacturers and service providers, to support service innovations along product-service development lifecycle. The roadmap supports the following business objectives:

(1) Support increasingly demands on customized products/services and manufacturing capabilities to rapidly respond to market needs at different market segments, greater integration of in-company manufacturing resources/capabilities and outsourced/crowdsourced ones from global and/or local regions, integration of products and services and service delivery.

(2) Ensure better customer or third-party engagement in product design, manufacturing and maintenance as advanced services require very high levels of integration between the focal firm, customers and suppliers (Raja *et al.*, 2018). Thus, the platform is required to link with not only physical products (devices) via IoT, but also various human participants (actors) via Internet of human being. So putting them together, the platform needs to extend its support from IoT to the Internet of Beings (IoB); thus, both the performance of a product or service and the performance of human participants with their user experience (UX) will be captured and utilized in the platform.

(3) Support the development of innovative business models around the concept of ‘Everything as a Service (XaaS)’ on ‘Purchase side’ such as Design as a Service and Maintenance as a Service. On the ‘Sales side’, selling points could include input-oriented services such as the installation of new equipment, maintenance, and spare parts delivery and output-oriented services such as pay by use, uptime guarantee and pay by performance (Meierhofer *et al.*, 2020).

(4) Support the prevailing business paradigm of open innovation 2.0 (Tao *et al.*, 2019) with data support from end users and end products/services.

(5) Support both lifecycle and low-carbon development principles for product and service systems.

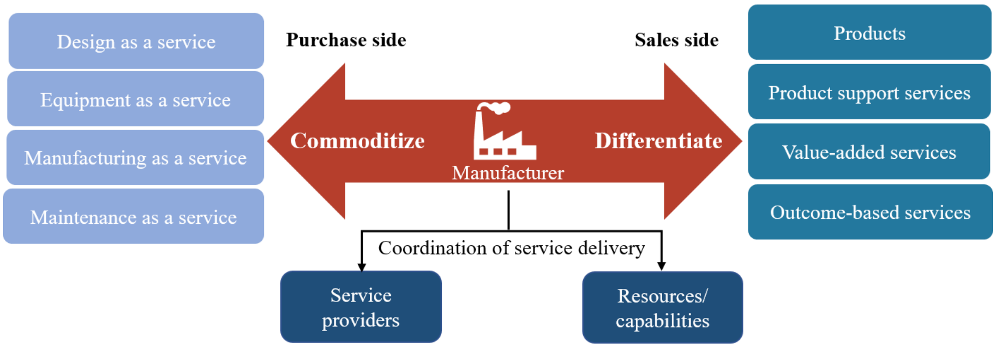


Figure 7-18 Development roadmap for the integrated crowdsourcing platform

From this development roadmap, customer-journey maps around each service concept or selling point can be explored first and then the requirement for the platform supports will be identified as a basis for the detailed platform design and development.

7.4.3 Development of the integrated crowdsourcing platform

7.4.3.1 The conceptual model

Based on the industrial application context and in order to support the business objectives, a conceptual model of the DT platform was developed. It can be used as a cloud-based manufacturing platform, having its frontend as a Web App and its backend as a Web service, underpinned by new business models, service-/crowd-sourcing, product, service and user DT technologies supported by IoT, IoU, and IoS. It will not only integrate existing smart products with smart services, but also engage all stakeholders such as customers and service providers along the lifecycle of smart product and service system evolution. The conceptual model of the DT platform for smart PSS is shown in Figure 7-19 as a close loop.

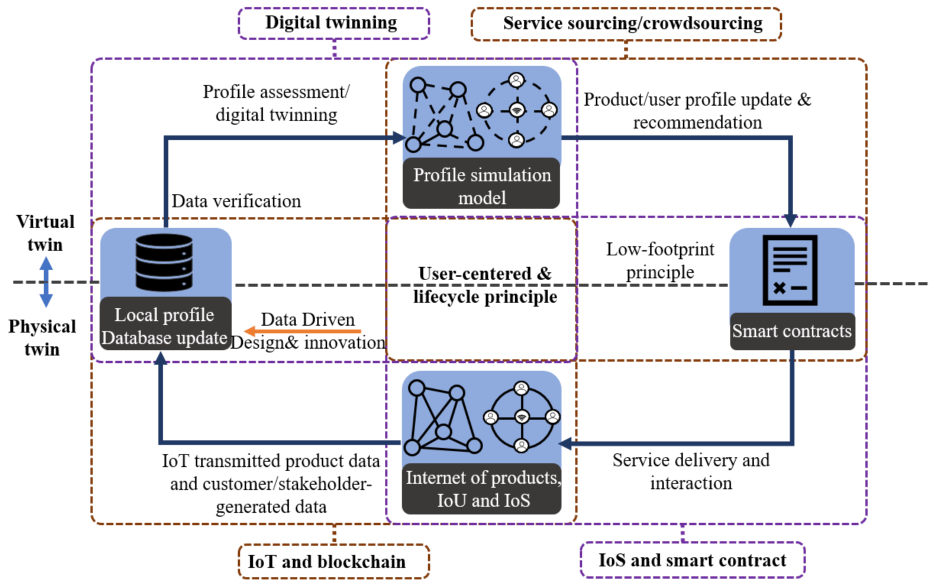


Figure 7-19 The conceptual model of the integrated crowdsourcing platform with information flow

In the conceptual model, the digital twinning process could start from the smart product generated data such as an annual service notice to landlords or householders or customer-generated data such as a repairing or training service request in the physical world. Once these data are verified by the platform based on IoT and Blockchain technologies, a service request is confirmed, crowdsourcing-based service sourcing will be performed in the virtual world based on the profile (simulation) models of the product, users, and service providers with their virtual twins, and as a result, a smart contract on the service provider, service requester and service delivery will be formed. Finally, the smart contract will be executed, and the requested service will be delivered in the physical world, resulting in the physical product status changes as virtual-to-physical twining. In this loop, all data associated with the service and generated by both the machine and the human users will be recorded and the associated databases will be updated. Thus, when a service is delivered physically, the changes in user-generated data are combined with the product generated data via IoT, IoU and IoS to trigger a physical-to-virtual twinning that updates their corresponding profile models of the product, service, and users. These updated profiles of a machine and human stakeholders will feed forward to the next round service outsourcing, crowdsourcing and service recommendation for delivering next round services.

The web App (User client) will link the updated virtual models to related digital serving tools to deliver better services. For example, by assessing service providers according to their availability, location, or historical service quality and then recommending most appropriate provider to the customer according to the low-footprint principle.

7.4.3.2 The architecture of the integrated crowdsourcing platform prototype

With inspiration from the integration architecture of blockchain with crowdsourcing and DT (Altun, Tavli and Yanikomeroglu, 2019; Li *et al.*, 2019), the conceptual model of the integrated crowdsourcing platform in Figure 7-19 can be realized by its five-layered computational architecture as shown in Figure 7-20. The five layers are the service layer, perception layer, application layer, blockchain layer, and storage layer.

Service layer packages capacities and resources as services to serve stakeholders involved in the product-service ecosystem. Perception layer perceives the real-time status of smart products in physical space enabled by IoT infrastructure. These two layers form the network of humans and products, respectively. The application layer consists of user client and DT-based crowdsourcing platform. User client is designed for role players involved in the product-service ecosystem including requesters, crowd workers acting as designers, evaluators, installers, and other stakeholders as web-based user interface that allows users to interact with the underlying blockchain. The DT-based crowdsourcing platform implements connections not only among platform users but also between physical product and its virtual counterpart enabled by IoT devices. When requesters post tasks through user client, the platform will design the tasks and transform them into the smart contracts of blockchain, then the platform crowdsources the tasks to crowd workers with expected skills. In addition, the source of physical product data is also transformed into the smart contract to enable the reliability of physical product data. To improve the capability of data storage in the platform, the blockchain layer only stores task/service request metadata such as task owner, hash value, and pointer, while the large number of raw data collected from tasks, users, and physical products are stored in the storage layer. Thus, the users can verify the integrity and reliability of data and their sources. Since the developed architecture is based on CrowdBC (Li *et al.*, 2019), here only the application layer is detailed.

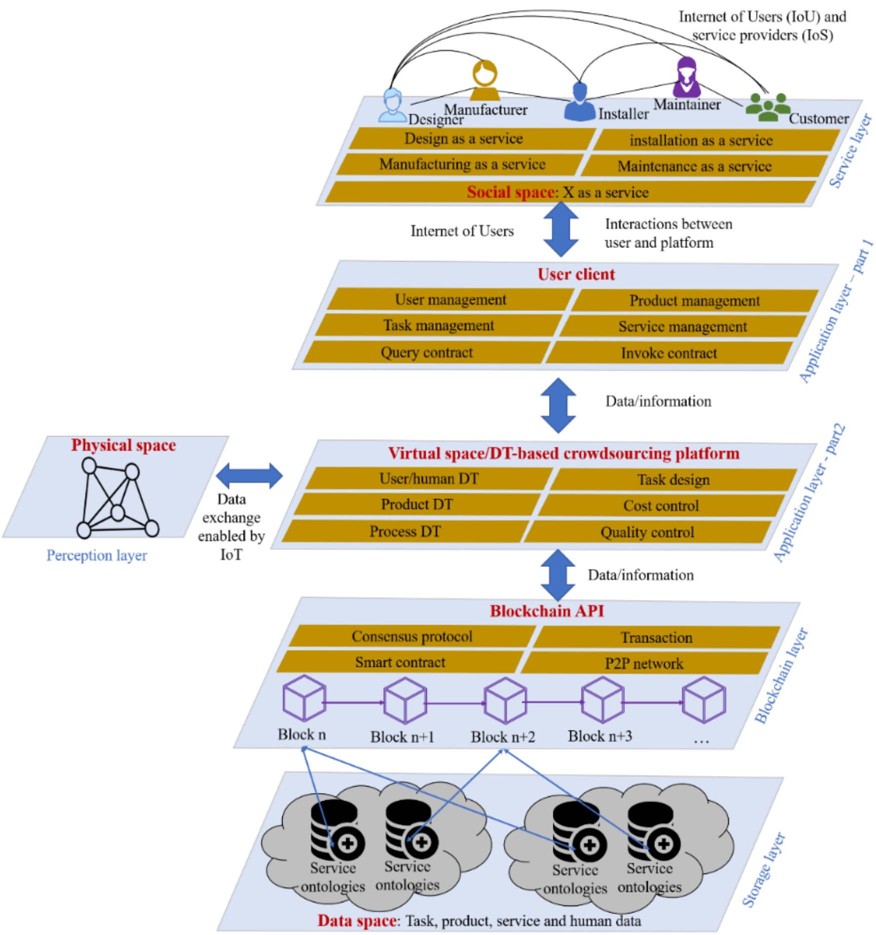


Figure 7-20 The overall architecture of the integrated crowdsourcing platform

User Client mainly provides users with entrance to finish a crowdsourcing task/service request. It consists of four modules: User management (UM), task management (TM), product management (PM), and service management (SM). UM mainly helps user registration and user profile management. User registration is the first action the user should do in the integrated crowdsourcing platform. They only need to register with public key and address (post code), and their initial reputation values will be automatically assigned as defaults and will be updated through digital twinning in the due course. The user can register successfully only when their registration data are transformed to the blockchain layer successfully. Then, he/she can post or receive tasks/service requests.

TM is used to write the crowdsourced task/service request into the blockchain, including task posting, task crowdsourcing, task receiving, task execution, and reward assignment. Remarkably, to enable the satisfactory outcome of task execution, only qualified crowd workers can receive the task request. PM and SM are responsible for depicting the smart product and corresponding services around the product into the blockchain when they are added to the product-service ecosystem and when interactions among product, service, and users happen. The detailed description about the smart contract used in these four modules will be given in section 7.4.4.3.

Once the data in databases are sufficiently rich, they will be able to drive both updates of existing products/services and development of new products/services from a data-driven product/service design perspective. In this way, the data updates and virtual model updates are happening in turn to support a gradual and incremental digital twinning process along the product/service lifecycle, making the manufacturing system into an ecosystem.

7.4.4 Realizing technologies and prototyping

7.4.4.1 Service ontology description

In order to define various services for data capturing and service twinning, service ontology description is used to identify the necessary building blocks for describing services, defining the general concept of a service (Ameri and Dutta, 2006). In the integrated crowdsourcing platform, service is a set of design, manufacturing, installation, and maintenance capabilities that are delivered by stakeholders involved in the ecosystem through service processes and enabled by service resources. As the provision and upgrade of the services around a product are driven by customer needs/requirements, customer needs are treated as the starting point of the service ontology. The service ontology for this product-service ecosystem is developed from a design perspective based on a literature survey to communicate and reuse the applicable knowledge in the domain.

On the platform, the information flow including both the forward and backward ones should be captured among products, services, and involved stakeholders (Hajimohammadi, Cavalcante and Gzara, 2017). To cover these interactions, the service ontology in the product-service ecosystem should elicit the information flow throughout the product-service lifecycle. Using the identified root concepts such as customer needs, stakeholders, infrastructure, business elements, business models, supply network and benefits for describing ontology of product service system (Annamalai *et al.*, 2011), we extract the concepts with a direct effect on service ontology within the ecosystem. The properties to each concept (class/entity) in the service ontology can be found in literature (Ameri and Dutta, 2006; Annamalai *et al.*, 2011; Hajimohammadi, Cavalcante and Gzara, 2017). To describe the service ontology, ORM is selected to graphically express knowledge about the identified concepts and their interrelations.

The developed service ontology for the product-service ecosystem represented in Figure 7-21 is developed with NORMA.

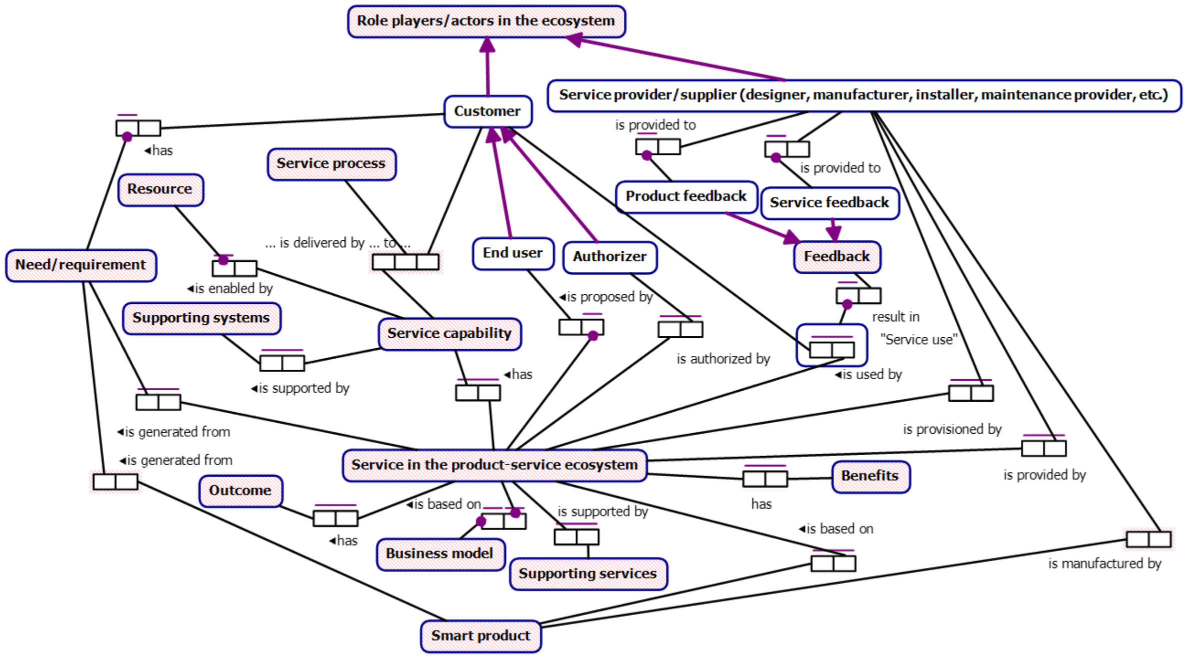


Figure 7-21 Service ontology for the integrated crowdsourcing platform

The core concepts/classes of the service ontology are described below:

- **Customer needs/requirements**: This is the central class of the service ontology because services cannot exist without the root cause.
- **Feedback**: This is another central class of the service ontology because it promotes the evolution of the product-service ecosystem. In the ecosystem, it consists of two subclasses: product feedback and service feedback.
- **Services in the ecosystem**: The services including design, manufacturing, installation, and maintenance etc. are formally defined as service classes. Any instance of the service class is related to one service process and is enabled by some service resources such as machines and tools. Also, it is supported by some supporting systems such as communication system and is based on a specific business model. A service delivers expected outcome to end users and bring benefits to involved actors in the service

process. Initially, the service is requested by the end user and authorized by the authorizer. The authorizer is usually the owner of the product that the requested service is based on.

- **Service providers/stakeholders**: Service providers are responsible for delivering the services such as product delivery, installation, and repair to customers.
- **Smart product (Intelligent IoT)**: Smart products are designed with embedded sensors or SIM card so that they can transmit the real-time data of the product to the server. The services such as product delivery and maintenance are based on the smart products.

7.4.4.2 Implementation of the integrated crowdsourcing platform

This section details the realizing technologies that enable the information flow of the integrated crowdsourcing platform conceptual model in Figure 7-19.

7.4.4.3 Realization technologies

Service-/Crowd-sourcing

Posting a service request is regarded as a start point of the ecosystem evolution. Crowdsourcing integrating with service recommendation is considered as a tool to find the right service providers (crowd workers) with best value for the tasks/services required. Therefore, we formulate the service crowdsourcing problem into a combinatorial optimization one. The goal is to find a small set of service providers from a big crowd pool based on a requested service (task) profile by broadcasting the service request with highest possibility of finding at least one qualified service provider and the minimum unnecessary information burden to the rest of service providers in the pool.

Before proceeding further, we start with the following definitions from an overall perspective of the product-service ecosystem based on ordinary crowdsourcing (Yuen, King and Leung, 2011b; Li, 2015).

Definition 1: A product-service ecosystem based on a crowdsourcing platform can be described as a time-related state system with a 5-tuple (M, O, W, C, S).

(1) $M = \{m_a | a = 1, 2, \dots, M_N\}$ is a set of machines on the crowdsourcing platform and M_N is the total number of machines. Assuming that a machine is only used by one end user and owned by an owner at time t, then corresponding end users (such as tenants) set is donated by $C = \{c_b | b = 1, 2, \dots, M_N\}$ and the owners (such as landlords) set by $O = \{o_x | x = 1, 2, \dots, O_N\}$, where $O_N \leq M_N$. A new service request could be initiated by a machine m_i's owner $o_x, x \epsilon [1, O_N]$ after receiving the system remainder and problem report from the corresponding end user c_i .

(2) $W = \{w_y | y = 1, 2, \dots, W_M\}$ is a set (pool) of service providers who work on service requests on the crowdsourcing platform and W_M is the total number of service providers.

(3) $S = \{s_i | i = 1, 2, \dots, S_N\}$ is a set of service packages around machines and S_N is the total number of service packages.

In the product-service ecosystem, each key element can be regarded as a live being-B such as a machine, its states at time t can be described as triple (B^{t-}, B^{t}, B^{t+}). B^{t-} represents its history state, B^{t} represents its current state and B^{t+} represents its future state. Exemplar data to describe each state for each element are shown in Table 7-2. In this ecosystem, B^{t-} is used for service/crowd-sourcing, B^{t} is used for service provider recommendation, and B^{t+} is used for representing the updated states of beings after smart contracts end.

Table 7-2 Being state descriptions

Symbol	**History state B^{t-}**	**Current state B^{t}**	**Future state B^{t+}**
$\boldsymbol{M}$	Design and manufacturing related data, service history record data, historical performance data, etc.	Machine's current performance data, warning information or codes and/or faculty codes transmitted by IoT devices, etc.	Predictive maintenance or scheduled annual service/check, etc.
$\boldsymbol{O}$	Location and contact information, the machine ownership history and the machine service management history, etc.	A service request, urgency, current availability, etc.	Appointments for scheduled machine service and planned ownership change, etc.
$\boldsymbol{C}$	Location and contact information, the machine usership history and the machine service management history, etc.	A service request, urgency, current availability, etc.	Appointments for scheduled machine service and planned usership change, etc.
$\boldsymbol{W}$	Location and contact information, crowd qualifications, professional training and certifications, experience and quality of the previous services on M, pricing history for the services, etc.	Current location, availability, pricing expectation, etc.	Appointments for delivering services, etc.
$\boldsymbol{S}$	Service design and associated business models, service quality and associated user experience, service history data, etc.	Service requests to be processed with current resource constraints, etc.	The following up service scheduling, etc.

Definition 2: A service task T_i is related to M_i and generated from the inputted request R_i which is started by C_i and authorized by O_i. With a service analysis tool f, T_i can be defined with five dimensions: complexity (P), required skills (K), estimated service cost (SC), urgency level (SL), and detailed service request description ($):

$$T_i = f(M_i, R_i, O_i) = T_i < P, K, SC, SL, \$ > \tag{7.1}$$

Based on the previous definition, given a service task T_i around machine M_i, broadcasting T_i on the crowdsourcing platform to a sub-set of W who are qualified to take the service job. For each candidate $W_j (j = 1, 2, \dots, \phi)$, the following constraints must be met. ϕ can be a predefined small number such as 10 for crowdsourcing in order to minimise the unnecessary interruption to most of the members in W.

Constraint 1: Potential service provider w_j must have the skills required by the task. Denoting the threshold for measuring the minimum value between two skills as ε_1, then the constraint 1 can be formulated as

$$dis1(w_j) = distance(w_j(K), T_i(K)) \geq \varepsilon_1 \tag{7.2}$$

Constraint 2: The estimated service cost is close to the service provider's historical average price for similar services. Denoting the cost threshold as ε_2, then constraint 2 can be formulated as

$$dis2(w_j) = distance\left(\overline{w_j(Cost)}, T_i(SC)\right) \leq \varepsilon_2 \tag{7.3}$$

Constraint 3: The potential service providers must be locationally close to machine M_i to have a shorter traveling distance for lower CO_2 footprints from the service. Denoting the distance threshold as ε_3, then constraint 3 can be formulated as

$$dis3(w_j) = distance(w_j(location), M_i(location)) \leq \varepsilon_3 \tag{7.4}$$

Constraint 4: The performance of the potential service providers must be accepted by the service requester. Assuming that the accepted performance and performance threshold are denoted by θ_p and ε_4, then the constraint 4 can be formulated as

$$dis4(w_j) = distance\big(w_j(performance), \theta_p\big) \le \varepsilon_4 \tag{7.5}$$

To measure the performance of a service provider w_j in constraint 4, we quantitively describe it by a 3-tuple (AR, CS, SQ) where AR, CS, and SQ denote acceptance rate, customer satisfaction and service quality, respectively.

(1) Acceptance rate $AR(w_j)$ of service provider w_i:

$$AR\big(w_j\big) = \frac{Num(T_{accepted}(w_j))}{Num(T_{all}(w_j))} * 100\% \tag{7.6}$$

where $Num(T_{all}(w_j))$ and $Num(T_{accepted}(w_j))$ denote the overall and accepted number of service tasks taken by w_j.

(2) Customer satisfaction $(CS(w_j))$. Assuming service provider w_j has taken N service tasks, and the customer satisfaction scores marked by end users are denoted by $CS_i, i \in [1, N]$, then the average customer satisfaction of w_j is calculated by

$$\overline{CS\big(w_j\big)} = \frac{\sum_{i=1}^{N} CS_i(w_j)}{N} \tag{7.7}$$

(3) Service quality $(SQ(w_j))$. Assuming service provider w_j has taken N service tasks, and the service quality scores marked by end users are denoted by $SQ_i, i \in [1, N]$, then the average service quality of w_j is calculated by

$$\overline{SQ\big(w_j\big)} = \frac{\sum_{i=1}^{N} SQ_i(w_j)}{N} \tag{7.8}$$

Then normalize $\overline{CS\big(w_j\big)}$ and $\overline{SQ\big(w_j\big)}$ through Min-Max Normalization to make them belong to [0, 1], and the normalized customer satisfaction and service quality are denoted by

$\overline{CS(w_j)}^* \ and \ \overline{SQ(w_j)}^*$. If the weightings of acceptance rate, customer satisfaction, and service quality are denoted by q_{AR}, q_{CS}, and q_{SQ}, respectively, then the historical performance of w_j is formulated as

$$W_j(performance) = AR(w_j) * q_{AR} + \overline{CS(w_j)}^* * q_{CS} + \overline{SQ(w_j)}^* * q_{SQ} \qquad (7.9)$$

Constraint 5: The selected ϕ service providers must have the maximum skills, best performance, and the minimum service cost and distance. Assuming the weighting functions for constraint 1, 2, 3, and 4 are donated by f_1, f_2, f_3 and f_4, respectively, then the constraint 5 can be formulated as

$$\min \sum_{j=1}^{\emptyset} \frac{dis2(w_j)*f_2 + dis3(w_j)*f_3}{dis1(w_j)*f_1 + dis4(w_j)*f_4}, \emptyset \in [1, W_M] \qquad (7.10)$$

With Formula (2) to (10), ϕ service providers satisfying constraints will be screened out as candidates that will receive the broadcast of the requested service.

Service provider recommendation

Service provider recommendation is one typical application scenario of recommendation algorithms which have been one of the research hotspots for many years to suggest proper items to users. On a crowdsourcing platform, recommendation principles such as low-footprint, superior quality and whole lifecycle principles are usually adopted (Mountney *et al.*, 2020), and they should be balanced during the recommendation process to provide high-quality services around products to customers/end users while bring maximum benefits to involved actors. For worker recommendation in crowdsourcing context, the jointly considered factors include skills and activeness of the worker (Liu and Chen, 2017). Besides these factors, we also consider their availability and location at the expected service time, and their real quote for providing the requested service to calculate their recommendation priorities denoted by $Rank$.

When the ϕ service providers receive the crowdsourcing call, they are required to confirm their availability and provide their quotes for the requested services. Assuming that their availability, locations, and quotes are donated by A, L, and Q, respectively, if w_j is not available at the expected service time, then $Rank\left(w_j\right) = 0$, or the rank of w_j should be re-calculated.

When w_j provides his/her real quote $Q(w_j)$ and current location $L(w_j)$, the $dis2$ and $dis3$ will be updated as

$$dis2'(w_i) = distance(Q\left(w_j\right), T_i(SC)) \tag{7.11}$$

$$dis3'(w_i) = distance(L\left(w_j\right), M_i(Location)) \tag{7.12}$$

Then based on low-cost recommendation principle, the rank of w_j is

$$Rank\left(w_j\right) = \frac{dis2'(wi) - dis2_{min}}{dis2_{max} - dis2_{min}} * 100\% \tag{7.13}$$

where $dis2_{max}$ and $dis2_{min}$ denotes the maximum and minimum distance the quotes to estimated service cost, respectively.

Based on low-carbon footprint recommendation principle, the rank of w_j is

$$Rank(w_i) = \frac{dis3'(w_j) - dis3_{min}}{dis3_{max} - dis3_{min}} * 100\% \tag{7.14}$$

where $dis3_{max}$ and $dis3_{min}$ denotes the maximum and minimum distance the locations to machine location, respectively.

Although the rank of the ∅ service providers has been calculated, which one will be chosen for performing the requested service is determined by the service requester.

Smart contract

Smart contract is a disruptive technology for business processes (Zheng *et al.*, 2020). It enables contractual terms of an agreement to be enforced automatically without intervention and verification. Smart-contract-based online crowdsourcing mechanism has been investigated to enable trust among crowdsourcing participants, information and privacy security (Gu, Chen and Wu, 2018). In this product-service ecosystem, five smart contract templates, User Profile Contract (UPC), Product Profile Contract (PPC), Service Profile Contract (SPC), Task Profile Contract (TPC), and Requester-Worker Relationship Contract (RWRC) have been implemented to support the service coordination process. The structure of smart contracts in product-service ecosystem and their relationships are shown in Figure 7-22.

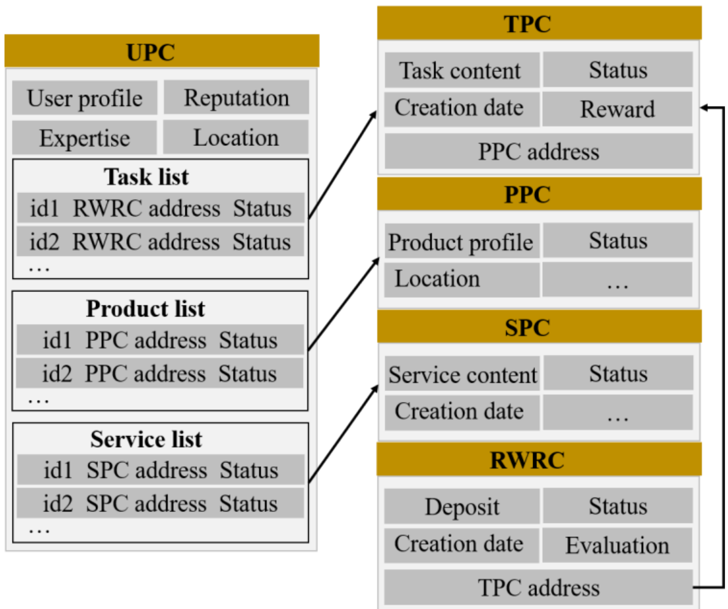


Figure 7-22 The structure of smart contracts in the product-service ecosystem and their relationships

UPC is used to register user roles in the product-service ecosystem. It stores the personal information like expertise, profession, location (post code), service acceptance rate, customer satisfaction score, and service quality score etc. Service acceptance rate, customer satisfaction score, and service quality score are key reputation indicators and they are updated automatically based on user's past behaviours and cannot be changed by the user and any single third party. The UPC also includes a task list that the user has received, a product list that the user provides, and a service list that the user offers.

PPC, SPC and TPC are used to describe smart product, service, and task/service request profiles. The information contained in PPC mainly includes product identifier, product location, and status, etc. SPC is to describe service content, creation date, and status, while the TPC is to depict task description, status, and reward, etc.

RWRC is used to describe the relationship among requester and crowd worker in terms of locations, deposit, evaluation results to the requested service, and status etc. When the requester posts the service request and pays the deposit successfully, the RWRC will be generated automatically and be ready for crowdsourcing. In the due course, with the task accepting, task performing, service evaluating, and reward assigning information, the RWRC status and UPC reputation indicators will be updated.

When a requested service T_i is finished/the smart contract RWRC containing T_i ends, the machine status and the profile of the selected service provider w_i, primarily the acceptance rate, customer satisfaction score and service quality score will be updated automatically. Denoting the service satisfaction score and service quality score given by the end user as $Score_{CS}$ and $Score_{SQ}$, then the updated scores are:

$$CS(w_i)^+ = \frac{\overline{CS(w_i)} * Num(T_{all}(w_i)) + Score_{CS}}{Num(T_{all}(w_i)) + 1} \tag{7.15}$$

$$SQ(w_i)^+ = \frac{\overline{SQ(w_i)} * Num(T_{all}(w_i)) + Score_{SQ}}{Num(T_{all}(w_i)) + 1} \tag{7.16}$$

The acceptance rate is updated by:

$$AR(w_i)^+ = \begin{cases} \frac{Num(T_{accepted}(w_i))}{Num(T_{all}(w_i))+1} * 100\%, T_i \text{ is not accepted.} \\ \frac{Num\left(T_{accepted}(w_i)\right)+1}{Num(T_{all}(w_i))+1} * 100\%, T_i \text{ is accepted.} \end{cases} \tag{7.17}$$

Blockchain-enabled data cross verification mechanism

Most existing manufacturing systems adopt unauthorized access control mechanisms where cybersecurity attacks such as free riding and false reporting (Kogias *et al.*, 2019; Zhu *et al.*, 2020) often happen. To improve data integrity, data security, and nonrepudiation in existing crowdsourcing systems (Kogias *et al.*, 2019; Li *et al.*, 2019), blockchain is utilized to provide a secure environment for running smart contracts. It allows sharing accessible, transparent, and trusted information among participants. Here, blockchain concept is mainly used to cross verify information in terms of information sources and information reliability.

(1) Verification of information sources. The DT-enabled product-service ecosystem dynamically establishes relationships among ecosystem entities including machines, machine owners, service providers, and end users, etc. Thus, the transactions between peers or role players can be found and verified following certain agreed rules (Kogias *et al.*, 2019). For example, when a machine-based service request comes in, the platform is required to validate the request through two steps. First, it retrieves the machine information with the machine ID from database to check if the service is requested by the right machine owner. Then it retrieves the real-time machine status transmitted by IoT devices to check if the machine status matches the problem in service request. After the service request is validated, the platform will analyse the machine maintenance history to predict service complexity, required qualification skills, estimated service cost, and urgency level for processing the service request.

(2) Verification of information reliability. In the product-service ecosystem, all DTs including user DT, product DT, and service DT are managed by blockchain so that they are trusted. Additionally, transparency in the ecosystem is enforced by smart contracts that enable only authorized user to view related transactions. For example, to ensure the reliability of service providers, their performance, i.e., acceptance rate, customer satisfaction score, and service quality score, is only marked by end users who use the machine. And during the service crowdsourcing process, only the involved users, namely the end user requesting the service, the machine owner, and crowd workers accepted the service request can view the service process details.

7.4.5 Evaluation of the integrated crowdsourcing platform

The primary goal of the integrated crowdsourcing platform is to build an ecosystem involving not only the network of smart products but also the network of users and stakeholders. The incrementally evolving process of the product-service ecosystem supported by the integrated crowdsourcing platform and its effectiveness in delivering services are evaluated by the case study 'Heat as a service'.

7.4.5.1 Case study background

The case study 'Heat as a service' is a collaborative project funded by the EPSRC (the Engineering and Physical Sciences Research Council). Figure 7-23 shows the ecosystem scope and key actors over time in the case study. Initially, the entities in the ecosystem include the manufacturer and machines (their interaction is represented by the red line between them). Next, when machines are sold out to or rented by customers/social housing landlords, landlords join the ecosystem, making the ecosystem role players increase to 3 (light blue area). Then when a tenant signs tenancy contract with the landlord, tenant role is added to this ecosystem (the light blue and red area) and mainly has interactions with the machine and the landlord.

When some problems occur to the machine, the tenant reports the problem to the landlord and then the landlord coordinates with service providers in the ecosystem (the light blue, red, and plum area) to deal with reported problems. In the ecosystem, the connections among key system actors are established dynamically and incrementally.

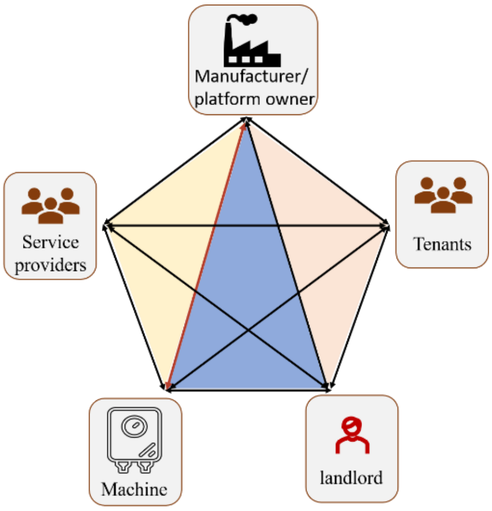


Figure 7-23 The platform ecosystem scope and key actors over time

7.4.5.2 Evaluation by 'Maintenance as a service' concept

In this case study project, 10 advanced service concepts in total have been identified (Mountney *et al.*, 2020). Here, service concept 1 and 2 (shown in Table 7-3) were chosen to evaluate how the physical machine interacts with its virtual model (simulated machine with digital ID) in the ecosystem and to simulate the crowdsourcing and data validation process. Under each service concept, possible advanced services are identified as listed in Table 7-3. The key role players in these service concepts include machine, landlord, tenant, and serviceman/engineer. Tenants and landlord act as end users and authorizer, respectively. Servicemen/engineers act as crowd workers.

Table 7-3 Key features of SC1 and SC2 identified in literature (Mountney *et al.*, 2020) and the corresponding advanced services

Service concept (SC)	**Key features**	**Advanced services under the concept**
SC1-Getting the gas and heating up and running for the customer	An advisory/intelligent system/liaison type service that guides the tenant through this process.	(1) An advisory service (2) Interactive and intelligent training on routine operations as a service
SC2-Managing access around the annual gas safety check	Opening up communication channels with the tenant and scheduling inspection visits based on engineer locations and availability	(1) Service engineers' training and certification as a service (2) Crowdsourcing or service outsourcing as a service (3) Smart contract enabled 'warm hours' as a service (4) User Experience as a Service (UXaaS) embedded in the smart service recommendation

Key interface prototypes based on 'Maintenance as a service' concept

Around SC1 and SC2, the key interfaces for key actors involved in the ecosystem were prototyped in Figure 7-24, Figure 7-25, and Figure 7-26, respectively. Different actors have different operation permissions on a specific machine. The detailed introduction to the functions implemented on these interfaces and their interactions with landlord, tenant, and serviceman can be found in Appendix D.

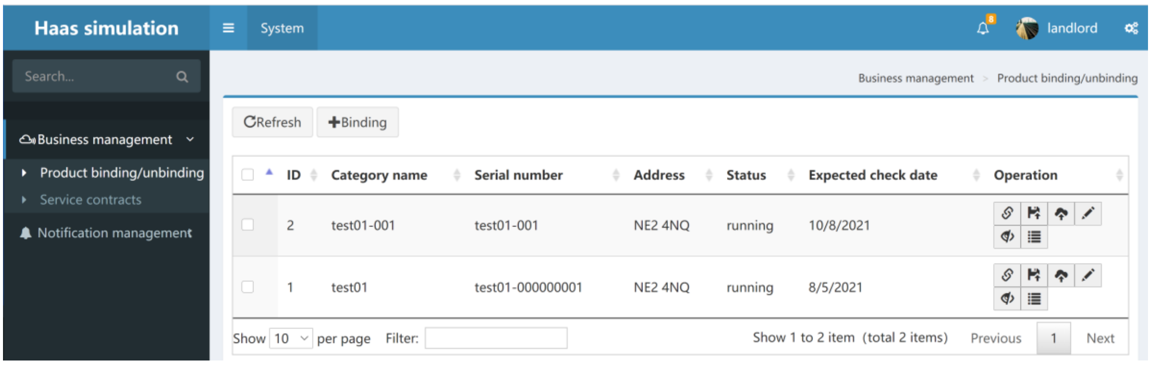


Figure 7-24 Key interface prototype for landlord

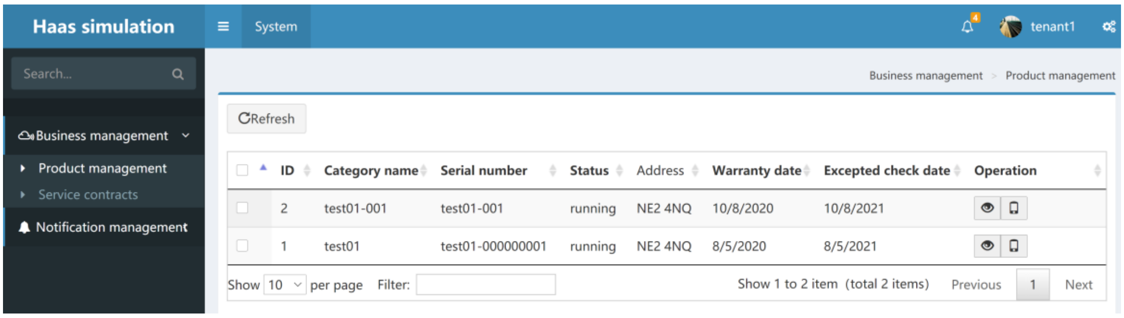


Figure 7-25 Key interface prototype for tenant

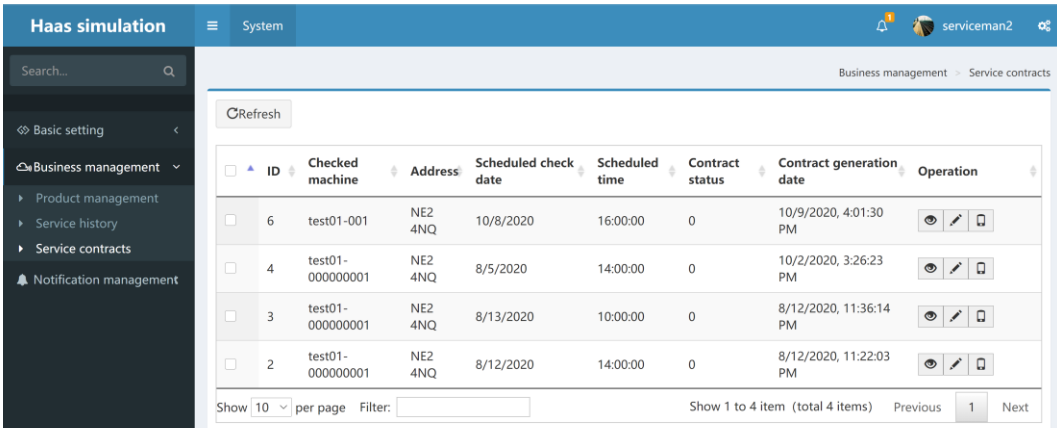


Figure 7-26 Key interface prototype for serviceman/engineer

Evaluation of SC1

SC1 shows how a physical machine interacts with the virtual one. The physical machine and its virtual one is connected by a SIM card or an embedded sensor. The virtual machine can reflect the real-time status of the physical machine and make the physical machine respond to user's (landlord's and tenant's) input data, especially machine operation instructions. For example, when the machine is under repair, if the user tries to turn it on, the alert information will be communicated to the corresponding user on the virtual machine and the status indicators on the physical machine will be changed to red. The simulated virtual machine interface is shown in Figure 7-27. The key commands for controlling a machine and key status indicators, such as power, repair, machine working mode, and mode level are simulated by buttons. Through the simulated buttons, a step-by-step training on routine machine operations can be realized.

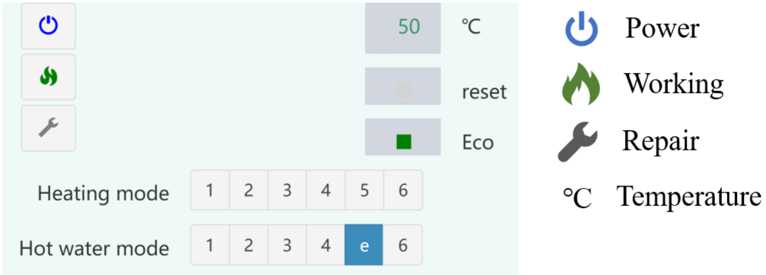


Figure 7-27 Simulated virtual machine interface

Evaluation of SC2

Under SC2, these identified advanced services form three typical scenarios, namely online routine machine check, offline routine machine check, and annual machine check. Taking annual machine check as an example, the service interaction process among involved participants is illustrated in Figure 7-28, consisting of four steps: service appointment, crowdsourcing and service recommendation, smart contract, and service evaluation. The achievement of the service process is supported by the following developed tools, such as communication tools among landlord, tenant, and serviceman, bind/unbinding machine tool, and service history track tool, etc.

Service appointment

The annual check date is determined by the installation date of the machine. Before a given period of the expected machine check date, such as two weeks, the machine DT (simulated machine) automatically reminds the tenant to request annual machine check with the landlord. When the machine DT notifies the tenant to check the machine, the tenant is required to request the service from the landlord. After the landlord authorizes the service request, the DT-based crowdsourcing platform requests the historical data from the machine DT to diagnose machine problem and calculate the required skills to solve the problem. How to diagnose machine problem and calculate the required skills is beyond the scope of this paper. The key output from authorized service request is the requested service type, i.e., machine annual check. When the

DT platform validate the service request to be true, a RWRC is created which contains the information of the machine that needs service, the information about the requested service, the machine end user, the machine owner (landlord), the expected service date and time, etc.

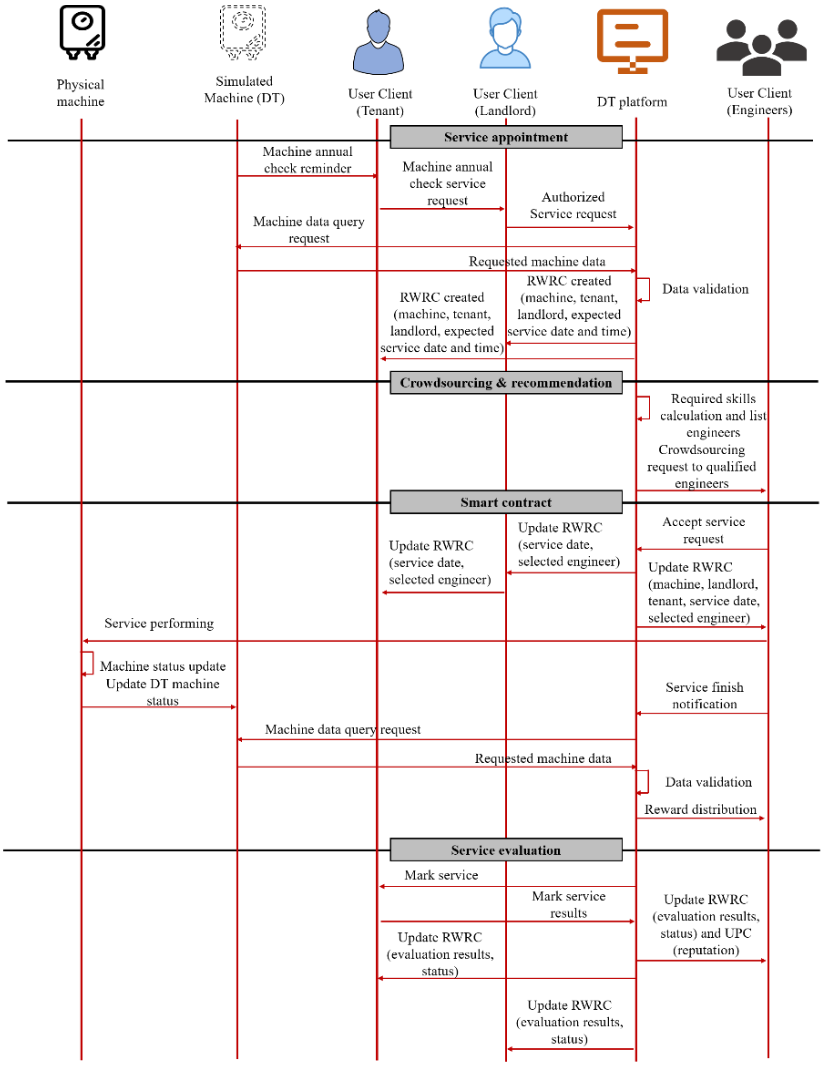


Figure 7-28 The interaction process in annual machine check service

Service crowdsourcing and recommendation

Notice that all indicators measuring the qualification of an engineer, namely AR, CS, and SQ, are initially set as 0. With the increase of performed services in past, these indicators are calculated by formula (7.6), (7.7), and (7.8) and will be updated automatically according to formula (7.15), (7.16) and (7.17) when a new service is performed by the engineer. Before broadcasting the service request, the platform calculates CS, SQ, the recommendation rate based on engineer's performance with (9), distance to machine address, and duration by driving of each engineer registered in the ecosystem. In recommendation rate calculation, the weighting parameters to AR, SQ, and CS are 0.5, 0.3, and 0.2, respectively. Based on the calculation results, the top three engineers with higher recommendation rate are shortlisted to broadcast the service request to. The engineers who receive the broadcast service request can decide whether or not to accept the service request. Among those who accepted the service request, low-cost or low-carbon footprint principle can be applied to shortlist them. In our simulation, low-carbon footprint principle (shortest distance to the destination) is adopted. In this process, the landlord can decide which engineer is eventually selected for the requested service. An example of service crowdsourcing and recommendation results is shown in Figure 7-29.

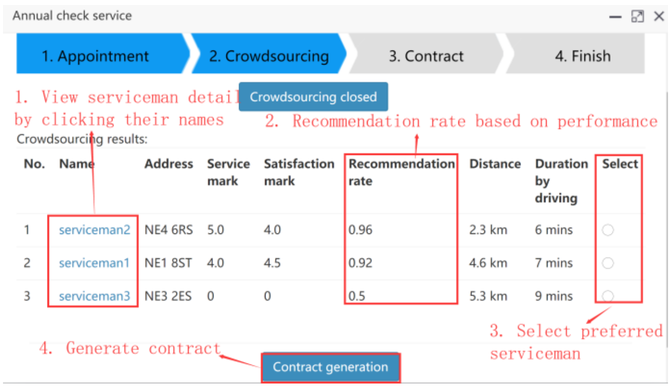


Figure 7-29 Service crowdsourcing and recommendation results interface

When service providers are recommended to the requested service, the newly registered service providers usually have lower recommendation rate than others as his/her previous work experience and skills are unknown to the platform (which is known as cold-start problem in recommender systems). To maintain the sustainable evolution of the product-service ecosystem, the cold-start problem in service provider recommendation should be addressed in the future.

Service contract

When the landlord selects an engineer for the requested service, the RWRC will be updated automatically and then notifies the tenant, the landlord, and the selected engineer about the service date and time. Then at the expected date, the engineer will perform the service physically and then tell the service results to the DT platform. After DT platform verifies the service results by cross-checking it with the real-time machine data, the platform will distribute the reward to the selected engineer.

Service evaluation

After the requested service is performed by the engineer, the tenant will be asked to mark or evaluate the service experience and quality. The service evaluation results will be written into RWRC and the reputation of the engineer in UPC will be updated accordingly. The service evaluation interface is shown in Figure 7-30. The service evaluation results will affect the qualification of the selected engineer for later service requests on the platform.

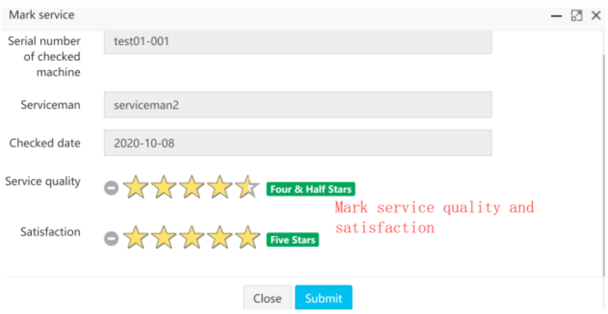


Figure 7-30 Service evaluation interface

The core code and detailed instructions and corresponding interfaces for different role players on the integrated crowdsourcing platform were provided in Appendix C and D, respectively.

7.4.5.3 Evaluation by focus groups

During a 12-month journey of this case study, four formal focus groups with the project founder and collaborators and bi-weekly zoom meetings with project collaborators were organized for understanding issues, collecting data, refining preliminary findings from collaborators, and demonstrating the findings. The focus groups consisted of 9 experts with 7 from research institutions and 2 from the business (project founder). According to research interests, the distribution of project collaborators is shown in Table 7-4.

Table 7-4 Distribution of participants in focus group according to research interests

Research interest	**Servitization**	**User-centred design**	**Servitization platform**	**Customer insights**	**Service management**
Number	3	2	1	2	1

The integrated crowdsourcing platform for the delivery of advanced heating services is tailor-made from the intermediary crowdsourcing platform. In the first three focus groups, they gave feedback on how to design the platform especially in terms of the service process when the platform is presented to them via zoom meetings. Before the fourth focus group, 6 external volunteers were invited to simulate the interaction process in delivering SC2 with 1 acting as the landlord, 2 acting as tenants, and 3 acting as repair engineers (service providers). Then the interaction processes of the three identified service scenarios of SC2 were recorded into three short videos that are used for platform representations in the fourth focus group. The detailed interfaces for the service interaction process are attached in Appendix D. After seeing the demonstrated platform videos, they all agreed that the developed platform is effective in creating and delivering digitally advanced heating services.

The focus groups in this case study only verified the service scenarios around SC1 and SC2. More platform development and verification work should be done so to make it extensible for supporting the creating and delivering of other advanced service along the product-service lifecycle.

7.5 Conclusion

This chapter developed two crowdsourcing platform prototypes, the intermediary one for SMEs and the integrated one for large companies. The intermediary crowdsourcing platform developed enabling tools like discussion board, team up tool, notification tool, and communication tool to support design information communication and sharing among platform users on the platform. The integrated crowdsourcing platform created a product-service ecosystem that was not only able to map physical and virtual worlds of a product and its associated services but also able to provide the digital platform support for the effective deliveries of the products and associated services through the product-service lifecycle. In addition, the integrated crowdsourcing platform has the capability to cross validate data on the platform and transfer raw data to actionable operations, assisting users to understand process information and make evidence-based service decisions. With information accumulation on the platform, it can help optimize the allocation of local manufacturing/service resources and capabilities and help create win-win service-centred business ecosystems.

Both of the developed crowdsourcing platforms were qualitatively evaluated through case studies and we found that the intermediary platform helped share design information at different design phases among designers and the integrated one helped platform actors gain more values from personalized services with improved user experience.

The research in this chapter has led to the following publication and submission for peer-reviewed publication:

Mountney, Sara, Tracy, Ross, May, Andrew, Qin, Shengfeng, Niu, Xiaojing, King, Melanie, Kapoor, Kawaljeet, Story, Vicky and Burton, Jamie (2020) Digitally supporting the co-creation of future advanced services for ‘Heat as a Service’. In Proceedings of the Spring Servitization Conference (SSC), pp. 64-71.

Niu, Xiaojing and Qin, Shengfeng (2021) Integrating Crowd-/Service-sourcing into Service-oriented Digital Twin for Enabling Advanced Manufacturing Services. IEEE Transactions on Industrial Informatics. (Under review)

Chapter 8 Conclusions and Future Work

This PhD research investigates how to feasibly realize the benefits of crowdsourcing in product design and development from a lifecycle viewpoint. To accomplish this aim, this research explored factors affecting product design quality under both traditional in-house and crowdsourcing environments and key crowdsourcing technologies for PDD, then a PDLIM was developed to support design information communication and sharing in a PDD process. And based on the PDLIM, two crowdsourcing platform prototypes have been developed for SMEs as intermediary crowdsourcing platform and for large enterprises as integrated crowdsourcing platforms that help them create product-service ecosystems, respectively. The purpose of this chapter is to summarize the research findings and contributions, research limitations, and future research directions.

8.1 Findings of this study

This study prototyped two crowdsourcing platforms for the PDD process. The intermediary one is for using in SMEs and the integrated one is for large enterprises that expect to get crowdsourcing integrated with their existing innovation platforms. It focused on three gradually proposed questions:

- Can product design quality be controlled when introducing crowdsourcing into the product design process?
- Are there proper technologies to enable crowdsourcing PDD process in order to have guaranteed product design quality?
- How to develop a product design lifecycle information model and test its utility in the crowdsourcing platforms for two types of businesses?

These three questions have been answered in Chapter 4, Chapter 5, Chapters 6 and 7, respectively. The corresponding research findings are listed below.

Finding 1: Key factors affecting product design quality

Product quality control is one of the most important activities conducted by manufacturers to enable the achievement of their design goals. Crowdsourcing has attracted many research attentions due to its low cost and fast speed, and it has been applied to many product design scenarios. However, quality concerns stop manufacturers applying crowdsourcing into their through-life PDD practice. Furthermore, there are few studies focusing on quality control of product design quality in crowdsourcing design environments.

So far, the interpretation to product design quality varies from person to person. In order to better understand it and the key factors affecting it in both in-house and crowdsourcing design environments, this research first gave a definition of product design quality and identified its key attributes and sub-attributes. The key quality attributes are functionality, reliability, usability, maintainability, and creativity. And each attribute is affected by many factors. For example, in the traditional in-house design environment, the key factors affecting product design quality can be classified into three categories: team management, design process, and information management, while in crowdsourcing design environments, due to the openness of the design process and the uncertainty in participated crowds and their skills, three more categories were added, namely, task, request, and platform. And in crowdsourcing design environments, the design quality was controlled from individual, group, and computation levels.

Based on the investigation results, it is found that the quality control challenges on crowdsourcing platforms for PDD mainly came from information management, product design representation, the communication among designers, and the protection of intellectual property.

Then the requirements of a crowdsourcing PDD platform targeted at the identified challenges were indicated.

Finding 2: Key crowdsourcing technology

With the increased application of crowdsourcing, it has been investigated by researchers from various points of view, such as crowdsourcing models (Evans *et al.*, 2016), components and functions (Hetmank, 2013), etc. Existing studies have indicated that crowdsourcing has the potential to benefit the whole lifecycle product design and development (Qin *et al.*, 2016). However, lack of a foundation of crowdsourcing technology theory for lifecycle PDD process is the main research shortage.

This study analysed crowdsourcing technology in terms of the framework, platform, tools, and techniques. The techniques helping the implementation of a crowdsourcing platform for PDD include open call generation, rewards, crowd qualification for working, organization structure of crowds, solution evaluation, workflow, and quality control, etc. The identified challenges of crowdsourcing PDD process are: (1) collaborative product design process on a crowdsourcing platform, (2) information communication and sharing, (3) presentation and evaluation of the design solution, and (4) synthesis of evaluation results and feedback. To address the identified challenges, collaborative design tool, design presentation tool, design evaluation tool, and the integration tool of evaluation results are needed.

Finding 3: Product design lifecycle information model (PDLIM)

To implement a crowdsourcing platform for a through-life PDD process, the design of an information model to support the application domain is vital. The developed PDLIM is to describe the relationship of design information in the whole lifecycle of product design and development in an in-house and crowdsourcing combined design environment. It is multi-layer structured and extensible. The PDLIM classified a design process into pre-design and PDS, design, manufacturing, product launch & in use, and maintenance & recycling stages, and identified design phases to each design stage. The design information at each design phase was accommodated in the PDLIM 'design phase' layer. While the other two sub layers were to represent information related to traditional in-house and crowdsourcing design environments, respectively. Case study evaluation shows that the identified information is necessary in practical design process, and ORM modelling method demonstrates that the relationships and interactions of information entities in the PDLIM can be modelled. With the PDLIM, it can be easier to record the progression of design information during the design process. Moreover, it can enhance the communication and collaboration between collaborators, making the design process more effective.

Finding 4: Crowdsourcing can be used as an intermediary crowdsourcing platform or 'crowdsourcing as a service'

The two crowdsourcing platforms are prototyped to demonstrate that they can support the crowdsourcing process and 'crowdsourcing as a service'. The intermediary crowdsourcing platform developed team up tool, discussion board, notification tool, and real-time communication tool, etc. to support the interactions among different role players when performing iterative PDD activities. Integrating with digital twin, block chain, and smart contract, the integrated crowdsourcing platform creates a product-service ecosystem that connects not only smart products, but also customers, end users, and service providers such as designers and maintainers. The developed product-service ecosystem could coordinate service providers on the platform automatically to serve service requesters, delivering values to all involved actors in the service process. With data accumulation over time, the coordination process could get smarter and more accurate, and then data-driven PDD could be achieved.

8.2 Contributions to knowledge

Contribution to better understanding of product design quality and its quality control measures in crowdsourcing design environments

This research fills the knowledge gap of product design quality control theory in crowdsourcing design environments. This study investigated the product design quality control mechanisms in terms of key factors affecting product design quality, quality control models/approaches and quality assurance policies in both conventional and crowdsourcing design environments. The broader investigation identified the quality control challenges of developing a crowdsourcing platform for PDD and indicated the requirements of the crowdsourcing platform targeted at the identified challenges. It has great practical value to guide manufacturer to control product design quality in crowdsourcing PDD activities.

Contribution to better understandings of crowdsourcing enabling technologies for PDD

The second contribution is better understanding of crowdsourcing technologies for PDD from the technical perspective. This study defined the crowdsourcing technology from techniques, frameworks, platforms, and tools perspectives. It summarized crowdsourcing techniques in terms of open call generation, incentive mechanisms, crowd qualification, organization structure, solution evaluation, workflow, and quality control, and analyzed the existing crowdsourcing frameworks, platforms, and corresponding enabling tools. Based on the investigation results, key challenges in a crowdsourcing PDD process are identified and key guidelines for coping with the challenges are provided. It can guide the development of a crowdsourcing-based collaborative design platform.

Contribution to a novel product design lifecycle information model

The third contribution is a novel product design lifecycle information model that enables product through-life design and development under an in-house and crowdsourcing combined design environment. The multi-layered and extensible PDLIM can accommodate key design information in a PDD process and it treats each design phase as an information entity. The relationships and interactions among these information entities were graphically modelled by the ORM modelling method and it showed that the identified information in the PDLIM can be managed by a database. The proposed PDLIM could provide practical value on designing information database for crowdsourcing PDD systems.

Contribution to the development of intermediary and integrated crowdsourcing platforms for PDD

The fourth contribution is how to design and develop intermediary and integrated crowdsourcing platforms for iterative PDD process from the technical perspective. Based on the analysis of iterative PDD process on crowdsourcing platforms, what functions the platforms should be realized and what tools should be developed were identified. And the overall architectures for these two platforms were proposed and the corresponding enabling technologies were analysed. The evaluation results of these two platform prototypes with case studies show that the intermediary crowdsourcing platform could support the iterative PDD process and the integrated one could create a product-service ecosystem, delivering value to all actors in the ecosystem. These two crowdsourcing platform prototypes could provide technical guidelines for future crowdsourcing platforms development.

8.3 Research limitations

The limitation of the PhD research work presented in this thesis is mainly in the development and evaluation of the PDLIM and its supported crowdsourcing platform prototypes.

The development of the PDLIM is limited by a large volume of reviewed studies and case studies conducted by undergraduates in design students training programs. Since there are some gaps between the laboratory design process and the practical one, the identified design information may be limited compared to practical design application scenarios. In addition, the proposed PDLIM was mainly qualitatively evaluated by case studies which focus on evaluating the identified information with various information representations. In the PDD process, some design information elements at a specific design phase could be further improved at due design phases. Furthermore, the developed PDLIM in terms of the overall structure and information elements at each design phase is quantitatively evaluated by a small sized questionnaire survey. And the respondents of the survey mainly work in academic institutions.

The crowdsourcing platform prototypes and enabling tools were mainly implemented to support the iterative crowdsourcing PDD process and the creation of a product-service ecosystem for ‘Maintenance as a service’. The investigation of tools supporting complex PDD activities is still required. In addition, the two prototypes were mainly qualitatively evaluated by a case study, respectively. The case study for the intermediary crowdsourcing platform is to evaluate its effectiveness in representing design information identified at each design phase and sharing information among designers in the same group. ‘Maintenance as a service’ is another case study used to evaluate the effectiveness of the integrated crowdsourcing platform in creating a product-service ecosystem in which the platform coordinates service providers to serve service requesters, providing values to all involved actors in the service delivery process. The evaluation results from these two case studies are limited because there are still some gaps between a simulated PDD process enabled by a crowdsourcing platform and a traditional in-house one, so some issues occurring in the traditional in-house PDD process might be ignored in a simulated one.

8.4 Future work

There are many possible directions for future research. Some of them directly respond to the research limitations, whilst others address opportunities for new research directions.

- Further quantitative evaluation of the developed platform prototypes and corresponding enabling tools. Currently, the developed crowdsourcing platforms are mainly qualitatively evaluated by case studies in experimental setting. To better measure its effectiveness in supporting iterative PDD process and creating product-service ecosystems, the developed crowdsourcing systems should be used and evaluated by as many practical case studies as possible so that the effectiveness of enabling tools can be measured by statistic data. The results of the statistical analysis will reflect the strong points and weak points of the developed platforms and help to adopt suitable measures to further develop them.
- Development of enabling tools to support more complex PDD activities. Currently, the investigation of the developed crowdsourcing platforms supported by the PDLIM is still at the early stage. To make them applied in practical scenarios, there are still many investigations should be progressed, such as the design and implementation of the design solution evaluation tool in terms of evaluator selection and weighting set up, tool for analysing and synthesising solution evaluation results, and smart guidance tool for product design, etc.
- Integration with commonly used social media. The developed crowdsourcing systems face the cold-start problem for newly registered crowds as the crowdsourcing process requires the analysis of crowd previous behaviours and work experience. Integrating the platform with social media could not only make crowds get easier access to the platform with their social media accounts but also provide a way to evaluate or predict their reliability and work quality by analysing their previous social behaviours.
- Integration with blockchain technology. The developed crowdsourcing systems are centralized as most existing crowdsourcing systems, where cybersecurity attacks such as free riding and false reporting (Kogias *et al.*, 2019; Zhu *et al.*, 2020) are frequently

resulted from unauthorized access control mechanisms. Additionally, the protection of intellectual property and privacy of users is vital. Because of such reasons, blockchain technology should be integrated with the crowdsourcing platform to improve data transparency, integrity, and security.

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APPENDICES

Appendix A: Product Design Lifecycle Information Model Evaluation Questionnaire

Dear participant:

Thank you for joining my survey! It should take you 10 to 15 minutes to finish! I am a PhD research student in School of Design, Northumbria University. My research is focused on how product design evaluation and feedback affect product design quality in a crowdsourcing-based design environment. This questionnaire is designed as a part of my research work, mainly aiming to developing a Product Design Lifecycle Information Model (PDLIM) throughout the product lifecycle in in-house and crowdsourcing combined design environment. The PDLIM can support the capture of design information during the whole product design process and provide insights on next round product design and development.

According to our previous research, an overall structure of the PDLIM which identifies key design stages and corresponding phases at each stage, key information at each phase, the information affecting product design quality in both traditional in-house and crowdsourcing-based design environment, and the information exchanged by existing product data exchange models. However, due to the large amount of information during this process, some important information may be missing. The results could make the PDLIM more comprehensive, having the potential to support the product through-life design process.

All the data collected from the questionnaire will be utilized for this research only. Please look through the following questions carefully, and then provide the best answer as you could.

Thank you for your cooperation! If you have any questions or concerns about completing the questionnaire or about being in this study, you may contact me on +44-7928885229 or my email address: xiaojing.niu@northumbria.ac.uk

Yours sincerely,

Xiaojing Niu

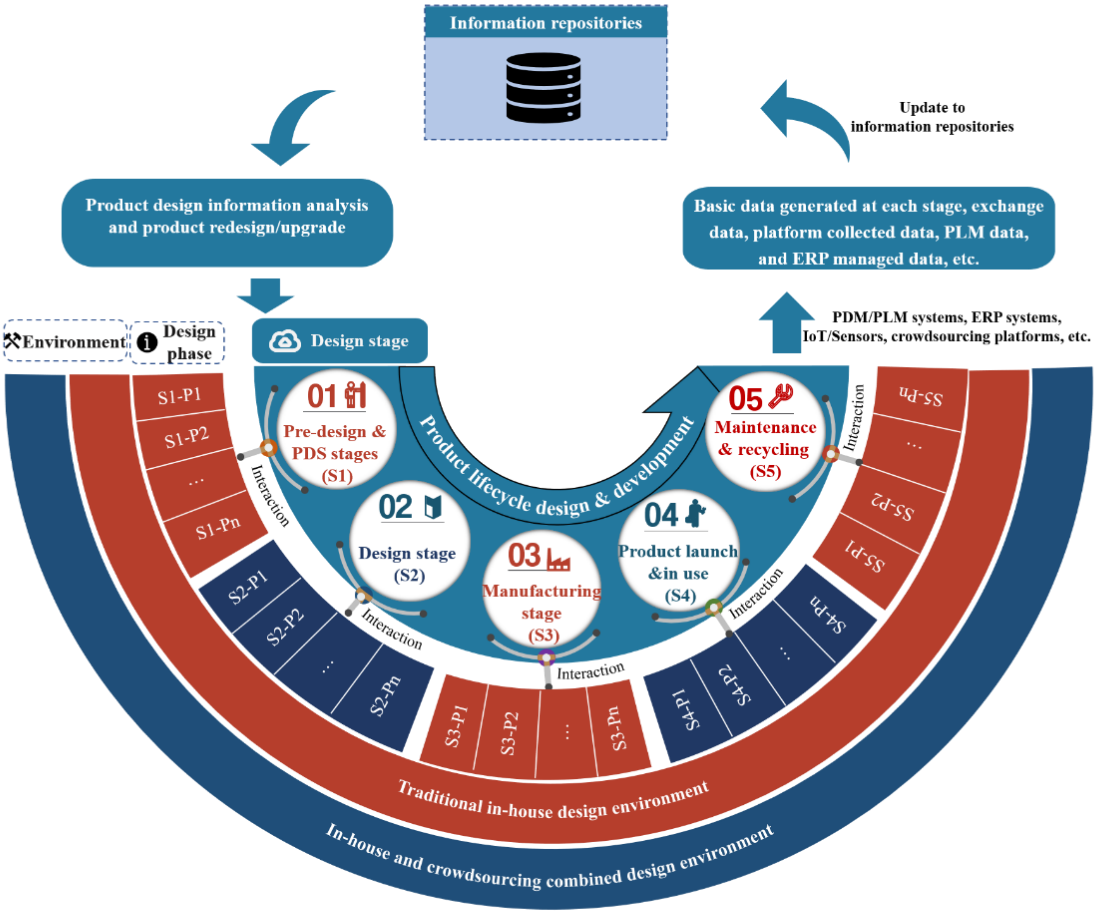
PhD Candidate

Part 1 Participant information:

1. Your organization:
   ☐ Design company ☐ Research institution
2. Your area of expertise:
   ☐ Design strategy ☐Design management ☐Engineering design
   ☐Graphics design ☐Human factors design ☐Industrial design
   ☐User interfaces design ☐others
3. How long have you worked on your field?
   ☐ 1-2 years ☐ 3-4 years ☐ 5-9 years ☐more than 10 years

Part 2 PDLIM structure evaluation:

To support not only the three main trends of product design and development (PDD), product family design, crowdsourcing PDD, and digital twin-enabled data-driven PDD, but also the through-life product design process, an overall structure of the PDLIM throughout the product lifecycle is developed. The information categories covered by the PDLIM structure include design stages and corresponding phases, information in traditional in-house design environment (including that collected and managed by product data exchange models, PDM/PLM systems, ERP systems, and digital twin platforms), additional information in combined design environment with crowdsourcing. The captured information can provide insights on product design and development on next round design process.



4. Do you think the overall PDLIM structure covers all information categories during a PDD process? If not, what information category should add to or delete from the PDLIM?

   The information category should add to PDLIM: ________________________________

   The information category should delete from PDLIM: ____________________________

Part 3 Information evaluation in PDLIM

To make the PDLIM more vivid and concrete, key information in each category is explored. In the PDLIM, the PDD process includes pre-design & PDS stage, design stage, manufacturing stage, product launch & in use stage, and product maintenance & recycling stage. At each stage, key phases are identified as in the figure.

Pre-design & PDS stage (S1)	Design stage (S2)	Manufacturing stage (S3)	Launch & in use stage (S4)	Maintenance & recycling stage (S5)
Market needs analysis (S1-P1)	Design concept generation (S2-P1)	Manufacturing scheduling (S3-P1)	Product launch (S4-P1)	Product maintenance (S5-P1)
User needs analysis (S1-P2)	Concept development and evaluation (S2-P2)	Actual product parts manufacturing (S3-P2)	Product in use (S4-P2)	Product recycling (S5-P2)
Product design specification (S1-P3)	Service development (optional) (S2-P3)	Product assembly (S3-P3)		
	Design evaluation & review (S2-P4)	Product transportation (S3-P4)		

5. At each design phase, the following information has been identified, do you have any other information that should be added to or to deleted from each design phase?

Design Phase	Market needs analysis (S1-P1)	User needs analysis (S1-P2)	Product design specification (S1-P3)	Design concept generation (S2-P1)	Concept development (S2-P2)	Service development (optional) (S2-P3)	Design evaluation & review (S2-P4)
Information	1. Competitor products 2. Development trends 3. Marketing strategies of competitors 4. Packaging 5. Market potential 6. Product positioning 7. Targeting strategy 8. Market share 9. Marketing context	1. Customer segments 2. Customer motivations 3. Customer personas 4. Frustrations/pain points for each customer segment 5. Customer journey maps 6. Customer experience 7. Customer comments on the product 8. Human context 9. Stakeholders 10. Stakeholders' comments on the product 11. Work flow, etc.	1. Product size & weight 2. Performance requirements 3. Service environment 4. Safety requirements 5. Reliability standards & requirements 6. Ergonomic requirements 7. Product aesthetics 8. Maintenance/recycling requirements 9. Material requirements 10. Market/company constraints 11. Patents & standards 12. Prototype testing requirements 13. Schedule requirements, etc.	1. Sketches with annotation 2. Low fidelity model	1. Sketching 2. Intention map 3. CAD models 4. Rendering 5. Materials 6. Interacting process 7. Product structure 8. Mechanisms 9. Costing	1. Company's policies & procedures 2.Company culture 3. Compliance & legal regulations 4. Tools to deliver a service 5. Service information flow 6. Interactive touchpoints 7. Service evaluation	1. Evaluation criteria 2. Feasibility 3. Compatibility 4. Completeness 5. Previous evaluation experience 6. Evaluation methods .

Design Phase	Manufacturing scheduling (S3-P1)	Actual parts manufacturing(S3-P2)	Product assembly (S3-P3)	Product transportation(S3-P4)	Product launch (S4-P1)	Product in use (S4-P2)	Product maintenance (S5-P1)	Product recycling (S5-P2)
Information	1. Bill of Materials (BOM) 2. Component's routing 3. Raw materials availability in stock 4. Cost of raw materials 5. Material & component orders 6. Suppliers' lead times and prices 7. Availability of workstations and workers 8. Information about other works on the machine 9. Manufacturing capacity and productivity 10. Costs related to machines and workers on the workstations 11. Scheduling tool, etc.	1. Monitoring of manufacturing process 2. Manufacturing environment 3. Government manufacturing regulations 4. Changes to components/parts 5. Changes to manufacturing process 6. Changes to manufacturing technology 7. Performance indicators 8. Manufacturing flow 9. Actual material cost 10. Actual labour cost 11. Actual overhead cost, etc.	1. Assembly cost 2. Assembly standards 3. Assembly process 4. Functional requirements 5. Functional analysis 6. considerations/ Assumptions 7. Number of parts 8. Number of interfaces 9. Mistake proofing 10. Handling 11. Insertion 12. Secondary operations, etc.	1. Packaging 2. Transportation mode selection 3. Transportation cost 4. Transportation strategy 5. Customer requirements 6. Carrier relationships 7. carrier's performance 8. Product transportation track history 9. Transportation quality, etc.	1. Launch date 2. Product promotion channels 3. Sales strategy and training 4. Technical data sheets 5. Technical support materials 6. Product launch cost 7. Infrastructure changes 8. Communications plan both inside and outside the organization 9. Analyst briefings, etc.	1. Product real-time conditions 2.Product operational environment 3. Feedback from end users 4. User behavior data 5. Tools for collecting product-generated and user-generated data 6. real-time data analysis tool, etc.	1. Failure data and causes 2. Product maintenance record 3. component/part status and quality 4. Maintenance service providers 5. Maintenance cost, etc.	1.The cost of recycling and disassembly 2. The reusable state 3. Remaining service time of parts/ components 4. Recycling technology 5. Recycling process, etc.

Please add and delete information according to design phase:

Design phase	Information added	Information deleted
Market needs analysis		
User needs analysis		
Product design specification		
Design concept generation		
Concept development		
Service development		
Design evaluation & review		
Manufacturing scheduling		

Actual parts manufacturing		
Product assembly		
Product transportation		
Product launch		
Product in use		
Product maintenance		
Product recycling		

6. The following information in traditional in-house environments has been identified, do you have any other information that should be added to or be deleted from each information dimension?

Product information managed by PDM/PLM	**Manufacturing information managed by ERP**	**Product and end user generated information managed by DT platforms**
1. Real-time BOM information 2. Details for understanding and approving engineering change requests 3. Engineering change orders 4. real-time product development status 5. Milestone tracking during development process 6. Data version control 7. Visualization of involved stakeholders 8. Approved manufacturer lists, etc.	1. Team structure 2. Team members' ability 3. Company culture, rules & policies 4. risks 5. Supply chain operations 6. Team members' satisfaction 7.Team members' education background 8. Record of purchasing 9. Inventory and procurement, etc.	1. Real-time product conditions 2. Product's operating environment 3. Customers' comments 4. Historical product operation data 5. Historical interaction data between physical and virtual twins, 6. Connection to data sources, etc.

Please add and delete information according to information dimension:

Information dimension	Information added	Information deleted
Product information managed by PDM/PLM		
Manufacturing information managed by ERP		

Product and end user generated information managed by DT platforms		

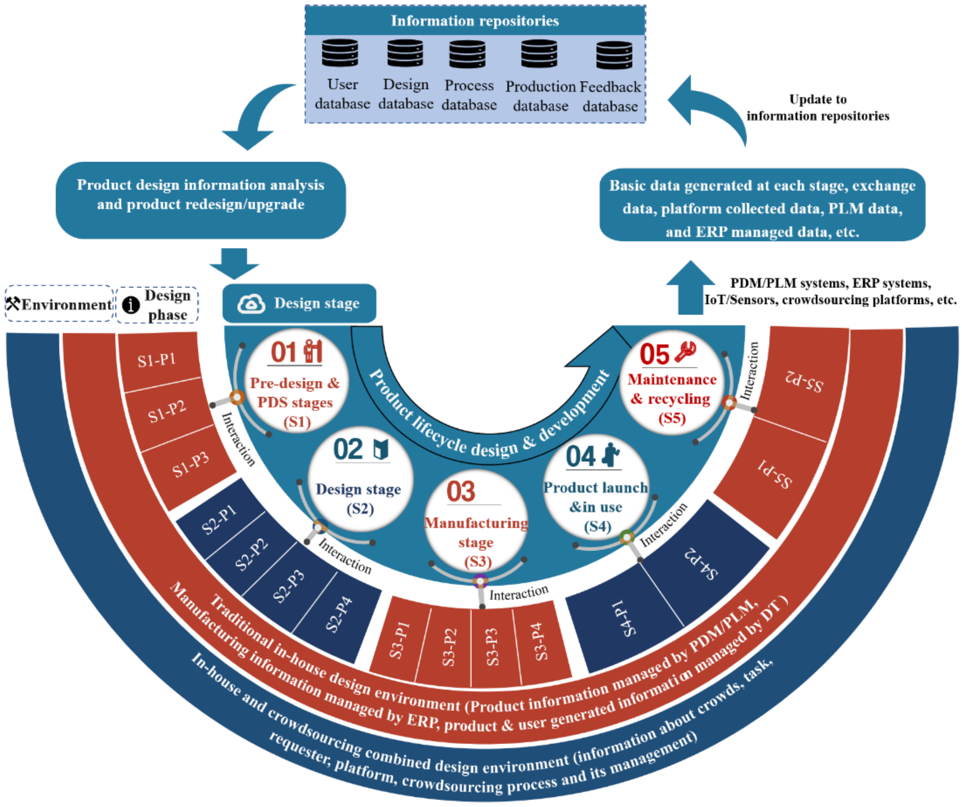
7. The additional information in crowdsourcing environments has been identified, do you have any other information that should be added to or be deleted from each information dimension?

Crowds/service provider (Team management)	Information management	Task	Requester	Platform	Design process
1. Work histories 2. Location 3. Qualification 4. Reputation 5. Expertise 6. Participation motivation, etc.	1. Information structure 2. Information repositories 3. The performance of information management software, etc.	1. Task definition 2. Task decomposition 3. Technical resources 4. Incentives mechanism, etc.	1. Open call design 2. Privacy provision repositories 3. Ethicality provision 4. Incentives provision, etc.	1. Platform performance 2. Interaction tools for crowds and requester 3. Platform facilities, etc.	1. Crowds selection criteria 2. Open task design requirements, etc.

Please add and delete information according to information dimension:

Information dimension	Information added	Information deleted
crowds		
Information management		
task		
requester		
platform		
Design process		

The extracted information throughout the PDD process is stored in five basic databases: user (including customers, end users, and other stakeholders) database, embodiment/design database, process database, manufacturing information database, and feedback database. These databases play an important role in helping create the closed loop of product design process ecosystem, expecting to realize product automatic upgrade/improvement by coordinating stakeholders on the supplier chain to respond to the real-time changes of product status, market needs, and customer needs. The updated PDLIM structure is :



Based on the updated structure of PDLIM,

8. To what extent do you think the PDLIM is effective in supporting the closed loop product design and development (PDD) process?

☐ Less than 30% ☐ 30%-50% ☐ 50%-70% ☐ 70%-90%
☐ more than 90%

To make PDLIM better support the closed loop PDD process, do you have any suggestions?

---

9. To what extent do you think the PDLIM promotes design collaboration and communication among the involved design teams/departments?

☐ Less than 30% ☐ 30%-50% ☐ 50%-70% ☐ 70%-90%
☐ more than 90%

To make PDLIM better support the collaboration and communication among participants, do you have any suggestions?

---

10. To what extent do you think the PDLIM is effective in product performance analysis and predictive maintenance?

☐ Less than 30% ☐ 30%-50% ☐ 50%-70% ☐ 70%-90%
☐ more than 90%

To make PDLIM better support product performance analysis and predictive maintenance, do you have any suggestions?

---

11. Do you think the PDLIM can be applied in evaluating product design quality at each stage?
    ☐ Yes ☐ No

    If no, what information should be involved in the PDLIM so to make it support the evaluation of product designs at a given time?

---

12. Do you think the PDLIM is able to help make design or business decisions?
    ☐ Yes ☐ No

    If no, what information should be involved in the PDLIM so to make it supports evidence-based decision-making?

---

13. Do you have any suggestions on the PDLIM?

Appendix B: Core code of the intermediary crowdsourcing platform

```
@login_required
def create_task_call(request):
    if request.is_ajax():
        task_title = request.GET['task_title']
        task_description = request.GET['task_description']
        print(task_description)
        user_temp = User.objects.get(username=request.user.username)
        user = PlatformUser.objects.get(user=user_temp)
        ocd = OpenCallDocument.objects.create(task_title=task_title,
PlatformUser=user,
                                              task_description=task_description)

        json_data = {'valid': 'ok'}
    else:
        json_data = {'valid': 'no'}
    return JsonResponse(json_data)


@login_required
def submit_solution(request):
    if request.is_ajax():
        solution_name = request.GET['solution_name']
        solution_description = request.GET['solution_description']
        selected_call = request.GET['selected_call']
        print(solution_description)

        user_temp = User.objects.get(username=request.user.username)
        print(user_temp)
        user = PlatformUser.objects.get(user=user_temp)
        open_call = OpenCallDocument.objects.get(id=selected_call)
        solution_created =
DesignSolution.objects.create(solution_name=solution_name, platform_user=user,

solution_description=solution_description,

open_call_document=open_call,
                                                         solution_version='V1.0')
        if solution_created:
                json_data = {'valid': 'ok'}
        else:
                json_data = {'valid': 'error1'}
    else:
        json_data = {'valid': 'no'}
    return JsonResponse(json_data)


@login_required
def add_group(request):
    if request.is_ajax():
        group_name = request.GET['groupName']
        call_id = request.GET['callId']
        group_introduction = request.GET['groupIntroduction']

        user_temp = User.objects.get(username=request.user.username)
        print(group_name)
        print(group_introduction)
        user = PlatformUser.objects.get(user=user_temp)
        call_selected = OpenCallDocument.objects.get(id=call_id)
        if group_name != "" and group_introduction != "":
            group = WebGroup.objects.filter(name=group_name, owner=user)
            print(group)
            if group:
                return_data = {'valid': 'exists'}
```

```
            else:
                new_group = WebGroup.objects.create(name=group_name,
brief=group_introduction, owner=user,
                                                    document_focused=call_selected)
                new_group.admins.add(user)
                new_group.members.add(user)
                return_data = {'valid': 'ok'}
        else:
            return_data = {'valid': 'notNull'}
    else:
        return_data = {'valid': 'no'}
    return JsonResponse(return_data)


class SolutionsWithFeedbackView(ListView):
    model = DesignSolution
    template_name = 'solutionsWithFeedback_designer.html'
    context_object_name = 'solutionsList'

    def get_queryset(self):
        solution_owner = PlatformUser.objects.get(user=self.request.user)
        return DesignSolution.objects.filter(platform_user=solution_owner)

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)

@login_required
def participate_in_case(request):
    if request.is_ajax():
        case_id = request.GET['case_id']
        participant = PlatformUser.objects.get(user=request.user)
        task_call = OpenCallDocument.objects.get(id=case_id)
        task_call.participants.add(participant)
        json_data = {'valid': 'ok'}
    else:
        json_data = {'valid': 'no'}
    return JsonResponse(json_data)



@login_required
def team_chat(request, call_id, group_id):
    selected_group = WebGroup.objects.get(id=group_id)
    group_members = selected_group.members.all()
    return render(request, 'teamChat.html', locals())


@login_required
def add_member(request):
    if request.is_ajax():
        member_name = request.GET['memberName']
        member_email = request.GET['memberEmail']
        group_id = request.GET['groupId']
        call_id = request.GET['callId']
        send_invitation_email(request.user.username, member_email, member_name,
call_id, group_id, "invitation")
        jason_data = {'valid': 'ok'}
    else:
        jason_data = {'valid': 'no'}
    return JsonResponse(jason_data)


@login_required
def join_group(request, call_id, group_id, active_code):
    if request.method == 'GET':
        invitation_record = EmailVerificationRecord.objects.get(code=active_code)
        if invitation_record:
```

```
            user_temp = User.objects.get(email=invitation_record.email)
            user_invited = user_temp.platformuser
            call_joined = OpenCallDocument.objects.get(id=call_id)
            participants_all = call_joined.participants.all()
            if user_invited in participants_all:
                flag = 'yes'
            else:
                flag = 'no'
            if flag == 'no':
                call_joined.participants.add(user_invited)
            group_invited = WebGroup.objects.get(id=group_id)
            group_invited.members.add(user_invited)
        else:
            return HttpResponse('fail')
        return HttpResponse('Congratulations! You have successfully joined to the
design group.')


GLOBAL_MSG_QUEUES = {}


@login_required
def send_message(request):
    msg_data = request.POST.get('msg_data')
    if msg_data:
        msg_data = json.loads(msg_data)
        msg_data['timestamp'] = time.time()
        if msg_data['type'] == 'single':
            if not GLOBAL_MSG_QUEUES.get(int(msg_data['to'])):
                GLOBAL_MSG_QUEUES[int(msg_data['to'])] = queue.Queue()
            GLOBAL_MSG_QUEUES[int(msg_data['to'])].put(msg_data)
        if msg_data['type'] == 'group':
            group_id = int(msg_data['to'])
            group = WebGroup.objects.get(id=group_id)
            for member in group.members.all():
                if not GLOBAL_MSG_QUEUES.get(member.user.id):
                    GLOBAL_MSG_QUEUES[member.user.id] = queue.Queue()
                if member.user.id != int(msg_data['from']):
                    GLOBAL_MSG_QUEUES[member.user.id].put(msg_data)

    print(GLOBAL_MSG_QUEUES)
    return HttpResponse('message received')


@login_required
def get_new_msg(request):
    if request.user.id not in GLOBAL_MSG_QUEUES:
        GLOBAL_MSG_QUEUES[request.user.id] = queue.Queue()
    msg_count = GLOBAL_MSG_QUEUES[request.user.id].qsize()
    q_obj = GLOBAL_MSG_QUEUES[request.user.id]
    msg_list = []
    if msg_count > 0:
        for msg in range(msg_count):
            msg_list.append(q_obj.get())
        print("new msgs:", msg_list)
    else:
        print(GLOBAL_MSG_QUEUES)
        try:
            msg_list.append(q_obj.get(timeout=60))
        except queue.Empty:
            print("no message for [%s][%s]" % (request.user.id, request.user))
        pass
    print("returned dumps data " + json.dumps(msg_list))
    return HttpResponse(json.dumps(msg_list))


class SolutionsEvaluatedView(ListView):
    model = InvitationRecord
```

```
    template_name = 'personalCenter_evaluator_evaluatedSolutions.html'
    context_object_name = 'evaluatedList'

    def get_queryset(self):
        platform_user = PlatformUser.objects.get(user=self.request.user)
        invitations = InvitationRecord.objects.filter(evaluator=platform_user,
is_marked=1, status=1, is_evaluated=1)
        return invitations

    def get_context_data(self, **kwargs):
        context = super(SolutionsEvaluatedView, self).get_context_data(**kwargs)
        platform_user = PlatformUser.objects.get(user=self.request.user)
        context['unread_invitation'] =
InvitationRecord.objects.filter(evaluator=platform_user, is_marked=0)
        return context

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)

class EvaluatedSolutionDetailView(DetailView):
    model = SolutionEvaluationResult
    template_name = "evaluatedSolutionDetail.html"
    context_object_name = "solutionEvaluatedSelected"

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)


class InvitationContentView(DetailView):
    model = InvitationRecord
    template_name = "invitationContent.html"
    context_object_name = "invitationContent"

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)


class EvaluateSolutionView(DetailView):
    model = InvitationRecord
    template_name = 'evaluateSolution.html'
    context_object_name = 'evaluateSolution'

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)


@login_required
def submit_evaluation(request):
    if request.is_ajax():
        evaluation_mark = request.GET['evaluation_mark']
        evaluation_results = request.GET['evaluation_results']
        invitation_id = request.GET['invitation_id']
        user_temp = User.objects.get(username=request.user.username)

        user = PlatformUser.objects.get(user=user_temp)
        invitation = InvitationRecord.objects.get(id=invitation_id)
        print("invitation:", invitation.id)
        evaluation =
SolutionEvaluationResult.objects.create(invitationRecord=invitation,

evaluation_results=evaluation_results,

evaluation_mark=evaluation_mark)
        invitation.is_evaluated = 1
```

```
        invitation.save()
        json_data = {'valid': 'ok'}
    else:
        json_data = {'valid': 'no'}
    return JsonResponse(json_data)


@login_required
def accept_invitation(request):
    if request.is_ajax():
        invitation_id = request.GET['invitationId']
        invitation_specific = InvitationRecord.objects.get(id=invitation_id)
        invitation_specific.accept_reject_date = datetime.datetime.now()
        invitation_specific.is_marked = 1
        invitation_specific.status = 1
        invitation_specific.save()
        evaluation_record =
SolutionEvaluationResult.objects.create(invitationRecord=invitation_specific)
        json_result = {'valid': 'success'}
    else:
        json_result = {'valid': 'fail'}
    return JsonResponse(json_result)


@login_required
def reject_invitation(request):
    if request.is_ajax():
        invitation_id = request.GET['invitationId']
        invitation_specific = InvitationRecord.objects.get(id=invitation_id)
        invitation_specific.is_marked = 1
        invitation_specific.status = 0
        invitation_specific.save()
        json_result = {'valid': 'success'}
    else:
        json_result = {'valid': 'fail'}
    return JsonResponse(json_result)


class SolutionToCertainRequireView(ListView):
    model = DesignSolution
    template_name = 'designSolutionList.html'
    context_object_name = 'designSolutionList'

    def get_queryset(self):
        print(self.kwargs)
        if self.kwargs:
            user = PlatformUser.objects.get(user=self.request.user)
            requirement =
user.opencalldocument_set.get(id=self.kwargs['require_id'])
            solution_list = requirement.designsolution_set.all().order_by('-
submitted_date')
            print(solution_list)
            return solution_list

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)


@login_required
def view_solution_detail(request, require_id, solution_id):
    user = User.objects.get(username=request.user.username)
    if user.is_superuser:
        requirement = OpenCallDocument.objects.get(id=require_id)
        solution_selected = requirement.designsolution_set.get(id=int(solution_id))
        invitation_list = solution_selected.invitationrecord_set.filter(status=1)
    else:
        if user.platformuser.user_type == 1:
```

```
            requirement = user.platformuser.opencalldocument_set.get(id=require_id)
            solution_selected =
requirement.designsolution_set.get(id=int(solution_id))
            invitation_list =
solution_selected.invitationrecord_set.filter(status=1)
        if user.platformuser.user_type == 2:
            requirement = OpenCallDocument.objects.get(id=require_id)
            solutions =
DesignSolution.objects.filter(platform_user=user.platformuser)
            solution_selected = solutions.get(id=solution_id)
            invitation_list = solution_selected.invitationrecord_set.all()
    return render(request, 'designSolutionDetail.html', locals())


@login_required
def feedback_to_certain_solution(request, username, solution_id):
    user = User.objects.get(username=username)
    solution = user.platformuser.designsolution_set.get(id=solution_id)
    invitation_record = solution.invitationrecord_set.all()
    return render(request, 'feedbackList.html', locals())


@login_required
def view_feedback_to_solution(request, require_id, solution_id, invitation_id):
    user = User.objects.get(username=request.user.username)
    if user.is_superuser:
        requirement = OpenCallDocument.objects.get(id=require_id)
    else:
        requirement = user.platformuser.opencalldocument_set.get(id=require_id)
    solution_selected = requirement.designsolution_set.get(id=solution_id)
    invitation = solution_selected.invitationrecord_set.get(id=invitation_id)
    feedbacks =
SolutionEvaluationResult.objects.filter(invitationRecord=invitation)
    return render(request, 'feedbackDetail.html', locals())


@login_required
def view_feedback_detail(request, username, solution_id, invitation_id):
    user = User.objects.get(username=username)
    solution = user.platformuser.designsolution_set.get(id=solution_id)
    invitation = solution.invitationrecord_set.get(id=invitation_id)
    feedbacks =
SolutionEvaluationResult.objects.filter(invitationRecord=invitation)
    return render(request, 'feedbackDetail.html', locals())

class CallDeleteView(DeleteView):
    model = OpenCallDocument
    template_name = 'callDelete.html'
    context_object_name = 'deleteSelected'
    success_url = reverse_lazy('personalCenter')


class SuperUserCenterView(ListView):
    model = DesignSolution
    template_name = 'personalCenter_superUser.html'
    context_object_name = 'designSolutions'

    def get_queryset(self):
        solutions_list = DesignSolution.objects.all().order_by('-submitted_date')
        print(solutions_list)
        return solutions_list

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)


class EvaluatorsToSolutionView(ListView):
```

```
    model = InvitationRecord
    template_name = 'evaluationProgress.html'
    context_object_name = 'evaluatorsToSolution'

    def get_queryset(self):
        print(self.kwargs)
        if self.kwargs:
            if self.kwargs['pk']:
                solution_selected =
DesignSolution.objects.get(id=self.kwargs['pk'])
                return
InvitationRecord.objects.filter(designSolution=solution_selected).order_by('-
accept_reject_date')

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)

class SolutionsDistributedView(ListView):
    model = DesignSolution
    template_name = 'personalCenter_superUser_solutionsDistributed.html'
    context_object_name = 'solutionsDistributed'

    def get_queryset(self):
        print(datetime.datetime.now())
        solutions_show =
DesignSolution.objects.filter(design_phase__end_date__lte=datetime.datetime.now())
\
            .order_by('-submitted_date')
        print(solutions_show)
        return solutions_show

    @method_decorator(login_required)
    def dispatch(self, request, *args, **kwargs):
        return super().dispatch(request, *args, **kwargs)


@login_required
def distribute_solution(request, solution_id):
    solution_selected = DesignSolution.objects.get(id=solution_id)
    return render(request, 'distributeSolution.html', locals())


@login_required
def search_by_keywords(request):
    if request.is_ajax():
        keywords = request.GET['keywords']
        evaluators_searched = PlatformUser.objects.filter(user_type=3)
        evaluators_list = []
        for evaluator in evaluators_searched:
            if evaluator.research_interests.filter(field_name=keywords):
                evaluators_list.append(evaluator.user)
        print(evaluators_list)
        data = serializers.serialize('json', evaluators_list)
        print(data)
        json_data = {'valid': data}
    else:
        json_data = {'valid': 'no'}
    return JsonResponse(json_data)


def send_evaluation_invitation(request):
    if request.is_ajax():
        username = request.GET['username']
        email = request.GET['email']
        print(email)
        solution_id = request.GET['solution_id']
        print(solution_id)
```

```
        invitation_title = 'Invitation for evaluation design solution with id=' +
solution_id
        print(request.user)
        inviter = PlatformUser.objects.get(user=request.user)
        print(inviter)
        eva_temp = User.objects.get(email=email)
        print(eva_temp)
        evaluator = PlatformUser.objects.get(user=eva_temp)
        solution = DesignSolution.objects.get(id=solution_id)
        record_add =
InvitationRecord.objects.create(invitation_title=invitation_title,
platformuser=inviter,
                                                     evaluator=evaluator,
designSolution=solution)
        if record_add:
            send_evaluation_invitation_email(email, username, 'evaluation')
            json_data = {'valid': 'ok'}
        else:
            json_data = {'valid': 'no'}
    return JsonResponse(json_data)


@login_required
def view_evaluation_invitation(request, active_code):
    if request.method == 'GET':
        invitation_record = EmailVerificationRecord.objects.get(code=active_code)
        if invitation_record:
            user = User.objects.get(email=invitation_record.email)
            auth.login(request, user)
            return HttpResponseRedirect(reverse('evaluatorInvitations'))
    return HttpResponse('Sorry, some errors occur when redirecting you to your
personal account. '
                        'Please check you network and try again!')
```

Appendix C: Core code of the integrated crowdsourcing platform

```
class ProductView(LoginRequiredMixin, BreadcrumbMixin, TemplateView):
    template_name = 'product/productcategory.html'

    def get_context_data(self, **kwargs):
        context = super(ProductView, self).get_context_data(**kwargs)
        current_user = UserProfile.objects.get(id=self.request.user.id)
        user_role = current_user.roles.all()
        print(user_role)
        permissions = list()
        for role in user_role:
            permission = role.permissions.all()
            for permit in permission:
                permit_code = permit.code
                permissions.append(permit_code)
        print(permissions)
        context['permissions'] = permissions
        return context


class Product2UserView(LoginRequiredMixin, View):
    """
    binding product to user
    """

    def get(self, request):
        ret = dict()
        purchaser = User.objects.get(id=self.request.user.id)
        added_products = purchaser.purchaser.all()
        all_products = ProductCategory.objects.all()
        un_add_products = set(all_products).difference(added_products)
        ret = dict(purchaser=purchaser, added_products=added_products,
un_add_products=list(un_add_products))
        return render(request, 'product/productcategory_product2user.html', ret)

    def post(self, request):
        res = dict()
        id_list = None
        purchaser = User.objects.get(id=self.request.user.id)
        print(purchaser)
        if 'to' in request.POST and request.POST['to']:
            id_list = map(int, request.POST.getlist('to', []))
        purchaser.purchaser.clear()
        if id_list:
            for product in ProductCategory.objects.filter(id__in=id_list):
                purchaser.purchaser.add(product)
        res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')



class ProductBindingListView(LoginRequiredMixin, View):

    def get(self, request):
        fields = ['id', 'category_name', 'serial_number', 'post_code',
'expected_check_date', 'status']
        ret =
dict(data=list(ProductCategory.objects.filter(purchaser=self.request.user).values(*
fields)))
        return JsonResponse(ret)


class ProductUnbindingView(LoginRequiredMixin, View):
    """
```

```
    Unbinding product
    """
    def post(self, request):
        res = dict()
        product = get_object_or_404(ProductCategory,
pk=int(request.POST.get('id')))
        # print(product)
        product.purchaser = None
        product.save()
        res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')


class ProductCheckHistoryView(LoginRequiredMixin, View):
    """
    product check history
    """
    def get(self, request):
        productcategory = get_object_or_404(ProductCategory,
pk=int(request.GET['id']))
        check_history = productcategory.annualcheckhistory_set.all()

        ret = {
            'check_history': check_history
        }
        return render(request, 'product/annualcheckhistory.html', ret)


class AnnualCheckServiceStep2View(LoginRequiredMixin, View):

    def get(self, request):
        if 'id' in request.GET and request.GET['id']:
            notification = get_object_or_404(Notification,
pk=int(request.GET['id']))
            check_service = get_object_or_404(AnnualCheckService,
pk=int(notification.action_object_object_id))
            actor = get_object_or_404(UserProfile, pk=notification.actor_object_id)
            notification.unread = False
            notification.save()
            ret = {
                'notification': notification,
                'actor': actor,
                'check_service': check_service
            }
        return render(request, 'notification/notification-servicestep2.html', ret)

    def post(self, request):
        res = dict()
        print(request.POST)
        if 'notificationId' in request.POST and request.POST['notificationId']:
            notification = get_object_or_404(Notification,
pk=int(request.POST['notificationId']))
            crowdsourced_service = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.POST['notificationId']))
            recipient_role = Role.objects.get(name='Service provider')
            recipient =
list(UserProfile.objects.filter(roles__exact=recipient_role))
            annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=crowdsourced_service,
                                                    recipient=recipient,
                                                    request=request)

            res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')
```

```
class ServicemanConfirmationView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            notification = get_object_or_404(Notification,
pk=int(request.GET['id']))
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=int(notification.action_object_object_id))
            actor = get_object_or_404(UserProfile, pk=notification.actor_object_id)
            notification.unread = False
            notification.save()
            ret = {
                'notification': notification,
                'actor': actor,
                'service_crowdsourced': service_crowdsourced,
            }
        return render(request, 'notification/notification-servicestep3.html', ret)

    def post(self, request):
        res = dict()
        if 'notificationId' in request.POST and request.POST['notificationId']:
            notification = get_object_or_404(Notification,
pk=int(request.POST['notificationId']))
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=int(notification.action_object_object_id))
            serviceman_accept = get_object_or_404(UserProfile,
pk=int(request.POST['userId']))
            if service_crowdsourced:
                service_crowdsourced.serviceman_confirmed.add(serviceman_accept)
                service_crowdsourced.request_flag = 1
                service_crowdsourced.reply_date = datetime.now()
                service_crowdsourced.save()

annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service_crowdsourced,

recipient=serviceman_accept,
                                                        request=request)
                res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')


class Product2TenantView(LoginRequiredMixin, View):
    """
    binding product to tenant
    """
    def get(self, request):
        selected_product = get_object_or_404(ProductCategory,
pk=int(request.GET['id']))

        tenant_role = Role.objects.get(name='Tenants')
        tenants = UserProfile.objects.filter(roles__exact=tenant_role)
        binding_record_flag =
ProductToTenant.objects.filter(product_bind=selected_product, current_tenant=1)
        if binding_record_flag.exists():
            binding_record =
ProductToTenant.objects.get(product_bind=selected_product, current_tenant=1)
        else:
            binding_record =
ProductToTenant.objects.create(product_bind=selected_product, current_tenant=1)
        ret = {
            'binding_record': binding_record,
            'tenants': tenants
        }
        return render(request, 'product/productcategory_product2tenant.html', ret)

    def post(self, request):
```

```
        res = dict()
        if 'product_id' in request.POST and request.POST['product_id']:
            selected_product = get_object_or_404(ProductCategory,
pk=int(request.POST['product_id']))
            tenant = get_object_or_404(UserProfile,
pk=int(request.POST['selected_tenant']))
            bind_record_flag =
ProductToTenant.objects.filter(product_bind=selected_product, current_tenant=1)
            print(selected_product)
            if bind_record_flag.exists():
                bind_record =
ProductToTenant.objects.get(product_bind=selected_product, current_tenant=1)
                print(bind_record)
                if bind_record.tenant_bind is None:
                    bind_record.tenant_bind = tenant
                    bind_record.save()
                    res = {
                        'result': True,
                        'message': u'Bingding {name_} to product (serial number:
{product_} '
                                   u'successfully'.format(name_=tenant.name,

product_=selected_product.serial_number)
                    }
                elif bind_record.tenant_bind.id == tenant.id:
                    res = {
                        'result': 'yes',
                        'message': u'{name_} has already been binded to product
(serial number: {product_})'
                                   u' successfully'.format(name_=tenant.name,
product_=selected_product.serial_number)
                    }
                else:
                    bind_record.current_tenant = 0
                    bind_record.save()
                    new_record =
ProductToTenant.objects.create(product_bind=selected_product, tenant_bind=tenant,
                                                                        current_tenant=1)
                    if new_record:
                        res = {
                            'result': True,
                            'message': u'Bingding {name_} to product (serial
number: {product_} '
                                       u'successfully'.format(name_=tenant.name,

product_=selected_product.serial_number)
                        }
                    else:
                        res = {
                            'result': False,
                            'message': u'Bingding {name_} to product (serial
number: {product_} '
                                       u'failed'.format(name_=tenant.name,
product_=selected_product.serial_number)
                        }
            print(res)
        return HttpResponse(json.dumps(res), content_type='application/json')


class SendMessageToTenantView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            product_selected = get_object_or_404(ProductCategory,
pk=int(request.GET['id']))
            binding_record =
ProductToTenant.objects.get(product_bind=product_selected, current_tenant=1)
            print(binding_record.tenant_bind.name)
```

```
            ret = {
                'binding_record': binding_record
            }
        return render(request, 'product/productcategory_product2tenant-contact-
tenant.html', ret)

    def post(self, request):
        res = dict()
        if 'binding_id' in request.POST and request.POST['binding_id']:
            record = get_object_or_404(ProductToTenant,
pk=int(request.POST['binding_id']))
            msg_content = request.POST['msgContent']
            new_message =
ContactMessage.objects.create(msg_sender=record.product_bind.purchaser,
                                                        msg_to=record.tenant_bind,

product_involved=record.product_bind, send_date=datetime.now(),
                                                        msg_content=msg_content)
            if new_message:
                contact_message_posted.send(ContactMessage,
contactMessage=new_message)
                res['result'] = True
            else:
                res['result'] = False
        return HttpResponse(json.dumps(res), content_type='application/json')


class SendMessageToLandlordView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            product = get_object_or_404(ProductCategory, pk=int(request.GET['id']))
            binding_record_flag =
ProductToTenant.objects.filter(product_bind=product, tenant_bind=request.user,
                                                                 current_tenant=1)
            if binding_record_flag.exists():
                binding_record = ProductToTenant.objects.get(product_bind=product,
tenant_bind=request.user,
                                                             current_tenant=1)
                ret = {
                    'binding_record': binding_record
                }
        return render(request, 'product/productcategory_product2tenant-contact-
landlord.html', ret)

    def post(self, request):
        res = dict()
        if 'binding_id' in request.POST and request.POST['binding_id']:
            record = get_object_or_404(ProductToTenant,
pk=int(request.POST['binding_id']))
            msg_content = request.POST['msgContent']
            new_message =
ContactMessage.objects.create(msg_sender=record.tenant_bind,

msg_to=record.product_bind.purchaser,

product_involved=record.product_bind, send_date=datetime.now(),
                                                        msg_content=msg_content)
            if new_message:
                contact_message_posted.send(ContactMessage,
contactMessage=new_message)
                res['result'] = True
            else:
                res['result'] = False
        return HttpResponse(json.dumps(res), content_type='application/json')


class SendMessageBetweenTenantAndEngineerView(LoginRequiredMixin, View):
```

```
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            contract = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.GET['id']))
            print(contract)
            print(request.user.name)
            print(contract.selected_serviceman.name)
            print(contract.check_service.product_tenant_involved.tenant_bind.name)
            if request.user.id == contract.selected_serviceman.id:
                message_to =
contract.check_service.product_tenant_involved.tenant_bind
            if request.user.name ==
contract.check_service.product_tenant_involved.tenant_bind.name:
                message_to = contract.selected_serviceman
            ret = {
                'contract': contract,
                'message_to': message_to
            }
        return render(request, 'product/contract-contact-the-other.html', ret)

    def post(self, request):
        res = dict()
        if 'contract_id' in request.POST and request.POST['contract_id']:
            record = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.POST['contract_id']))
            product = record.check_service.product_tenant_involved.product_bind
            msg_to = request.POST['messageTo']
            person_to = UserProfile.objects.get(name=msg_to)
            msg_content = request.POST['msgContent']
            new_message = ContactMessage.objects.create(msg_sender=request.user,
                                                        msg_to=person_to,
                                                        product_involved=product,
send_date=datetime.now(),
                                                        msg_content=msg_content)
            if new_message:
                contact_message_posted.send(ContactMessage,
contactMessage=new_message)
                res['result'] = True
            else:
                res['result'] = False
        return HttpResponse(json.dumps(res), content_type='application/json')


class ServiceAppointmentView(LoginRequiredMixin, View):
    def get(self, request):
        items = list()
        productcategory = get_object_or_404(ProductCategory,
pk=int(request.GET['id']))
        service_crowdsourced_flag =
ServiceCrowdsourcing.objects.filter(check_service__product_tenant_involved__product
_bind=productcategory,

check_service__service_status__lt=4,

contract_status=1)
        if service_crowdsourced_flag.exists():
            service_crowdsourced =
ServiceCrowdsourcing.objects.get(check_service__product_tenant_involved__product_bi
nd=productcategory,

check_service__service_status__lt=4,

contract_status=1)
            servicemen_list = list(service_crowdsourced.serviceman_confirmed.all())

            destination =
service_crowdsourced.check_service.product_tenant_involved.product_bind.post_code
```

```
            gmaps =
googlemaps.Client(key='AIzaSyAKiJ5qWYkwhUA5VyJNBL1gdOtV8l40snw')

            for serviceman in servicemen_list:
                dis = gmaps.distance_matrix(origins=serviceman.post_code,
destinations=destination,
                                            mode='driving')
                print(dis)
                service_mark =
QualificationOfServiceman.objects.filter(serviceman=serviceman).aggregate(
                    Avg('service_quality'))
                satisfaction_mark =
QualificationOfServiceman.objects.filter(serviceman=serviceman).aggregate(
                    Avg('satisfaction'))
                if satisfaction_mark['satisfaction__avg'] is None:
                    satisfaction_mark['satisfaction__avg'] = 0
                if service_mark['service_quality__avg'] is None:
                    service_mark['service_quality__avg'] = 0
                recommendation_rate = 0.5 + 0.3 *
service_mark['service_quality__avg'] / 5 + 0.2 *
satisfaction_mark['satisfaction__avg'] / 5
                temp = {
                    'serviceman': serviceman,
                    'distance_to_destination':
dis['rows'][0]['elements'][0]['distance']['text'],
                    'duration': dis['rows'][0]['elements'][0]['duration']['text'],
                    'service_mark': service_mark,
                    'satisfaction_mark': satisfaction_mark,
                    'recommendation_rate': round(recommendation_rate, 2),
                }
                items.append(temp)
            print(items)
            items = sorted(items, key=lambda x: x['recommendation_rate'],
reverse=True)
        else:
            product_to_tenant =
ProductToTenant.objects.get(product_bind=productcategory, current_tenant=1)
            annual_check_service =
AnnualCheckService.objects.create(product_tenant_involved=product_to_tenant,

check_date=product_to_tenant.product_bind.expected_check_date)
            service_crowdsourced =
ServiceCrowdsourcing.objects.create(check_service=annual_check_service)

        check_history =
AnnualCheckHistory.objects.filter(checked_product=productcategory).last()

        ret = {
            'productcategory': productcategory,
            'service_crowdsourced': service_crowdsourced,
            'items': items,
            'check_history': check_history
        }
        return render(request, 'product/annualcheckservice.html', ret)

    def post(self, request):
        print(request.POST)
        res = dict()
        product_id = request.POST.get('productId')
        expected_date1 = request.POST.get('expected_check_date')
        additional_information = request.POST.get('additional_information', '')

        product = ProductCategory.objects.get(id=product_id)
        crowdsourced_service_flag =
ServiceCrowdsourcing.objects.filter(check_service__product_tenant_involved__product
_bind=product,

contract_status=1)
```

```
        if crowdsourced_service_flag.exists():
            crowdsourced_service =
ServiceCrowdsourcing.objects.get(check_service__product_tenant_involved__product_bi
nd=product,

contract_status=1)
        crowdsourced_service.check_service.request_date = datetime.now()
        crowdsourced_service.check_service.check_date = product.expected_check_date
        crowdsourced_service.check_service.request_flag = 1
        crowdsourced_service.check_service.additional_information =
additional_information
        crowdsourced_service.check_service.save()
        annual_check_service_posted.send(sender=ServiceCrowdsourcing,
crowdsourcedService=crowdsourced_service,
                                         request=request)
        res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')


class ActiveServiceAppointmentView(LoginRequiredMixin, View):
    """
        landlord requests service except annual check
    """

    def get(self, request):
        items = list()
        productcategory = get_object_or_404(ProductCategory,
pk=int(request.GET['id']))
        service_crowdsourced_flag =
ServiceCrowdsourcing.objects.filter(check_service__product_tenant_involved__product
_bind=productcategory,

check_service__service_status__lt=4,

contract_status=1)
        if service_crowdsourced_flag.exists():
            service_crowdsourced =
ServiceCrowdsourcing.objects.get(check_service__product_tenant_involved__product_bi
nd=productcategory,

check_service__service_status__lt=4,

contract_status=1)
            servicemen_list = list(service_crowdsourced.serviceman_confirmed.all())

            destination =
service_crowdsourced.check_service.product_tenant_involved.product_bind.post_code
            gmaps =
googlemaps.Client(key='AIzaSyAKiJ5qWYkwhUA5VyJNBL1gdOtV8l40snw')

            for serviceman in servicemen_list:
                try:
                    dis = gmaps.distance_matrix(origins=serviceman.post_code,
destinations=destination, mode='driving')
                except (KeyError, TypeError):
                    pass
                service_mark =
QualificationOfServiceman.objects.filter(serviceman=serviceman).aggregate(
                    Avg('service_quality'))
                satisfaction_mark =
QualificationOfServiceman.objects.filter(serviceman=serviceman).aggregate(
                    Avg('satisfaction'))
                temp = {
                    'serviceman': serviceman,
                    'distance_to_destination':
dis['rows'][0]['elements'][0]['distance']['text'],
                    'duration': dis['rows'][0]['elements'][0]['duration']['text'],
                    'service_mark': service_mark,
```

```
                    'satisfaction_mark': satisfaction_mark
                }
                items.append(temp)
        else:
            product_to_tenant =
ProductToTenant.objects.get(product_bind=productcategory, current_tenant=1)
            annual_check_service =
AnnualCheckService.objects.create(product_tenant_involved=product_to_tenant,

check_status_type=1)
            service_crowdsourced =
ServiceCrowdsourcing.objects.create(check_service=annual_check_service)

        check_history =
AnnualCheckHistory.objects.filter(checked_product=productcategory).last()

        ret = {
            'productcategory': productcategory,
            # 'annual_check_service': annual_check_service,
            'service_crowdsourced': service_crowdsourced,
            'items': items,
            'check_history': check_history
        }
        return render(request, 'product/usualcheckservice.html', ret)

    def post(self, request):
        res = dict()
        product_id = request.POST.get('productId')
        expected_date1 = request.POST.get('expected_check_date')

        additional_information = request.POST.get('additional_information', '')
        fmt = '%Y-%m-%d'
        time_tuple = time.strptime(expected_date1, fmt)
        year, month, day = time_tuple[:3]
        expected_date = date(year, month, day)

        product = ProductCategory.objects.get(id=product_id)
        crowdsourced_service_flag =
ServiceCrowdsourcing.objects.filter(check_service__product_tenant_involved__product
_bind=product,

contract_status=1)
        if crowdsourced_service_flag.exists():
            crowdsourced_service =
ServiceCrowdsourcing.objects.get(check_service__product_tenant_involved__product_bi
nd=product,

contract_status=1)
            crowdsourced_service.check_service.request_date = datetime.now()
            crowdsourced_service.check_service.request_flag = 1
            crowdsourced_service.check_service.check_date = expected_date
            crowdsourced_service.check_service.additional_information =
additional_information
            crowdsourced_service.check_service.save()
            crowdsourced_service.save()
            annual_check_service_posted.send(sender=ServiceCrowdsourcing,
crowdsourcedService=crowdsourced_service,
                                             request=request)
            res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')


class TenantConfirmTimeView(LoginRequiredMixin, View):

    def get(self, request):
        if 'id' in request.GET and request.GET['id']:
            notification = get_object_or_404(Notification,
pk=int(request.GET['id']))
```

```
            check_service = get_object_or_404(AnnualCheckService,
pk=int(notification.action_object_object_id))
            actor = get_object_or_404(UserProfile, pk=notification.actor_object_id)
            notification.unread = False
            notification.save()
            ret = {
                'notification': notification,
                'actor': actor,
                'check_service': check_service,
            }
        return render(request, 'notification/notification-servicestep1.html', ret)

    def post(self, request):
        ret = dict()
        if 'notificationId' in request.POST and request.POST['notificationId']:
            notification = get_object_or_404(Notification,
pk=int(request.POST['notificationId']))
            available_time = request.POST.get('availableTime')

            service =
AnnualCheckService.objects.get(id=notification.action_object_object_id)
            if service:
                service.tenant_available_time = available_time
                service.reply_date = datetime.now()
                service.service_status = 2
                service.request_flag = 2
                service.save()
                annual_check_service_posted.send(sender=AnnualCheckService,
annualCheckService=service,
                                                 request=request)
                ret['result'] = True
            else:
                ret['result'] = False
        else:
            ret['result'] = False
        return HttpResponse(json.dumps(ret), content_type='application/json')


class ServiceCrowdsourcingByMainInterfaceView(LoginRequiredMixin, View):
    def post(self, request):
        res = dict()
        if 'serviceCrowdsourcingId' in request.POST and
request.POST['serviceCrowdsourcingId']:
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.POST['serviceCrowdsourcingId']))
            service_crowdsourced.crowdsourcing_status = 1
            service_crowdsourced.request_flag = 1
            service_crowdsourced.request_date = datetime.now()
            service_crowdsourced.save()
            service_crowdsourced.check_service.service_status = 2
            service_crowdsourced.check_service.save()
            recipient_role = Role.objects.get(name='Service provider')
            recipient =
list(UserProfile.objects.filter(roles__exact=recipient_role))
            print(recipient)
            annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service_crowdsourced,
                                                    recipient=recipient,
                                                    request=request)
            res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')


class ContractGenerationByMainInterfaceView(LoginRequiredMixin, View):
    def post(self, request):
        ret = dict()
        if 'serviceCrowdsourcingId' in request.POST and
```

```
request.POST['serviceCrowdsourcingId']:
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.POST['serviceCrowdsourcingId']))
            selected_serviceman = get_object_or_404(UserProfile,
pk=int(request.POST['selectedMan']))
            service_crowdsourced.selected_serviceman = selected_serviceman
            service_crowdsourced.crowdsourcing_status = 0
            service_crowdsourced.contract_date = datetime.now()
            service_crowdsourced.is_generated = True
            service_crowdsourced.save()

            service_crowdsourced.check_service.service_status = 3
            service_crowdsourced.check_service.save()

            tenant =
service_crowdsourced.check_service.product_tenant_involved.tenant_bind
            annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service_crowdsourced,
                                                    recipient=tenant,
                                                    request=request)
            annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service_crowdsourced,
                                                    recipient=selected_serviceman,
                                                    request=request)
        ret['result'] = True
        return HttpResponse(json.dumps(ret), content_type='application/json')


class StopCrowdsourcingView(LoginRequiredMixin, View):
    def post(self, request):
        ret = dict()
        if 'serviceCrowdsourcingId' in request.POST and
request.POST['serviceCrowdsourcingId']:
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.POST['serviceCrowdsourcingId']))
            service_crowdsourced.crowdsourcing_status = 0
            service_crowdsourced.save()
            print(service_crowdsourced)
            ret['result'] = True
        return HttpResponse(json.dumps(ret), content_type='application/json')


class ContractGenerationView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            notification = get_object_or_404(Notification,
pk=int(request.GET['id']))
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=notification.action_object_object_id)

            actor = get_object_or_404(UserProfile, pk=notification.actor_object_id)
            servicemen_list = list(service_crowdsourced.serviceman_confirmed.all())

            destination =
service_crowdsourced.check_service.product_tenant_involved.product_bind.post_code
            gmaps =
googlemaps.Client(key='AIzaSyAKiJ5qWYkwhUA5VyJNBL1gdOtV8l40snw')
            items = list()

            for serviceman in servicemen_list:
                dis = gmaps.distance_matrix(origins=serviceman.post_code,
destinations=destination, mode='driving')
                service_mark =
QualificationOfServiceman.objects.filter(serviceman=serviceman).aggregate(
                    Avg('service_quality'))
```

```
                satisfaction_mark =
QualificationOfServiceman.objects.filter(serviceman=serviceman).aggregate(
                    Avg('satisfaction'))
                temp = {
                    'serviceman': serviceman,
                    'distance_to_destination':
dis['rows'][0]['elements'][0]['distance']['text'],
                    'duration': dis['rows'][0]['elements'][0]['duration']['text'],
                    'service_mark': service_mark,
                    'satisfaction_mark': satisfaction_mark
                }
                items.append(temp)
            ret = {
                'notification': notification,
                'actor': actor,
                'service_crowdsourced': service_crowdsourced,
                'items': items
            }
        return render(request, 'notification/notification-servicestep4.html', ret)

    def post(self, request):
        ret = dict()
        print(request.POST)
        if 'notificationId' in request.POST and request.POST['notificationId']:
            notification = get_object_or_404(Notification,
pk=int(request.POST['notificationId']))
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=notification.action_object_object_id)
            selected_serviceman = get_object_or_404(UserProfile,
pk=int(request.POST['selectedMan']))
            service_crowdsourced.selected_serviceman = selected_serviceman
            service_crowdsourced.check_service.service_status = 3
            service_crowdsourced.check_service.save()

            service_crowdsourced.crowdsourcing_status = 0
            service_crowdsourced.contract_date = datetime.now()
            service_crowdsourced.is_generated = True
            service_crowdsourced.save()
            tenant =
service_crowdsourced.check_service.product_tenant_involved.tenant_bind
            annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service_crowdsourced,
                                                    recipient=tenant,
                                                    request=request)
            annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service_crowdsourced,
                                                    recipient=selected_serviceman,
                                                    request=request)
        ret['result'] = True
        return HttpResponse(json.dumps(ret), content_type='application/json')


class ContractResultView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            notification = get_object_or_404(Notification,
pk=int(request.GET['id']))
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=notification.action_object_object_id)
            actor = get_object_or_404(UserProfile, pk=notification.actor_object_id)
            ret = {
                'notification': notification,
                'actor': actor,
                'service_crowdsourced': service_crowdsourced,
            }
```

```
        return render(request, 'notification/notification-service-contract.html',
ret)


class ProductServicemanView(LoginRequiredMixin, BreadcrumbMixin, TemplateView):
    template_name = 'product/productcategory_service_history.html'

    def get_context_data(self, **kwargs):
        context = super(ProductServicemanView, self).get_context_data(**kwargs)
        current_user = UserProfile.objects.get(id=self.request.user.id)
        user_role = current_user.roles.all()
        permissions = list()
        for role in user_role:
            permission = role.permissions.all()
            for permit in permission:
                permit_code = permit.code
                permissions.append(permit_code)
        print(permissions)
        context['permissions'] = permissions
        return context


class ProductServiceHistoryView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            history = get_object_or_404(AnnualCheckHistory,
pk=int(request.GET['id']))
            ret = {
                'history': history
            }
        return render(request, 'product/productcategory_service_history_view.html',
ret)


class ProductServiceContractView(LoginRequiredMixin, BreadcrumbMixin,
TemplateView):
    template_name = 'product/productcategory_service_contracts.html'

    def get_context_data(self, **kwargs):
        context = super(ProductServiceContractView,
self).get_context_data(**kwargs)
        current_user = UserProfile.objects.get(id=self.request.user.id)
        user_role = current_user.roles.all()
        # print(user_role)
        permissions = list()
        for role in user_role:
            permission = role.permissions.all()
            for permit in permission:
                permit_code = permit.code
                permissions.append(permit_code)
        print(permissions)
        context['permissions'] = permissions
        return context


class ProductServiceContractUpdateView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            contract = get_object_or_404(ServiceCrowdsourcing,
pk=request.GET['id'])
            ret['contract'] = contract
        return render(request,
'product/productcategory_service_contracts_update.html', ret)

    def post(self, request):
        res = dict()
```

```
        if 'id' in request.POST and request.POST['id']:
            contract = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.POST['id']))
            checked_date1 = request.POST['checked_date']
            fmt = '%Y-%m-%d'
            time_tuple = time.strptime(checked_date1, fmt)
            year, month, day = time_tuple[:3]
            checked_date = date(year, month, day)
            contract.checked_date = checked_date
            contract.contract_status = request.POST['contract_status']
            contract.crowdsourcing_status = 2
            contract.request_flag = 0
            contract.save()

            contract.check_service.service_status = 4
            contract.check_service.save()
            serviceman = get_object_or_404(UserProfile, pk=self.request.user.id)
            checked_product =
contract.check_service.product_tenant_involved.product_bind
            if contract.check_service.check_status_type == 1:
                history =
AnnualCheckHistory.objects.create(checked_product=checked_product,
checked_by=serviceman,

expected_check_date=contract.check_service.check_date,

checked_date=checked_date, status=1, check_type=1)
            else:  # annual check
                history =
AnnualCheckHistory.objects.create(checked_product=checked_product,
checked_by=serviceman,

expected_check_date=contract.check_service.check_date,

checked_date=checked_date, status=1, check_type=0)
                checked_product.expected_check_date =
date(history.checked_date.year+1, history.checked_date.month,

history.checked_date.day)
                checked_product.save()

            evaluate_serviceman_invitation.send(sender=ServiceCrowdsourcing,
serviceCrowdsourcing=contract,
                                                request=request)
            res['result'] = True
            return HttpResponse(json.dumps(res), content_type='application/json')


class ServiceEvaluationView(LoginRequiredMixin, View):
    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            notification = get_object_or_404(Notification,
pk=int(request.GET['id']))
            service_history = get_object_or_404(ServiceCrowdsourcing,
pk=notification.action_object_object_id)
            ret = {
                'notification': notification,
                'service_history': service_history
            }
            print(ret)
            notification.unread = False
            notification.save()
        return render(request, 'product/annualcheckservice-evaluation.html', ret)

    def post(self, request):
        res = dict()
        if 'servicecrowdsourcingId' in request.POST and
```

```
request.POST['servicecrowdsourcingId']:
            service_crowdsourced = get_object_or_404(ServiceCrowdsourcing,
pk=int(request.POST['servicecrowdsourcingId']))

            serviceman =
UserProfile.objects.get(id=service_crowdsourced.selected_serviceman.id)
            marker = self.request.user
            quality_mark = request.POST['serviceQuality']
            satisfaction = request.POST['satisfaction']
            mark_record =
QualificationOfServiceman.objects.create(serviceman=serviceman,
service_quality=quality_mark,

satisfaction=satisfaction, marked_by=marker,

marked_date=datetime.now())
            service_crowdsourced.selected_serviceman_is_evaluated = True
            print(mark_record)
            res['result'] = True
        return HttpResponse(json.dumps(res), content_type='application/json')


class ServiceRequestConfirmationView(LoginRequiredMixin, View):

    def get(self, request):
        ret = dict()
        if 'id' in request.GET and request.GET['id']:
            notification = get_object_or_404(Notification,
pk=int(request.GET['id']))
            object_type = get_object_or_404(ContentType,
pk=notification.action_object_content_type_id)
            object_model = object_type.model_class()
            object_service = get_object_or_404(object_model,
pk=notification.action_object_object_id)
            print(object_service)
            if isinstance(object_service, AnnualCheckService):
                check_service =
AnnualCheckService.objects.get(id=notification.action_object_object_id)
                service_crowdsourced_flag =
ServiceCrowdsourcing.objects.filter(check_service=check_service,

crowdsourcing_status__gt=0)
                if service_crowdsourced_flag.exists():
                    service_crowdsourced =
ServiceCrowdsourcing.objects.get(check_service=check_service,

crowdsourcing_status__gt=0)
                else:
                    service_crowdsourced =
ServiceCrowdsourcing.objects.create(check_service=check_service)
            else:
                print(notification.action_object_object_id)
                service_crowdsourced =
ServiceCrowdsourcing.objects.get(id=notification.action_object_object_id)

            actor = get_object_or_404(UserProfile, pk=notification.actor_object_id)

            notification.unread = False
            notification.save()
            print(service_crowdsourced.check_service.service_status)
            print(service_crowdsourced.check_service.request_flag)
            print(service_crowdsourced.crowdsourcing_status)
            print(service_crowdsourced.request_flag)
            ret = {
                'notification': notification,
                'actor': actor,
                'service_crowdsourced': service_crowdsourced
            }
```

```
        return render(request, 'notification/notification-service-request-
confirmation.html', ret)

    def post(self, request):
        ret = dict()
        if 'step' in request.POST and request.POST['step']:
            if request.POST['step'] == 'tenantConfirm':
                service_flag =
ServiceCrowdsourcing.objects.filter(id=int(request.POST['serviceId']))
                available_time = request.POST.get('availableTime')
                if service_flag.exists():
                    service =
ServiceCrowdsourcing.objects.get(id=int(request.POST['serviceId']))
                    service.check_service.tenant_available_time = available_time
                    service.check_service.reply_date = datetime.now()
                    service.check_service.request_flag = 2
                    service.check_service.save()
                    annual_check_service_posted.send(sender=ServiceCrowdsourcing,
crowdsourcedService=service,
                                                     request=request)
                    ret['result'] = True
            elif request.POST['step'] == 'crowdsourcing':
                service_flag =
ServiceCrowdsourcing.objects.filter(id=int(request.POST['serviceId']))
                if service_flag.exists():
                    service =
ServiceCrowdsourcing.objects.get(id=int(request.POST['serviceId']))
                    recipient_role = Role.objects.get(name='Service provider')
                    recipient =
list(UserProfile.objects.filter(roles__exact=recipient_role))
                    service.check_service.service_status = 2
                    service.check_service.save()
                    service.crowdsourcing_status = 1
                    service.request_flag = 1
                    service.request_date = datetime.now()
                    service.save()

annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service,
                                                            recipient=recipient,
                                                            request=request)

                ret['result'] = True
            elif request.POST['step'] == 'servicemanConfirmation':
                service =
ServiceCrowdsourcing.objects.get(id=int(request.POST['serviceId']))
                serviceman_accept = get_object_or_404(UserProfile,
pk=int(request.user.id))
                service.serviceman_confirmed.add(serviceman_accept)
                service.reply_date = datetime.now()
                service.request_flag = 2
                service.save()


annual_check_service_crowdsourcing.send(sender=ServiceCrowdsourcing,

crowdsourcedService=service,

recipient=serviceman_accept,
                                                        request=request)
                ret['result'] = True
            else:
                ret['result'] = False
        else:
            ret['result'] = False

        return HttpResponse(json.dumps(ret), content_type='application/json')
```

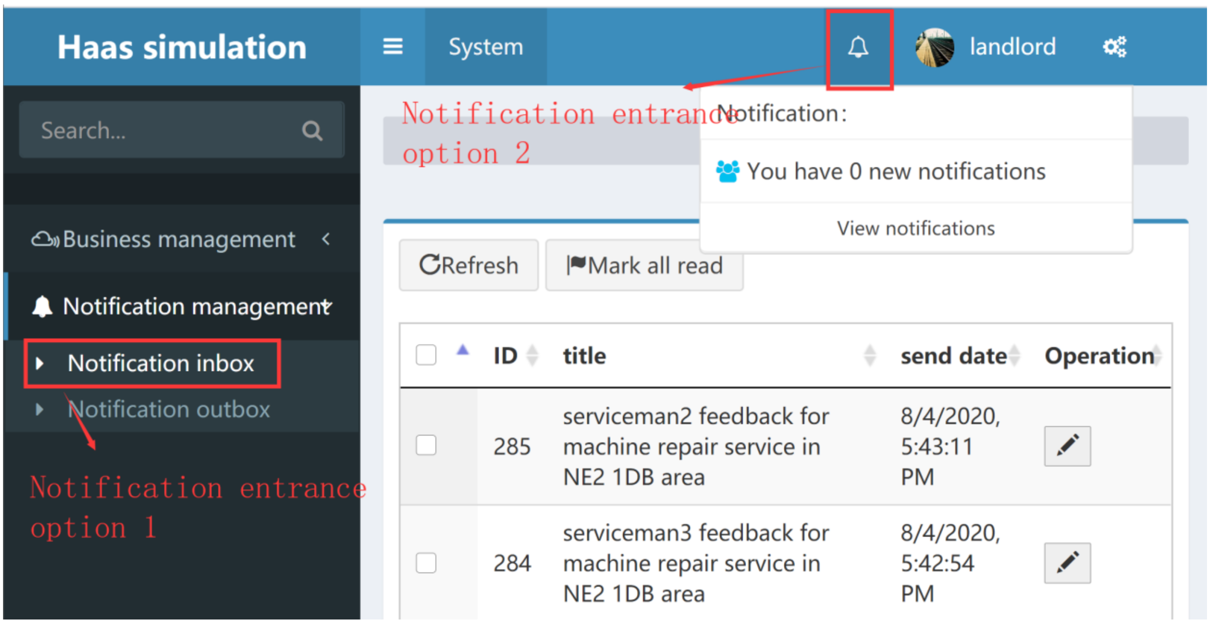
```
class ProductPowerView(LoginRequiredMixin, View):
    def post(self, request):
        ret = dict()
        if 'id' in request.POST and request.POST['id']:
            product_selected = get_object_or_404(ProductCategory,
pk=int(request.POST['id']))
            if product_selected.status != 'under repair':
                if product_selected.power_on is False:
                    product_selected.power_on = True
                    product_selected.status = 'running'
                    print(product_selected.status)
                    product_selected.save()
                    ret['result'] = 'on'
                else:
                    product_selected.power_on = False
                    product_selected.status = 'off'
                    product_selected.save()
                    print(product_selected.status)
                    ret['result'] = 'off'
            else:
                ret['result'] = 'maintenance'
        return HttpResponse(json.dumps(ret), content_type='application/json')


class ProductSetMachineView(LoginRequiredMixin, View):
    def post(self, request):
        print(request.POST)
        ret = dict()
        if 'id' in request.POST and request.POST['id']:
            product_selected = get_object_or_404(ProductCategory,
pk=int(request.POST['id']))
            print(product_selected.power_on)
            print(product_selected.status)
            if product_selected.power_on is True:
                ret['result'] = 'on'
            else:
                if product_selected.status == 'under repair':
                    product_selected.status = 'ready for running'
                    product_selected.save()
                    ret['result'] = 'ready'
                else:
                    product_selected.status = 'under repair'
                    product_selected.status = 'under repair'
                    product_selected.save()
                    ret['result'] = 'repair'
            print(ret['result'])
        return HttpResponse(json.dumps(ret), content_type='application/json')


class WaterModeView(LoginRequiredMixin, View):
    def post(self, request):
        print(request.POST)
        ret = dict()
        if 'id' in request.POST and request.POST['id']:
            product_selected = get_object_or_404(ProductCategory,
pk=int(request.POST['id']))
            if product_selected.power_on is True:
                water_level = request.POST['water_level']
                water_mode = water_level[-1]
                product_selected.water_mode = water_mode
                product_selected.save()
                ret['result'] = water_mode
            else:
                ret['result'] = 0
        return HttpResponse(json.dumps(ret), content_type='application/json')
```

```
class HeatingModeView(LoginRequiredMixin, View):
    def post(self, request):
        print(request.POST)
        ret = dict()
        if 'id' in request.POST and request.POST['id']:
            product_selected = get_object_or_404(ProductCategory,
pk=int(request.POST['id']))
            if product_selected.power_on is True:
                heating_level = request.POST['heating_level']
                heating_mode = heating_level[-1]
                product_selected.heating_mode = heating_mode
                product_selected.save()
                ret['result'] = heating_mode
            else:
                ret['result'] = 0
        return HttpResponse(json.dumps(ret), content_type='application/json')
```

Appendix D: Detailed instructions for different role players on the integrated crowdsourcing platform

General instructions for platform users

When platform users use this platform, a lot of messages will be received. The message entrance is notification inbox and notification icon in the top right corner of the page.



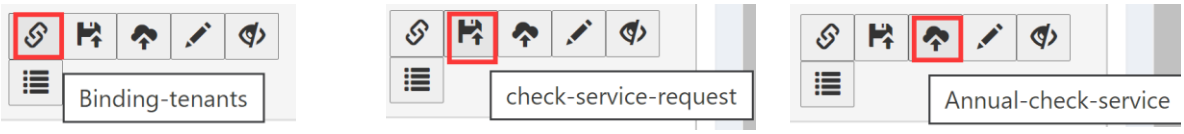
Instructions for Landlord

1. The introduction of the main interface for Landlord

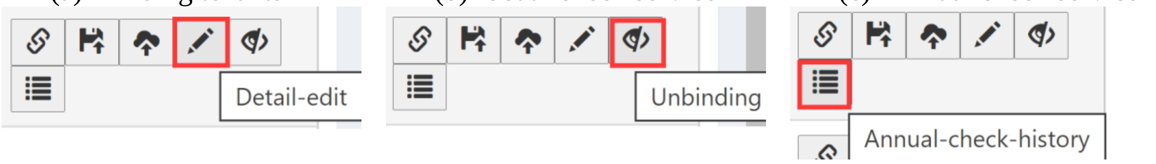
Fig. 1 The main interface for Landlord.

(1) The operations for a selected machine

The operations for a selected machine from left to right are binding tenant to the machine, usual check service, annual check service, update machine information, unbinding machine, and machine check history. A prompt will appear when mouse hovers over the button, which is helpful for users to get familiar with its function. The prompts locating at the bottom right for these actions are showed bellowed.



(a) Binding tenants (b) Usual check service (c) Annual check service



(d) Update machine info (e) Unbinding machine (f) Machine check history

Fig. 2 Operations for a selected machine.

Before requesting usual check service and annual check service, the landlord must bind the tenant first. (*)

(2) Introduction to actions in Fig. 2

a. Binding tenants

This action is a prerequisite for usual check service and annual check service. The interface for this action is shown in Fig. 3. The landlord is required to select the tenant to be binded and click the save button, then the tenant can be binded successfully to the selected machine. If new tenant moves in, the landlord can re-select the tenant and re-bind again. The operation is the same.

After tenant is binded to the machine, the landlord can send messages to tenant (contact tenant action) and request usual check service and annual check service.

a1. Contact tenant

The message is sent to the binded tenant.

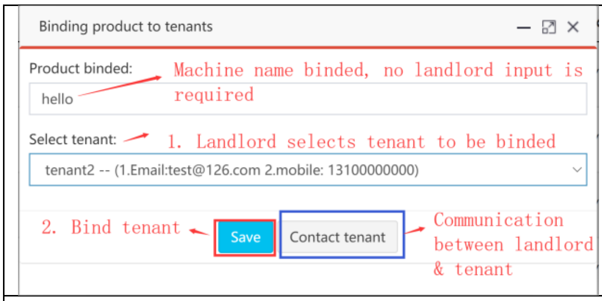


Fig. 3 The interface for binding tenants.

Fig. 4 Interface for contacting tenant.

b. Usual check service

Two typical service scenarios for this service is online and offline usual machine check.

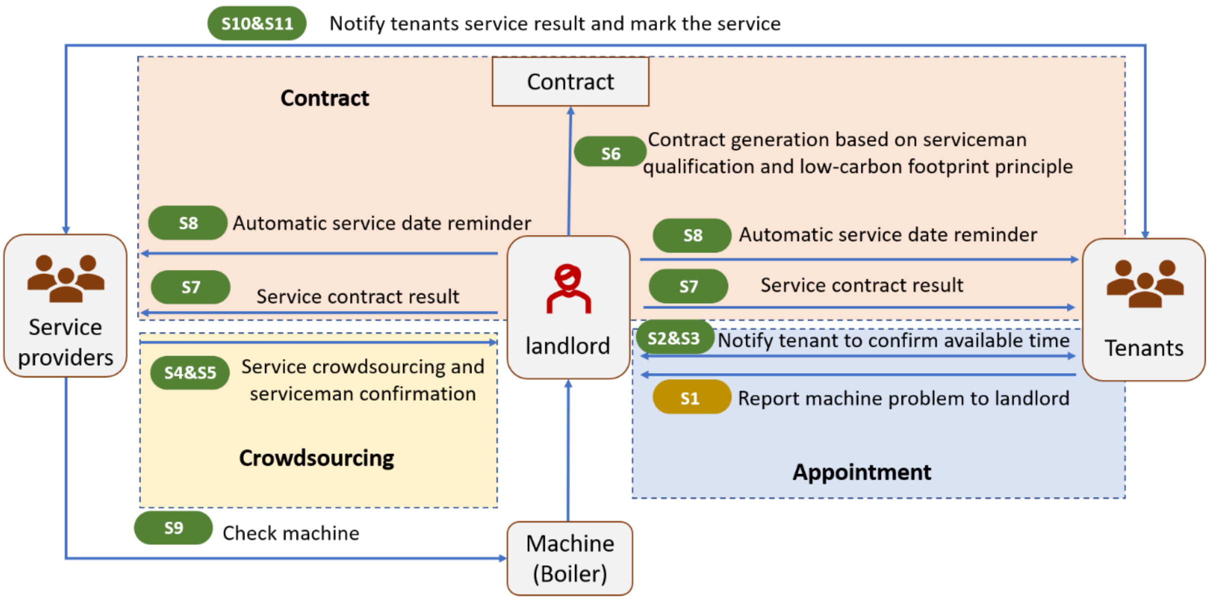


Fig. 5 Online usual machine check.

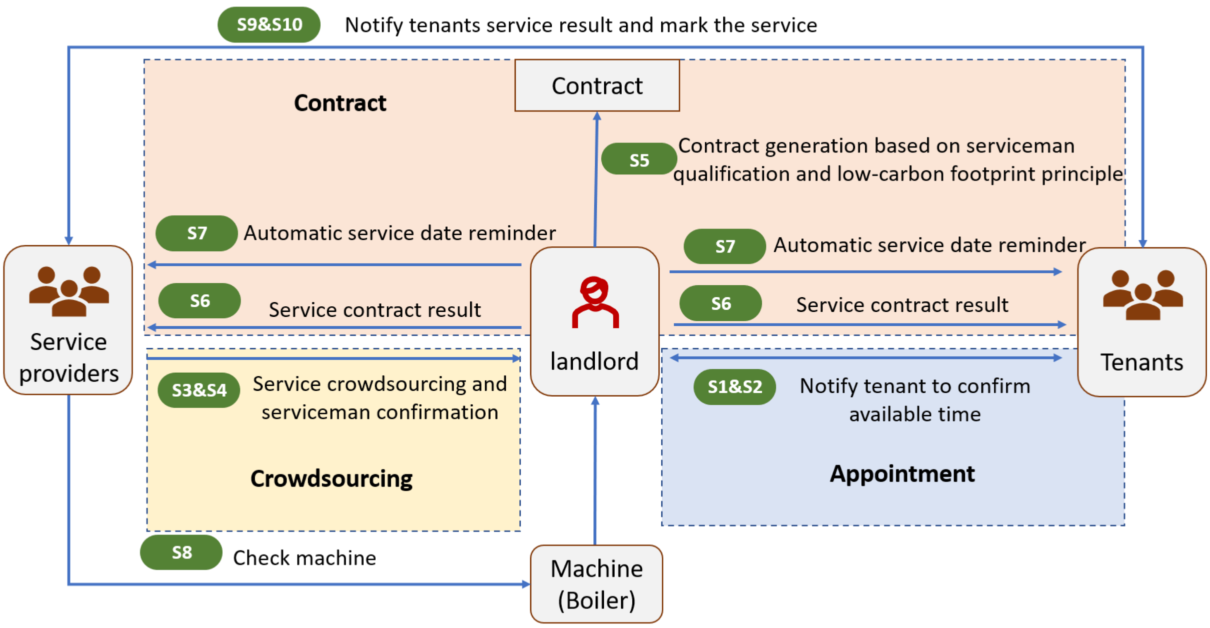


Fig. 6 Offline usual machine check scenario.

These two scenarios relied on the communication between landlord and tenant online and offline. The difference is that the online communication is recorded on the HAAS simulation platform, while offline not.

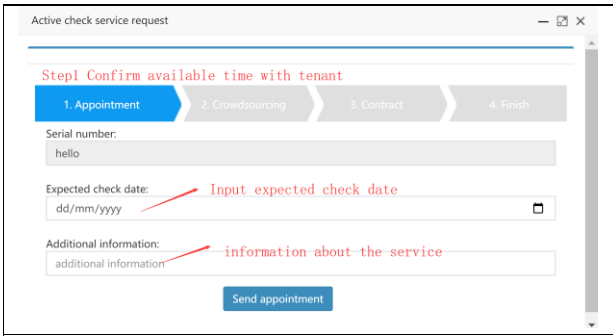
Whatever communication way is adopted by the landlord and tenant, the usual check service is requested by the landlord actively. And the service process includes 4 steps.

Step 1: Confirm available time (make appointment) with tenant (Fig. 7(a)). After sending appoint invitation, the landlord is required to wait for the confirmation from tenant. When the tenant confirms service time, the landlord can enter to the next step – crowdsourcing (Fig. 7(b)).

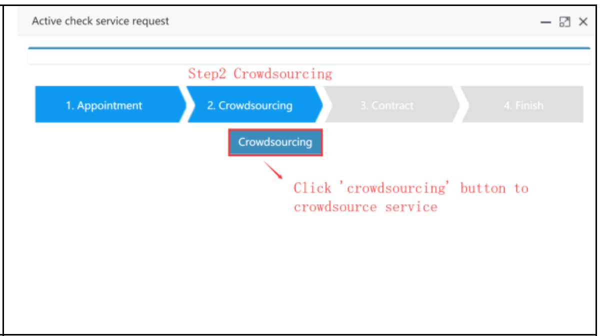
Step 2: Crowdsourcing service (Fig. 7(a)). The landlord can start crowdsourcing either from the appointment confirmation message from tenant (in notification inbox) or from the ‘usual check service’ button (in product binding/unbinding). On this platform, all serviceman will receive a message about this service request. When serviceman accept the service, the landlord can view the crowdsourcing results from ‘usual check service’ button. An example of crowdsourcing results is shown in Fig. 7(c).

Step 3: Landlord can receive a list of serviceman in terms of their service mark, satisfaction mark, distance to the machine, and duration by driving. Landlord can view the detailed information of serviceman by clicking their names. Once the landlord selects the serviceman to provide service and click ‘contract generation’ button, the service contract will generate successfully, and both the tenant and selected serviceman will receive a message about the contract.

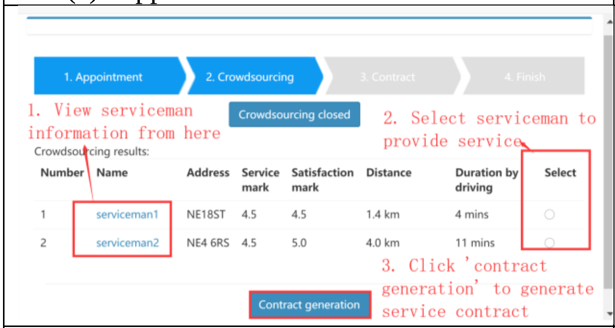
Step 4: After the service contract is generated, a contract result will be listed as shown in Fig. 7(d).



(a) Appointment with tenant.



(b) Crowdsourcing service.



(c) Contract generation.

Fig. 7 Usual check service interfaces.

c. Annual check service

The scenario for this service is shown in Fig. 8.

Annual check service is much similar to usual check service. The difference is that the expected check date is updated by the platform automatically based on the previous annual check date and cannot be changed by the landlord (Fig. 9). And before a given time period of the expected annual check date, the platform will send reminder message to the landlord automatically and then the landlord starts to request the annual check service.

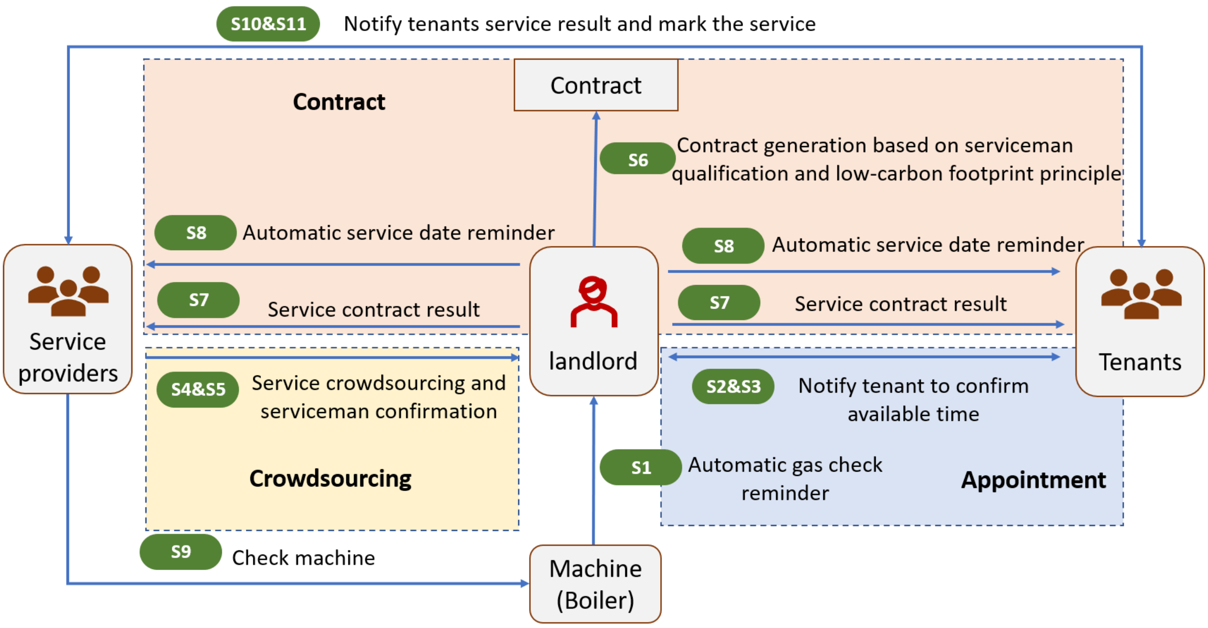


Fig. 8 Annual gas check scenario.

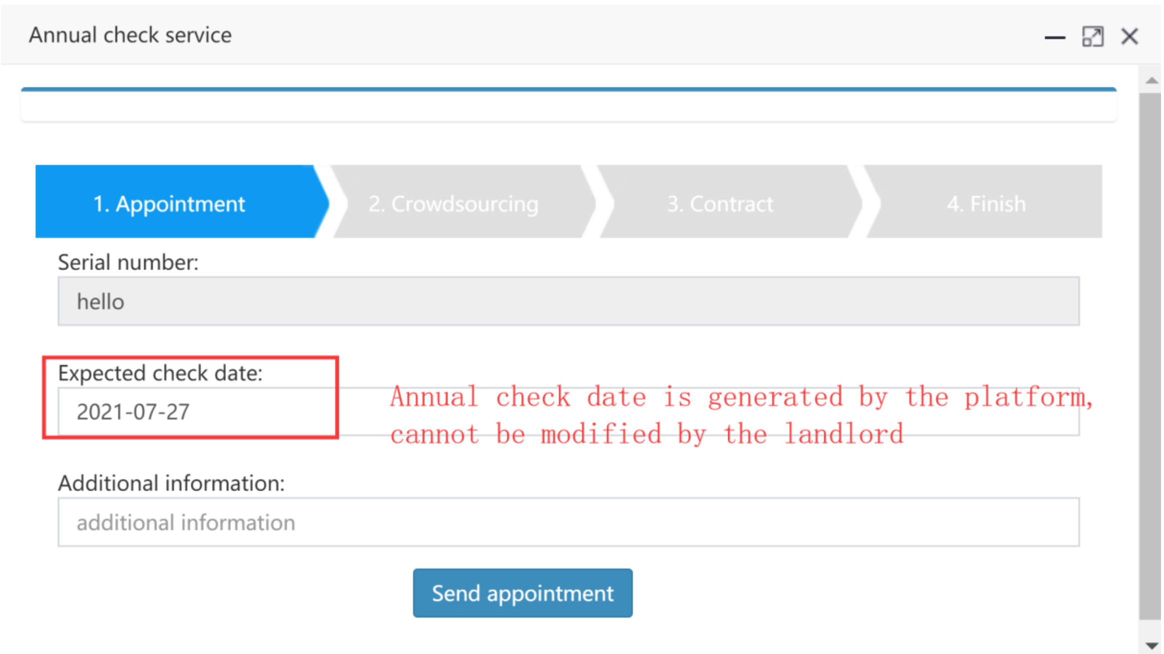
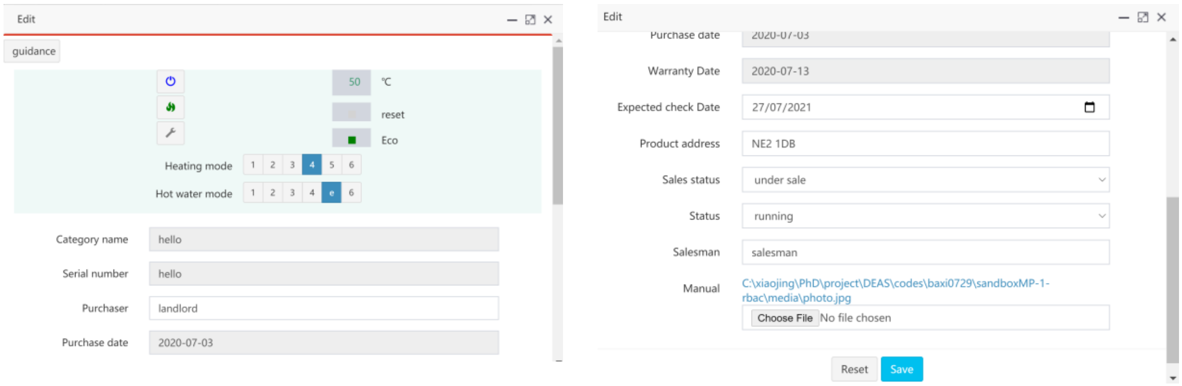


Fig. 9 Appointment interface for annual check service.

d. Update machine information

This is an interactive interface which shows the real-time status of the machine. Once the landlord operates on this interface, he/she can receive real-time feedback. In addition, a guidance for how to operate the machine is provided. The interface is shown in Fig. 10.



(a) Part A. (b) Part B.

Fig. 10 The interface for updating machine information.

e. Unbinding

When the 'unbinding' button is clicked, the platform will pop a warning box shown in Fig. 11. If the landlord click 'yes', the machine will be unbinded to the landlord. 'No' is cancel the operation.

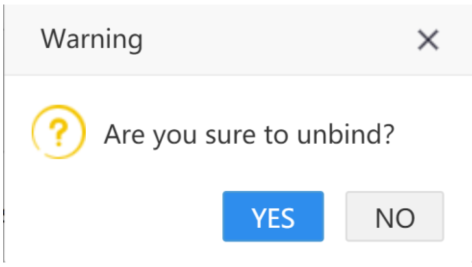
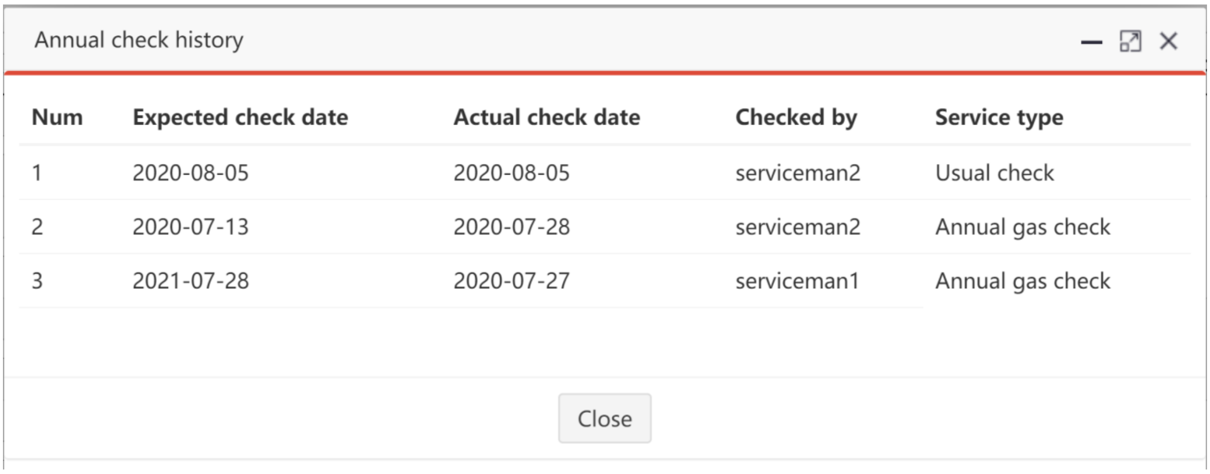


Fig. 11 Unbinding machine interface.

f. View machine check history

From 'machine check history' button, the landlord can view the check history in terms of expected check date, actual check date, checked by, and service type. The interface is shown in Fig. 12.



Annual check history

Num	Expected check date	Actual check date	Checked by	Service type
1	2020-08-05	2020-08-05	serviceman2	Usual check
2	2020-07-13	2020-07-28	serviceman2	Annual gas check
3	2021-07-28	2020-07-27	serviceman1	Annual gas check

Close

Fig. 12 The interface for machine check history.

Instructions for serviceman

1. Main interface for serviceman

The main interface for serviceman is shown in Fig. 13. The operations for a selected contract from left to right is view contract, update contract, and contact tenant.

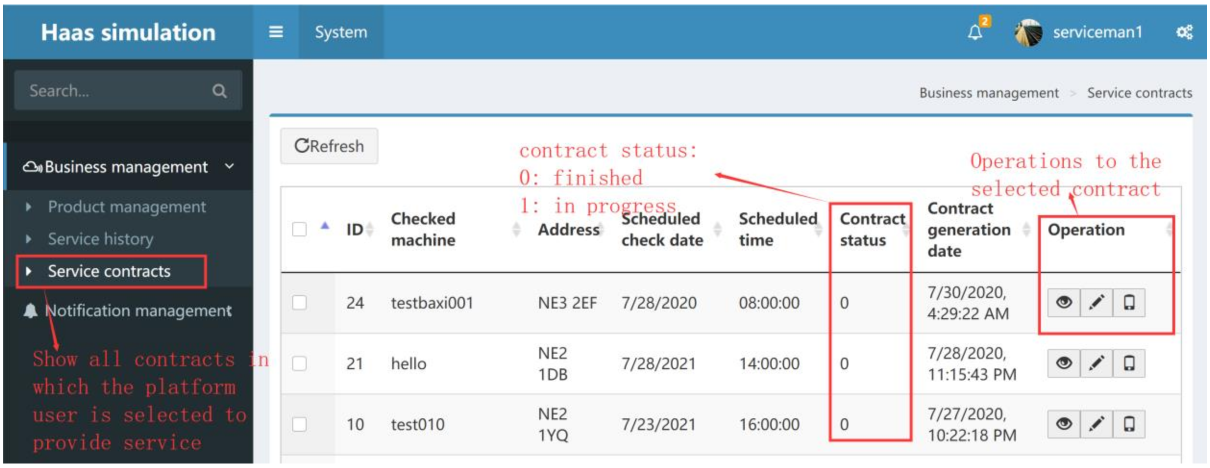


Fig. 13 The main interface for serviceman.

2. Introduction to contract operations

a. View contract

From view contract, the serviceman can see the contract details (Fig. 14), but he/she is not allowed to edit the detail.

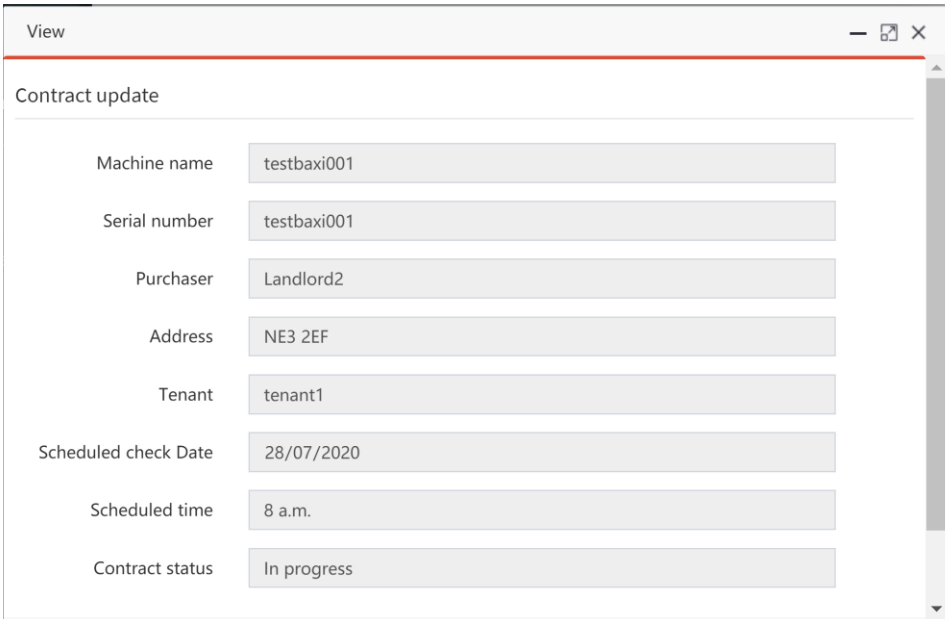


Fig. 14 View contract detail.

b. Update contract

When the serviceman received the message that he/she is scheduled to provide service at a given area at given time (when simulation, the information is ‘congratulations, you are selected to provide machine check service at given area at given time ’), he/she should go to ‘service contracts’ tab to update the contract status by inputting actual check date and marking the contract finished. The interface is shown in Fig. 15.

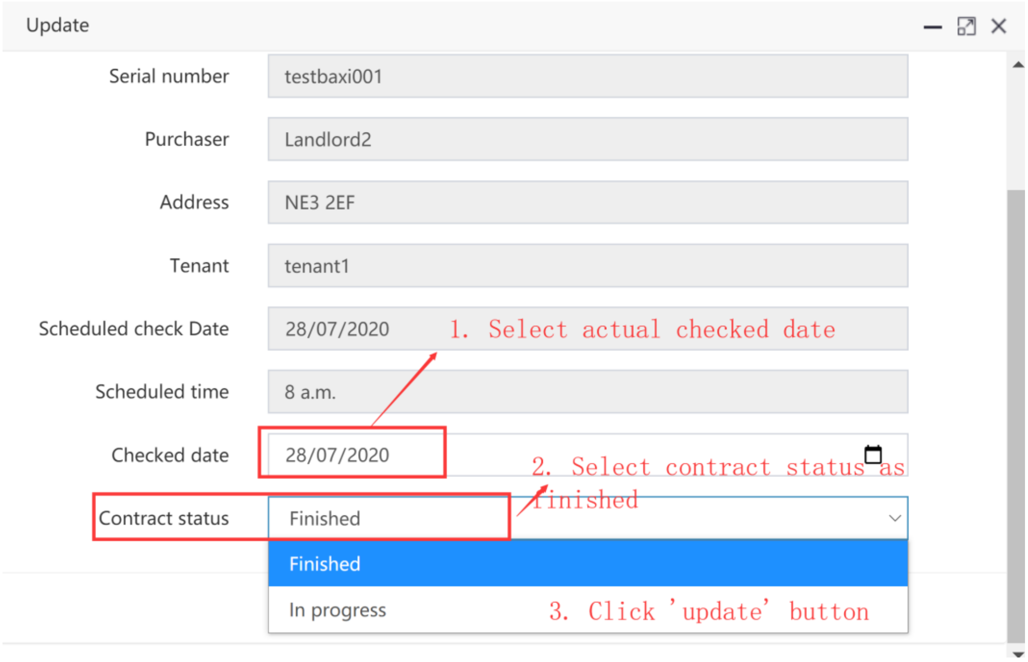


Fig. 15 Contract update interface.

c. Contact tenant

The serviceman is only required to input the message. The message is sent to the corresponding tenant automatically. The interface is shown in Fig. 16.

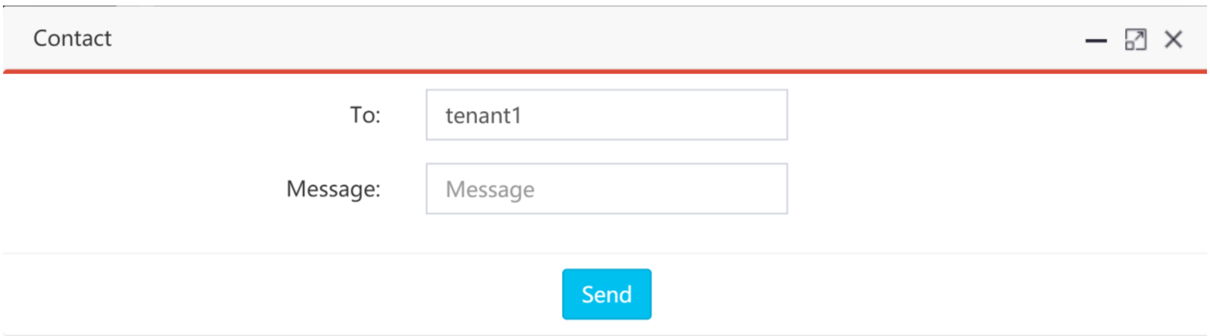


Fig. 16 Contact tenant interface.

Instructions to tenants

1. Main interface for tenant

On this interface, the tenant can (a) view all machines bind to him/her, view selected machine and contact corresponding landlord (Fig. 17), (b) view all contracts related to him/her, view contract details and contact corresponding serviceman (Fig. 18).

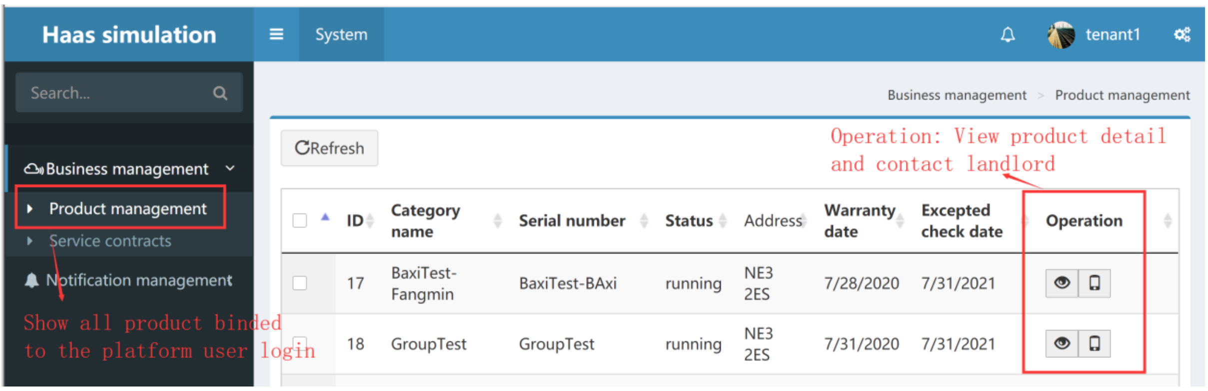


Fig. 17 Product management interface for tenant.

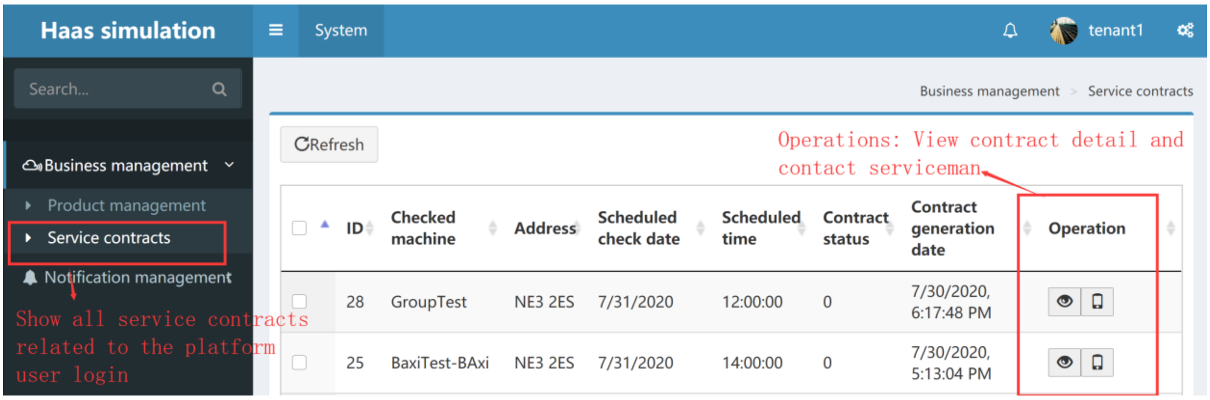


Fig. 18 Service contracts interface for tenant.

2. Introduction to operations

The operations to selected product on product management interface is view product detail and report problems to the landlord (contact landlord). While the operations to selected contract on service contracts interface is view contract detail and contact serviceman.

a. View product detail

The tenant can only operate the buttons in light green area. He/she can receive real-time feedback when interacting with the machine.

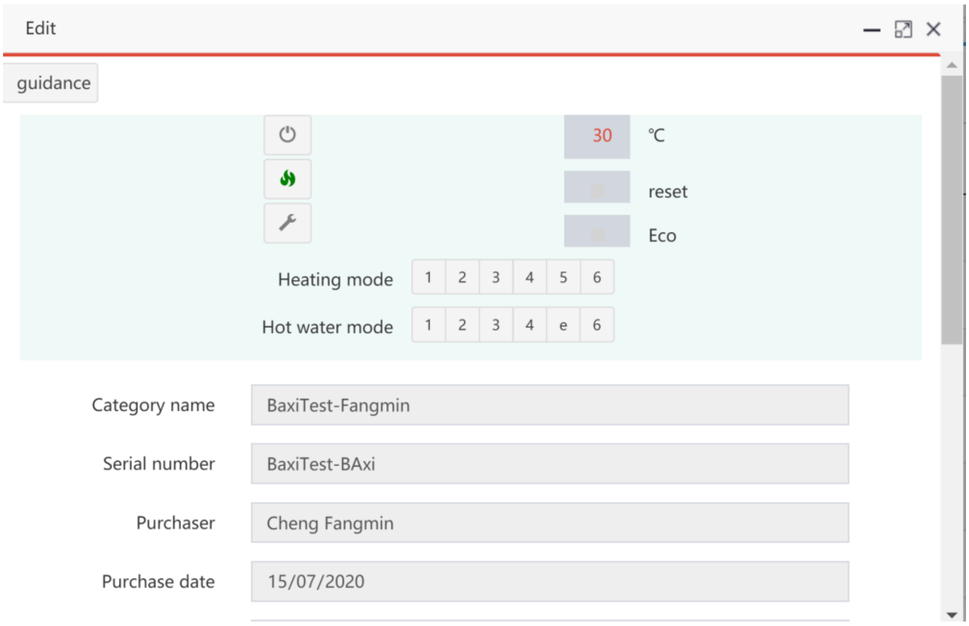


Fig. 19 View product detail.

b. Contact landlord

The tenant is only required to input message and click 'send' button, then the message will be sent to the corresponding landlord automatically. The interface is shown in Fig. 20.

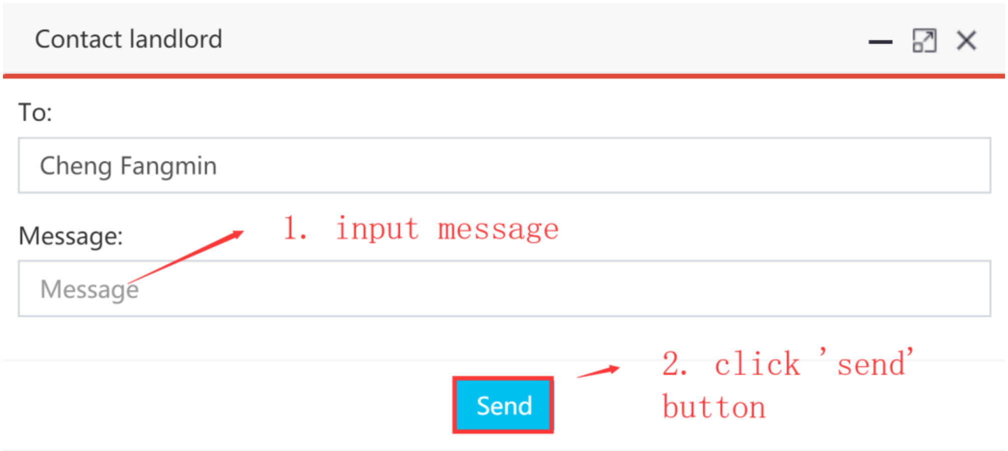


Fig. 20 Contact landlord interface.

c. View contract detail

The tenant is only allowed to view the contract detail. The interface is shown in Fig. 21.

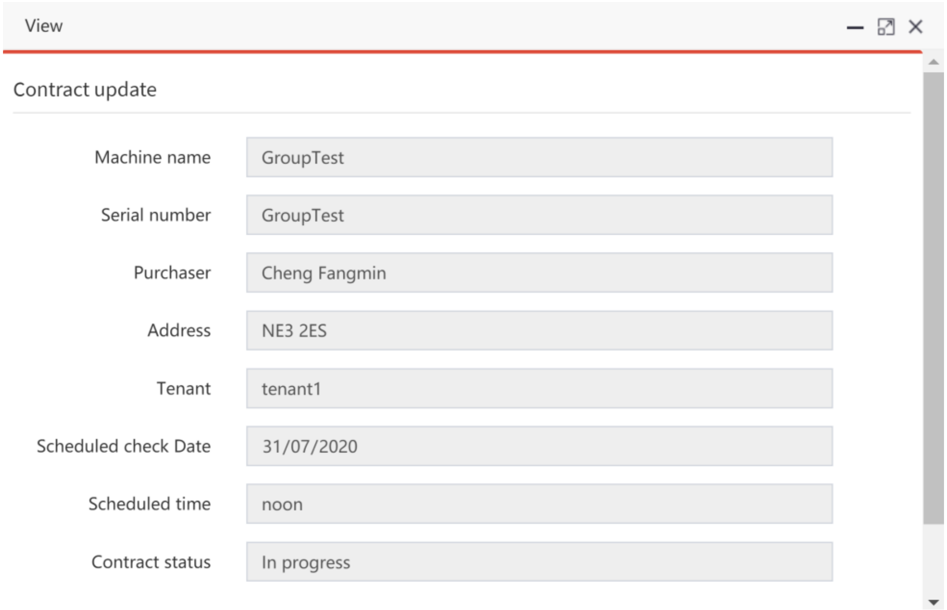


Fig. 21 Interface for viewing contract detail.

d. Contact serviceman

Tenant click ‘contact serviceman’ button, and input message and click ‘send’ button, then the message is sent to the corresponding serviceman. The interface is shown in Fig. 22.

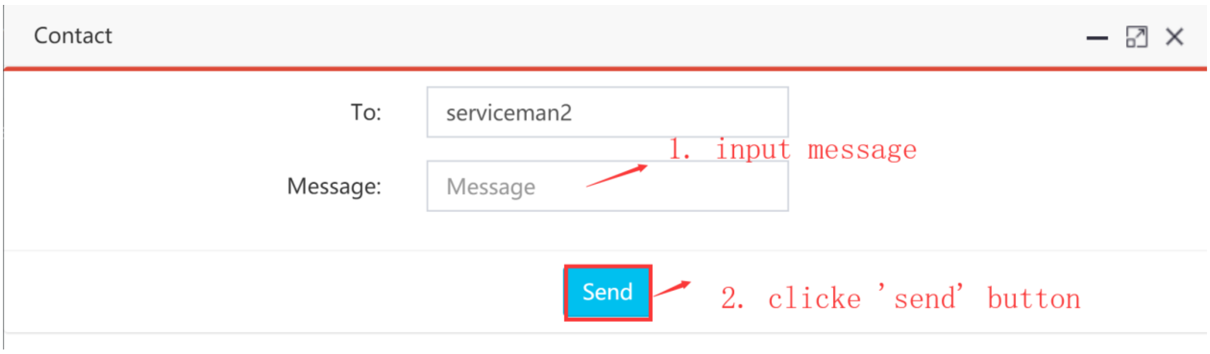


Fig. 22 Contact serviceman interface.

Contact tenant and contact serviceman functions are used after the service contract is generated and before the serviceman provides the check service.

e. Mark service

Only when the tenant receive the message ‘someone has finished your annual check service, please mark this service’, he/she should click the ‘mark’ button, or click another button. The notification inbox and mark service interfaces are shown in Fig. 23 and Fig. 24 respectively.

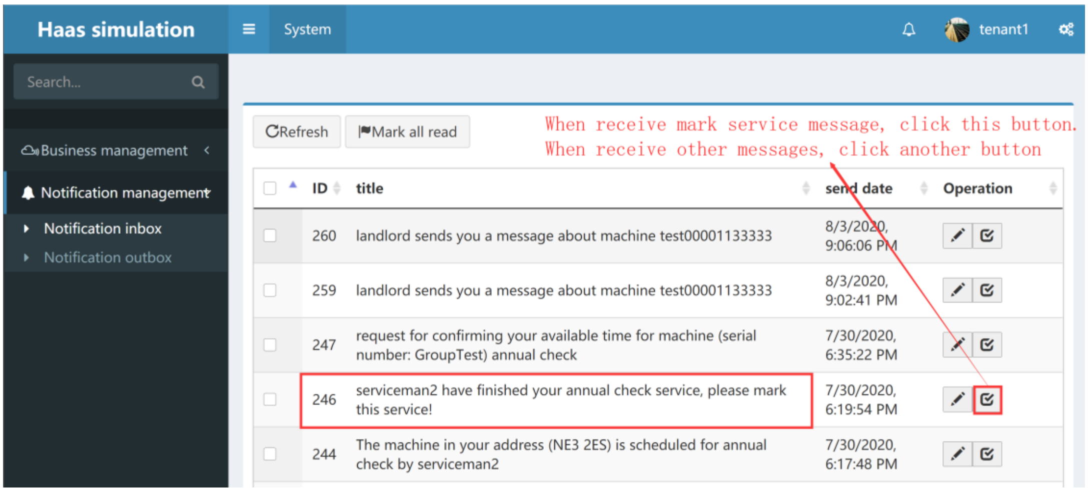


Fig. 23 Notification inbox interface.

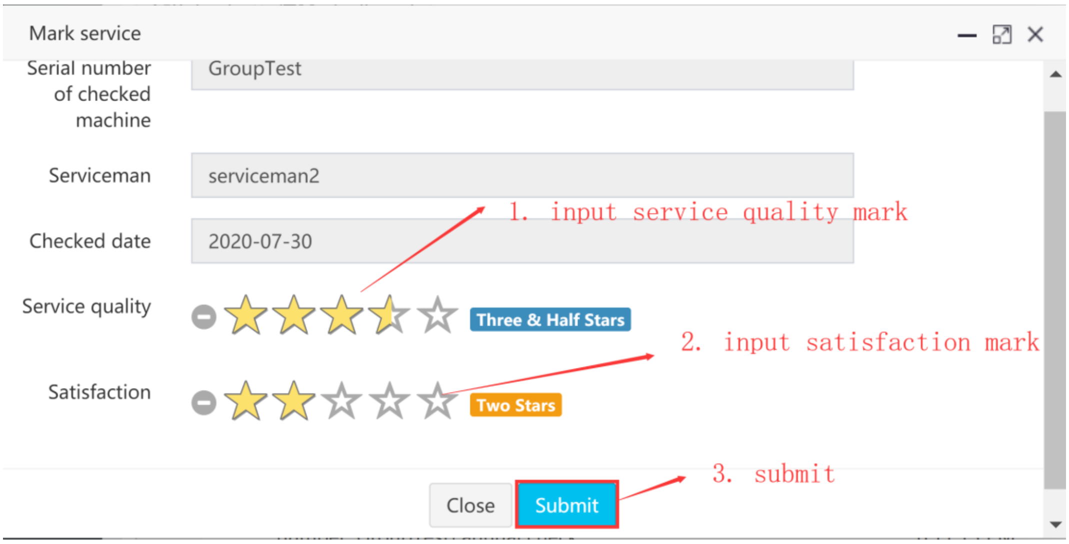


Fig. 24 Mark service interface.

Appendix E: Publication list

Published Journal Papers:

Niu, Xiaojing, Qin, Shengfeng, Vines, John, Wong, Rose and Lu, Hui Lu (2019) *Key crowdsourcing technologies for product design and development*. International Journal of Automation and Computing, 16(1). pp. 1-15.

Niu, Xiaojing, Qin, Shengfeng, Zhang, Haizhu, Wang, Meili and Wong Rose (2018) *Exploring product design quality control and assurance under both traditional and crowdsourcing-based design environments*. Advances in Mechanical Engineering, 10(12). pp. 1-23.

Published Conference Papers:

Mountney, Sara, Tracy, Ross, May, Andrew, Qin, Shengfeng, Niu, Xiaojing, King, Melanie, Kapoor, Kawaljeet, Story, Vicky and Burton, Jamie (2020) *Digitally supporting the co-creation of future advanced services for 'Heat as a Service'*. In Proceedings of the Spring Servitization Conference (SSC), pp. 64-71.

Niu, Xiaojing and Qin, Shengfeng (2017) *A review of crowdsourcing technology for product design and development*. In Proceedings of the 23rd International Conference on Automation and Computing (ICAC), pp. 1-6.

Journal Paper Submissions:

Niu, Xiaojing, Wang, Meili and Qin, Shengfeng (2021) *Product design lifecycle information model with crowdsourcing product design and development*. International Journal of Advanced Manufacturing Technology. (Under review)

Niu, Xiaojing and Qin, Shengfeng (2021) *Integrating Crowd-/Service-sourcing into Service-oriented Digital Twin for Enabling Advanced Manufacturing Services*. IEEE Transactions on Industrial Informatics. (Under review)

International Journal of Automation and Computing

16(1), February 2019, 1-15
DOI: 10.1007/s11633-018-1138-7

Key Crowdsourcing Technologies for Product Design and Development

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Abstract: Traditionally, small and medium enterprises (SMEs) in manufacturing rely heavily on a skilled, technical and professional workforce to increase productivity and remain globally competitive. Crowdsourcing offers an opportunity for SMEs to get access to online communities who may provide requested services such as generating design ideas or problem solutions. However, there are some barriers preventing them from adopting crowdsourcing into their product design and development (PDD) practice. In this paper, we provide a literature review of key crowdsourcing technologies including crowdsourcing platforms and tools, crowdsourcing frameworks, and techniques in terms of open call generation, rewarding, crowd qualification for working, organization structure of crowds, solution evaluation, workflow and quality control and indicate the challenges of integrating crowdsourcing with a PDD process. We also explore the necessary techniques and tools to support the crowdsourcing PDD process. Finally, we propose some key guidelines for coping with the aforementioned challenges in the crowdsourcing PDD process.

Keywords: Crowdsourcing technologies, product design and development (PDD), communication, information sharing, design evaluation, feedback.

1 Introduction

Having benefited from technology promoted by Web 2.0 and smart mobile devices, it is convenient for Internet users to get access to the Internet and share information with others. In this context, the Internet users distributed all over the world (the crowds) show great potential in creating amazing contents available online, and it is easier for them to take part in various aspects of our society. For example, Wikipedia is a great success which has benefited from their continuous contributions. Inspired by this, an increasing number of companies intend to take their potential customers into their decision-making process related to product development, services and policies, or to seek help from the crowds in addressing some problems that they cannot solve because of the shortage of skilled employees and sufficient resources or user engagements, especially for small and medium enterprises (SMEs). In this process, the crowds need to interact with each other and the computer. How they interact is a research focus of computer-supported cooperative work (CSCW). There are a number of research terms related to crowd interactions[1]: wisdom of the crowds, open innovation, citizen science, collective intelligence, human computation, social computing, social machines and crowdsourcing. The comparison[2–4] of these terms is shown in Table 1.

From the comparison of these terms in Table 1, it is clear that crowdsourcing shares some features with these terms. Crowdsourcing was first coined by Jeff Howe in *Wired Magazine* as "the act of taking a job traditionally

Table 1 Comparison of terms related to interactions

Term	Key features
Wisdom of the crowds	The input of a group of people rather than individuals is taken into account for decision making
Open innovation	A manifestation of the wisdom of the crowds in business environments, using internal and external ideas to accelerate internal innovation
Citizen science	Data collections under the direction of professional scientists and scientific institutions
Collective intelligence	Concerned with all forms of collective behavior, including animal and artificial intelligence
Human computation	Tackle technical tasks that computers still find challenging
Social computing	Emphasis on the information management capabilities of groups and communities
Social machines	Composed of crowd and algorithmic components, and less of a focus on an open call inviting contributions to a specific goal
Crowdsourcing	The emphasis is on human participants, the crowds respond to an open call, benefit from social computing technology

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performed by a designated agent (individual, institution, non-profit organization or enterprise) and outsourcing it to an undefined, generally large group of people in the form of an open call"[5]. It focuses on the gathering, representation, processing and use of information.

Kittur et al.[6] proposed a crowdsourcing framework which encompasses the following research topics: task decomposition, incentive mechanisms, organization hierarchy of crowds, task assignments, communication and coordination, collaboration workflow and quality control. In each part, certain technology is adopted to ensure the execution of the crowdsourcing process and the overall quality of work output. In a previous literature review paper[7], we have summarized the key techniques applied in incentive mechanisms, task assignments and communication. Here, we mainly describe technologies in other parts in more detail and discuss the technologies needed if applying crowdsourcing in product design and development (PDD) process.

Our main contribution is three-fold:

1) Summarize crowdsourcing techniques in terms of open call generation, incentive mechanisms, crowd qualification for working, organization structure of crowds, solution evaluation, workflow and quality control.

2) Investigate the technology necessary in a crowdsourcing PDD process.

3) Propose key guidelines for coping with the aforementiond challenges in crowdsourcing PDD process.

The remainder of this paper is organized as follows: Section 2 briefly introduces the crowdsourcing process. The technology used in the crowdsourcing process is described in Section 3, including research findings in terms of techniques, framework, platforms and tools. Section 4 presents the technology needed for crowdsourcing PDD process, and Section 5 summarizes the review work and proposes key guidelines for coping with the aforementiond challenges in the crowdsourcing PDD process.

2 Brief introduction of crowdsourcing process

2.1 Key elements of a crowdsourcing process

On intermediary crowdsourcing platforms, whatever task it crowdsources, the crowdsourcing process consists of four key elements: the requester, the crowds, the task which needs to be crowdsourced and the crowdsourcing platform. The platform provides the requester a way to get access to large crowds conveniently and involve them into their production process and decision-making process. A simplified crowdsourcing process is shown in Fig. 1. "Interactions 1" mainly means task input and the feedback from the platform, while "Interactions 2" refers to the broadcast of a task to crowds and crowd's submissions of the performed task (including other communications with the platforms).

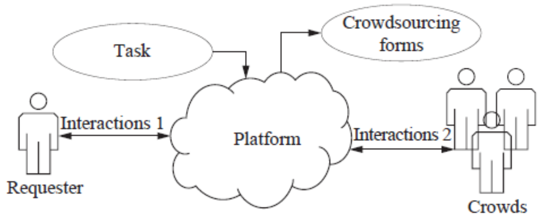

Fig. 1 A simplified crowdsourcing process

In the process, "Requester" refers to an individual or institution seeking help from crowds. "Crowds" refer to a large group of people working on an internet-based crowdsourcing platform and they take on tasks that are advertised via an open call. Only when the crowdsourcing task is well-defined, then the proper crowds with specific knowledge and skills will be selected. The crowdsourcing task proposed by the requester needs to be mapped from the high-level goal to specific subtasks to be completed by the crowds. The crowdsourcing form depends on the nature of crowdsourcing tasks. Before crowdsourcing the task, an open call including the specific task and its evaluation criteria need to be defined first. The evaluation criteria can be provided by the requester directly or be collected through crowdsourcing. The related technology in each element will be presented in later parts.

2.2 Crowdsourcing forms

There are a lot of ways[3, 8] to crowdsource a task, which are shown in Table 2. The crowdsourcing forms could be used for classifying crowdsourcing platforms.

In these crowdsourcing forms, micro tasks and macro tasks are classified by the granularity of tasks. Compared to macro tasks, micro tasks are highly parallelizable and can be divided into smaller pieces, which can be completed in seconds to minutes. Micro tasks are always the tasks that are simple and easy to be accomplished by hu-

Table 2 Ways of crowdsourcing a task

Form	Description	Platform examples
Micro tasks	The crowdsourced routine work is broken down into smaller and independent units	Mturk, microtask.com, Clickworker
Macro tasks	Close to classical outsourcing	Quirky, InnoCentive
Challenges	Competitions targeting grand scientific, technology, business, or social questions	OpenIDEO, InnoCentive
Volunteer campaigns	Initiatives seeking ideas and contributions for the public good	Crowd4U
Contests	Asking crowds to work and only providing compensation to the winner	99designs, crowdSPRING

mans but are challenging for computers, such as recognizing things in images. Macro tasks are difficult to be decomposed and the resolutions for macro tasks require much sharing of contextual information or dependencies to intermediary results.

Other crowdsourcing forms, i.e., challenges, volunteer campaigns and contests, cannot be classified into the same category as neither can they be divided into micro tasks, nor can they depend on the context information and intermediary results. To some extent, product design belongs to macro task, but it is much more complex than that as product design is an iterative process and the final design is an evolutionary result of countless refinement and improvement based on the initial design ideas.

3 Crowdsourcing technology

3.1 Crowdsourcing framework

The goal of crowdsourcing is to obtain desired high-quality product within a given time scale and with as low a cost as possible. Based on the previous analysis, the crowdsourcing framework[6] which we used in our previous work[7] is for micro tasks. Regardless of the crowdsourcing forms, the crowdsourcing framework (Fig. 2) is shown as follows.

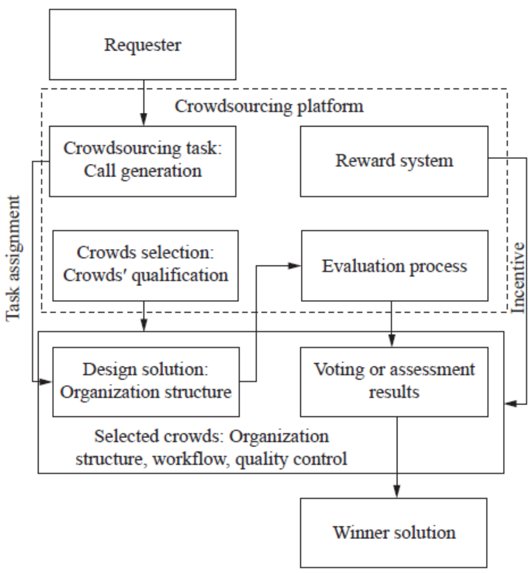

Fig. 2 Crowdsourcing framework

In the crowdsourcing process, the general task is usually performed by an individual crowd as the task is simple enough for individuals to tackle. As for complex tasks, the crowds may need to build his/her own team as in conventional setting. When they finish the task, they can submit their results to the platform for later evaluation. The output evaluation here is relatively simple, as the selection of the winning solution is achieved by the voting of crowds. For some tasks, the solution is assessed by a group of experts in a traditional way, e.g., the innovation process of Jovoto[9].

In the proposed framework, the techniques mentioned are: call generation, incentive mechanisms, crowd qualification for working, the organization structure of crowds, solution evaluation, workflow and quality control.

3.2 Crowdsourcing techniques

Based on the crowdsourcing framework in Fig. 2, this part elaborates crowdsourcing techniques related to the mentioned aspects.

3.2.1 Call generation techniques

Call generation is the first step of the crowdsourcing process. Clear instructions provide a larger possibility of receiving high-quality responses from the crowds[6]. However, there is no related research discussing how to generate a good open crowdsourcing call (or challenge brief). In conventional working environments, Jin et al.[10] investigated how to prioritize engineering characteristics for quality function deployment and Pedersen et al.[11] proposed a quantitative method for requirements development using quality loss function.

In order to fill in this gap, we analyzed 14 cases from OpenIDEO[12], Herox[13], challenge.gov[14], devpost.com[15] and 5 cases from Northumbria Design School and summarized 8 key elements of an open call that are shown as follows:

1) Description

The text description should explain the task background and the goals of the task. If the task is to design a specific product or component, the text description should explain its features and functionality and how it will affect the task goals.

2) Timeline

It lists the duration of each phase and incorporates it with the crowdsourcing process.

3) Submission requirements

It tells the crowds which format of submission is acceptable. It may include a prototype or demonstration video, related text description, image and video requirements, language requirements, intellectual property, financial or preferential support, and so forth.

4) Judging and prizes

Sometimes, the judges may be announced. Eligible submissions will be evaluated by a panel of selected judges. The judging criteria may not apply to every prize. Each prize has its own judging criteria that is more specific and concrete.

5) Criteria and disqualifications

The description of criteria could be derived from goals for the challenge and the target customer group. It may include three parts: what type of ideas they are looking for, what stage of ideas they are looking for and evaluation criteria. For a specific product or component, the criteria may be in terms of the following aspects: a) User experience (UX) and design appeal, including the degree to which the design reinvents the user experience–focusing on utility, usability, intuitiveness, and design appeal. b) Effectiveness and efficiency. c) Functional properties, emotional and experiential qualities. d) Aesthetics, and practicality, and so forth.

6) Crowd qualification requirement

It tells the crowds who can participate in the task (participation eligibility) and how to get involved.

7) Rules and regulations

It includes goals for the task, resources to spur ideas and other additional information, such as reference information.

8) About the sponsor

In an open call, not all the eight elements are needed. For instance, when the task is open to all crowds, the crowd qualification requirements are not necessary. On most crowdsourcing platforms, the generation of an open call is generally by an interactive way of answering preset questions.

3.2.2 Incentive mechanisms techniques

Incentive mechanisms play an important role in motivating crowds to involve in performing crowd tasks. A lot of research[16–21] has been focused on the relationship between incentives and crowd participation. Crowds do not have to participate, since crowdsourcing systems or platforms are typically open to everyone and do not rely on contracts. Thus, certain measures must be adopted to compel crowds to participate. Otherwise, crowd tasks cannot be performed. The ways of attracting crowds could be categorized into two distinct categories: extrinsic (e.g., reward, building of their personal reputation, etc.) and intrinsic (e.g., enjoyment, being part of the common good, etc.)[22]. The most common three motivations are reward, enjoyment and reputation.

1) Reward

Reward is the dominant motivation in the crowdsourcing processes. This includes cash bonuses, discount coupons, free use of product, and virtual money. For instance, Mturk and Figure Eight offer small financial rewards to an anonymous crowd engaged with tasks posted by various requesters. Generally, most crowds are money-driven and higher pay would usually get more crowds to perform more tasks more quickly[23]. In some boring and tedious tasks, such as transcribing countless hand-written documents, monetary compensation must be guaranteed, or few crowds are likely to participate in the task. However, money is not necessary to enable the high quality of completed tasks, which was found by Mason and Watts[23] and Rogstadius et al.[24].

2) Enjoyment

In crowdsourcing processes, crowds usually choose the tasks that interest them. When crowds are really interested in them or love doing them, they would like to devote themselves to it, even if there is no reward. They are self-incentivised because of the feel of achievement brought by finishing challenging tasks and the opportunities to exercise skills and talents that they have no chance to use in their ordinary lives[25].

Besides, some crowds are encouraged to engage in the task by a game-like environment[26], where points, leaderboards and other common game elements are included. By playing tasks of this kind, they can relax themselves, as well as get some rewards.

3) Reputation

A large proportion of crowds are driven to compete for the recognition by their peers or their personal values. Each time they finish the task, they will be scored or ranked by the server according to their work quality. If one has good reputation, it will be easier for him/her to be chosen to perform other crowd tasks later.

Reward, enjoyment and reputation are just three main incentives. Crowdsourcing platforms can adopt one or several of them according to different task types.

3.2.3 Crowds′ qualification techniques

Different crowdsourced tasks have different skill and qualification requirements for their participants, such as open to all, reputation-based and credential-based. Generally, complex and domain-specific tasks have higher requirements for their participants.

However, crowdsourcing platforms know little about their users′ (crowds′) expertise and skills, they can only rely on the matching between the requirements from the requester and the profiles or participation histories of crowds to judge whether a crowd is suitable or not to participate in a specific task. Since the profile is provided by the crowds themselves, there is a possibility that some crowds fill in information that is not matched to their actual capabilities. Due to the anonymous nature of participation on a crowdsourcing platform, some techniques are used to avoid such cheating behaviors of the crowds. The most often adopted measure is verification questions (gold questions)[27, 28] that are inserted to test the performance of crowds. However, it is only useful in micro tasks. In other forms of crowdsourcing tasks, it is useless.

Besides cheating behaviors, some crowds do not perform the task carefully as a result of poor platform control of the submissions. In order to ensure the quality of work submitted by crowds, worker agreement is usually signed before participating in the task. This measure is adopted by most of the crowdsourcing platforms, but it works little on the final output. The core problem here is the identification of high-quality work, which is a research question in quality control as well. In order to assess a worker′s quality, Ipeirotis et al.[29] seamlessly integrated the gold data for learning the quality of the crowds and their algorithm can be applied when the crowds are asked to answer a multiple choice question to complete a task.

A promising approach for selecting qualified crowds is to identify their strong points by analyzing their work experience and behaviors, thus ensuring the reliability of their submissions. Although this method is powerful, the cold-start question[30] that is common in recommendation system cannot be neglected.

3.2.4 Organization structure techniques

In conventional settings, reasonable organization structures benefit cooperation among employees, decision making and quality control[31]. Generally, organizations adopt hierarchical structure as their management strategy, which could enable groups of employees to tackle complex tasks and increase work efficiency.

In the context of crowdsourcing, hierarchical structure is the most popular organizational structure. Since the crowds have various professional skills and experience, they are good in one or some specific domains, but not in others. As a result, they play different roles in different crowdsourcing tasks. In a hierarchical structure with many layers, the position of a crowd depends on his or her capability. The hierarchical structure is more suitable for performing micro tasks. The crowds at the lowest level perform subtasks with the smallest granularity, while those at higher levels integrate the results submitted by the crowds at the lower layer.

As for tasks that are not easy to decompose, the hierarchical structure is useless as all employees work collaboratively targeted at the same goal and their work may have dependency to others. Take software design and development, which usually consists of various functional modules, as an example. On the whole, the task of software design and development is a micro task, but when focusing on the lowest level of decomposition (module), it is a macro task, as each module is still complex and cannot be decomposed anymore, which will be realized by the collaboration of a group of individuals with various specialities. On this occasion, a team structure should be more effective and efficient. Thus, the traditional team structure can be applied in the virtual environment if it can be well organized and controlled.

3.2.5 Solution evaluation techniques

The evaluation of submitted solutions is a necessary step in the selection of better solutions, and it is also an important way to ensure the quality of submissions. It reduces the volume of the alternative solutions for the winning one[32]. However, the solution evaluation on general crowdsourcing platforms, such as quirky[33], 99Designs[34] and Jovoto[33], are relatively simple, as the key ways for selection are crowd voting[33, 34] and assessment of a group of experts[35] or the combination of these two methods. Crowd voting effectively reduces the number of solutions, and expert assessment rates submissions, selects winners and adjusts rewards[36].

The existing evaluation approaches include the scale of every submission on a five-star rating[37], and the evaluation data from external experts[38]. However, these methods are not sufficient to evaluate the submitted solutions and a multi-attribute scaling including ratings from both experts and crowds should be more reliable. Generally, the submissions on a crowdsourcing platform usually increase rapidly in both volume and complexity. In order to reduce evaluation time and cost, a text-mining approach[36, 39] was applied in evaluating submissions from crowds. Although the text-mining approach is effective in reducing the volume of submissions, it does not work when the submission is presented in other formats, such as image and animation.

3.2.6 Workflow management techniques

Workflow management plays an important role in achieving high-quality output. It concerns where the data comes from and where it goes, as well as the integration of data steams coming from various sources. It is affected by many factors, such as the organizational structure of crowds, the volume of submitted solutions and task integration mechanisms[32]. In micro tasks, subtasks can be accomplished in parallel and the independent output can be aggregated through voting or majority rule[6]. But macro tasks have dependencies and require multiple types of expertise, sometimes, their requirements change with the progress of the crowdsourcing process. In this circumstance, workflow management is urgently needed. Aniket et al.[40, 41] has found that enabling more complex workflows can result in large differences in output quality even with small differences in rewards and task order.

Generally, the structured workflow[42] is usually used to provide interpretative and diverse feedback. Besides, Dai et al.[43] improved crowdsourcing workflows by micro-diversion. They provide timely relief to crowds and hope to improve productivity by retaining crowds to work on their tasks longer or to improve the work quality. They also used decision theory to model the iterative workflows and defined equations that govern the various steps of the crowdsourcing process[44]. Kittur et al.[6] indicated that existing workflows should be improved on a large space of parameters, instructions, incentives and decompositions so that they can be able to support the execution of complex tasks.

3.2.7 Quality control techniques

Quality control is an issue throughout the whole crowdsourcing process and it has received the most attention so far[45]. Aniket et al.[40, 46] found that 30% or more of submissions on MTurk may be low quality. Since verifying the quality of a large pool of submitted results is hard, some crowds may submit answers with low quality[29]. Thus, quality control of the crowdsourcing process plays an important role in obtaining high-quality output. The quality control approaches could be classified into two categories[45]: design-time and runtime. The design-time approaches include the open call generation and crowds′ qualification, as described previously. There are a lot of runtime quality control approaches. For example, workflow management, expert review, output agreement, ground truth and majority voting[45]. These approaches can be adopted together for better quality as using one approach alone may contribute to cheating behaviours. For instance, when using output agreement, if independent workers give the same response as the received input, their output is accepted as a quality answer. But, Kittur et al.[6] found that some crowds may agree to coordinate answers, which made this method useless. Besides workflow management, four other approaches are used to filter out poor quality work after results have been submitted. In ground truth, the submitted results can be compared to a gold standard, such as known answers or common sense facts. For instance, Figure Eight relies on its gold standard to judge the answers submitted by crowds. However, gold standards may not be possible for subjective or creative tasks (e.g., designing a new product). Three other methods measure the quality of a submission according to how well that crowd agrees with others[29, 47] or according to the crowds' votes.

All these seven aspects work together to achieve higher quality of submissions rather than working separately.

3.3 Crowdsourcing platforms

This research only focuses on online crowdsourcing platforms. Crowdsourcing platforms connect requesters with crowds and shape the practical interactions between them[6]. Table 2 shows the types of crowdsourcing platforms. The general phases of these platforms' work process are as follows: ideas, review, refinement, final review, top ideas, awards and impact. However, these platforms only support relatively simple and independent tasks (e.g., idea generation, challenge solution and so forth) from the start to finish or graphic designs from idea to realization. For complex tasks that need cooperation from a group of individuals, such as product design, these platforms seem to be helpless.

Most of the crowdsourcing platforms are developed for various applications[8], such as challenge solving, idea generation and graphic designs. Quirky is a crowdsourcing invention platform where great ideas from general people could come into reality[33] and an e-commerce platform as well. Through it, the produced products would be sold. OpenIDEO and Innocentive are examples of crowdsourcing platforms for making ideas grow, while CrowdSpring, 99Designs and DesignCrowd provide design options for selection from the requester. Other crowdsourcing platforms, like Figure Eight, are used for data processing and analysis. Regardless of application scenarios of the crowdsourcing platforms, the tasks performed on it are simple and independent. In order to support the crowdsourcing process of complex tasks, the platform needs to be improved in some aspects, e.g., solution evaluation, the communication and cooperation among crowds.

3.4 Crowdsourcing tools

Crowdsourcing platforms integrate tools to help requesters realize specific purposes, such as new inventions, innovations and products. Since the crowdsourcing process is different because of various crowdsourcing tasks, certain tools are needed in various crowdsourcing phases. In the previous part, a general crowdsourcing process is given. As the process is iterative, some phases can be realized by the same tool. For example, the review and the final review phase can be realized by the same tool. Referring to various crowdsourcing phases, the classification of crowdsourcing tools is shown in Table 3.

Table 3 Classification of crowdsourcing tools according to various crowdsourcing phases

Crowdsourcing phases	Functions	Example of platforms including the tool that realizes the associative function
Idea	Idea or solution generation	Quora[48], the category of idea platforms in [8], ideascale[49], social media like WeChat, Facebook, Email, etc.
Review	Idea evaluation	Realized by social media like WeChat, Facebook, Microblog
Final review		
Refinement	Idea selection	Vote function realized by most of the crowdsourcing platforms in [8]
Top ideas		

As social media can only realize relatively simple and independent purposes like idea gathering and comments, crowdsourcing platforms that integrate various tools are easier for requesters to use. In addition, crowdsourcing platforms provide better services for managing mass data collected from crowds and the requester can achieve his/her aim with just a few clicks of the mouse. Besides the aforementioned tools, other tools like an assistive tool that help the requester to input their needs and evaluation criteria to generate an open crowdsourcing call and providing rewards to the winning designer are needed as well.

On a crowdsourcing platform, all these tools work in sequence to ensure the execution of crowdsourcing processes rather than working in isolation. These kind of crowdsourcing platforms are useful for general simple tasks, but they seem useless when handling complicated design tasks.

4 Crowdsourcing technology in PDD

4.1 Research background for crowdsourcing PDD

Traditionally, manufacturing SMEs rely heavily on a skilled, technical and professional workforce to increase productivity and remain globally competitive. Crowdsourcing[5] offers an opportunity for SMEs to get access to online communities who may provide requested services such as generating design ideas or problem solutions. Qin et al.[50] explored the challenges and opportunities in adopting crowdsourcing in new product development in manufacturing SMEs and found that crowdsourcing-based product design and development is interesting to many SMEs but there are some barriers preventing them from adopting crowdsourcing into their new product development practice. For example, how to achieve good quality of product design over a crowdsourcing platform is one of the main concerns for many SMEs. Xu et al.[51] have investigated a service model for product Innovation design. Differently, here, we analyse the existing platforms for designs and explore the possible processes and framework of crowdsourcing PDD and the necessary techniques and tools.

4.2 Analysis of existing platforms for designs

Among crowdsourcing platforms, those for designs could be classified into two categories: graphic design supported and product design supported. The typical crowdsourcing platforms for graphic designs are 99Designs and crowdSPRING. Taking 99Designs as an example, it works as follows[34]: a) Build a design brief; b) Pick a design package; c) Launch the design contest; d) Receive dozens of designs; e) Give feedback; f) Pick your favorite and get the full design copyright. On this platform, any internet users who are registered on it can participate in the contest and contribute their thoughts and ideas. crowdSPRING has a similar work process to 99Designs.

Jovoto is an open innovation platform, but it could be used for product design[35]. Its work process for product design is: a) project definition; b) brief creation; c) talent matching; d) project directing & guiding; e) results presentation; f) transfer of rights. In this process, all participants are professional designers. They help the customer (the requester who submitted his business goals in the project definition stage) to create the design brief and give feedback to the designers to shape their ideas. Jovoto can support the PDD process, but in the project directing & guiding stage, it seems that the professional designers evaluate the product designs in a conventional way.

4.3 PDD process on a crowdsourcing platform

Before introducing the crowdsourcing PDD process, the general PDD process in conventional working environment is presented first. It starts with identifying customer/market needs, establishing product design specifications, conducting product concept design and creating detailed designs[52].

Referring to Ulrich and Eppinger[53], a product concept design process is shown in Fig. 3, involving product concept generation, concept evaluation, selection and feedback in an iterative form. This design process starts from market research to identify the customer needs and then establishes a design brief (or product design specification (PDS)). Based on the PDS, a wide range of product concepts can be generated and then evaluated with reference back to the PDS and even the customer needs. After that, a design decision is made to select good concepts for further development in the next stage, or the discarding of bad ones, or feedback is provided based on the evaluation to improve the good concepts. The feedback can be provided to guide the concept improvement, or even to guide the PDS update. This is a typical iterative concept development process. The process does not stop, until otherwise, one or several concepts are accepted. In this process, the activities of concept generation, evaluation, selection and feedback are progressed in a loop and the feedback guides the next design cycle. In the product concept generation stage, the designers can perform product concept design individually or in a collaborative team. After concept evaluation, the designers can improve their designs referring to feedback from the evaluation results.

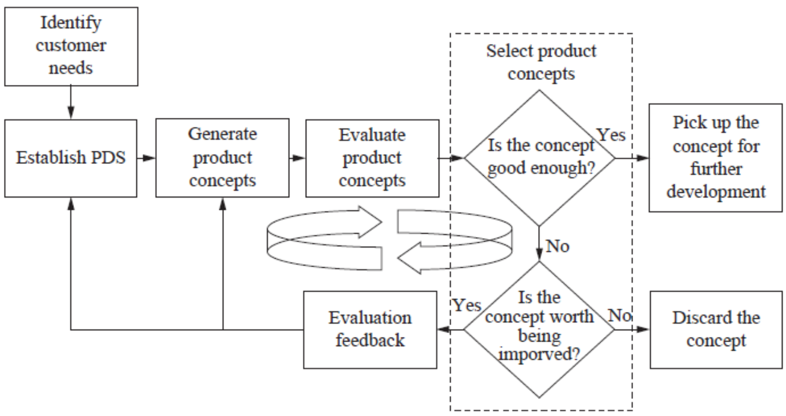

Fig. 3 Iterative product design process of consumer product design

Previous research[54, 55] found that about 80% of overall product quality and up to 70% of the development cost is committed in the early stages of design for concept generation and improvement. Thus, in crowdsourcing PDD processes, more attention should be paid to the design evaluation and feedback that are not supported enough by general purposed crowdsourcing platforms.

When designing a specific product on a crowdsourcing platform that supports PDD, a team consisting of crowds with various skills and experience work collaboratively. Since product design heavily depends on information sharing and intermediary results, the crowdsourced PDD processes need to put more emphasis on communication and information sharing, design evaluation and integration with evaluation results during the design process. The cooperation effectiveness plays a vital role on the output quality. When PDD is executed on a crowdsourcing platform, the crowdsourcing-based product design process is summarized in Fig. 4 with reference to [50, 53]. It indicates the main activities and challenges during the process.

The steps of the crowdsourcing PDD process are shown as follows:

S1. The requester (e.g., a design project manager), defines product design tasks (challenges) through a form of product design brief (e.g., PDS) or a design challenge brief and sets the evaluation criteria and crowdsourcing conditions/terms.

S2. The design challenge is broadcast online via a crowdsourcing platform and crowds registered on the platform are invited to perform the product design task.

S3. Once a crowd agrees to take on the product design task, he or she can work on product concepts individually or in a group ongoing formed on the platform. They can also work either online on the platform or offline.

S4. At some points, product concept design results will be submitted by a individual crowd or a group of crowds to the platform for evaluation. The concept design results can be submitted with a concept presentation or design pitch document to better communicate or explain the designers' ideas or rationales.

S5. Submitted product design concepts will be evaluated via suitable approaches such as automatic evaluation based on machine intelligence or crowdsourcing-based methods.

S6. After concepts have been evaluated, better design concepts will be shortlisted based on the evaluation results and the corresponding evaluation results will be summarized to generate constructive feedback that will be communicated back to the related designers, thus guiding them to improve their designs and entering the next loop of the product concept design process.

Referring to Fig. 4, in order to involve crowdsourcing in the PDD process while ensuring better output quality, the following challenges need to be addressed:

Challenge 1. How to organize a group of crowds and what measures need to be adopted to ensure the communication and cooperation among crowds when they work together on the same product.

Challenge 2. How to support the crowds (or designers in the context) to effectively present their design concepts in order to evaluate them fairly and decrease the possibility of missing some good concepts or rationales.

Challenge 3. Given a design concept presentation, how to evaluate it, and what is the best concept evaluation method on a crowdsourcing platform.

Challenge 4. If a design is evaluated by crowds (design peers, experts and other stakeholders), how to integrate the evaluation results with weightings from a large number of crowd evaluators and provide feedback to the concept designers to improve their design.

4.4 Framework of crowdsourcing PDD process

The framework of the crowdsourcing PDD process is transformed from the general one. Compared to the general one, the communication and cooperation among the crowds, the evaluation of product design and feedback play a more important role in the crowdsourcing process. The framework is shown in Fig. 5.

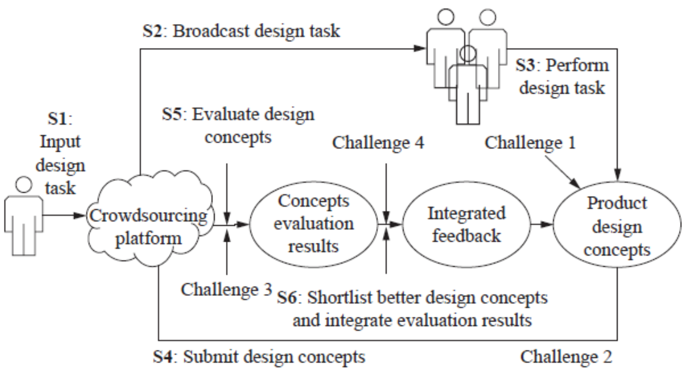

Fig. 4 PDD process on a crowdsourcing platform

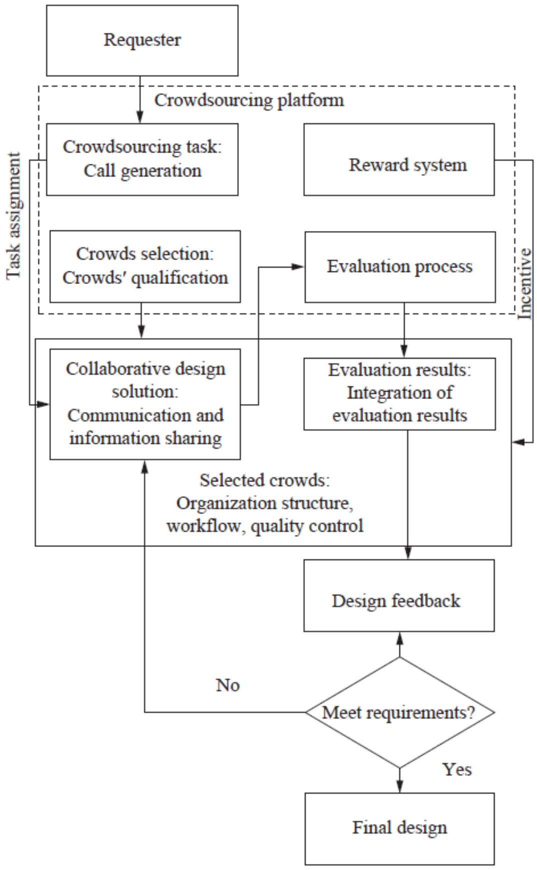

Fig. 5 Crowdsourcing framework for PDD process

Differing to the general crowdsourcing process, the PPD one pays more attention to design evaluation and provides feedback to corresponding designers as product design is an iterative process. Thus, the techniques for communication and information sharing, product design evaluation and the integration of evaluation results need to be investigated.

4.4.1 Communication and information sharing

Communication and information sharing play an important role in a crowdsourcing PDD process, which is also demonstrated to be important to virtual manufacturing and collaborative design[56]. In the process, all participating crowds must be well-organized so that they could collaborate effectively. Recently, Gray et al.[57] argued that social interaction is a basic need for human beings and this social need must be fully addressed by crowdsourcing platforms. Their research findings indicated the inevitability of collaboration among crowds[58, 59] and the significance of combining collaboration with crowdsourcing workflows.

PDD processes always involve multiple stages, which need to be completed by distributed teams or individuals with professional skills and experience. However, the distributed crowds have always faced with challenges in cultural differences and coordination[6]. Effective communication approaches could enable crowds to spend less time understanding their tasks and improve the work efficiency.

In order to improve communication and work output in expert crowdsourcing, Alex et al.[60] investigated a structured handoff method where participants were asked in live (live conference and screen share are used) and recorded scenarios (short screen capture video with voiceover) respectively. Their experiments indicated that higher work quality could result and the adherence to the original intent could be increased by the structured handoff approach. Since crowds are located at various places and they are not available to participant in the task at any time, the structured handoff may be useful for them to know the working process.

Generally, discussion forums, blogs and microblogs (e.g., SinaWeibo[61]) are commonly used by crowds as their communication medium, which is not real-time and may lead to some delays. Also, such kind of communication is not suitable in a large scale[62, 63]. Social media, like Facebook, Twitter and WeChat, are real-time, but they only support the sharing of information and asynchronous edition of documents. In order to satisfy the increasing need of synchronous collaboration, tencent instant messenger (TIM) is developed as a free cloud-based and platform independent office software that not only supports instant messaging and the synchronous edition of simple documents, such as Word and Excel, but also integrates social interaction functions. However, when it is applied to product design and development, the platform can only support the sharing of documents in various formats, but it is inconvenient for users to view and edit them unless corresponding software or tool is installed.

4.4.2 Product design evaluation

Product concept evaluation is an important activity in the PDD process[64, 65]. Traditionally, firms depend on their internal designers to review and evaluate design concepts. Better design concepts can be selected with internal designer's design knowledge and experience. However, this activity usually involves a small number of product concepts, thus when the number of concepts is increased dramatically in a crowdsourcing environment, it may be time-consuming and needs alternative ways to do it.

In order to evaluate concepts more efficiently, a lot of automatic approaches have been developed to perform this task by utilizing the indicators and judgement proposed by designers. These approaches could be classified into two categories: numerical and non-numerical[62, 64, 65]. Non-numerical methods are simple and graphics-based, and they are easy to use to select design concepts. However, these approaches cannot effectively deal with uncertain, vague and subjective judgement from decision makers. As for numerical approaches[57–60, 66–68], they could support both quantitative and qualitative judgement of design criteria. One limitation of these methods is that it is difficult to quantify the design criteria and indicators accurately during early design stages.

Until now, little research has focused on design concepts evaluation in the context of crowdsourcing. Chang and Chen[28, 69] were the first to address this problem. However, their research only focused on the data-mining based approach. In their research[28], domain ontology is adopted to hierarchically represent the types, properties and interrelationships of design concepts in order to better support the selection of promising design concepts. Differently, Qi et al.[70] focused on presenting product design information with extensible markup language (XML), thus enabling the data integration, sharing and exchange in later design stages. The structured representation of product design concepts can effectively decrease the time used on understanding and evaluating the design concepts.

4.4.3 Integration of evaluation results

After evaluating product designs, these designs can be ranked according to their scores obtained in the design evaluation phase, thus a list of top designs can be selected. For the shortlisted concepts from the selection process, summarized feedback from evaluation results needs to be provided to the corresponding designers for further refinement and development. The feedback can motivate designers and improve productivity. The feedback to designers might be provided for future engagement and better interaction. Content of feedback can consist of four different categories[71]: descriptive, effective, evaluative and motivational. Each category has a specific purpose.

After evaluation, the obtained evaluation results need to be integrated under the four categories before they are prepared for feeding back to the designers. However, how to summarize concept evaluations from various evaluators in different media forms into a brief and clear feedback statement is a big challenge. Jackson[72] provides a method called Sticky Notes for summarization of large numbers of comments and for small numbers of comments (say 50 or less), he suggests to use MS Excel to organize them into categories. Besides, text clustering methods maybe useful. For example, Ma et al.[73] proposed two models to group comments into topic clusters and yield better intra-cluster topic cohesion.

For crowdsourcing applications, there is a lot of research about how to produce high-quality feedback. For instance, Hui et al.[74] have adopted techniques including anonymity and communal efforts to improve the quality of feedback from crowds. In order to address superficial and disorganized feedback[75, 76] from unknown members, previous work[77, 78] has also created tools to support structured feedback online. During the product design process, if evaluation results and the corresponding feedback are well-structured, it is more helpful for designers to improve their designs.

4.4.4 Quality control techniques

The emphases of crowdsourcing PDD process have higher requirement for workflow management that ensure the fluent execution of the crowdsourcing process.

Based on [31, 40, 45, 79–81], we summarize the factors that influence product design quality in Fig. 6. It is clear that the final design quality is affected by the generated product concept's quality and enhancement quality. The product concept's enhancement quality is ensured by product design evaluation and feedback. The integrated feedback can enhance the generated concepts and promote the design process to the next loop.

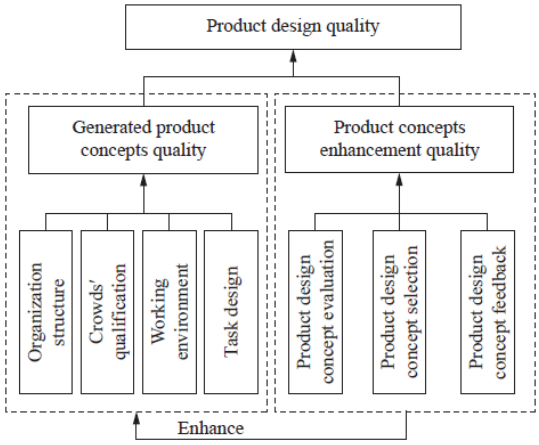

Fig. 6 Factors influencing product design quality

Besides the aforementioned quality control techniques, the design evaluation and feedback techniques influence the design quality as well. The existing techniques for these aspects have been presented previously. But in the context of crowdsourcing, new techniques need to be explored in order to address the challenges.

4.5 Tools needed in crowdsourcing PDD process

4.5.1 Collaborative design tool

In PDD, design is generally performed by a team of professional designers located in different places, thus a collaborative design tool needs to be provided to help them work together and monitor the design process and progression. The tool provides a virtual workspace for the crowds in a team.

4.5.2 Design presentation tool

When the design is finished, it needs to be submitted to the platform for later evaluation. The evaluation results will be in feedback for further refinement and improvement. In order to describe the product design briefly and clearly, the tool should generate a presentation file by integrating together the common file formats, such as jpg, txt, audio and flash.

4.5.3 Design evaluation tool

After submitting the design presentation file, it is ready for later evaluation. It will be sent together with the evaluation criteria to proper crowds for assessment. The tool will generate an evaluation template with reference to product design specifications and even user needs, crowds only need to fill their evaluation results in the evaluation template, and then submit their evaluation results.

4.5.4 Integration tool of evaluation results

The integration tool can extract and classify evaluation results into various categories, thus reduce the heavy burdens of the designers from reviewing large numbers of evaluation results from the crowds.

4.6 Assessment of crowdsourcing PDD process

In order to measure the effectiveness of involving crowdsourcing in the PDD process, the product design obtained on a crowdsourcing PDD platform will be compared to the one accomplished by traditional methods in terms of cost, time duration, performance, ergonomics, aesthetics, safety, reliability, etc.

5 Discussion and conclusions

This paper analyzes the framework, platform, tools and techniques used in crowdsourcing processes in terms of open call generation, rewards, crowd qualification for working, organization structure of crowds, solution evaluation, workflow and quality control. Here, we propose a framework for applying crowdsourcing in the PDD process and investigate what techniques and tools are needed in the process while indicating the main challenges. Mainly, collaborative product design in virtual environment, communication and information sharing, design evaluation and feedback generation by integrating evaluation results are four key challenges in the PDD process.

Although specific tools supporting functions similar to activities in product design process, such as communication, have been developed, they are still not well integrated by a crowdsourcing platform to support the activities of product design and development. Meanwhile, the successful integration of crowdsourcing and product design process will offer a possibility for SMEs to get access to a large pool of crowds with various skills and experience, which can effectively overcome their difficulties on the shortage of skilled employees and related resources. In order to deal with these challenges, a crowdsourcing platform that considers all these challenges needs to be developed. Here, we propose some key guidelines for the development of such a crowdsourcing-based collaborative design platform:

1) The platform should be cloud-based. Therefore, crowds can access, edit and share related documents anytime and from anywhere. From the cloud-based workflow, they can make updates in real-time and have a full visibility of their collaborations.

2) The platform should be user-centred. The platform can guideline the crowds perform tasks including product design and evaluation, while providing a comfortable and satisfactory user experience.

3) The platform should integrate a communication tool that supports both private chats (one to one) and group meetings while sharing the related design documents.

4) An assistive design tool or specified design software should be provided in order to ensure crowd participants can view and edit the design documents.

5) The platform can be integrated with blockchain technology to ensure the trustworthiness of crowd contributions and effective protection of intellectual property (IP). Since the crowdsourcing process is open to the crowds who have been registered on the platform, the IP protection faces more risks than in traditional environment. It also benefits the selection of qualified crowds as all design experience on the platform can be retrieved and their actual skills and capabilities have been verified by previous design tasks he/she takes part in.

6) The platform should provide application programming interfaces (APIs) to common social media so that the platform user could invite his or her trusted friends with specific capabilities and experience to the platform to take part in product design activities. If participants are all trust-based, it is more likely to yield satisfactory design results.

7) The platform should provide a tool that can help the crowds evaluate design concepts. As both product design and the evaluation are subjective activities, it is hard to judge automatically whether the design satisfies the design requirements and needs or not. Therefore, a method combining automatic calculation of quantitative variables with manual evaluation of qualitative variables would be a better choice. In the assessment of qualitative variables, crowds are employed to extract relevant information about how design requirements and needs are expressed in the design concept and then assess them. Then design experts verify the evaluation results.

8) The platform should provide a tool that can classify evaluation results into different categories according to evaluation criteria. The evaluation results in the same category can be analysed by clustering approaches so that the similar information will be given back to corresponding crowds only once.

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Exploring product design quality control and assurance under both traditional and crowdsourcing-based design environments

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Abstract

Small and medium-sized enterprises face the challenges that they do not have enough employees and related resources to produce high-quality products with limited budget and time. The emergence of crowdsourcing provides an opportunity for them to improve their products by leveraging the wisdom of a large community of crowds, including their potential customers. With this new opportunity, product design could be conducted partially in a traditional design environment (in-house design) and partially in a crowdsourcing environment. This article focuses on product design stages to investigate what key factors affect product design quality and how it can be controlled and assured. First, we define the concept of product design quality and then identify its attributes and sub-attributes. Second, we separately survey key factors affecting product design quality in traditional and crowdsourcing-based design environments, quality control approaches/theories and quality assurance policies in traditional design environment. Third, a comparison of product design quality issues between the traditional and crowdsourcing-based design environments is progressed focusing on various aspects influencing product design activity quality. Finally, we discuss product design quality control approaches and quality assurance policies, quality control challenges and corresponding solutions in crowdsourcing-based design environment.

Keywords

Product design, quality control, assurance, crowdsourcing, collaborative challenges

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Introduction

Product design is an essential activity in the modern life as it can generate and develop ideas through a process that leads to new products to meet the ever-changing user needs and expectation.[1,2] Products with high quality will not only meet needs of both manufacturing enterprises and various users along the product life cycle but also bring good user experience and better social and environmental benefits to our society, thus helping the enterprises remain globally competitive in the fierce competition. Therefore, the control of

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product quality through the whole life cycle is a vital activity to enterprises. The aim of product quality control is to make a compromise between cost and product quality. However, product quality is a nebulous concept and it may be viewed in different perspectives.[3] And the existing literature usually pays too much attention to quality control of manufacturing and activities after the product is manufactured. For example, anastasia[3] shows that quality control of product quality is controlling production, carrying out repairs and warranty costs through defect discovery and maintenance, which ignores the importance of product design quality. From the incline of product quality through the whole life cycle (see Figure 1) in literature,[4,5] it is clear that product design quality is the key factor determining product quality.

As a stand-alone product is not sufficient to fulfil customer requirements, product service systems (PS2 or PSS) are usually combined with the product to provide product-related services such as maintainability, repair, update and quality warranty throughout the whole life cycle to better fulfil user requirements.[6,7] Therefore, we define product quality as the sum of product design quality, manufacturing quality, maintainability and recycling. Correspondingly, we consider that the product life cycle consists of four stages, that is, design, manufacturing, maintenance and recycling. The relationship among these terms is shown in Figure 2.

In manufacturing aspect, many studies have been conducted to ensure the product quality from various perspectives such as manufacturing methods and modelling approaches,[8] the influence of human factors,[9] key technologies of intelligent design for customized products[10] and challenges and future of manufacturing in engineering.[11] Key factors affecting manufacturing quality can be classified into two categories: hard and soft factors.[12] After the product is manufactured and sold out, after-sale service, such as maintenance and recycling, plays a critical role in the successful marketing of many products as it enables customers to get the full value from its products.[13]

After-sale services attempt to resolve problems met by a customer, for example, product failure restoration and problem with using the product, which will cause dissatisfaction if the problem is not well resolved.[14] Due to the increasing importance of after-sale service, Rolstadaas et al.[15] discussed various aspects of after-sale services with regard to business model, service-delivering methodology, performance metrics, service portfolio and product planning and control. While Takeuchi and Quelch[16] summarized the measures that are used for ensuring the quality of after-sale services, Markeset et al.[14] considered that the key factors affecting maintainability include cost consideration, technological consideration, human factors, statutory requirements and accidents and so on. Product collection method, local authority facilities, charging structure and support, geographical location[17] are considered to influence recycling quality. Compared to manufacturing, at maintenance and recycling stages, there are relatively less studies focusing on how to integrate product design quality into product after-service qualities despite that design for manufacturing, design

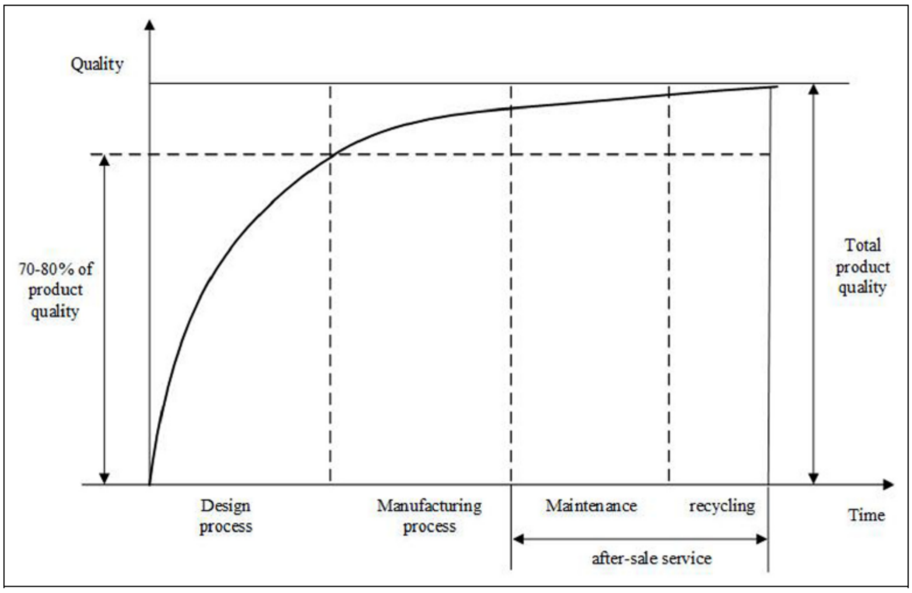

Figure 1. Incline of product quality through the whole life cycle.[4,5]

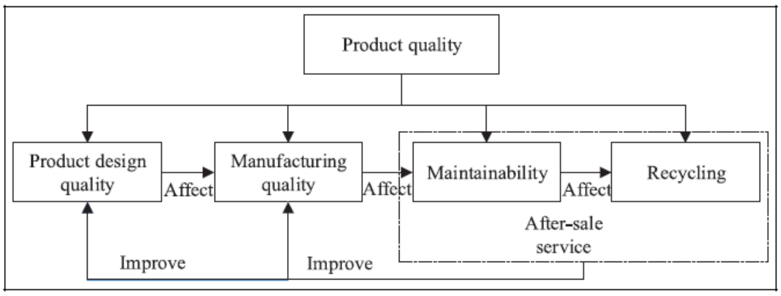

Figure 2. The relationship among quality-related terms through product whole life cycle.

for assembly and design for disassembly are proposed as design guidelines.

In conventional design environments, product design activities are usually performed by an in-house design team consisting of individuals with different expertise and experience. This kind of design collaboration mode is effective for large-scale enterprises but not for small and medium-sized enterprises (SMEs) who are lack of enough skilled employees and related resources to support their product design activities. Benefitted from the advantages of crowdsourcing, such as cost-effectiveness and global participation of crowds, SMEs show great interests in leveraging crowdsourcing-based platforms to perform their product design activities or improving their products as crowdsourcing has the potential to overcome their shortcomings in employees and related resources. In parallel to traditional product design processes, more and more SMEs[18–20] are moving part of their product design processes on to a crowdsourcing platform, benefitting from the participation of a large number of crowds including their potential customers to the fast speed and cost-effectiveness of the solutions generated. Although crowdsourcing has shown great potential to create more values in product design domain, there are no crowdsourcing platforms that fully support product design activities.[18,21] Thereby, SMEs just rely on these platforms to perform some specific product design activities such as idea generation and selection. Until now, many researchers have devoted to exploring how to support product design processes in crowdsourcing context.[18,20–23] Since product design research over a crowdsourcing platform is still in its early stages, there are few studies on how to control the product design quality over a crowdsourcing-based platform.

This article intends to give a definition of product design quality, survey the key factors affecting it in both traditional design environment and the crowdsourcing-based design environment and conduct a comparison between them. It also identifies product design quality control challenges over a crowdsourcing platform and investigates possible solutions to deal with these challenges.

Our main contributions in this article are fourfold:

1. Giving a hierarchy of product design quality attributes and defining their sub-attributes;
2. Surveying the key factors affecting product design quality, quality control models/approaches and quality assurance policies in conventional design environments, and summarizing product design quality control studies in terms of four research focuses: the management of information, the sharing of information, quality control approaches and quality assurance policies;
3. Analysing key factors affecting product design quality in crowdsourcing context and comparing the traditional design environment and the crowdsourcing context in terms of various aspects affecting product design quality;
4. Discussing product design quality control challenges over a crowdsourcing platform and proposing corresponding solutions to deal with these challenges.

The rest of this article is organized as follows. The 'Definition of product design quality' section gives a definition of product design quality, in which key quality attributes and sub-attributes of product design quality are given. The 'Research method' section presents our literature searching rules, the analysis results of found literature and the classification results of some literature that are conducted to ensure quality of different design quality attributes. The main contributions of this article are described in the 'Research findings of quality control studies in traditional design environments' and 'Research findings and quality control challenges in crowdsourcing context' sections. The 'Research findings of quality control studies in traditional design environments' section presents research finding in traditional design environments, including key factors affecting product design quality at different level of product design quality hierarchy, key quality control theories/methods and quality assurance policies. The 'Research findings and quality control challenges in crowdsourcing context' section mainly describes the research finding in the context of crowdsourcing, including key dimensions and factors affecting product design quality, and discusses quality control and assurance policies in crowdsourcing context and the product design quality control challenges in crowdsourcing context. Final section concludes the article and indicates the benefits of crowdsourcing in product design and development (PDD).

Definition of product design quality

At the product design stages, quality control is one of the most important activities as it ensures to achieve the design goal.[4] The aim of product design quality control is to check the key aspects of design quality against a set of standards or specifications. The quality control process can be achieved by a three-step iterative loop of design process in its simplest terms:[24] ideate, prototyping and evaluate phase, which is shown in Figure 3. In this process, design idea/concept is first generated, then it is prototyped, after that the design team would evaluate the design via prototypes. Finally, the design feedback generated from evaluation via prototypes will be fed back to corresponding designers for design improvement. The iteration of the design process helps designers discover unknown variables and their interrelationships,[25] and this iteration process is helped by idea prototypes with different fidelities ranging from two-dimensional (2D) sketches, three-dimensional (3D) computer aided design (CAD) models, 2D/3D mock-ups and printed 3D models. Lim et al.[26] have explored the role and characteristics of prototypes in the domain of design. And impact of prototyping on design results has been investigated by Dow[25] and he found that prototyping can initiate a conversation with the space of design possibilities. By integrating design feedback generated from prototypes that represent a class of a generalized heterogeneous grouping of elements derived from alike design cases that provides the basis for the start and continuation of a design into their designs,[27] the designers can improve their current design concept. However, since the interpretation of product design quality varies from person to person, it is hard to give it a specific definition. Nevertheless, many studies have tried to define it. The various definitions of product design quality can be found in Table 1.

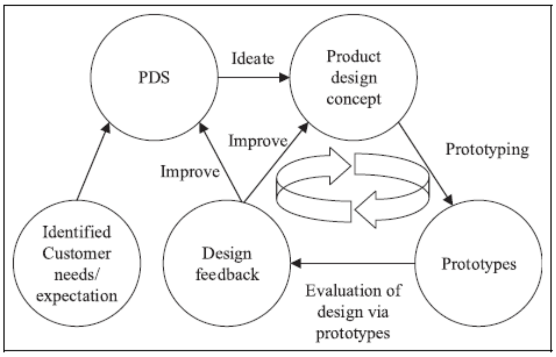

Figure 3. Product design quality control process.

According to the relationship between Maslow's hierarchy of needs and emotion design,[34,35] Bradley[36] proposed a five-level design hierarchy of needs, including functionality, reliability, usability, proficiency and creativity. Most of the existing product design quality control approaches are used to ensure the lower levels of user needs, that is, functionality, reliability and usability. Nevertheless, in the domain of industrial design, the maintenance of product is an important aspect affecting quality as well. Therefore, the maintainability should be taken into consideration when designing the product and it is treated as a key quality attribute in our product design quality hierarchy. In addition, we treat proficiency as a sub-attribute of functionality. Figure 4 shows the product design quality hierarchy of this research.

Table 1. The definition of product design quality.

Source	Definition or arguments of product design quality
Zhu et al.[5]	Design specification should conform to the requirement of customers
Zhu et al.;[28] BBC	Design requirements reflect the voice of the customer or the demands of the market
Aas;[29] Mrugalska and Tytyk[30]	Design object satisfies its specification
Salimun et al.;[31] ISO 9000: 2005	The degree to which a set of inherent characteristics fulfils requirements
Spacey[32]	The value of a design to customers
BusinessDictionary[1]	Level of effectiveness of the design function in determining a product's operational requirements (and their incorporation into design requirements) that can be converted into a finished product in a production process
IBM; Hermans and Liu[33]	The degree in which customer requirements are met

BBC: british broadcasting corporation; ISO: international organization for standardization; IBM: international business machines corporation.

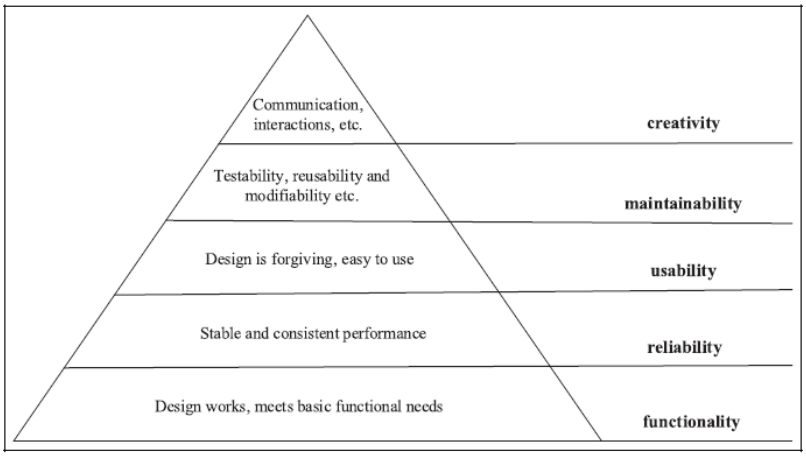

Figure 4. Product design quality hierarchy.

Taking both Table 1 and Figure 4 into consideration, this article defines product design quality as follows: the degree in which a set of inherent design characteristics of product meet requirements of hierarchical design quality of functionality, reliability, usability, maintainability and creativity; commercial requirements; and the required standards. In this definition, we consider not only the requirements of target audience (users) but also the requirements of other role players such as workers involved in the manufacturing, maintenance and recycling stages. From the perspective of product whole life cycle, all involved workers in the product life cycle are customers of the product.

In Figure 4, the highest level of design quality, creativity, is the last but very important aim of product design. Philips[35] and Schütte[37] have showed that making customers feel satisfied and happy could bring more benefits both in monetary and emotional aspects. Although a lot of research has been conducted on the controlling of one or two combinations of these five quality attributes, the ultimate goal of product design is to ensure the product quality in these five aspects. The five levels of design quality hierarchy are treated as design quality attributes in this research. Each design quality attribute consists of several sub-attributes. Referring to product quality characteristics defined by ISO 25010 Standards[38] in Software Engineering, the common types of design quality in Table 2 indicated by Spacey[32] can be treated as sub-attributes of these five design quality hierarchies. The aim of quality control at product design stages is to ensure the achievement of these five aspects. There are already related studies focusing on ensuring single and specific design quality attribute (see Table 2). In reliability design, there is already a review paper about analysing the research progress based on axiomatic design theory.[39]

Since reliability, usability, maintainability and creativity must be relied to functionality, more attention is often paid to the creation of functions and their combinations that satisfy established needs rather than the other four design quality aspects at earlier product design stages.[42] In order to obtain product designs with high quality, the design process has always been controlled. However, what factors affect design quality at different product design quality levels and what aspects should be controlled are still not clear. Therefore, the following method is adopted to extract research focuses from the existing literatures on quality control of product design at product design stages in both traditional design environment and crowdsourcing context.

Research method

All reviewed literature is searched from the following databases: Web of Science, ScienceDirect, ACM Digital Library and IEEE Xplore Digital Library. The keywords used to search articles are organized in three descriptor groups with rules listed below. In this review, Boolean operators 'AND' and 'OR' are adopted to make logical searches. R_1, R_2 and R_3 use the rule of 'OR' to represent the three descriptor groups, respectively. R_0 is the sum of R_1 and R_2 or R_1 and R_2 and R_3 with the rule 'AND'. For example, several keywords combinations such as 'industrial product design' with 'quality control', and 'conceptual design' with 'design for functionality' and 'crowdsourcing' have been examined

Table 2. Design quality attributes and sub-attributes.

Design quality attributes	Quality sub-attributes	Definition
Functionality[4,30,40,41]	Functional completeness	The extent to which the functions cover all specified tasks and objectives
	Functional correctness	The extent to which the product provides correct results with the needed degree of precision
	Functional appropriateness	The extent to which the functions facilitate the accomplishment of specified tasks and objectives
	Time behaviour	The extent to which the response and processing times meet requirements
	Resource utilization	The extent to which the amounts and types of resources used by a product meet requirements
	Capacity	The extent to which the maximum limits of a product meet requirements
	Sustainability/environment friendly	It is a requirement to the designer. The product must be friendly to environment
	Safety and security	The extent to which a product is safe for its users
Reliability[30,39,42–44]	Maturity	The extent to which a product meets needs for reliability under normal operation
	Fault tolerance	The extent to which a product continues in a reasonable way when errors occur
	Availability	The extent to which a product is operational and accessible when required for use
Usability[45–49]	Appropriateness recognizability	The extent to which users can recognize whether a product is appropriate for their needs
	Learnability	The extent to which a product can be used by specified users after learning
	Operability	The extent to which a product has attributes that make it easy to operate and control
	User interface aesthetics	The extent to which a user interface enables pleasing and satisfying interaction for the user
	Accessibility	The extent to which a product is useful for everyone in the context of use
Maintainability[50,51]	Analysability	The extent to which the product behaviours and performances are diagnosable and predictable
	Testability	The extent to which a product facilitates the establishment of acceptance criteria and supports evaluation of its performance
	Modularity	The extent to which a product is composed of discrete components
	Reusability	The extent to which a product or its components can be reused after disposal
	Modifiability	The extent to which a product can be modified without introducing defects or degrading existing product quality
Creativity[52–54]	User interaction/experience	Intangible elements of quality
	Emotional durability	A design that people value at an emotional level such that they do not easily throw it out

$$R_1 = keywords \in (product\ design\ OR\ conceptual\ design\ OR\ detail\ design\ OR\ idea\ development\ OR\ idea\ generation\ OR\ process\ design\ OR\ idea\ prototyping\ OR\ idea\ evaluation)$$
$$R_2 = keywords \in (quality\ control\ OR\ design\ for\ functionality\ OR\ design\ for\ usability\ OR\ design\ for\ reliability\ OR\ design\ for\ maintainability\ OR\ design\ for\ creativity)$$
$$R_3 = keywords \in (crowdsourcing\ OR\ cloud\ OR\ cloud-based)$$
$$R_0 = keywords \in ((R_1\ AND\ R_2)\ OR\ (R_1\ AND\ R_2\ AND\ R_3))$$

As a final retrieval result, a total number of 125 literatures from six categories of resources, that is, journal articles, conference proceedings, book sections, related webpages, standard and thesis, are found and classified. With the literature searching rules, the found studies could be classified into two categories according to the context: the traditional design environment and the crowdsourcing context. After getting the data set, all found literatures are screened manually to select out studies that are conducted at product design stages. As a result, 118 literatures from journal articles and conference proceedings are selected as most closely related to our research objective. The number of studies in these two different contexts are 100 and 18, respectively. Since we have reviewed key crowdsourcing technologies

Table 3. Literature distribution of studies in the traditional design environment.

Reference type	The number of references
Journal articles	63
Conference proceedings	16
Book sections	5
Related webpages	14
Thesis	1
Standard	1
Total	100

for PDD regarding to organization structure, solution evaluation, workflow management and quality control in literatures,[21,55] here only 18 literatures (10 journal papers, 7 conference papers and 1 book section) are mentioned to analyse the factors affecting product design quality in crowdsourcing context. Table 3 shows literature distribution of studies in the traditional design environment.

For these research papers appearing in journals and conference proceedings at product design stages in traditional environments, the TagCrowd was applied to extract keywords distributions to find out the research focuses. During this process, the searching keywords were excluded. The rest 258 words or word groups were collected and analysed. Figure 5 illustrates the top 50 words with the highest frequency. The result shows that the top-ranking keywords are management, collaborative, process, information, model, data, sharing, communication, knowledge, life cycle, systems and conflict. Based on this result, the extracted key research focuses in controlling product design quality in traditional design environments include the management and communication of relevant information and quality control approaches. After reading through these studies, another research focus, quality assurance policies, is found. The detailed analysis against each term is presented in the following sections.

The keywords analysis result from the 18 literatures related to crowdsourcing context is shown in Figure 6. The top-ranking keywords are communication, collaborative, co-creation, incentive, participation, motivation, feedback and assessment. It is clear that the research focuses in the crowdsourcing context are crowd participation, incentive mechanism, communication, feedback and assessment. However, the studies about these research focuses have been analysed by Niu et al., here we no longer describe them. Please refer to Niu and colleagues[21,55] for more details about these research focuses.

Research findings of quality control studies in traditional design environments

Traditionally, a successful product is achieved by the effort of a team.[56] A product design task is performed by a well-designated team, which consists of employees from different functional departments such as marketing, finance and technical department.[57] The budget for design, the capability of designers and the tool designers used definitely influence the product design quality at every design stage. Except these, there are many other factors[56] that are outside the direct control of designers affecting at least one attribute of product design

Figure 5. Distribution of articles by keywords in the traditional design environment.

Figure 6. Distribution of articles by keywords in the crowdsourcing context.

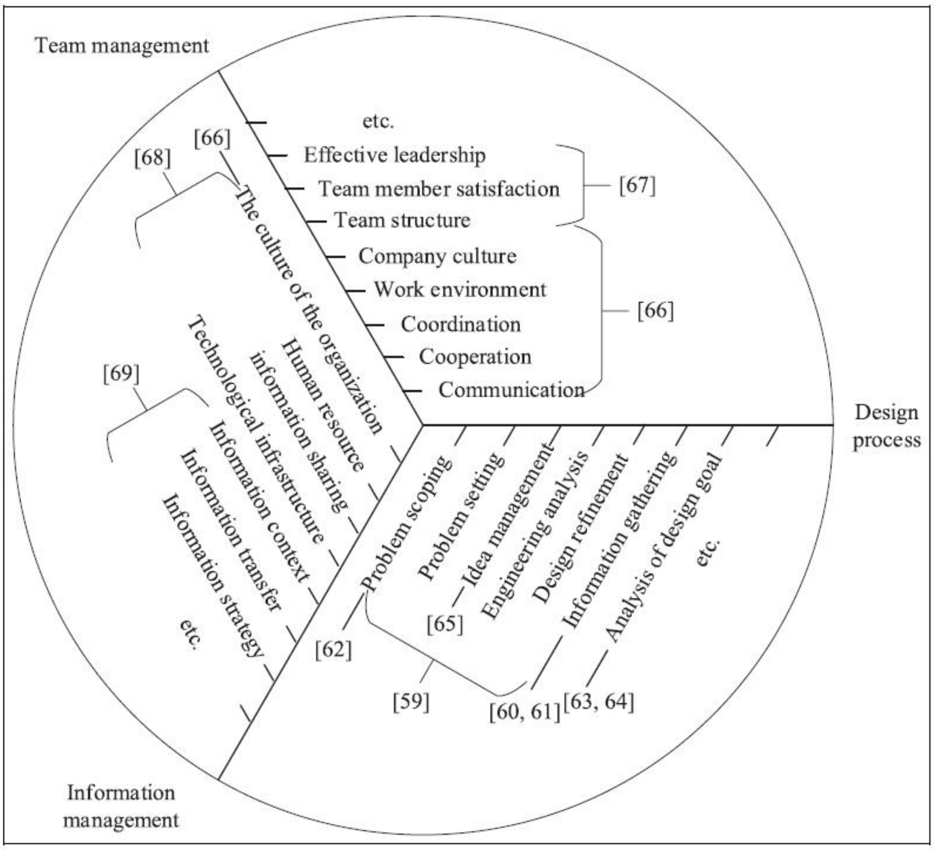

Figure 7. Factors affecting product design quality in terms of design process, team management and information management in traditional design environments.

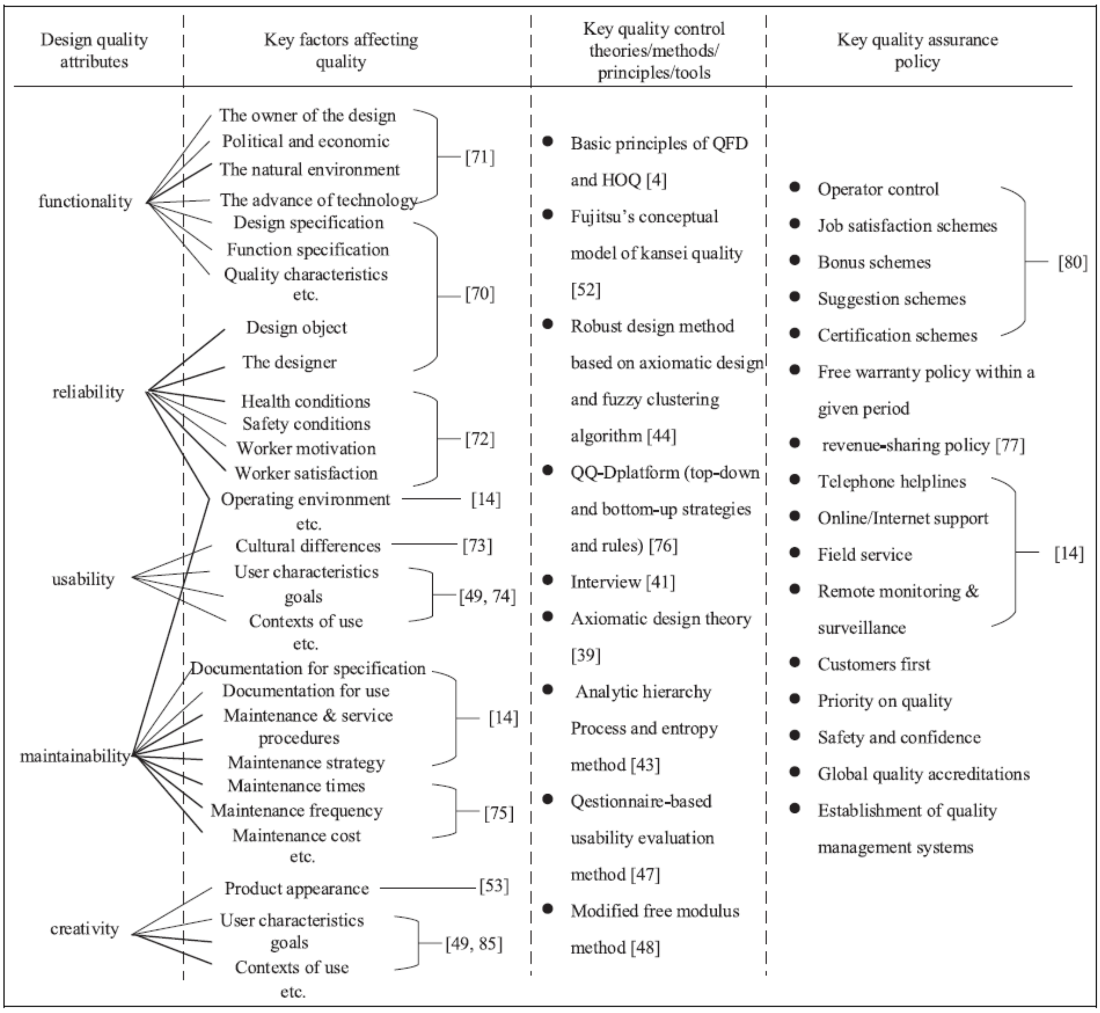

Figure 8. Summarization of research findings.

quality, for example, product development strategies, market orientation, technology and top management support. For a product design team, the support of design process, team environment and other assistance is to support team members to access the required knowledge and to utilize the knowledge for product design.[58] All these factors[56] have an important role to product design quality. They could be classified into three key aspects in terms of design process, team management and information management. The factors affecting product design quality in terms of these three aspects (design process,[59–65] team management,[65–67] information management[66,68,69]) are shown in Figure 7.

Knowing key factors affecting design quality in design process, team management and information management, we further investigate factors affecting product design quality at different quality levels, key quality control theories/principles/methods/tools and key quality assurance policies, which are shown in Figure 8. Some factors[70–75] affect single and specific design quality attribute and the others influence one or more attributes of product design quality.[4] In order to better understand how to ensure the product design quality, this article takes into consideration control theories,[39] approaches,[41,43,44,47,48,52] principles[4] and tools.[76] Quality assurance is a set of policies through product life cycle to make sure the product can systematically meet the quality standards and thus leave an impression to the customers that companies provide high-quality products that are reliable, durable and dependable.[14] The quality assurance policies on both supply chain[77] and after-sale service[14,78] have an influence on final product quality. It enables the quality of products according to Plan–Do–Check–Act ethos.[79]

Research focus	References
• Information management • The representation of information • The quality control of gathered information • The management of conflict information	Gao et al. [81]; Giannini et al. [82]; Gonzalez et al. [51]; Buskermolen et al. [89]; Van der Lelie et al. [90]; Van den Hende et al. [92]; Culley et al. [93]; Goto et al. [52]; Boess et al. [41]; Anwer et al. [94]; Yagci et al. [95]; Ouertani et al. [96]; Ouertani et al. [97]; Barclay et al. [98]; Lu et al. [99]; Rose et al. [100]; Lara et al. [101]; Ouertani et al. [102];
• Information sharing	Zhu et al. [5]; Gao et al. [81]; Zhang et al. [86]; Yam et al. [103]; Cummings et al. [104]; Giannini et al. [82]; Sudarsan et al. [83]; Ouertani et al. [105]; Mun et al. [106]; Lin et al. [107]; Hasby et al. [108];
• Quality control approaches • Quality control models/tools • Product design optimization	Zhang et al. [109]; Tang et al. [76]; Zhang et al. [110]; Chu et al. [4]; Goto et al. [52]; Cheng et al. [44]; Papalambros et al. [111]; Mrugalska et al. [30]; Chen et al. [112]; Taguchi et al. [113]; Cheng et al. [114]; Liu et al. [115]; Andersson et al. [116];
• Quality assurance policies	Markeset et al. [14]; Xiao et al. [77]; Dale et al. [80];

Figure 9. The classification of literatures according to research focuses.

Case studies from Dale and Duncalf[80] found that nearly all companies have quality assurance policies that usually exist in the form of written documents or verbal communications.

In order to ensure the quality of these five design quality attributes, the design process needs to be well controlled. Therefore, Tag Cloud (a data visualization tool) is utilized to analyse keywords from related literatures and four research focuses are identified. Figure 9 shows the classification of related literatures according to the research focuses: information management, information sharing, quality control approaches and quality assurance policies. The sections 'Information management', 'Information sharing', 'Quality control approaches' and 'Quality assurance policies' present the related studies under the terms of these four research focuses.

Information management

Information management is to identify, capture, evaluate, retrieve, maintain and share all of the information assets in an enterprise.[81] The effective management of information can help the enterprise find out valuable information, thus earning more economic benefits. Whatever scale the enterprises are, they should pay attention to the management of relevant information. For SMEs, they usually collaborate with other companies that are geographically distributed; thus, effective information management is needed to achieve a specific market objective.[82] For large companies, they need to well manage the information to support the collaboration of employees.

With the objective of knowing what kind of information is interchanged during a collaborative design project, Giannini et al.[82] analysed the design activities currently carried out in the technical offices of typical SMEs and found that designers always needed to communicate a subset of the whole information describing the product to be designed to co-designers. In this process, it is necessary to effectively and securely track, control, manage and share the rich information.[51] The management of information at design stages is vital to the success of final product and it is often achieved by PLM (product life cycle management) systems. PLM systems are gaining acceptance for managing all

Table 4. The existing information framework/model.

Framework/model	Information managed at design stages	References
Based on CPM and its extensions, OAM, DAIM and PFEM	Product information, design rationale, assembly and tolerance information, the evolution of products and product families	Sudarsan et al.[83]
Product manager	Product-specific knowledge, concepts pertaining to the description of the product whose design is in charge of the node and its lower level co-designers	Giannini et al.[82]
Process manager	The description of the processes: needed activities, dependencies between them, rules to follow, time schedules and constraints, planning of work, participant organization and synchronization of all of them	Giannini et al.[82]
Cloud-based design	Product data, customer feedback, market information	Wu et al.[84]
Satisfaction importance evaluation model	Personal information, product feedback, feedback on service, feedback on product modules, extra comments	Mourtzis et al.[85]
PDMM	Design data, material properties, geometric and topology models, dimension information, finite element analysis and optimization, process planning, scheduling	Zhang et al.[86]
Quality function knowledge deployment model	Domain knowledge, design standards, design specifications, comprehensive knowledge, material, mechanical assembly, CAD technology and related design experience, the social background, technology development, production resources, schedule	Zhang et al.[87]

PDMM: product data master model; CPM: core product model; OAM: open assembly model; DAIM: design-analysis integration model; PFEM: product family evolution model.

Table 5. The dimensions of information available during a product design process.[88]

Dimension	Explanation
Formal	Embedded in product documents, repositories, product function and structure description, problem-solving routines, technical and management systems, computer algorithms, expert knowledge systems and so on
Tacit	Tied to experiences, intuition, unarticulated models or implicit rules of thumb
Product	Includes requirements, various kinds of relationships between parts and assemblies, geometry, functions, behaviour, various constraints associated with products and design rationale
Process	Design process knowledge refers to design methods in representing designs, providing mechanisms for realizing design details
Compiled	Gained from experience that can be compiled onto rules, plans or scripts, cases of previously solved problems and so on
Dynamic	Qualitative and quantitative knowledge: qualitative knowledge consists of commonsense reasoning, approximate theories, causal models of processes, general problem-solving knowledge and so on; quantitative knowledge consists of constitutive, compatibility, equilibrium equations, numerical techniques, closed-form equations and so on

information about products acting as a collaboration result of designers from different departments or enterprises throughout their life cycle. The existing studies have proposed some information modelling framework trying to identify design information and product knowledge. The proposed information frameworks/models and the information managed are shown in Table 4.

In this section, the following questions need to be considered for design quality control: the representation of information, the quality of gathered information and the management of conflict information.

The representation of information. During a product design process, there is a large amount of information available such as product information and knowledge (knowledge is extracted from the analysis results of information), process information, the version and status of design solutions and customer feedback. This information is often stored at designated servers and is organized through basic elements so that it can be easily handled and monitored. In order to better represent this information, Chandrasegaran et al.[88] defined it in three dimensions: formal versus tacit, product versus process and compiled versus dynamic (see Table 5). The aim of information representation is to communicate the attributes and benefits of the design concept and to help users judge whether the design concept matches his or her needs and interests.[89]

The most common and classical representation of design concept is storyboard. Such a representation usually consists of a sequence of sketchy pictures with captions.[90] This representation is considered to be effective in communicating the role that the design would have in the lives of people. Another typical representation of design concepts is prototype. It helps minimize design errors that may otherwise occur both early and late in the process. Prototypes often help designers identify design issues and learn from failures, and they support both design concepts evaluation and design exploration.[26,91] Feedback elicited from prototypes often frames subsequent actions around the existing design solution.[25] However, new technologies, such as virtual reality, make it possible for designers to create more advanced representations through utilizing animations and videos, even early in the design process. These media integrate sounds, motion and light effects into the product design representation to enable an immersive feeling.[89]

In user-centred design, the users should be taken into consideration as they can help to evaluate the design concepts holistically. Therefore, their feedback on design concepts is meaningful to corresponding designers. Buskermolen et al.[89] and Van den Hende et al.[92] have explored the effect of different representations on user's responses to early design concepts. Van den Hende et al.[92] found that the presentation format of design concepts did not have significant effects on perception and comprehension of concept, but it has distinctive effects on absorbing the participants in the narrative world. After analysing the effects of visual quality and animation of concept representation on users' responses to early design concepts, Buskermolen et al.[89] suggested that sketchy representations provided more elaborate feedback and suggestions grounded on past experience, while visually refined representations were more helpful in eliciting definite judgements.

The quality control of gathered information. During a product design process, high-quality product information is essential as low quality often makes product development delay and can negatively impact the overall quality of the final product.[51] The gathered information may be in many forms such as document, dialogue, audio and video. In order to quantify the quality of a document, Culley et al.[93] have explored the existing tools for gathering and analysing information, and summarized information assessment criteria in a comprehensive list of 94 criteria. However, the gathered information in the product design process is not only presented in documents. The quality of information in other forms, such as web reviews and user feedback, needs to be measured as well. In addition, providing feedback to the corresponding designer is a key step in the product design process, and it promotes the improvement of product designs. Therefore, this section mainly concerns the control of feedback quality.

Although there are a lot of ways to gather feedback from customers, such as on-site observations, questionnaires and interviews,[52] the proper measures need to be adopted to ensure the feedback quality as the quality of gathered feedback relies on many different elements, for instance, the gathering criteria and process, the reliability of participants involved in this process, information quality checks and so on.

Boess[41] found that how people use products is quite different from the expectations of designers, so the users need to be involved into the design process. Their feedback is potentially valuable for designers. In addition, user review is an important part of information at product design stages. Both the designers and manufacturers should pay attention to these reviews as they contain information about product and service experiences and they have an influence on buyers making their purchase decisions.[94] It can be treated as feedback from users about use experience. For product designers, these potentially valuable reviews could help them to identify customer likes, dislikes and desires. Yagci and Das[95] introduce the design-level information quality measure to evaluate the content, complexity and relevancy of the product-related reviews. The number of reviews, sentences, words, noun words and feature matching noun words in a review database are found to be key determinants in measuring information quality.

The management of conflict information. When designing a product, designers need to take into consideration a lot of interdependent aspects such as functional requirements and geometrical, behavioural and structural features.[96] Each aspect of these has its own set of constraints in which conflicting or unsatisfied requirements may be contained, and it is hard for designers to oversee the various alternatives and constraints all the time. The final product design is a compromised result of such constraints. In collaborative design, due to the participation of many designers with different technical background and expertise and their interactions, they may have disagreements about proposed designs.[96,97] In addition, the product design data may change frequently until the final product is manufactured as more than one designer works on the same product project. The ever-changing data versions and status should be well managed. All these information are treated as conflict and the management of them is critical in collaborative design.[97]

Barclay[98] argues that there were three common types of conflict identified in product design: (a) imagined or perceived conflict, (b) latent or substantive conflict and (c) affective conflict. All these three conflict types are accompanied by process-related conflicts. With better understanding of the conflict types and causes that lead to conflicts, the management of them can make the outcomes of conflicts constructive.

The conflict management process includes five phases: conflict detection, forming the conflict resolution team, negotiation management, solution generation and solution impact evaluation.[96,97] A lot of research about conflict management have been conducted in collaborative design, but most of them have proposed methods to support the conflict detection[99,100] and the conflict resolution.[101] Quertani and colleagues[97,102] also developed solutions to manage the negotiation process by tracking product specification dependencies. In order to assess the impact of a selected solution on the product as well as on the design process organization, Quertani[96] proposed a process organization framework based on data dependencies network.

Information sharing

PDD always involves many participants with different professional knowledge and background such as marketing and engineering design. All these participants work together towards a specific design objective. Collaboration is found to be a key to enhance competitiveness[103] and to improve product quality.[5] Communication and information sharing is the foundation for collaborative product design.[86] Information sharing disseminates information with a community, which plays a crucial role in information management in product design process.[81] Effective information sharing drives organizational and individual learning, which in turn speeds up and improves the quality of product. Due to its importance to product design, here we present it in a separate section.

From the existing literature available, information sharing is found to be useful in helping individuals, teams and organizations to improve their work performance.[104] At the same time, effective information sharing can help short the time taken to introduce the products to the market, which will give the company an edge in the fierce competition.[81] In order to help designers work together effectively, certain measures must be adopted to enable the exchange of design information. ISO 10303 has provided an ISO standard for the computer-interpretable representation and exchange of product manufacturing information. However, there is still no similar standard for the exchange of product information at product design stages.

During the collaborative design process, the design-related and process-related information can be classified into two categories: public and exchanged information.[82] Public information describes and indicates the main characteristics of the product and can be treated as a set of technical requirements, to which all participants involved in the process can get access. While the exchanged information can only be seen by certain participants and their versions depend on the sender, for example, customer, co-designer or supplier, and the states of the project development . In information sharing, only exchanged information is considered.

Based on collected product and process information, proper information sharing and communication mechanisms enable designers and their partners to collaborate effectively, which is a critical determinant of collaboration.[83,105] The main contents of communications are the product data and the process data.[82] In traditional collaborative design scenarios, the designers usually have to spend much time on communicating with their partners through emails or phones. As for the design-related data stored at designated servers, they have to be authorized to have access to them. In the work of Zhang et al.,[86] a data access mechanism from different perspectives, functional views, personal workspace, work table and personal storage space, is provided, and even from the same perspective, different users have different data access authorizations. However, the proposed product model can only support static product information, which cannot satisfy the needs of real-time collaborative design. As for the systems on which all information are public, the protection of intellectual property is threatened.[106] Mun et al.[106] suggest just share the essential data with their collaboration partners.

In collaborative environment, the sharing of information is usually achieved through various design representation formats such as 3D models, images, videos and XML extensible markup language (XML) files.[107] One problem that needs to be considered in this process is that the users should exchange their ideas as instantly as possible. Hasby and Roller[108] proposed a CAD system that can facilitate the conceptual-embodiment design stage in a collaborative manner. Through the system, the designers can communicate their opinions and ideas freely. In addition, the system must avoid the possibility of losing some information.[82] In order to prevent this possibility, the system should automatically create a list of changes that the user has made and notify relevant users to update their information.

Quality control approaches

Quality control models/tools. Quality control is an activity throughout the whole product design and development process. The aim of quality control is to satisfy the customer needs as well as to decrease the design and development cost in terms of time and money.[109] In this process, customer requirements and product design specification (PDS) are benchmarks of the controlled quality of product design.[76] In order to control the quality of product design, many researchers linked customer requirements with quality characteristics. For example, Tang et al.[76] argued that quality characteristics are the key control factors in the whole product design and development process and the focus of quality control is on how to translate customer requirements into product quality characteristics. Similarly, Zhang et al.[110] developed a vector-based mapping tool that can provide reasonable mapping among PDS, behaviour parameters and structure parameters. Chu et al.[4] converted user requirements into the relevant technical requirements of design using quality function deployment (QFD) and house of quality (HOQ). Although customer requirements provide benchmarks for the designated product, one problem that cannot be neglected is that the customer requirements change over time. In order to understand how requirement changes propagate in the design of complex product systems thus helping to select best options to guide design, Zhang et al.[109] proposed a PDS-Behaviour-Structure-based design change model that can systematically analyse and search change propagation paths.

The quality control models can be classified into computer-oriented and human-oriented. Among computer-oriented quality control models, Tang et al.[76] translated customer requirements into product quality characteristics and achieved their quality control aim by controlling these quality characteristics. As for human-oriented quality control models, a typical one is Fujitsu's conceptual model of Kansei quality.[52] The model has six elements:[52] product/service usage situations, stimuli produced in usage situation, somatic sensations (perception/cognition), personality and past experience, impressions/emotions, behaviour. The somatic sensations is the contact point between the user and the outside world. These elements are controlled in the Plan–Do–Check–Act cycle.

Product design optimization. During product design and development process, the initial design may be functional, but it may be far from optimal in terms of quality and cost.[44] Hence, it is necessary to optimize the initial product design to make it meet the design requirements. Product design optimization is an effective way to improve the quality of a product through minimizing the effect of the causes of variation.[44] The optimization involves product design optimization and design process optimization. Product design optimization means improving the design in terms of one or more performance aspects of a specific type of product,[111] while design process optimization could benefit nearly all corresponding product designs produced by adopting the optimized design process.

When a product design is finished, it is expected to maximize performance as well as be less sensitive to variation in practical situations such as environmental changes.[30,44] Design optimization is usually achieved by mathematical optimization techniques.[111] The mathematical model allows to choose the optimal values of parameters of the model that accurately reflect customers' expectations.[30] In the mathematical model, experiments based on fractional factorial designs and orthogonal arrays can be applied to improve it. However, there are still some challenges in design optimization such as mathematical challenges, topologies and configurations, systems design, controlled artefacts and enterprise-wide design (indicated by Papalambros[111]). Whatever the optimization technique is adopted, the aim is to make the product design as robust as possible. In order to achieve this goal, robust design method can be considered during product design process. In addition, different sources of uncertainties and variations in design and manufacturing process, such as model uncertainty, parameters uncertainty and noise, should be taken into consideration.[30]

Chen and Li[112] proposed a computerized team approach for process design optimization. In their work, they treat design teams as game players in a multi-player game and classify different types of team interactions from the view of game theory. Finally, the satisfaction metric is utilized to evaluate the effectiveness of the proposed approach. Different from their work, Taguchi and Rafanelli[113] divide the design process into three stages – system design, parameter design and tolerance design – and the design focuses of these three stages are basic functional prototype design, controlling parameters to make the design insensitive to variations and the upper limit of the number of variation or noise factors allowed in the design, respectively. Compared to research work in system design, more work is conducted in parameter design and tolerance design.[44] For example, Cheng and Lin[114] took any deviations of design parameters into sensitivity analysis and robust optimization design of suspension system so that the system would have better performance. Liu et al.[115] utilized goal programming approach that incorporated analytic network process and cost budget limitation to determine the variant components to be focused on redesign. However, system design determines the attainable level of product robustness in the parameter stage, argued by Andersson.[116] Due to the importance of system design, Cheng et al.[44] proposed a frame on the basis of system modelling, cluster analysis and design of experiments for the development of robust system.

Quality assurance policies

Quality assurance policies are adopted to satisfy the customers by supplying products that fully comply with customer, statutory and regulatory requirements. Most enterprises have their quality assurance departments to ensure the quality of their products and they have their own product or service quality rules such as customer first, priority on quality, safety and confidence and global quality accreditations.[78]

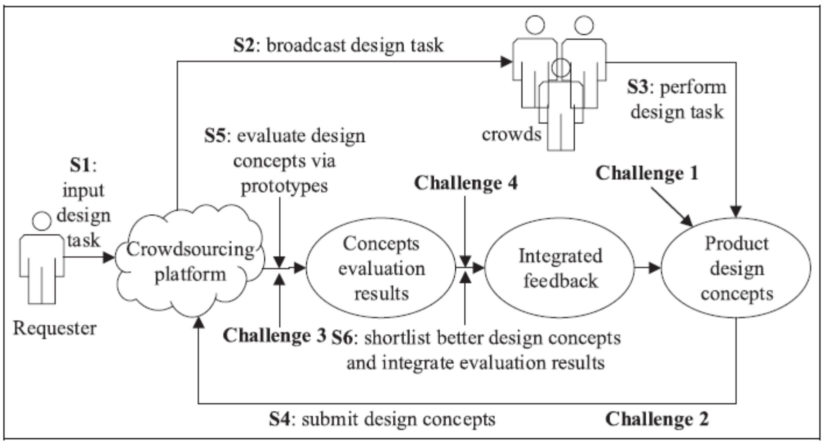

Figure 10. A simple design process over a crowdsourcing platform.[21]

In a questionnaire survey conducted by Dale and Duncalf,[80] they found that the majority of companies have quality assurance policies, and most of them make their policies in the form of written documents and statements, although some companies utilize verbal communications via the management structure to communicate quality policy information. The attainment level of quality objectives relies on constant examination, improvement and effective communications, and the way of quality assurance policies affects the communications and decision-making processes.[80] In order to obtain the correct quality products, all participants in the production process should be well controlled and should be motivated into the process. Therefore, operator control method can be combined with job satisfaction schemes, bonus schemes, suggestion schemes and certification schemes in production.[80]

However, the attainment of the desired quality level not only relies on the production enterprise but also relies on its suppliers.[77,80] In the game-theoretic model proposed by Xiao et al.,[77] they investigated how an enterprise coordinates the supply chain with a quality assurance policy via a revenue-sharing contract and found that the optimal service quality first decreases and then increases as the defective rate of the final product increases. After the product is launched on the market, the enterprises will provide online service by telephone helplines and online/Internet support or will provide field service for helping customers solve problems in the product use process fast.[14] In addition, they will use many databases and information systems to manage customer feedback, complaints and product problem resolution for future improvement of corresponding products.

Research findings and quality control challenges in crowdsourcing context

In the traditional design environment, it is hard to overcome the shortcomings of SMEs in employees and resources, sometimes in budget. Extending the design environment to crowdsourcing context, these shortcomings may be well addressed by leveraging the globally distributed crowds and the cost-effectiveness of crowdsourcing. Therefore, this section mainly analyses the factors affecting product design quality in crowdsourcing context, discusses quality control models and quality assurance policies and investigates quality control challenges over a crowdsourcing platform.

Research findings of quality control studies in crowdsourcing context

When extending the traditional design environment to the crowdsourcing context, the possible design process over a crowdsourcing platform (see Figure 10) has been explored by Niu et al.[21] They indicated four challenges (please refer to Niu et al.[21] for more details) when performing product design tasks in the crowdsourcing context.

During this process, there are more factors affecting product design quality. In the crowdsourcing context, three more factor dimensions can be added, that is, requester, task and platform. Figure 11 shows key factor dimensions and some of the key factors affecting the corresponding dimension. More factors affecting product design quality in terms of key elements of crowdsourcing process are shown in Table 6.

The explanation of each factor dimension is shown as follows:

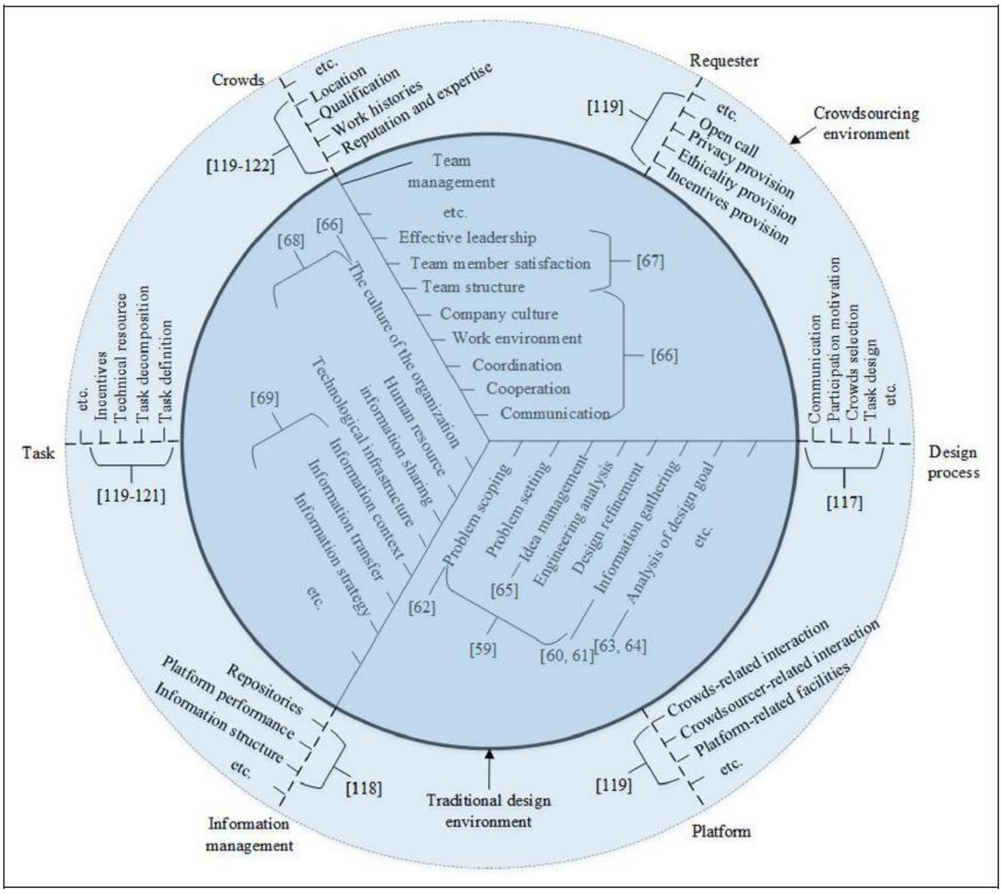

Figure 11. Factors affecting product design quality in crowdsourcing context.

Table 6. Factors affecting product design quality in terms of key elements of crowdsourcing process.

Key elements of crowdsourcing process	Factors affecting design quality
Requester[117]	Incentives provision, open call, ethicality provision, privacy provision
Platform[117]	Crowd-related interaction, crowdsourcer-related interaction, task-related facilities, platform-related facilities
Crowds[117–120]	Reputation and expertise, instruction and user interface, user identity, nationality, qualification, job title, entry date, department, location, accomplishment, diversity, unknown-ness, largeness, undefined-ness, suitability, social, learning, financial
Task[117–119]	Task definition, user interface, granularity, incentives and compensation policy, instruction, task description, target audience, complexity, type of action, modularization, nature of the reward, type of the reward, latency, submissior time, closure time, duration, visibility, confidentiality, human requirement, technical resource

1. *Crowds*: It is one of the key elements of a crowdsourcing process. It is extended from the traditional design team, so it can be treated as a virtual team. In traditional design environments, the capability of their employees is well mastered by their team leader. Thus, the team leader can assign tasks to the most right individuals. While in the crowdsourcing context, the truthfulness and reliability of these information provided by the crowds themselves are usually doubtful. In order to assign the task to right persons, these information must be verified.
2. *Requester*: It is one of the key elements of a crowdsourcing process. The requester is

Table 7. The comparison of traditional environments and the crowdsourcing context.

Comparison item	Traditional design environment	Crowdsourcing context
Design process	Controlled by team leader	Controlled by the requester and platform
Team management	Controlled by team leader	Controlled by the platform
Information management	Documents, videos and so on	Database
The number of participants	Limited	Unlimited
The qualification of participants	Known	Unknown
Incentive mechanism	Bonus, team-building activities and so on	Reward, enjoyment, reputation and so on
Organization structure of participants	Hierarchical structure and cross-functional organization structure	Hierarchical structure
Task description	Team members can discuss to better understand it	The crowd can interpret it by himself or herself or discuss it with other crowds through communication tools
Task decomposition	Performed by the team leader	Performed by the requester or the platform
Task assignment	Assigned by the team leader	Calculated by the platform
Communication	Regular meeting, workshop	Forum, social medium and related tools provided by the platform

responsible for proposing task requirements, incentives, timelines and so on.

3. *Task*: The task is proposed by the requester and crowds perform it to achieve expected outcomes. In order to better assign the task to crowds, it usually needs to be decomposed either by the requester or by the crowdsourcing platform runner.
4. *Platform*: The crowdsourcing platform is a workplace, which provides interfaces for its users including the crowds and the requester to interact with it. All information related to design process, information management, task, the requester and the crowds are controlled by the crowdsourcing platform.
5. *Design process*: In the crowdsourcing context, the product design process is controlled by the crowdsourcing platform. The process consists of many subprocesses such as task decomposition, task assignment, the selection of crowds and the synthesis of task results. In order to ensure the collaboration of crowds, the process should have the capability to involve enough qualified crowds by participation motivations and proper selection rules and support the communication among them.[121]
6. *Information management*: In the crowdsourcing context, all information including product-, process-, crowds- and tasks-related information are stored in database. The users only need to pay attention to the interactions between them and the crowdsourcing platform. Since the information management is controlled by the crowdsourcing platform, the factors affecting software system quality, such as platform performance and data structure, will influence the crowdsourcing platform quality, thereby influencing the quality of work conducted on the platform.[122]

As product design activity quality control studies in terms of four aspects, that is, crowds, platform, task and workflow, have been reviewed by Niu et al.,[21,55] here we do not review them repeatedly. Here, we mainly compare traditional design environment and crowdsourcing context in terms of the following aspects influencing design activity quality. The comparison is shown in Table 7.

Over the crowdsourcing platform, the design process, team management and information management in traditional design environment are all controlled by the crowdsourcing platform.

Discussion of quality control models and quality assurance policies

Literature[18,21,55] found that the existing crowdsourcing platforms can only partly support PDD activities, and the existing studies about product design quality control are relatively less. In crowdsourcing context, a crowdsourcing process with high quality makes it more likely to achieve better product designs. Therefore, many researchers have devoted in investigating crowdsourcing quality control. For example, Daniel et al.[121] have analysed the quality attributes, assessment techniques and assurance policies in crowdsourcing quality control. They mainly control the quality from the perspective of individual, group and computation. The corresponding assessment methods can be found in Daniel et al.[121] However, when PDD activities are performed in the crowdsourcing context, both the traditional product design quality control approaches and crowdsourcing quality control approaches should be considered. In literature,[21,55] we have reviewed some studies about product design quality control approaches (see Table 8). However, most of them focus on controlling the quality of a specific stage of product design process.

Table 8. Quality control approaches and quality assurance policies of crowdsourcing.[118,121]

Assessment perspective	Quality control approaches	Quality assurance policies
Individual	Rating, qualification test, self-assessment, personality test, referrals, expert review, usability check and so on	Improve data quality, select people, incentivize people, train people, improve task design, control execution and so on
Group	Voting, group consensus, output agreement, peer review, feedback aggregation, user study and so on	
Computation	Ground truth, outlier analysis, finger printing, achievements, implicit feedback, association analysis, content analysis, transfer learning, collusion detection and so on	

The quality control models/approaches through the whole product design stages will be investigated in the future.

As for the crowdsourcing quality assurance policies, Daniel et al.[121] have identified six strategies: (a) improve data quality, (b) select people, (c) incentivize people using extrinsic and intrinsic motivations, (d) train people, (e) improve task design and (f) control execution. These strategies aim to improve quality as first-order goal. In addition, some assessment measures have positive side effects on quality, especially when the assessment object are people. For example, reviews have been found by Zhu et al.[123] that it can improve the performance of both crowds and reviewers. And rating the performance of crowds has similar positive side effects.[124] Together with the product design quality assurance policies in traditional design environments such as job satisfaction schemes, certification schemes, free warranty policy, telephone helplines, remote monitoring and customer first, the crowdsourcing quality assurance strategies should make it possible to obtain high-quality product designs in the context of crowdsourcing.

The quality control challenges over a crowdsourcing-based platform

This section mainly focuses on discussing the challenges of product design quality control over a crowdsourcing-based platform. Based on the previous analysis results, it is found that most of the design work is finished by the collaboration of many designers as collaboration is found to be effective in improving product quality and work efficiency.[5] However, it is hard for SMEs to organize enough designers within their companies to perform the design task unless outsourcing parts of their work to related companies.[106] In addition, it has been demonstrated that crowdsourcing can enable the scaling up of design and manufacturing operations and improve design performance and quality.[18,125]

As a result, a lot of enterprises have utilized crowdsourcing to achieve specific goals such as to increase customer engagement and to choose better ideas. However, there are still some challenges on controlling the quality of generated ideas or solutions when product design activities are performed over a crowdsourcing-based collaborative platform. In our previous work, we have analysed the gaps and challenges in adopting crowdsourcing in PDD process from the perspective of crowdsourcing technologies[21,55] and have indicated the necessity of developing relevant tools to support product design and development activities. Except the problem that the existing crowdsourcing platforms and tools cannot fully support PDD activities, there are still other challenges in controlling the product design quality over such a crowdsourcing platform. The possible challenges include the following.

1. The management of information.
   On a crowdsourcing platform, there are more participants in the product design project than in conventional settings. The participants are globally distributed and have various cultural background and different levels of expertise, which may lead to more product design conflicts.
2. The representation of product design.
   On the crowdsourcing platform, the participants have various levels of design capabilities and they may not know how to present their designs as expected.
3. The communication of designers.
   Effective communication plays an important role on improving product design quality, which can help designers have a better understanding of design requirements and work done by their colleagues.
4. The protection of intellectual property. In order to support the collaboration of crowds, the platform has to support the information sharing and communication. Since crowdsourcing process is open to the crowds registered on the platform, the intellectual property protection faces more risks than in traditional environment.

Aimed at the above challenges, the following corresponding solutions are proposed:

1. The platform should be cloud-based. With the support of cloud technology, the distributed participants of product design process can easily get access to product and process-related information to effectively perform design activities.
2. The platform should provide a presentation tool to guide designers to present their designs and other users can pose queries about the design such as rationale and purpose, or the causality between physical and functional elements.
3. The platform should provide application programming interfaces (APIs) to common social medium because it not only helps designers to communicate with other designers more freely and in real time but also makes them have a connection with their friends.
4. The platform should integrate with blockchain technology as it supports the encrypted transmission of information.

As there is no such a crowdsourcing platform that fully supports product design process, these solutions cannot be verified until the platform is developed. However, these solutions would provide some guidelines for developing such a platform in controlling product design quality in the future.

Conclusion

This review article mainly analysed the key factors affecting product design quality both in traditional design environments and in the crowdsourcing context. And based on the analysis results, this article indicated product design quality control challenges over a crowdsourcing-based platform and proposed corresponding solutions.

In order to better understand key factors affecting product design quality, this article first gave a definition and sub-attributes of product design quality. Then Tag Cloud is adopted to analyse the keywords to find out the research focuses in these two design environments. In the traditional design environment, four research focuses including information management, information sharing, quality control approaches and quality assurance policies are found. Through analysis, we found that there are more factors affecting product design quality when the design environment is extended to the crowdsourcing context from the traditional design environment. While in the crowdsourcing context, we mainly analysed the key factors affecting product design quality, compared these two design environments and discussed quality control and assurance policies. Based on that, the article indicated four product design quality control challenges over a crowdsourcing-based collaborative platform and proposed corresponding solutions to these challenges.

If these challenges can be well addressed, SMEs will benefit a lot as they can get access to a large pool of crowds with various skills and experience, which will effectively relieve their pressure resulting from the lack of skilled employees and related resources. The research direction in the near future is to develop such a crowdsourcing platform to support PDD activities. This article can provide some guidelines for the platform development.

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DIGITALLY SUPPORTING THE CO-CREATION OF FUTURE ADVANCED SERVICES FOR 'HEAT AS A SERVICE'

Sara Mountney, Tracy Ross, Andrew May, Sheng-Feng Qin, Xiaojing Niu, Melanie King, Kawaljeet Kapoor, Vicky Story and Jamie Burton

ABSTRACT

Purpose: This paper is a preliminary exploration of how a digital prototype might be developed to support co-creation in developing future advanced services for 'Heat as a Service' (HaaS).

Design/Methodology/Approach: A user-centred design approach was undertaken with two customer segments to establish potential requirements for HaaS. A systems thinking approach was then used for the preliminary development of a digital tool to support new advanced services.

Findings: Further definitions of HaaS from the perspective of two different customer segments are presented, with emerging proposals on (i) how they can be managed in a system setting and (ii) suitable supporting digital tools.

Originality/Value: A user-centred approach to new advanced services development is presented to take into consideration current and future engineering and digital capabilities, moving beyond a conventional product-centric service development approach.

KEYWORDS: Advanced services, user-centred design, digital twin

1. INTRODUCTION

Advanced services are the provision of outcome-based solutions, creating a risk and value sharing partnership between the customer and the supplier. Advances in digitalized technology create an opportunity to increase the scope of such advanced services, whether this be through the addition of smart technology into the service itself, or the use of digital techniques to model and explore new advanced service concepts. An example of an advanced service is the move towards providing heat in the home as 'Heat as a Service' (HaaS), based on the provision of thermal comfort, rather than the payment of physical products and units of energy. For a manufacturing organisation looking to move into the provision of advanced services in this area, there are challenges in translating the HaaS concept into a range of flexible solutions to suit wide ranging customer needs and expectations. Digitalized methods to support and create opportunities for novel advanced services through co-creation therefore require further investigation.

This work is part of a larger multi-disciplinary project that takes a customer-focused perspective to develop a better understanding of the HaaS concept. This understanding will then be used to design a digital prototype to digitally map the future services, providing an environment for service co-creation to occur. This paper specifically reports on the preliminary findings of the user-centred design approach with customer preferences reflecting potential advanced service opportunities. A systems thinking approach is then taken to explore the digital resources available to support the prototyping of new advanced services to meet these preferences. The concept for a digital prototype to support this is then presented.

2. BACKGROUND

Advanced Services are a type of servitization that deliver customer value based on outcome rather than ownership; sharing risk, revenue and value (Musson et al. 2019). Such business models are being adopted by manufacturing organisations to widen the scope of their customer offerings to offer a mix of products and services (Kowalkowski, Gebauer and Oliva, 2017). Advances in digitalized technologies offer significant opportunities to such organisations, in that they can be exploited to increase the scope of potential services offered both within the existing product in use (i.e. condition monitoring), and those not embodied in the product definition and / or of higher value (Coreynen et al. 2017, Chowdhury et al. 2018).

HaaS is an example of a potential advanced service. Rather than paying for units of energy delivered (i.e. KWH), customers pay for units of experience, in this case, the provision of 'warm hours' or 'smart thermal comfort', often delivered via smart systems (Catapult 2019). The drivers for HaaS lie in the decarbonisation of UK home heating, more efficient energy provision and providers seeking more consistent revenue streams. However, delivering HaaS presents a series of challenges both to the energy provider and the network of organisations that provide various parts of the infrastructure for delivering such a service. Examples are: the range of property types and ages, and their varying efficiencies, particularly for existing housing stock; and the range of users of such HaaS systems and their own individual circumstances, requirements, and behaviours towards the system (Catapult 2019). The Energy Systems Catapult highlights '3Cs' (Comfort, Control and Convenience)' as key customer requirements for an acceptable alternative to their current (often gas-fired) systems (Catapult 2019). Delta-EE have highlighted five risks normally borne by the customer that would need to be transferred to the supplier in order to deliver HaaS. They are financial, technical, performance-related, behavioural and energy price fluctuations (Delta-EE 2019). Organisations operating in this environment, therefore, need to know how and where they will contribute to the new HaaS value chain, and develop capabilities to ensure they can deliver value (Bustinza et al., 2015). Essentially the customer is defining the value to be added but flexibility is needed to both understand what this value might look like and understand how, as a network of providers in a value chain, these organisations respond. Thus, in defining what a new advanced services to deliver HaaS might be, a method that involves customer co-creation activities is clearly advantageous.

It is worthwhile examining current digital approaches that could be used in the development of advanced services. Digital modelling approaches, particularly digital twins, are being increasingly developed to support the introduction of new products and services into the marketplace. Kritzinger et al. (2018) distinguish between three stages of digital modelling (digital models, digital shadows and digital twins), depending on the level of interaction between the physical model and the virtual model. With a digital twin, there is a real-time connection between both spaces with updating in both directions (Kritzinger et al., 2018). However, this real-time, two-way interaction is most developed through product in-use or operation data and represents a challenge for the early stages of concept product design due to the availability and uniformity of the data (Jones et al 2019). Ströer et al. (2018) discuss how most service-related data is generated during use and fed back for product design. In the absence of such data, simulation and machine learning can be used to predict the data required and inform the design progression.

In terms of design methods utilising digital modelling, the dominant approach is an extension of product lifecycle management, so that new developments are primarily product-centric, and services support the existing product in use. The emphasis is on the efficient integration of data across each stage of the product lifecycle. As an example, Tao et al. (2018) considered a product-centric digital twin approach that spanned across all stages of product lifecycle management, with the primary aim of improving the efficiency of data integration across each stage. The purpose of adding value through services (servitization) was not acknowledged, only services related to maintaining the product in use. However, the integration of customer data was acknowledged as a requirement during the concept stage of design and the digital twin presented as a suitable means of integrating this. Zheng et al. (2018) also presented the potential of a digital twin as an enabler for smart service innovations due to its linking of physical and digital spaces. They demonstrated this with a smart product service system, using wearable technology (a respirator) as an example. An opportunity for designing new service opportunities around the data generated from its use was highlighted. Hence, there was an opportunity for the value in services to transcend those directly related to the product and the scope of the digital twin was increased. Furthermore, Rambow-Hoeschele et al. (2018) extended the scope of a digital twin beyond the scope of the physical product to business models, creating a digital model builder, which encompassed elements of product, service and value offering modelling from a business modelling perspective. This was defined as a digital twin due to the real time exchange of data between the physical and virtual spaces.

An opportunity, therefore, exists to consider in detail, the generation and use of customer user data for the co-creation of digitally enhanced advanced services, focusing on a HaaS solution. A digital approach is required that enables an organisation to explore potential advanced services and capabilities to respond, but without tying this to a conventional product-centric design approach.

To investigate this further, a two-stage study design approach was adopted. Study 1 was a user-centred design approach to understand the end user perspective and uncover future potential service opportunities for HaaS. These were then used to inform study 2, which used a systems thinking approach to explore potential digital prototyping opportunities. These studies are reported in the next two sections respectively.

3. STUDY 1: THE DESIRED USER EXPERIENCE FROM TWO PERSPECTIVES

3.1 Approach and Study

In the context of everyday tasks, user-centred design can be considered to offer both a philosophy and a process (Haines and Mitchell, 2013). The philosophy is that design should focus on the needs of the user as a central tenet, seeking to ensure that the needs and wants of users are considered throughout the process (Norman, 1998). The process is characterised by an early focus on users and tasks (Gould and Lewis, 1985) and stresses the importance of user goals, behaviours, contexts, characteristics and decision-making (Sharp et al. 2007). User-centred design is widely accepted as leading to the design of useful, usable and desirable products, services and systems.

The user-centric design approach was taken to uncover future opportunities and requirements for the heat as a service concept. Two key end-user groups were identified in collaboration with the focal manufacturer: householders and social housing landlords. These groups were selected in order to explore two diverse scenarios of use to take forward into the next phases of research.

The first group comprised 15 householders with the following characteristics: a mix of owner-occupier and rental with 1-5 occupants; 6 male and 9 female; predominantly gas boilers plus a range of additional heating or log burners; some with smart meters or intelligent thermostats; and a range of attitudes to technology. A participatory design approach was used to take the householders through 3 stages of a semi-structured interview: (i) sensitisation to the context (describing their current heating situation and experiences); (ii) a design fiction ("your heating is stripped out and you have your own 'thermal comfort PA' what would they need to know and what could they do for you?"); and (iii) idea-generation, based on (ii) and exploring three main phases of the personalised thermal comfort 'system' - planning, using, and leaving (e.g. moving house). All sessions were audio recorded, transcribed and subjected to a thematic analysis to extract the key functional and experiential needs.

The second group comprised social housing landlords. These are an interesting use case since they act as an intermediary between equipment and service suppliers and the end consumer. Social landlords provide rented housing to selected community groups (including vulnerable sectors) and are responsible for providing a tenancy service that enables good value, comfortable and healthy living (legal requirement) environments. Two large social landlord organisations based in the UK took part in the study – large organisations were chosen as they have a wide range of staff with various roles and technical expertise, and can provide a multi-disciplinary contribution to service-related insights centred around heating. A total of eight staff took part in two semi-structured discussion groups, each lasting about one and half hours. The specialisms of the staff within these organisations were as follows: new technology and innovation, technology and process transformation, operations management, customer service, and external and internal communications. The discussions followed the approximate format of: research background, consent and ethics, introductions, key measures of success, problems they face, needs they have, new ideas to meet needs and capitalize on opportunities, paths and barriers relating to implementation. A range of user and service focussed tools were used including stakeholder and customer journey mapping, as preferred by the participants.

3.2 Results

The results from the householder interviews elicited some key high-level insights. Firstly, there was a wide variation in needs and wants, influenced by factors such as personal comfort preferences, occupants (e.g. babies, visitors), schedules (daily, weekly, annual) and attitudes to technology and data usage. In addition, participants varied in their prioritising of what we have identified as the '5Cs' – comfort, control, convenience, cost and carbon-reduction (with the latter two factors adding to the three identified previously (Energy Systems Catapult, 2019). Results based on the three main phases of the personalised thermal comfort 'system' (planning, using, and leaving) indicated what knowledge/data the 'thermal comfort PA' would need to access and are presented in Table 1.

Table 1. Knowledge and actions required for the 'thermal comfort PA'

Planning	**Using**	**Leaving**
Occupants Personal temperature preferences (un)known Household routines (or lack of) & exceptions Room usage level and activity/function Priorities ('5Cs': comfort, convenience, control, cost and carbon-reduction) House structure, insulation, decoration, sun location Aesthetic	Moving in and out of house Moving around house Instantaneous heat when enter (room/house) Room-by-room variation Privacy of schedule/activity data (wide variety of opinions) Automation? But with user control, awareness, assurances Learning then stabilising + user intervention Reports, hints & tips, to 'help the grid'	Take my profile with me Adjust to new home/schedule/occupants Need to re-coup my investment What data do I leave behind? 'take the brain!' How would it work re the 'supplier'? Chance for complete transformation e.g. Passive House Reduce the stress!

The results from the social housing landlords focused on generating some specific service concepts that would meet their needs in relation to 'heat as a service' provision to tenants. Table 2 gives an outline of the ten service concepts (SC1-SC10) generated with the Social Landlords, together with the key features for service interaction. They are shown in a temporal order that relates to key touchpoints and processes on the customer journey from SC1 to SC10 of a social housing tenant, and include some specific, and other more general, and future focussed concepts.

Table 2. Service Concepts and Key Features for Social Housing Landlords

Service concept	**Key features**
SC1 -Getting the gas and heating up and running for the customer	An advisory/intelligent system/liaison type service that guides the tenant through this process
SC2 -Managing access around the annual gas safety check	Opening up communication channels with the tenant and scheduling inspection visits based on engineer locations and availability
SC3 -Diagnosis/resolution of heating problems	A single, manufacturer agnostic, diagnostic dashboard that can be used by the customer service team in conjunction with the engineering team, it sends back fault data from the boiler to enable remote fault finding and diagnosis.

Table 2. Continued

Service concept	Key features
SC4 -Predictive boiler performance and preventative maintenance	A predictive tool that enables the landlord to identify when a boiler is starting to work non-optimally, and flags this up to the landlord for maintenance
SC5 -Optimising the thermal performance of the housing stock	A service that does an audit on each landlord property, and recommends to the landlords a variety of retrofit options with alternative costs and benefits profiles.
SC6 -Using data to 'look after' the customer	A tool that enables a landlord to identify tenant behaviours which are contrary to good wellbeing, centred around heating, but could extend to broader safety and wellbeing.
SC7 -The (healthy, enabling) connected home (link with above)	Service solutions around the 'connected home' using a portal and heat and other sensor data.
SC8 -Managing the transition away from gas boilers (the future limits on installing gas-fired boilers into new properties)	An educational service, aimed at enabling social landlords, customers and heating manufacturers to understand and develop future heating solutions
SC9 -Provision of 'warm hours'	Centralised heat provision, tailored service plans, hot-swappable provision
SC10 -Maximising organisational operational efficiency	A service that maximise operational efficiency for the social landlords based on optimising trade-offs between: customer (internal and external) satisfaction; operational efficiency; compliance; future proofing; environment concerns.

4. STUDY 2: PRELIMINARY STUDY OF SUPPORTING DIGITAL TOOLS

In terms of the method by which new advanced services developments could be investigated, and requirements understood, a Systems thinking perspective was adopted. In this context, systems thinking can be defined as a '*framework for seeing wholes and interrelationships*' (Arnold and Wade, 2015). Systems thinking involves looking entirely at the bigger picture while understanding the relationships between all the separate parts and how they work together. Systems thinking can be applied by understanding the system of interest, its inherent and emergent behaviour while trying to reduce complexity through modelling (Kossiakoff et al. 2011). Systems thinking is important in this context, as the HaaS solution will necessitate a multi-stakeholder collaboration in order to deliver a variety of systems and services and, therefore, it is important to consider the socio-technical capabilities that each organisation will need to deliver, and to whom, as the beneficiary of the service or system. In other words, the 'end-user' or customer of one system, may well be the service provider to the end-user of the HaaS experience, i.e. the occupant. Additionally, this creates an environment where potential solutions can be explored without them being tied specifically to an existing or new product proposal. Therefore, the full scope of advanced services – and the capabilities required to deliver them – can be investigated.

From the end-user insights indicated in Table 1 and Table 2, a preliminary exploration was conducted using the systems thinking approach. The system key elements were first identified from six dimensions including human players, machine (equipment), services (already identified in the user perceptions data), data, service tools and the system structure. The human players include householders, landlords with their tenants, and service providers (in/outside of the manufacturer). The machine includes all individual heating equipment, each with a unique product ID and embedded sensors for receiving instructions or sending product running data/information to the system via IoT for SC3-5. Data includes user-generated data, machine-generated data and service generated data. Examples of user-generated data include occupants' profiles and behaviour data for SC1 and 6, the machine-generated data includes machine-specific faults and performance data to support SC3 and 5, and the service generated data includes third-party service providers' generated data, such as problem diagnostic data and gas inspection data for SC2 and 3. The service tools include service advisory tools for SC1 and 5, communication tools in SC2, predictive tools in SC4 and 6, and educational tools in SC 8.

A digital twinning platform is now being explored as the system backbone, with a front-end as a web app and the back-end as a web service, to integrate all system key elements together and through incrementally digital twinning processing, eventually make it an ecosystem. The system structure is illustrated in Figure 1, outlining the key interactions and enabling tools that will be required.

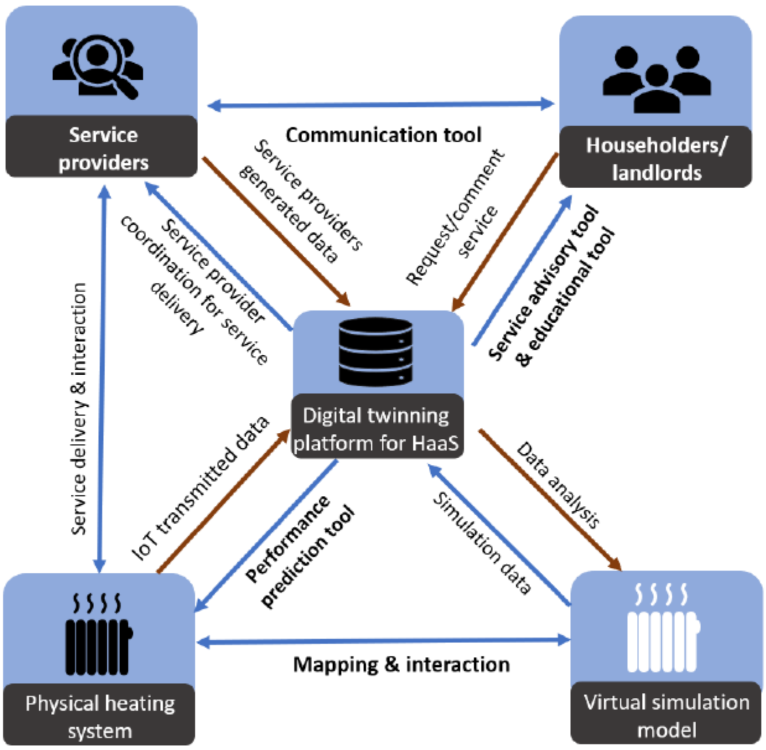

Figure 1: Key interactions and enabling tools on HaaS digital twinning platform.

The key to developing a digital twinning platform is to connect heating devices and key system players to the platform and to implement platform enabling tools, providing householders, and social landlords and their tenants, an easy way to get their requested services delivered in a timely way, thus, bringing them a better user experience. In turn, with more data (the red arrows in Fig. 1) adding to the platform, the simulation model gets more accurate over time, making the platform more reliable in delivering high-quality digital heating services and in providing data to help shape/upgrade heating devices and services in the future.

An early stage demonstrator for the platform, with simulation, is now being considered. A small selection of the key service concepts from those identified in table 2 will be selected and used to design and prototype the supporting tools in the demonstrator. The aim of this work will be to demonstrate and evaluate the principle of digital twinning technology for advanced services.

5. CONCLUSIONS

In this work, we have investigated how digitalization can support the development of new advanced services within the HaaS environment by capturing customer requirements and feedback. Potential opportunities for Haas developments were explored with two customer segments to generate a deeper understanding of the desired user experience. Following on from this, a digital twin platform approach, using simulation, is being used to prototype a demonstrator for evaluation on two accounts. The first is to evaluate how desired user experiences can be used to explore future advanced services opportunities. The second is to evaluate the digital twin platform to explore opportunities in advanced services development beyond the product-centric approach, and the suitability of its application at the concept stage.

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A review of crowdsourcing technology for product design and development

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***Abstract*—With the ever improving availability of social media platforms, the internet and mobile devices, crowdsourcing becomes a popular business development strategy in outsourcing various tasks to outside crowds. In product design and development, one of the crowdsourcing objectives is to engage various users into human-centered design processes and outsource tasks to crowds for better design efficiency, quality and business benefits. There are many studies about crowdsourcing from different viewpoints, but none of them focuses on crowdsourcing technology review, especially in product design and development. In this paper, we report a literature review of crowdsourcing technology including the task assignment techniques, incentive mechanism and communication skills, crowdsourcing framework, and platforms. We also discuss the existing problems: 1) current crowdsourcing platforms only partly support product design activities; 2) crowd workers' privacy may be threatened; 3) some cheat phenomenon may exist on some platforms. Finally, we suggest the future directions on the related crowdsourcing technology.**

Keywords-crowdsourcing technology; task assignment; incentive mechanism; communication techniques; product design and development

I. Introduction

In modern society, a wide range of professional and complex tasks cannot be accomplished by individual or a single computer, instead, they need to be done by collaborations from thousands of workers all around the world with the help of computers. On the other hand, a new product design and development requires a human-centered design approach to engaging users into various design and development activities. Thus, the research of Computer-Supported Cooperative Work (CSCW) has always been a hot topic as a result of technological advance. Among those, crowdsourcing is one of the most promising research directions as it is a new business model where computers and smart devices are utilized to achieve that purpose. Crowdsourcing was first coined by Jeff Howe in Wired Magazine as "the act of taking a job traditionally performed by a designated agent (individual, institution, non-profit organization or enterprise) and outsourcing it to an undefined, generally large group of people in the form of an open call" [1]. In order to achieve that function, a lot of crowdsourcing technology are needed. Here, we define crowdsourcing technology in terms of techniques, frameworks, platforms and tools that are used to accomplish a crowdsourcing task.

Benefited from its fast speed and cost effectiveness, crowdsourcing is regarded as a quite popular paradigm for collecting and processing a large volume of tasks and data from crowd workers. It has been applied to a wide range of disciplines (e.g. political science [2], software engineering [3, 4, 5], and psychology [6]) and utilized to accomplish many projects and tasks, such as citizen science project [7], translation [8, 9], the evaluation of online labor markets [2, 10] and the research of human behaviors [6]. In the near future, it will still exist and affect various aspects of our daily life deeply.

Actually, there are a growing number of research on crowdsourcing and extensive studies about crowdsourcing platforms, models and techniques [11, 12, 13] from different perspectives, such as human resource management [14], components and functions [15], barriers and opportunities of new product development in manufacturing SMEs [16]. However, what is the state-of-art of the crowdsourcing technology? It is not very clear given the rapid development in this field over the last ten years. There is no recent work focused on the reviewing of the crowdsourcing technology, especially in product design and development (PDD) field.

Our contributions mainly are two-fold:

a. Summarize crowdsourcing technology in different stages of crowdsourcing, especially task assignment, incentive mechanism and communication among crowd workers.

b. Indicate the existing problems and predict the future directions.

The remaining of this paper is organized as follows: Section 2 outlines our literature review methods. The review results are described in Section 3, including research findings in terms of techniques used in task assignment, incentive mechanism and communication skills, crowdsourcing framework, platforms and tools. Final section summarizes the review work and discuss the future directions.

II. Literature Review Methods

The resources of literatures are from conference proceedings, journal articles, posters, design magazines and crowdsourcing websites. The online database of ScienceDirect, ACM Digital Library, IEEE Xplore Digital Library are used as database sources. In this paper, Boolean operator 'OR' and 'AND' are adopted to manage

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searching rules. R and S represent the two descriptor groups respectively with the rule of 'OR'. Q is the sum of R and S with rule 'AND'.

R=keywords ∈ (crowdsourcing OR crowdwork OR crowd work OR the crowd)

S=keywords ∈ (task assignment OR incentive OR motivation OR communication OR collaboration)

$Q = keywords \in (R \text{ AND } S)$

After retrieval, more than 100 papers were found. Then we read their abstracts and chose the ones that we believed to be more related to our research content. At last, a number of 54 literatures are considered as the most valuable sources.

In these academic publications, whatever situations crowdsourcing focuses on, the context is related to crowdsourcing process, computation and crowd workers. Specifically, crowdsourcing process aims to solve problems such as collaborative workflow, task assignment, real-time crowd work, Asynchronous and synchronous collaboration and the quality control of crowd work. In crowdsourcing computation, the interaction mechanism between crowd workers and computers is investigated and it will be utilized to guide the design of crowdsourcing platform. Crowd workers' motivation and the principles of reward after accomplishing a task are explored in crowd workers.

Some reviewed papers may involve two or three of the contexts. Following up this initial paper analysis, crowdsourcing technology are associated with three contexts: process/techniques with 42.6% surveyed papers, computation with 35.2% and crowd workers with 37.0% surveyed papers respectively. The distribution is quite even. The research findings are detailed and discussed in the following sections.

Table 1 The distribution of papers by context

context	papers	percentage
Process/ techniques	[2,3,5,8,17,18,19,20,21,22,27,31,32,38,39,40,41,43,45,46,47,48,49]	42.6%
computation	[2,22,28,34,35,36,37,39,40,41,42,43,45,46,48,49,52,53,54]	35.2%
Crowd workers	[2,6,10,22,23,24,25,26,28,29,33,34,35,39,44,45,50,51, 52, 53]	37.0%

III. Research Findings

A. Crowdsourcing techniques

the crowdsourcing process can be divided into task decomposition, task assignment, the organization of crowd workers, workflow, quality assurance, etc. In each part, specific techniques are adopted. Here, we mainly focus on the techniques used in task assignment, motivation mechanism and the communication among crowd workers. Figure 1 shows the related techniques in a crowdsourcing process.

a. Task assignment.

No matter online (web-based) or mobile crowdsourcing, both requesters (company or individual) and crowd workers need to register with a centralized server that acts as a broker among them and often plays an important part in assigning tasks to crowd workers. The aim of task assignment is to get as many tasks as possible finished within a fixed time and budget and to make the requester get maximum benefits from the completed work done by crowd workers. In a formalized task assignment problem, the requester owns a fixed set of tasks of different types and a budget that specifies how many crowd workers s/he need and how soon s/he would like the task to be accomplished. Before assigning the task, many matches about reputations and interests will be done to guarantee that all employed crowd workers have the potential to accomplish the tasks with high quality. Information about crowd workers and their actions are contained in the reputation mechanisms, which are available to the task requester [49]. Generally, ranking, rating, collaborative filtering, explicit peer-based and implicit peer-based are five common reputation mechanisms as described by Jensen et al. [50]. Differently, Mark et al. [51] evaluated each crowd worker's quality by double-blind peer assessment, they demonstrated their findings that the reputation signals were more correlated to their real quality by a two-week field experiment.

Figure 1 Related technology in crowdsourcing process.

There are two different assignment types: worker selected and server assigned. In worker selected task mode, the server publishes the tasks and it is totally the crowd workers' call to choose any tasks they are interested in. One drawback of this mode is that the server does not have control over the allocation of tasks. This may lead to some tasks not be assigned while others do. Differently, in server assigned task mode, the task is totally assigned by the server according to certain rules. This mode has a global picture of the tasks. Here are three typical techniques that are used to assign tasks in the server assigned task mode: Greedy algorithm [27], online primal-dual framework [17] and least popular priority [19].

Among these three techniques, both Greedy algorithm and least popular priority could get a local optimal answer at each time snapshot. In order to improve the result of the whole time span, some improved approaches are proposed based on them, for example, nearest neighbor priority algorithm [27], heuristic-enhanced greedy algorithm [28] and an adaptive strategy [20] to dynamically allocate tasks. Online primal-dual technique is generally used to analyze optimization problems. Ho and Vaughan [17] are the first to apply this framework to crowdsourcing. Their proposed algorithm proved that it is competitive with respect to the optimal offline algorithm which has access to the unknown skill levels of each worker. However, it is a little unrealistic because it is impossible for a requester to evaluate the quality and accuracy immediately, especially when there are a large number of crowd workers involved. Further, Ho and Vaughan [18] derived a near-optimal adaptive assignment algorithm which was proved to lead to more accurate predictions at a lower cost. Different from [17], each task could be assigned to a worker more than once in their model. Besides, their results can be used to handle such cases where different prices are charged by different crowd workers and tasks with various structure.

Besides aforementioned task assignment techniques, other factors, such as the workers' reputation and work experience, also should be taken into account in practical crowdsourcing process.

b. Incentive mechanism

Incentive mechanism plays an important role in motivating crowd workers to involve in performing crowd tasks. A lot of research [21, 22, 23, 24, 52, 53] have been focused on the relationship between incentives and workers' participation. Crowd workers do not have to participate, since crowdsourcing systems or platforms are typically open to everyone and do not rely on contracts. Thus, certain measures must be adopted to compel crowd workers to participate, otherwise, crowd tasks cannot be performed. There are many ways to attract crowd workers, and they could be classified into two distinct categories: extrinsic (e.g. reward, building of their personal reputation, etc.) and intrinsic (e.g. enjoyment, being part of the common good, etc.) [54]. Among them, the most common three motivations are reward, enjoyment and reputation.

(1) Reward

Reward is the dominant motivation in crowdsourcing process. This includes cash bonus, discount coupons, free use of product, virtual money, etc. Generally, most crowd workers are money-driven and higher pay usually could get more crowd workers to perform more tasks more quickly [25]. In some boring and tedious tasks, such as transcribing countless hand-written documents, monetary compensation must be guaranteed, or few crowd workers are likely to participate in the task. However, money is not necessary to enable the high quality of completed tasks, which was found by Mason et al. [25] and Rogstadius et al. [26].

In the work of Archak and Sundararajan [34], they presented how to design crowdsourcing contests to obtain significant outcomes and provided an optimal prize structure. Their research could be used for guiding the design of crowdsourcing contests [35,36] to gather creativity.

(2) Enjoyment

In worker selected mode, crowd workers usually choose the tasks that interest them. When crowd workers are really interested in them or love doing them, they would like to devote themselves into it, even if there is nothing for a reward. They are self-incentivised because of the feel of achievement brought by finishing challenging tasks and the opportunities when they can exercise their skills and talents that they have no chance to use in their ordinary lives [29].

(3) Reputation

A large proportion of crowd workers are driven to compete for the recognition by their peers or their personal values. Each time when they finish their assigned task, they will be evaluated by the server according to the quality of their completed work. If one has good reputation, it will be easier for him to be chosen to perform some crowd tasks later.

In mobile crowdsourcing, both the distance between the task's location and where crowd workers live and the socioeconomic status of the task area affect crowd workers' willingness to perform the task, which was found by Jacob et al. [23].

During a crowdsourcing process, it is found by Xiao Chen et al. [48] that participation rate plays a vital role in the final outcomes. They argued that when participation rate was less than individual contributions, the outcomes could be compensated by good data gathering approaches. If machine learning and data mining algorithms could be applied to assemble large-scale data, it may yield satisfactory results.

c. Communication techniques

Just as in the real world, communication also plays an important role in crowdsourcing process, especially when crowdsourcing complex tasks. In the process, all participated crowd workers must be well-organized (like in a hierarchy structure) so that they could collaborate effectively.

Complex and professional tasks are often large and involve multiple stages, which need to be completed by specialized and remote teams or individuals. The process of crowdsourcing complex tasks is complicated because of communication difficulties among crowd workers. It is a challenge to coordinate a large number of crowd workers to work together effectively while minimizing the information losses during crowdsourcing process. Effective communication approaches could enable crowd workers to spend less time understanding their tasks and improve the work efficiency. In sequential tasks, good communication skills can help crowd workers understand the input of their tasks and reduce the integration cost, thus improving the quality of final product.

Generally, discussion forums, Facebook and similar tools are commonly used by crowd workers as their communication medium, which is not real-time and may lead to some delays. Also, such kind of communication is not suitable in a large scale [39].

In order to improve communication and work output in expert crowdsourcing, Alex Embirico et al. [40] investigated a structured handoff method in the web design and implementation process. Participants were asked in live (live conference and screen share are used) and recorded scenarios (short screen capture video with voiceover) respectively, but in a control group, no instructions were given to perform the handoff. Their contrast experiments indicated that higher work quality could be resulted in and the adherence to the original intent could be increased by the structured handoff approach.

Recently, Gray et al. [41] argued that social interaction is a basic need for human beings and this social need must be fully addressed by crowdsourcing platforms. Their research findings indicated the inevitability of collaboration among crowd workers [42, 43] and the significance of combining collaboration with crowdsourcing workflows. A valuable case study offered by Michael et al. [44] identifies the potential issues (like social loafing) about friendsourcing and collaborations among crowd workers. They contended that the quality improvement of output outweighs the challenges it may bring.

B. *Crowdsourcing frameworks*

There are quite a lot of contents that are worth studying in crowdsourcing. Most papers focus on a specific aspect and investigate it deeply. Here an overall framework of crowdsourcing process (Figure 2) is presented [45].

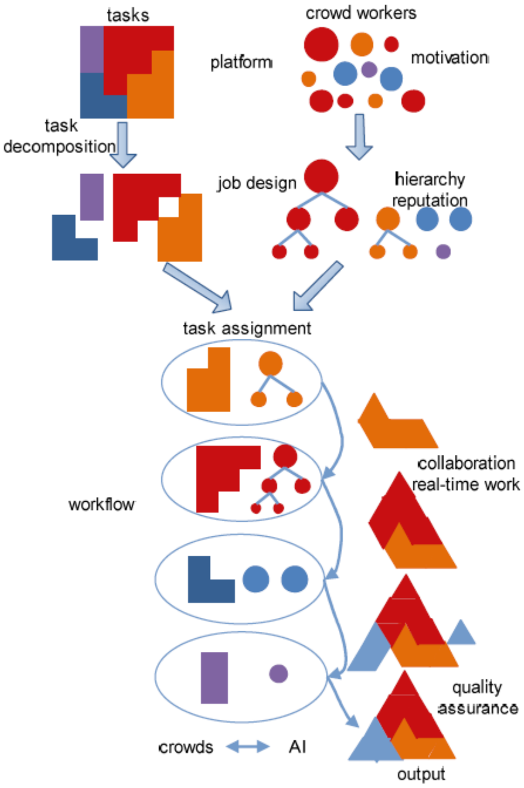

Figure 2 The overall framework of crowdsourcing process

The framework in Figure 2 shows the whole process of crowdsourcing from initial complex tasks to final output. During this period, a platform is needed for managing various tasks and a large pool of crowd workers. Except the aspects we focused on above, it is clear that there are other questions that are worth investigating, for example, how to decompose complex tasks into micro-tasks and what principles should follow, how to organize crowd workers and how to evaluate the final outcomes.

In this work, we are concerned with product design and development using crowdsourcing technology, but we did not find any platforms that fully support it. Current platforms only provide different levels of support to product design activities [16]. So specific platforms need to be developed to support product design activities, which is also one aspect of our future work. In PDD, crowdsourcing has been recognized as an effective way to improve the design concepts by utilizing the wisdom of as many crowd workers as possible. A lot of research about the application of crowdsourcing, for example, the generation of innovative concepts [46], new product development and marketing, and design contests, have been conducted. Though the potential of crowdsourcing for promoting concept generation has been further recognized, few efforts have been put into the exploration of crowdsourcing methods to support the evaluation and selection of design concepts, and it is a question that is worth being further explored.

C. *Crowdsourcing platforms & tools*

Crowdsourcing platforms can be classified into two categories: web-based and mobile-based.

a. *Web-based crowdsourcing platforms*

Web-based crowdsourcing platforms could be divided into volunteer-based and paid ones. Volunteer-based crowdsourcing platforms like Wikipedia and Open source software have gained significant success due to the continuous contribution from the volunteers at an inter/national scale. The most well-known paid crowdsourcing platform is Amazon Mechanical Turk, by which, both amateurs and professionals can gain a certain reward according to the micro-tasks they have done. The website-boardofinnovation.com classifies intermediary crowdsourcing platforms into six categories according to various purposes and gives some examples and their brief introductions to each categories (details please see [30]).

Most of the platforms are developed for business purpose, such as providing creative solutions and creating a brand. And they are nearly all based on a mode where many designers participate in a specific task and their designs are chosen by the requester. The existing platforms could partly support the PDD process, for example, concept generation and information collection at the early design stages.

Although online crowdsourcing platforms allow task requesters to finish a short and simple task through recruiting a large number of workers from online communities, they cannot accomplish tasks that are situated in specific sites such as the usage of shared space and taking pictures or collecting air quality information in a specific location. In order to solve these kind of problems, crow workers are required to use smart devices to enable them to give feedback instantly.

b. Mobile-based crowdsourcing platforms

Mobile-based crowdsourcing platforms exist mainly to overcome the drawbacks of web-based crowdsourcing platforms. Similar to online crowdsourcing platforms, mobile crowdsourcing platforms have gained extensive attention of both industry and academia as a recent crowdsourcing development. These platforms push tasks in the physical world to crowd workers by mobile phones anywhere and anytime [23, 33], also, they can collect extensive large-scale data from crowd workers effectively [31, 32].

IV. Discussion and Conclusion

In this paper, a comprehensive technology review of academic publications is conducted in the field of crowdsourcing. Specifically, this paper presented the key techniques used in task assignment, incentive mechanism and communication.

In task assignment, we have known that the crowd workers need to share their locations with the server so that the server could allocate tasks near them. The downside is that their privacy may be threatened [21]. Since the information of tasks or projects that are finished by crowdsourcing platforms is shared by all crowd workers, this approach is not suitable for those tasks that contain privacy.

Horton et al. [37] gave the portions of nearly all jobs that can be accomplished by crowd workers. From which, it is clear that crowdsourcing market continues to expand and provides abundant work opportunities. Because of the advantages of crowdsourcing platforms, some companies may turn to online marketplaces rather than employ workers as usual. However, the accompanied problems cannot be ignored. Since all crowd workers work in a virtual environment, where they cannot meet or communicate with each other or the employer, thus they may be considered to be replaceable and untrustworthy, their rights may also not be guaranteed [38]. Besides, it is hard to guarantee the motivation and qualifications of crowd workers, and there is a risk that some workers may not meet the task requirements. For instance, they are likely to accomplish the task and ignore the quality of their response when they are under time pressure [46].

After above discussion, it is possible to identify and predict future directions in relation to crowdsourcing. These are as follows:

(1) Based on current crowdsourcing platforms, develop a new one for product design activities, which should integrate with the social computing platforms and techniques.

(2) Investigate the mechanism of how to recruit reliable crowd workers under the condition of guaranteeing the benefit of both requesters and crowd workers.

(3) Social networks should be incorporated into crowdsourcing platforms, new interaction models should be explored, which is also suggested by Kurt Luther et al. [22].

(4) Task assignment approach of complex tasks with privacy also should be explored.

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