A systematic literature review of product platform design under uncertainty

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With intense global competition, many enterprises adopt platform strategies to develop diverse products with a lower corresponding increase in cost and a shorter lead time. In the past, enormous efforts have been made in investigating product platforms. Recent researches and practices show that developing Uncertainty-Oriented Product Platform (UOPP) is a promising approach to improving the adaptability of enterprises to meet uncertain markets, customer requirements, technologies, policies, and regulations, etc., which includes flexible product platform, adaptable product platform, market-driven product platform, and sustainable product platform. This paper provides a comprehensive review in this field, including the connotation of uncertainty, the concepts of emerging UOPPs, the development process of UOPP, as well as the development technologies in each step. It also highlights the future research framework, opportunities and challenges. This literature review lays the foundation for future research of product platform design under uncertainty.

Keywords: Product platform; Product family; Uncertainty; Adaptability; Dynamic

1. Introduction

With the rise of mass customization, enterprises and academia have proposed product platform and product family strategy (Simpson 2004). In general, a product family is broadly defined as a group of similar products that are derived from a product platform (Simpson, Maier, and Mistree 2011), while a product platform is 'a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced' (Meyer and Lehnerd 1997). Product platform and product family strategy can meet the diverse customized requirements as much as possible without sacrificing the scale economies of the enterprises (Park and Simpson 2008). At present, many enterprises have adopted product platform and product family strategy (Otto et al. 2016), such as ABB, IBM, Ford, and Airbus, etc.

There are no uniform development steps for product family, but most studies consider the steps proposed by Jiao, Simpson, and Siddique (2007) as feasible ones, including four phases: (i) translating customer requirements into functional requirements, namely product portfolio design; (ii) mapping functional requirements into proper design variables, namely product platform design; (iii) planning and determining process variables, namely process platform design; (iv) finding logistics variables, namely supply platform design. Customer requirements are the source of product family development, affecting the design of product platform, process platform, and supply chain platform. Product platform is the core of product family development, providing common modules and standardized interfaces to satisfy the predefined requirements. However, in today's market environments, customer requirements are dynamic and change over time. The traditional product platform lacks the ability to respond to these changes because its commonality is mostly limited to common modules defined by fixed physical standards. Therefore, some scholars propose the concept of product platform needs to be extended to accommodate changing customer requirements, such as flexible product platform (Suh, de Weck, and Chang 2007; Suh et al. 2007; Li et al. 2013), and adaptable product platform (Schuh, Lenders, and Arnoscht 2009; Madni 2012). Besides, Kumar, Chen, and Simpson (2009), Moon and McAdams (2012), and Ma and Kim (2016) propose market-driven product platform to deal with uncertain product demand and price. Kim and Moon (2017a, 2017b) propose sustainable product platform not only to deal with uncertain customer requirements, but also environmental sustainability requirements. Considering these emerging product platforms mainly deal with uncertain factors including customer requirements, markets, policies, and regulations, etc., this paper refers to them as Uncertainty-Oriented Product Platform (UOPP). Compared to Modular Product Platform (MPP) and Scalable Product Platform (SPP), UOPP has the adaptability to accommodate uncertain factors at a lower additional investment. However, due to the lack of systematic analysis of uncertainty, these innovative UOPP concepts are confusing and inconsistent, and their investigations are separated from each other. Therefore, this paper provides a comprehensive review of these innovative platforms to define the basic natures of UOPP and presents the development framework of UOPP.

As the concept of product platform has been put forward for more than two decades, the authors first examine the literature reviews on product platform and product family and summarize the contributions of each article in Table 1. The early reviews investigate the clarification of the research foundation of product platform, which have summarized the concept, development process, and development methods of MPP or SPP. These reviews lay a good foundation for the academia to unify the concept of product platform and define key technologies for product platform development, and also provide an effective solution for the industries to achieve the transformation from mass production to mass customization, such as Simpson (2004), Jose and Tollenaere (2005), Jiao, Simpson, and Siddique (2007), Pirmoradi and Wang (2012), and Otto et al. (2016). In recent years, as the manufacturers change their product-centered strategy to customer-centered strategy, the academia have begun to study the evolutions and emerging trends of product platform under uncertainty, such as Zhang (2015) and Facin et al. (2016). However, the connotation of uncertainty for product platform still does not have a unified theoretical explanation, resulting in the following problems: (i) how to identify uncertainty, (ii) how to design product platform under uncertainty, and (iii) how to evaluate the platform's value under uncertainty. At present, there is no comprehensive review of these issues.

Table 1. Summary of literature reviews on product platform and product family.

Time	Authors	Titles	Contributions
2004	Simpson	Product platform design and customization: status and promise	The concept and development method of the modular and scalable product platform before 2004
2005	Jose and Tollenaere	Modular and platform methods for product family design: literature analysis	A comprehensive review of modular product platform development before 2005
2007	Jiao, Simpson, and Siddique	Product family design and platform-based product development: a state-of-the-art review	The concept and development method of the modular and scalable product platform before 2007
2012	Pirmoradi and Wang	Recent advancements in product family design and platform-based product development: A literature review	New achievements in product family research during 2006-2011
2015	Zhang	A literature review on multi-type platforming and framework for future research	The trends in platforming research during 2007-2015
2016	Facin et al.	The Evolution of the Platform Concept: A Systematic Review	The evolution and emerging trends in the literature during 1993-2015
2016	Otto et al.	Global views on modular design research: linking alternative methods to support modular product family concept development	Generic development process and method of modular product platform

Therefore, this research is dedicated to a systematic review of product platforms under uncertainty. The specific objectives are: (i) to illustrate/define the basic natures of uncertainty and UOPP, (ii) to propose the development framework of UOPP, and (iii) to identify the future research framework, opportunities, and challenges of platform development. The results of this work will provide references for future research in the area of UOPP. The remaining sections of this paper are organized as follows. Section 2 gathers, classifies and analyzes the literature samples on UOPP. Section 3 discusses the connotation of uncertainty and UOPP. Section 4 presents a generic development process of UOPP and reviews the related technologies in each step. Section 5 shows the prospects for future research framework, opportunities, and challenges. In the final section, the conclusions are drawn.

2. Literature analysis

2.1 *Sampling methods*

The literature samples of this review were searched via the ISI Web of Science (WOS) database of Thomson Reuters. To ensure an efficient, yet comprehensive, literature collection, the first step of this study is to develop the criteria for searching papers (Zhang 2015). There are six criteria for the collection and filter of literature in this paper: database, theme, research areas, document types, publication years and language. (i) For database, Science Citation Index Expanded was chosen. (ii) For theme, search criteria were considered for the following topics: ("Product platform" or "Product family") or ("Uncertainty" and ("Product Platform" or "Product Family")) or ("Uncertainty" and ("Requirement" or "Market" or "Technology" or "Policy" or "Regulation") and "Product" and "Design"). (iii) For research areas, to identify all relevant articles, journals from diverse disciplines, such as engineering, operations research, management science, computer science, and business economics, were considered. (iv) For document types, to achieve the highest level of quality, this collection only considered articles and reviews, and excluded conference papers, book chapters, working papers, master theses, and Ph.D. dissertations. (v) For publication years, the product platform extending to accommodate uncertain customer requirements was first proposed by Suh, de Weck, and Chang (2007), so the literature of the last 13 years (2007-2019) was chosen. (vi) For language, English was chosen because it is the primary communication language in academia.

The literature was searched via WOS by the above six criteria, and 1255 papers were obtained. Although keywords can improve the efficiency of literature retrieval, the redundancy of literature is inevitable. This is because the meaning of words is more ambiguous than sentences and paragraphs. Therefore, abstracts of papers were examined to check whether one or more topics were covered, including the concept of uncertainty, the concept of product platform under uncertainty, and the product platform development methodologies under uncertainty. 81 papers were identified through the examination of the papers' abstracts. Once papers were identified their reference lists were reviewed to assist in locating additional articles, resulting in a 'snowball sampling effect'. So, some classic conference papers, earlier than 2007, are also included in this sample for review. In total, 102 papers were identified for further study. Table 2 summarizes the number of literature and research scope per journal.

2.2 *Literature classification*

Based on reviewing of the 102 papers in Table 2, to better analyze the concept, development processes and technologies of the emerging product platforms under uncertainty, the collected literature is further classified into three general streams: (i) the uncertainty concepts, (ii) the UOPP concepts, and (iii) the development methodologies related UOPP, as shown in Table 3.

Table 2. Number of literature and research scope per journal.

Journals	Numbers	Research Scope
Research in Engineering Design	**12**	The innovative platform concept, product platform architecture design, and product platform evaluation
Journal of Engineering Design	**7**	The innovative platform concept and product platform architecture design
Journal of Mechanical Design	**7**	The innovative platform concept, requirement analysis, product platform architecture design, and product platform evaluation
Technological Forecasting and Social Change	**6**	The technology forecasting and the identification of emerging technologies
International Journal of Production Research	**4**	The innovative platform concept, product platform architecture design, and product platform evaluation
Journal of Intelligent Manufacturing	**4**	The innovative platform concept and product platform architecture design
IEEE Transactions on Engineering Management	**4**	The uncertainty concept and requirement analysis
The International Journal of Advanced Manufacturing Technology	**3**	The requirement analysis and product platform architecture design
Computers in Industry	**2**	The requirement analysis and product platform architecture design
45 others	**53**	The related methodologies of product platform development
Total	**102**	

Table 3. Summary of literature on product platform under uncertainty.

Items		References	No.
1.The uncertainty concepts	Definition& classification	Hastings and McManus (2004); Haimes (2005); de Weck, Eckert, and Clarkson (2007); Clarkson and Eckert (2010); Dantan et al. (2013); Kumar and Tandon (2017)	**6**
2.The UOPP concepts	2.1 Flexible product platform	Suh, de Weck, and Chang (2007); Suh et al. (2007); Li et al. (2013); Wei et al. (2017)	**4**
	2.2 Adaptable product platform	Gu, Xue, and Nee (2009); Schuh, Lenders, and Arnoscht (2009); Briere-Cote, Rivest, and Desrochers (2010); Madni (2012); Levandowski, Jiao, and Johannesson (2015); Li et al. (2016); Cheng et al. (2017); Zheng et al. (2017)	**8**
	2.3 Market-driven product platform	Kumar, Chen, and Simpson (2009); Moon and McAdams (2012); Ma and Kim (2016)	**3**
	2.4 Sustainable product platform	Kim and Moon (2017a, 2017b); Wang et al. (2018, 2019)	**4**
3. The development methodologies related UOPP	3.1 Identification of uncertainty	Saaty (1988); Kota, Sethuraman and Miller (2000); Martin and Ishii (2002); Messac, Martinez, and Simpson (2002); Eckert, Clarkson, and Zanker (2004); Suh, de Weck, and Chang (2007); Thevenot and Simpson (2007); Zhang (2007); Cheng and Chen (2008); Chen and Wang (2008); Khadke and Gershenson (2009); Chong and Chen (2010); Liu, Wong, and Lee (2008, 2010); Moon, Simpson, Kumara (2010); Hsu et al.(2011); Chiu and Ying (2012); Jiao (2012); Wu and Wang (2012); Withanage et al. (2012); Huang and Wang (2013); Jun and Park (2013); Kent and Saffer (2014); Randt (2015); Yousuf and Asger (2015); Afshari and Peng (2015); Hu and Cardin (2015); Nilashi et al. (2015); Tuarob and Tucker (2015); Cheng et al. (2016); Hansen et al. (2016); Ma and Kim (2016); Jiang, Kwong, and Yung (2017); Joung and Kim (2017); Kim and Moon (2017a); Kim and Bae (2017); Purohit and Sharma (2017); Song, Kim, and Lee (2017); Song (2017); Lee et al. (2018); Mesa, Esparragoza, and Maury (2018); Wang et al. (2019)	**42**
	3.2 Platform design under uncertainty	Ericsson and Erixon (1999); Martin and Ishii (2002); Suh, de Weck, and Chang (2007); Jiao et al. (2008); Liu,Wong, and Lee (2008, 2010); Helmer, Yassine, and Meier (2010); Moon, Simpson, and Kumara (2010); Simpson et al. (2012); Zhang (2012); Li et al. (2013); Perlman (2013); Levandowski, Michaelis, and Johannesson (2014); Wagner et al. (2014); Hu and Cardin (2015); Hu, Peng, and Gu (2015); Bonvoisin et al. (2016); Jung and Simpson(2016); Otto et al. (2016); Kim and Moon (2017a); Hou et al. (2017); Schuh, Riesener, and Breunig (2017); Zhang et al. (2017); Chen, Peng, and Gu (2018)	**24**
	3.3 Platform evaluation under uncertainty	Gonzalez-Zugasti, Otto, and Baker (2001); Otto and Holtta-Otto (2007); Suh, de Weck, and Chang (2007); Alizon, Shooter, and Simpson (2009); Deng et al. (2013); Cardin, de Neufville, and Geltner (2015); Hu and Cardin (2015); Kim et al. (2016)	**8**

(i) **The uncertainty concepts**. Uncertainty is a non-negligible factor in product platform development, such as uncertain markets, customer requirements, technologies, policies, and regulations, etc., affecting the success of product platform development. Only through understanding of uncertainty correctly, can product platform have reasonable adaptability or flexibility. However, at present, the connotation of uncertainty for product platform still does not have a unified theoretical explanation. Therefore, we identify the literature related to the definition and classification of uncertainty, to explore the connotation of uncertainty for product platform.

(ii) **The UOPP concepts.** In recent years, to improve the adaptability or flexibility of product platform, some scholars have proposed some innovative platform concepts, such as flexible product platform, adaptable product platform, market-driven product platform, and sustainable product platform. However, at present, there is no mutual definition for UOPP. Therefore, we identify the literature related to these emerging UOPPs, and try to explore the connotation of UOPP.

(iii) **The development methodologies related UOPP.** Uncertainty will result in the changes of the research methodologies of product platforms. Although a complete and operable product platform construction path has not been formed yet, some valuable research results have appeared in some technical fields, including the identification of uncertainty, platform design under uncertainty, and platform evaluation under uncertainty. Therefore, we identify the literature related to UOPP methodologies, to explore a unified development process and summarize the related technologies in each step.

Effective classification of the literature helps us better read and understand these papers. The next section will analyze the connotation of uncertainty and UOPP, and Section 4 will investigate the development process and technologies of UOPP by analyzing these papers listed in Table 3.

3 The connotation of uncertainty and UOPP

3.1 *The connotation of uncertainty for product platform*

Uncertainty is a term used in a number of fields, including philosophy, statistics, economics, finance, insurance, psychology, engineering and science (de Weck, Eckert, and Clarkson 2007). This article mainly focuses on the uncertainty in the engineering design field. Effectiveness of a product development strongly depends on how it handles uncertainty (Kumar and Tandon 2017). However, at present, there is no unified definition for uncertainty in the design field. Haimes (2005) refers to the term 'uncertainty' to the inability to determine the true state of affairs of a system. While de Weck, Eckert, and Clarkson (2007), define the term 'uncertainty' as an amorphous concept that is used to express both the probability that certain assumptions made during design are incorrect as well as the presence of entirely unknown facts that might have a bearing on the future state of a product or system and its success in the marketplace.

To further understand the connotation of uncertainty in the design field, some scholars have studied the classification of uncertainty, which has different connotations from various perspectives: (i) uncertainty can be divided into 'exogenous uncertainty' and 'endogenous uncertainty' depending on whether the source of uncertainty is outside or within the system boundary, such as de Weck, Eckert, and Clarkson (2007); (ii) uncertainty can be divided into 'aleatory uncertainty' and 'epistemic uncertainty' depending on whether the uncertainty is objective irreducible or subjective reducible, such as Dantan et al. (2013), Kumar and Tandon (2017); (iii) uncertainty can be divided into 'data uncertainty' that the data itself is incomplete and inaccurate, and 'description uncertainty' that the description of information is unclear and has not a specific boundary, such as Hastings and McManus (2004) and Clarkson and Eckert (2010). In fact, the above uncertain classifications also have mutual relations, as shown in Figure 1.

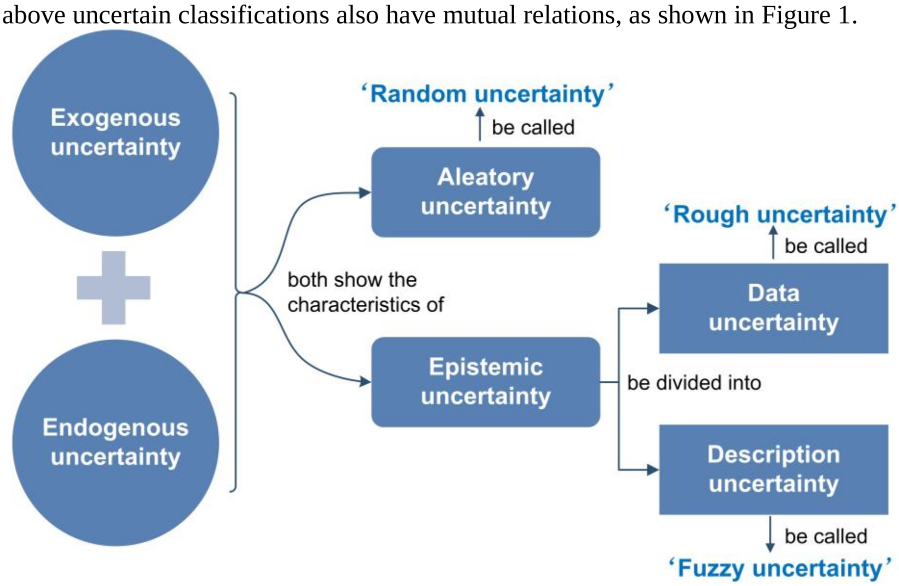

Figure 1. Classification of uncertainty in the design field.

Firstly, the uncertainty in product design includes exogenous uncertainty and endogenous uncertainty. Next, 'exogenous uncertainty' and 'endogenous uncertainty' both have aleatory and epistemic characteristics. 'Aleatory uncertainty' can be called 'random uncertainty', which describes the intrinsic variability associated with a physical system (Dantan et al. 2013). 'Epistemic uncertainty' refers to the lack of knowledge, meaning that the uncertainty can be reduced through increased availability of relevant data (Dantan et al. 2013). It can be further divided into data uncertainty and description uncertainty. ‘Data uncertainty’ can be called ‘rough uncertainty’, which refers to some essential information about the events cannot be known because of insufficient data. ‘Description uncertainty’ can be called ‘fuzzy uncertainty’, which means that some events cannot be known because of vague information. In sum, the uncertainty in product design includes exogenous and endogenous uncertainty, and each uncertainty shows three characteristics of randomness, roughness, and fuzziness. The randomness focuses on the uncertainty about whether the event occurs, which can be modeled based on probability theory by counting the probability of the event occurrence. Roughness focuses on the uncertainty about whether the information of the data itself is complete, which can be modeled based on rough set theory by using partially known and accurate information. While the fuzziness focuses on the uncertainty about whether the description of the data itself is clear and has a specific boundary, which can be modeled based on the theory of fuzzy by introducing human subjective experience.

For product platform design, the uncertainty also includes exogenous and endogenous uncertainty, as shown in Figure 2, and each uncertainty shows three characteristics of randomness, roughness, and fuzziness. For example, customer requirement for guiding product platform architecture design has random uncertainty, i.e. the requirement is dynamic and its future state cannot be determined. Besides, customer requirement also has rough uncertainty, i.e. the collected requirement data is usually incomplete. In addition, customer requirement has fuzzy uncertainty, i.e. the functions or performance needs for a product proposed by customers are usually ambiguous. At present, the emerging product platforms mainly focus on the ‘randomness’, which aims to identify and predict the state of the exogenous and endogenous factors affecting product platform development and update, thereby improving the flexibility or adaptability of enterprises to continuously accommodate uncertain factors. Compared to rough and fuzzy uncertainty, random uncertainty is objective irreducible and has a greater impact on the development and update of product platform. Therefore, the uncertainty in this paper also focuses on randomness.

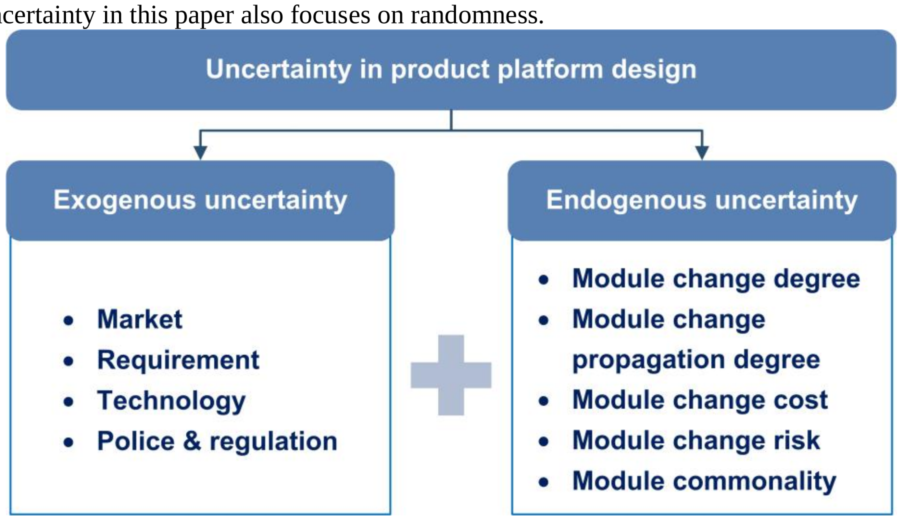

Figure 2. Types of uncertainty in product platform design.

Based on the uncertainty concept discussed above, the uncertainty of product platform in this paper refers to *situations in which the future state of some exogenous and endogenous factors affecting product platform development and update cannot be definitely determined.* Next, we will discuss the emerging product platforms under uncertainty, and define the connotation of UOPP.

3.2 *The connotation of UOPP*

After clarifying the connotation of uncertainty, the next issue that restricts UOPP research is to define the connotation of UOPP. After reviewing four innovative product platforms including flexible product platform, adaptable product platform, market-driven product platform, and sustainable product platform, we give a unified definition of UOPP and compare the characteristics of MPP, SPP, and UOPP.

3.2.1 *Flexible product platform*

Flexible product platform is first proposed by Suh, de Weck, and Chang (2007) and Suh et al. (2007). It is composed of common elements and flexible elements, which aims to respond to changing customer requirements quickly and efficiently. The flexibility of a product platform is its capability achieved by modifying parameters of flexible elements which are defined as ‘elements that can accommodate each product variant’s different requirements through modification at lower additional investment levels, relative to other unique elements that can achieve the same purpose’. Li et al. (2013) proposes another concept of flexible product platform, which is composed of individualized modules in addition to common and flexible modules. The flexibility of product platform is an ability that can satisfy dynamic adaptive performances by the parametric variant design in flexible modules, and satisfy dynamic individualized functions by adding or removing individualized modules. The connotation of common and flexible modules proposed by Li is the same as Suh's. However, whether an individualized module is considered as a kind of platform element is questionable, because the premise that it can effectively combine with other platform modules is that the combination form (interface) must be predetermined, which is not suitable for most complex customized products. In addition, Wei et al. (2017) proposes a flexible product platform based on a scale product platform, to improve the ability of product platform to respond to requirement changes by adjusting flexible platform parameters.

As discussed above, flexible product platform is to improve the flexibility of product platform to respond to uncertain customer requirements through two technical paths: (i) the adaptive variant design of flexible modules; (ii) the replacement, addition, and remove of pre-defined module instances. For example, Suh, de Weck, and Chang (2007) propose a flexible platform of car body-in-white. In addition to the common modules (e.g. body outer panel-lower), the flexible modules (e.g. body inner panel-low rear) are identified and designed. These flexible modules can modify their structural sizes to response to uncertain customer requirements (e.g. space size) at a lower additional investment. The detailed process can refer to Suh, de Weck, and Chang (2007).

3.2.2 *Adaptable product platform*

To meet dynamic changing customer requirements rather than predefined requirements, Schuh, Lenders, and Arnoscht (2009) propose an adaptable product platform, which can be understood as degrees of freedom (DOF) for product and process design defining the necessary design spaces for innovation and individualization of technical solutions. The adaptability of the proposed product platform is an ability that can satisfy uncertain customer requirements by rapidly generating design and process solutions through the reuse of working principles, solution principles, product geometry, and processes resources. Similarly, Madni (2012) believes traditional platform cannot accommodate changing requirements, and thus an adaptable product platform is proposed, which is an enabler of resilient systems to achieve resilience. The adaptability of the proposed product platform is an ability to rapidly generate a design solution to accommodate both anticipated and unanticipated changes through the reuse of design resources, technologies, and computational methods.

To solve the problem that the current Configure to Order (CTO)-oriented product platform cannot effectively handle the dynamic customer requirements of Engineering to Order (ETO) products, an adaptive generic product structure (Briere-Cote et al. 2010), an adaptive product platform (Levandowski, Jiao, and Johannesson 2015), and an adaptable open architecture product platform (Zheng et al. 2017) are proposed. These proposed adaptable product platforms include unconfigured modules, alternative modules, and parameterized modules, which provides adaptability to meet changing requirements through the reuse of unconfigured modules, the configuration of alternative modules, and the parametric variant design of parameterized modules. Similarly, Li et al. (2016) and Cheng et al. (2017) also propose an adaptable product platform to handle the changing customer requirements of complex products, which consists of common modules and adaptable modules.

As discussed above, to meet changing customer requirements, an adaptable product platform should have the following adaptability: (i) design adaptability and (ii) process adaptability. At present, the academia mainly focuses on the design adaptability that is the capability of an existing design to be adapted to create a new or modified design based on the changing requirements (Gu, Xue, and Nee 2009). Design adaptability is further reflected in the adaptability of function, principle, and structure. Functional adaptability refers to that the customers could propose some changing functional requirements in addition to basic functional requirements. Principle adaptability refers to that dynamic functional requirements can be responded by using multiple principles. Structural adaptability is the most concerned in the adaptable product platform, which means that dynamic customer requirements can be responded through the parameters adjustment of adaptable modules. For example, Levandowski, Jiao, and Johannesson (2015) propose an adaptable platform of Turbine Rear Structure (TRS). The TRS platform has two design solution alternatives (i.e. H-section and T-section vanes) and three manufacturing solution alternatives (i.e. electric beam, laser, and tungsten inert gas wielding). To accommodate the customer's high requirements on geometrical robustness, the H-section vane and laser welding are chosen. Furthermore, the number and thickness of adaptable modules (i.e. vanes) are changed to be able to take the higher loads. The detailed process can refer to Levandowski, Jiao, and Johannesson (2015).

3.2.3 *Market-driven product platform*

Market-driven product platform is first proposed by Kumar, Chen, and Simpson (2009). They believe the current product platforms focus on cost-savings benefits by the reuse of components, and seldom consider seizing market shares to obtain the scope economic benefits. Therefore, they integrate market factors (e.g. product demand, customer preferences, and competitor factors, etc.) into traditional product platform development, and propose a market-driven product platform to enable enterprises to obtain both scale and scope economic benefits. The market-driven product platform mainly responds to uncertain product demand by launching the most appropriate product in the most appropriate market segment through the evaluation of future profit under uncertain market factors. Similarly, Moon and McAdams (2012) propose a market-driven product platform to design a humanized product for the person with disabilities, which helps the enterprises seize market share and obtain considerable profits. Unlike Kumar and Moon, Ma and Kim (2016) propose a market-driven product platform not only responds to uncertain product demand but also uncertain product price. It integrates predictive analytic technology into the product platform design, which aims to help enterprises decide which products should be launched in which market segment by evaluating the future profit. The conceptual design schemes of these products can be obtained by using the SPP design strategy.

As discussed above, it can be seen that the product demand and price are dynamic changing. Before enterprises develop a product platform, these uncertain market factors need to be considered. Unlike flexible and adaptable platforms responding to uncertain customer requirements, market-driven product platform mainly responds to uncertain product demand and price. Market-driven product platform integrates market factors into engineering design domain, helping enterprises to decide which product should be launched in which market segment, and then the conceptual design schemes of these products can be obtained by using maximizing profit optimization. For example, Kumar, Chen, and Simpson (2009) propose a market-driven platform of universal motor. Firstly, the demand of each segment is simulated based on the choice simulator. Then, based on the demand, cost, and product performance model, the number of product platforms and the platform-based product conceptual schemes are determined. The detailed process can refer to Kumar, Chen, and Simpson (2009).

3.2.4 *Sustainable product platform*

A sustainable product platform is proposed by Kim and Moon (2017a, 2017b). At present, environmental issues are getting more and more attention, and many environmental regulations have been promulgated affecting product design. Therefore, in view of uncertain environmental, economic and social factors, the sustainable product platform is proposed, which defined as a product platform considering sustainability performance to reduce harmful effects on the environment while satisfying customer requirements. The sustainable platform shows three characteristics of high sustainability, low risk to product redesign, and high commonality, which can respond to environmental sustainability requirements by sustainable & common modules. Similarly, Wang et al. (2018, 2019) propose a low carbon product platform to decrease greenhouse gas emissions from products. For example, Kim and Moon (2017a) propose a sustainable platform of coffee maker. The sustainable platform has added sustainable modules (e.g. main cord) compared to current product platforms. As a result, although the cost of the sustainable platform has increased, the emissions of CO_2/SO_2 of the platform-based products have been greatly reduced. The detailed process can refer to Kim and Moon (2017a).

3.2.5 *Discussion*

Based on the systematic review of UOPP related product platform concepts, in terms of flexible product platform, adaptable product platform, market-driven product platform, and sustainable product platform, it is obvious that the research goal of UOPP is to improve the flexibility or adaptability of product platform under uncertainty. Flexible and adaptable product platforms mainly deal with uncertain customer requirements. The market-driven product platform mainly deals with uncertain product demand and price. The sustainable product platform not only deals with uncertain customer requirements but also environmentally sustainable requirements. Obviously, these emerging product platforms under uncertainty have expanded the concept of traditional product platforms that are mostly limited to physical standards defining common modules and standardized interfaces to respond to predefined requirements. To better accommodate uncertain customer requirements, markets, technologies, and environmental regulations, these emerging platform concepts have added uncertainty-related elements, which include not only the physical components responding to uncertain factors but also the principles and technology knowledge to be shared to implement these responses. Therefore, we define UOPP *as a product platform that is based on both modular and scale product platform and is consist of common and uncertainty-related elements, which has the ability to accommodate exogenous and endogenous uncertain factors at lower additional investment.*

In general, product platform is put forward in response to the rise of mass customization, which goes through three phases: MPP, SPP, and UOPP, as shown in Figure 3. MPP is suitable for a product with a modular architecture and facilitates horizontal leveraging. SPP is applicable to a product with an integrated architecture and forms vertical leveraging. UOPP is suitable for a product with both modular and integrated architecture, so it can facilitate horizontal and vertical leveraging. Besides, MPP and SPP mainly deal with pre-defined requirements, while UOPP deals with uncertain customer requirements, technologies, and markets, etc. The comparison of the three product platforms is shown in Table 4.

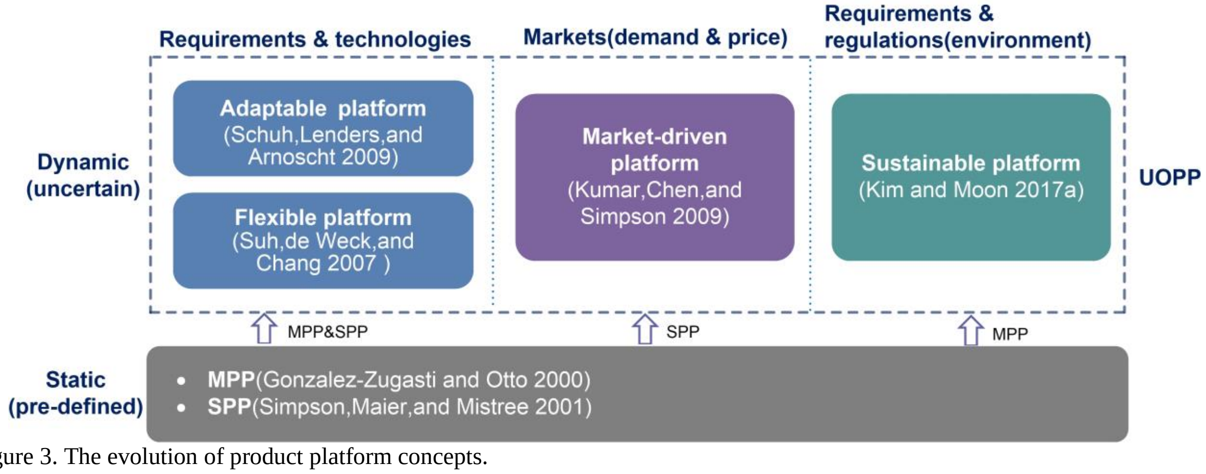

Figure 3. The evolution of product platform concepts.

Table 4. Characteristics of UOPP versus MPP and SPP.

Items	MPP	SPP	UOPP
Key problems	Tradeoffs between diversity and costs	Balancing the conflict between performance and cost	Dynamically responding uncertain factors at lower additional investment
Platform elements	• Common modules	• Common parameters	• Common modules • Flexible/adaptable modules • Sustainable modules
How to apply?	Getting a series of products with different functional requirements by the reuse of common modules, and the replacement of alternative modules	Getting a series of products with the same function and different performance by keeping the common parameters unchanged and extending or shrinking the adjustable parameters	Getting a series of products with different functions and performances under uncertain factors by the reuse of common/sustainable modules, the parametric variant design of flexible/adaptable modules, and the configuration of alternative modules.
Applications	• Volkswagen MQB (ElMaraghy et al. 2013) • Unmanned ground vehicle (Otto et al. 2016) • Prima power portal robot (Pakkanen, Juuti, and Lehtonen 2016)	• General aviation aircraft (Moon, Park, and Simpson 2014) • Automobile S-rail (Hosseini et al. 2019)	• Car BIW (Suh, de Weck, and Chang 2007) • Universal motor (Kumar, Chen, and Simpson 2009) • TRS (Levandowski, Jiao, and Johannesson 2015) • Coffee maker (Kim and Moon 2017a)

As mentioned earlier, the academia has proposed some emerging UOPPs. However, due to the lack of systematic analysis of uncertainty, these innovative platform concepts are confusing and inconsistence, resulting in that their investigations are separated from each other. The above problems make it difficult to form a unified development processes and methods of UOPP. Next, we will provide a comprehensive review of the UOPP development process and the related technologies in each step.

4 The development process and key technologies of UOPP

4.1 *The development process of UOPP*

At present, the researches on traditional product platforms including MPP and SPP have gradually matured, and their development processes have also been widely accepted. For example, Otto et al. (2016) review the literature related to MPP and provide a generic 13 development steps. Simpson (2004) propose the development process and methods of SPP. However, a unified development process of UOPP has not been formed. Therefore, this paper refers to the development process of the emerging product platforms under uncertainty, and presents a new generic development process of UOPP, as shown in Figure 4.

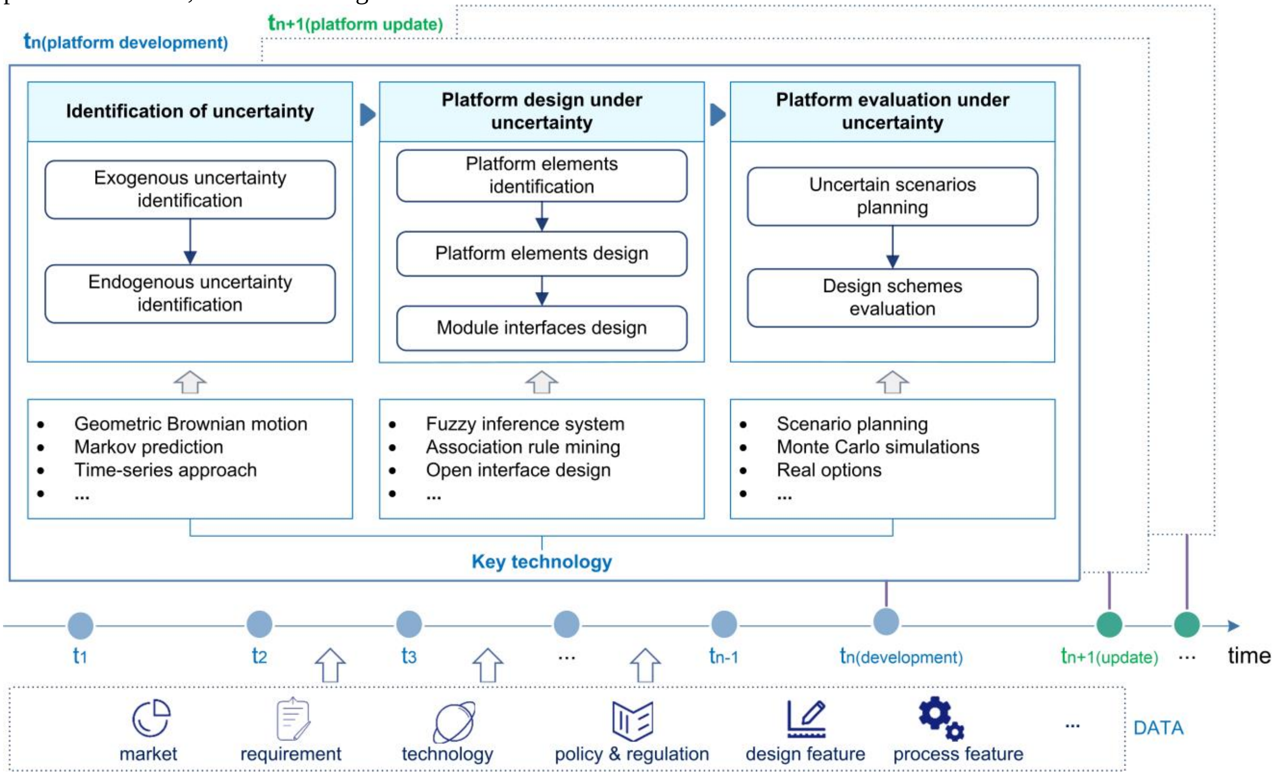

Figure 4. The development process of UOPP.

Compared to the development process of MPP and SPP, this process shows the following characteristics:

(i) It considers the exogenous and endogenous uncertainty. To better accommodate uncertain factors and reduce the risk of platform strategy, the identification and mitigation of uncertainty is necessary. Some methods for identifying and mitigating uncertainty are summarized. Furthermore, the platform design and evaluation under uncertainty are also discussed.

(ii) It emphasizes the dynamic nature of product platform. To ensure continuous adaptability of product platform to accommodate uncertainty, product platform update/upgrade is necessary. The key to achieving this is to establish quantifiable mathematical models or knowledge models to guide product platform design. Some data-driven methods in each step of product platform development or update are summarized.

In the next section, we will provide a comprehensive review of the development processes and related technologies.

4.2 *The key technologies of UOPP*

4.2.1 *Identification of uncertainty*

4.2.1.1 *Exogenous uncertainty*. As mentioned earlier, exogenous uncertainties include market, customer requirement, technology, policy, and regulation, etc., which are external drivers for product platform development, update, or upgrade. The changes of exogenous uncertainties will cause the variation of product platform elements. Each exogenous uncertainty shows the characteristics of randomness, which is irreducible, objective or stochastic. In general, uncertainty is detrimental to product platform design and cannot be eliminated, but it can be reduced or mitigated. An important method to reduce uncertainty is prediction (Chong and Chen 2010), which means to predict the future status of uncertainty based on historical data, thus helping companies to better guide product platform design. Identification and mitigation of exogenous uncertainties in the product platform design are shown in Table 5.

Table 5. Identification and mitigation of exogenous uncertainty

Uncertainty	Metrics	Identification method	References	Prediction Method	References
Markets	Demands	• Transaction data analysis	Suh, de Weck, and Chang (2007)	• Geometric Brownian motion	Jiao (2012)
				• Markov prediction	Hsu et al. (2011)
	Prices	• Transaction data analysis	Suh, de Weck, and Chang (2007)	• Linear regression	Ma and Kim (2016)
Requirements	Items	• Order data analysis	Zhang (2007)	• Scenario planning	Randt (2015)
		• Conversation	Yousuf and Asger (2015)	• Opinion mining	Tuarob and Tucker (2015); Jiang, Kwong, and Yung (2017)
	Levels	• Order data analysis • Conversation	Song (2017) Yousuf and Asger (2015)	• Scenario planning	Randt (2015)
	Preferences	• AHP	Saaty (1988)	• Time-series approach	Purohit and Sharma (2017)
		• ANP	Nilashi et al. (2015)	• Grey theory	Chen and Wang (2008)
		• Kano model	Wu and Wang (2012)	• Big data analytic	Afshari and Peng (2015)
		• SNS data mining	Tuarob and Tucker, (2015)	• Partial least square	Withanage et al. (2012)
		• E-commerce data mining	Jiang, Kwong, and Yung (2017)		
Technologies	Items	• Official release data analysis	Kim and Moon (2017a)	• Delphi method	Kent and Saffer (2014)
		• Expert experience	Kent and Saffer (2014)	• Scenario planning	Cheng et al. (2016); Hansen et al. (2016)
				• Patent-based data mining	Joung and Kim (2017); Kim and Bae (2017)
	Stages	• Logistic model	Cheng and Chen (2008)	• Logistic model	Chiu and Ying (2012)
	Progress rate	• Statistical analysis of patent data	Song, Kim, and Lee (2017)	• Regression model	Jun and Park (2013)
	Impact degree	• Statistical analysis of patent data	Huang and Wang (2013)	• Least square estimation	Lee et al. (2018)
				• Stochastic model	Lee et al. (2018)
Policies and Regulations	Items	• Official release data analysis	Wang et al. (2019)		

(i) **Market.** Market information includes product demand and price, which is closely related to the net profit of the platform-based products. It usually can be obtained through transaction data analysis. The uncertainty of market information will affect product platform design, which is reflected in three aspects: 1) product platform positioning, 2) product platform element identification, and 3) product platform evaluation. To better reduce the risk of product platform development, it is necessary to predict market information based on historical data. Methods for predicting future product demand can adopt Geometric Brownian motions (Jiao 2012) and Markov prediction (Hsu et al. 2011), while the prediction of product price can adopt linear regression (Ma and Kim 2016).

(ii) **Requirement.** Requirement, the most important exogenous uncertainty, is the source of product platform design, which largely determines whether the modules need to be changed or not. Requirement information includes three aspects: items, levels, and preferences. Requirement item is the need of function/performance for a product proposed by customers. For ETO products, it can be obtained through order data analysis. While for non-ETO products, it can be obtained through conversation (Yousuf and Asger 2015), such as interview and survey. Requirement item is dynamic and will emerge or disappear over time. The prediction of requirement item is mainly based on scenario planning (Randt 2015), but it requires manual intervention. In recent years, some scholars have proposed to identify emerging requirement items based on opinion mining from social network service (Tuarob and Tucker 2015) or e-commerce data (Jiang, Kwong, and Yung 2017). The requirement level is the customer's expected value for a certain attribute of the product. Similar to the requirement item, requirement level can be collected through order data for ETO products, and based on the conversation method for non-ETO products. Usually, the requirement level is difficult to predict. To date, there is no automatic method to predict it. However, some scholars have proposed using scenario planning to identify future requirement levels (Randt 2015). Requirements preference reflects customers' interested or attention degrees of product attributes. It can be obtained by using AHP (Saaty 1988), ANP (Nilashi et al. 2015), Kano model (Wu and Wang 2012), Social Network Service (SNS) data mining (Tuarob and Tucker 2015), and E-commerce data mining (Jiang, Kwong, and Yung 2017). At present, there are many methods for predicting requirement preferences. Generally, future requirement preferences are predicted based on the preferences of the past period. Typical methods include Time-series approach (Purohit and Sharma 2017), Grey theory (Chen and Wang 2008), Big data analytic (Afshari and Peng 2015), and Partial least squares (Withanage et al. 2012).

(iii) **Technology.** Technology is a key factor for a company's survival and development. It has an impact on the changes of module and therefore affects product platforms design (Khadke and Gershenson 2009). Technology information includes four aspects: items, stages, progress rate, and impact degree. Technology items are the ways to solve problems, such as methods, principles, and materials, etc. At present, the methods to identify future technology items are mainly based on expert experience, such as Delphi method (Kent and Saffer 2014) and scenario planning (Cheng et al. 2016; Hansen et al. 2016). Recently, the based-patent data mining is also used to identify emerging technologies (Joung and Kim 2017; Kim and Bae 2017). Technology stages refer to the life cycle of technology, including four stages of emerging, growth, maturity, and saturation. The companies generally use the technologies in the stages of maturity and saturation, and research the technologies in the stages of emerging and growth. The technology stages can be obtained by the Logistic model based on patent data (Chiu and Ying 2012). The progress rate reflects the growth speed of the technology's attention degree. It is often measured by the number of patent applications. The higher the number of patent applications, the higher the progress rate. The future progress rate can be predicted by the regression model (Jun and Park 2013). Impact degree reflects the spread speed of the technology, which is measured by the number of patent citations. The higher the number of patent citations, the higher the impact degree. The future impact degree can be predicted by the least square estimation and stochastic model (Lee et al. 2018).

(iv) **Policy and regulation.** Policy is the action guideline that should be followed during a certain period authorized by the international or national institution, such as the policies of real estate, trade, and environment, etc. Regulation is the instruction information about a project or behavior defined by the institutions, such as the regulations of economic and environment, etc. Obviously, politics/regulations will affect product platform design. For example, the regulations with higher emission standards of pollution gas will encourage companies to develop more environmentally, energy-efficient sustainable modules (Kim and Moon 2017a). In general, it is difficult to predict which environment-related regulations will be released in the future. However, companies can analyze the released environmental regulations/policies, and then organize experts to develop a set of sustainability indicators for product families (Mesa, Esparragoza, and Maury 2018), such as the emissions of SO_2 and CO_2. This will help companies to develop a product platform with higher environmental sustainability.

4.2.1.2 *Endogenous uncertainty*. As mentioned earlier, endogenous uncertainties include module change degree, module change propagation degree, module change cost, module change risk, and module commonality. They are influenced by exogenous uncertainties and are the key indicators for identifying product platform elements. For example, the modules with high commonality and low change risk are identified as common modules (Jung and Simpson 2016). To reduce the risk of product platform development/update, the endogenous uncertainty of the product platform should be analyzed. The identification of endogenous uncertainties in the product platform design is shown in Table 6.

Table 6. Identification and mitigation of endogenous uncertainty

Uncertainty	Metrics	Identification method	References	Prediction method	References
Module change degree	GVI	• GVI matrix	Martin and Ishii (2002)	• GVI matrix	Martin and Ishii (2002)
	VI	• AMM	Liu, Wong, and Lee (2008, 2010)	• AMM	Liu, Wong, and Lee (2008, 2010)
Module change propagation degree	CI	• CI matrix	Martin and Ishii (2002)	• CI matrix	Martin and Ishii (2002)
	CPI	• CPI matrix	Eckert, Clarkson, and Zanker (2004)	• CPI matrix	Eckert, Clarkson, and Zanker (2004)
	CPR	• Change prediction method	Clarkson, Simons, and Eckert (2004)	• Change prediction method	Clarkson, Simons, and Eckert (2004)
Module change cost	Switching cost	• Cost summation	Suh, de Weck, and Chang (2007)	• Experience estimation	Hu and Cardin (2015); Kim and Moon (2017a)
Module change risk	RSI	• Multiplying module change likelihood by change cost	Hu and Cardin (2015)	• Bayesian network	Hu and Cardin (2015)
	Redesign risk	• Multiplying module change likelihood by change cost	Kim and Moon (2017a)	• Bayesian network	Kim and Moon (2017a)
Module commonality	CV	• Statistical analysis	Moon, Simpson, Kumara (2010)		
	PCI	• Statistical analysis	Kota, Sethuraman, and Miller (2000)		
	CMC	• Statistical analysis	Thevenot and Simpson (2007)		
	PFPF	• Statistical analysis	Messac, Martinez, and Simpson (2002)		

(i) **Module change degree**. Module change degree reflects the design variation degree of a module due to requirements and technologies, etc., which can be are measured by Generational Variety Index (GVI) and Variety Index (VI). The GVI is an indicator of the expected amount of redesign required for a component to meet future market requirements (Martin and Ishii 2002), which can be obtained by GVI matrix. The VI is an indictor to estimate the design variation or effort on modules to meet customer-perceived requirements, which can be calculated by Attribute-Module Matrix (AMM) (Liu, Wong, and Lee 2008, 2010). Essentially, GVI matrix and AMM are the Quality Function Deployment (QFD) method, which relies on the experience of engineers. Therefore, the future GVI can be obtained by using GVI matrix. A little different from the GVI, the VI takes into account the impact of the requirements preferences on modules. Therefore, to more accurately predict the VI, it is necessary to use the prediction result of the requirement preference that mentioned earlier.

(ii) **Module change propagation**. Although there is a weak correlation between modules, changes in one module can cause the change of other modules. This is called module change propagation, measured by Coupling Index (CI), Change Propagation Index (CPI), and Change Propagation Risk (CPR). CI indicates the strength of coupling between the components. The stronger the coupling between components, the more likely a change in one will require a change in the others (Martin and Ishii 2002). The CI includes coupling index–supply (CI–S) and coupling index–receive (CI–R), which can be obtained by CI matrix. CPI measures the degree of physical change propagation, including four types of multiplier, carrier, absorber, and constant based on the size of the module's generation and absorption (Eckert, Clarkson, and Zanker 2004). CPR measures the change likelihood of drive-modules and the impact degree of this change on the driven-modules (Clarkson, Simons and Eckert 2004). The higher the change likelihood and impact degree, the higher the risk of the driven-modules. Essentially, CI and CPI are obtained by the design structure matrix, and the propagation strength between modules depends on the engineer's experience. Therefore, the future CI and CPI can also be obtained based on CI and CPI matrix. While for CPR, in addition to considering the impacts between modules, it needs to consider the change likelihood of drive-modules, i.e. module change degree. Therefore, to better predict CPR, the prediction results of module change degree (e.g. GVI and VI) that mentioned earlier should be considered.

(iii) **Module change cost**. To respond to the dynamic customer requirements, technologies, policies, and regulations, etc., the modules will change over time. This will result in a change cost, i.e. module change costs. Switching cost is the change-related investment cost, and is the engineering cost of design changes and additional fabrication and assembly tooling and equipment investment to implement the changes (Suh, de

Weck, and Chang 2007). At present, the prediction of switching cost is based on expert experience. For example, Hu and Cardin (2015) and Kim and Moon (2017a) propose the cost of change is assumed to be 80% of the initial cost for each module.

(iv) **Module change risk**. The module change risk reflects the risk index of module due to the changes of customer requirements or drive-modules. It can be measured by multiplying the change likelihood by the change cost, such as Risk Susceptibility Index (RSI) and redesign risk. RSI includes RSI-received index and RSI-generated index (Hu and Cardin 2015). RSI-received indicates the degree of risk received by module due to the impact of possible changes upstream (e.g. customer requirements and technologies, etc.). RSI-generated indicates the risk caused by module changes. Similar to RSI, Kim and Moon (2017a) propose redesign risk. Both RSI and redesign risk are related to the change likelihood and change cost, and therefore their future values depend on the prediction of these two indicators. Prediction of change cost has been mentioned earlier, while the change likelihood can be predicted based on Bayesian network (Hu and Cardin 2015; Kim and Moon 2017a).

(v) **Module commonality**. As the module changes due to exogenous uncertainty, the module commonality will change over time. To date, the commonality has been studied by many researchers, and its quantitative indicators include Commonality Value (CV), Product Line Commonality Index (PCI), Comprehensive Metric for Commonality (CMC), and Product Family Penalty Function (PFPF). The CV reflects the frequency of the module which is used in existing product instances (Moon, Simpson, and Kumara 2010). PCI is utilized to compute the commonality in a product family (Kota, Sethuraman, and Miller 2000). In addition to considering the use frequency, PCI also considers the geometric features, materials, manufacturing processes, part assembly and fastening schemes (Thevenot and Simpson 2007). Similar to PCI, CMC evaluates the similarity of modules in the product family. In addition to size, geometry, material, manufacturing process, assembly, the cost is also considered. PFPF is used to measure the dissimilarity among the different parameter settings for each design variable used to define the product family (Messac, Martinez, and Simpson 2002). The PFPF will determine which parameters should be common throughout the product family and which should be the scaling variables. In fact, module commonality changes over time, but it is difficult to predict. At present, there is no general method to predict the module commonality.

4.2.2 *Platform design under uncertainty*

After completing the identification of uncertainty, it needs to investigate the platform design under uncertainty, i.e. which modules should be common or uncertainty-related modules? How to design the instances of these modules? How to design the interface of these modules? Above these issues are the key issues of designing a product family architecture for supporting new product variants continuously derivation.

4.2.2.1 Platform elements identification. Before identifying platform elements under uncertainty, the module definition (or module partitioning) is required. Methods of module definition include function-based and component-based definition, which can refer to Otto et al. (2016), Helmer, Yassine, and Meier (2010), and Bonvoisin et al. (2016). After the module definition is completed, it needs to make a tradeoff between the commonality and variety in the product family architecture, i.e. platform elements type identification. At present, identification methods include qualitative and quantitative identification based on the metrics of endogenous uncertainty, as shown in Table 7.

Qualitative identification method means that the module types can be identified based on heuristic rules, which can be summarized as follows:

(i) To construct the mapping relationship between requirements and modules, and then to identify module types based on the requirements' types. For example, Li et al. (2013) determine module types based on the mapping relationship between the central component of the clustering module and functional requirements. If the central component is related to the basic functional requirement, the mapped module is the basic module. Similarly, flexible and individualized modules are identified.

(ii) To calculate the module's metrics (e.g. GVI, VI and change cost, etc.), and then to determine module types based on expert experience by using these metrics. For example, Martin and Ishii (2002) identify standardizing and modularizing components based on GVI, CI-R, CI-S, and Nonrecurring Engineering (NRE) costs. Specifically, the components with high GVI, high NRE cost, high CI-S, and low CI-R are considered standard components, and the components with high GVI, low CI-S, and high CI-R are considered as modular components. Similar methods can refer to Suh, de Weck, and Chang (2007) and Hou et al. (2017).

Quantitative identification method means that the identification of module types can be considered as the problems of classification, decision, optimization, and inference to deal with, which can be summarized as follows:

(i) **Classification**. That means to divide two regions by using one metric and its threshold or four regions based on two metrics, and then to identify module type based on which region it falls into. For example, Liu, Wong, and Lee (2008, 2010) calculate the VI and set its threshold to 0.5, and then treat these modules larger than the threshold as differentiating modules, otherwise common modules. Similarly, Jung and Simpson (2016) use two metrics of GVI and PCI to divide four regions, including properly platformed modules, unvalued uniqueness modules, valued variety modules, and confusing commonality modules. Similar methods can refer to Moon, Simpson, and Kumara (2010), and Hu and Cardin (2015).

(ii) **Decision**. That means to generate the configuration schemes consisting of common and differentiated modules, and then to evaluate these schemes based on some metrics (e.g. quality, cost, and risk, etc.). After obtaining the best scheme, module types are subsequently determined. For example, Perlman (2013) develops the possible configuration schemes for the low-end and high-end car markets, and then assesses the risk of each scheme. The common and differentiated modules are identified when the best configuration scheme is selected.

(iii) **Optimization**. That means to determine the value of module's design parameters by using multi-objective optimization, and then to identify the common module based on whether its value changes or not. For example, Simpson et al. (2012) take the unmanned ground vehicles as an example. They construct an optimization function with maximum effectiveness requirements and minimum PFPF, and then determine the value of module' design parameters by using the Pareto genetic algorithm. On this basis, the common modules are identified if their values do not change.

(iv) **Inference**. That means to identify module types based on inference rules. For example, Kim and Moon (2017a) use fuzzy inference system to identify common, sustainable & common, variant, and unique modules based on the three metrics of redesign risk, commonality, and sustainability. Specifically, the modules with high sustainability, high commonality, and low sustainability are considered as sustainable & common modules.

Table 7. Module type identification method

Method types		References	Metrics	Identification results	Exogenous uncertainties
1.Qualitative identification	1.1.Mapping relationship-based	Li et al. (2013)	• None	• Basic modules • Flexible modules • Individualized modules	• Customer requirements
	1.2.Heuristic rules-based	Martin and Ishii (2002)	• GVI • CI-R • CI-S • NRE cost	• Standardizing components • Modularizing components	• Customer requirements
		Suh, de Weck, and Chang (2007)	• CPI • Switching cost	• Common platform elements • Flexible platform elements • Unique elements	• Customer requirements • Product demands
		Hou et al. (2017)	• Changing cost	• Shared modules • Parameterized modules • Flexible modules	• Customer requirements
2.Quantitative identification	2.1.Classification	Liu, Wong, and Lee (2008,2010)	• VI	• Common modules • Differentiating modules	• Customer requirements
		Moon, Simpson, and Kumara (2010)	• Module value • CV	• Common modules • Unique modules • Redesignable modules • Sub-common modules	• None
		Jung and Simpson (2016)	• GVI • PCI	• Properly platformed modules • Unvalued uniqueness modules • Valued variety modules • Confusing commonality modules	• Customer requirements
		Hu and Cardin (2015)	• RSI-received • RSI-generated	• Flexibility design modules • Robustness design modules • Fixed design modules	• Environmental sustainability requirements
	2.2.Decision	Perlman (2013)	• Profit • Manufacturing cost	• Common components • Unique components	• Product demands
	2.3.Optimization	Simpson et al. (2012)	• PFPF	• Common modules • Differentiating modules	• Customer requirements
	2.4.Inference	Kim and Moon (2017a)	• Redesign risk • Commonality value • Sustainability value	• Common modules • sustainable & common modules • variant modules • unique modules	• Environmental sustainability requirements

UOPP aims to achieve the continuous adaptability of product platform to accommodate exogenous uncertain drivers, therefore the quantitative identification method is recommended to dynamically identify module types.

4.2.2.2 Platform elements instantiation. Module instantiation is to design the instances of platform modules. The instantiation of common modules is generally to select the best instance from existing module instances by using decision theory. While for uncertainty-related modules (e.g. flexible modules), because they change over time due to customer requirements and technologies, etc., so the instantiation of these modules first needs to define the bandwidth of modules (Schuh, Riesener, and Breunig 2017). Levandowski, Michaelis, and Johannesson (2014) propose the bandwidth describes the validity and applicability range of a configurable unit, including three aspects: 1) Functional Requirement (FR) bandwidth, 2) Design Solution (DS) bandwidth, and 3) Constraint (C) bandwidth. The bandwidth of FR represents the range of the required performance of the systems. Bandwidth of DS represents how the solution may vary to solve these requirements, while the bandwidth of C represents the non-functional limits for selecting a DS.

In addition, to better support the module to accommodate uncertain requirements and technologies, etc., it is necessary to define the relationship between the exogenous uncertain drivers and the modules. For example, Suh, de Weck, and Chang (2007) view a flexible module as a parametric module adapting to dynamic customer requirements by adjusting its structural parameters. The key to the instantiation of flexible module is to establish the mapping rules (MR) between technical requirements and structural parameters. Thus, once the technical requirements have changed, the flexible module can quickly adjust structural parameters to respond to these changes based on MR. MR can be a calculation formula or an experience rule, which can be achieved by data mining techniques, such as association rule mining (Jiao et al. 2008; Zhang 2012).

4.2.2.3 Module interfaces design. Interface plays an important role in the product operation and maintenance when upgrading and replacing modules. Interface design is an important aspect of product platform design for both MPP and UOPP. MPP advocates a standardized and fixed interface because it minimizes needed information flows (Ericsson and Erixon 1999), while UOPP needs to study open, adaptable and flexible interfaces to better satisfy diversity of customer requirements (Chen, Peng, and Gu 2018). Wagner et al. (2014) illustrate the need for an open interface to access the car by any mobile device. In recent years, some scholars have studied open or adaptable interfaces design. For example, Hu, Peng, and Gu (2015) apply the adaptable design concept to design adaptable interfaces between platform and add-on modules when developing an Open Architecture Products (OAPs). Interface plans are first generated based on the functional correlation matrix of modules, and then the possible solutions of the interface are obtained by applying the morphological matrix. Finally, the best adaptable interface scheme is determined by using the fuzzy analysis hierarchy process considering the criterions of adaptability, working performance, assemble performance, and economy. In addition, Zhang et al. (2017) propose an interface adaptability improvement method for OAPs. They quantitatively analyzes the adaptability of open interface in terms of functionality, structure, manufacturing, operation and maintenance based on open interface modeling, and then identifies the position with the maximal influence on the interfaces' adaptability, and finally modifies these positions to enhance the adaptability of modules.

4.2.3 *Platform evaluation under uncertainty*

Product platform evaluation can help an enterprise decide whether to develop, update, upgrade or delete a product platform. The evaluation indicators include profit, complexity, and customer satisfaction, etc. (Otto and Holtta-Otto 2007; Alizon, Shooter, and Simpson 2009; Kim et al. 2016). Compared to MPP and SPP, UOPP needs to consider uncertain market and customer requirements in the product platform evaluation, which includes uncertain scenarios planning and design schemes evaluation.

4.2.3.1 Uncertain scenarios planning. Market information (i.e. product demand and price) and customer requirements are uncertain and cannot be frozen in the development and use of product platform (Gonzalez-Zugasti, Otto, and Baker 2001). To reduce the risk of product platform development or update, it is necessary to plan uncertain scenarios when evaluating the performance of product platform. For example, Suh, de Weck, and Chang (2007) plan 12 uncertain scenarios by using scenario planning technique. The degree of uncertainty of each scenario is different. Some scenarios only consider product demand is uncertain, but some scenarios assume that both demand and customer requirements (e.g. styling change and length change, etc.) are uncertain. Similarly, Cardin, de Neufville, and Geltner (2015) define 5 scenarios for the major uncertainty source (i.e. product demand) inspired from scenario planning technique. The scenario planning technique may lead to different numbers and forms of representative scenarios, depending on users, context, and organization. Choosing which scenarios is critical as it influences the results of platform evaluation.

4.2.3.2 Design schemes evaluation. After planning the future uncertain scenarios, it needs to evaluate the economic performance of each design schemes by using the Discounted Cash Flow (DCF) analysis, such as Net Present Value (NPV). For example, Suh, de Weck, and Chang (2007) calculate the Expected NPV of flexible and non-flexible platforms under different scenarios based on Monte Carlo simulation, and subsequently help decision makers to select the best platform design scheme (maximum ENPV) for a given uncertainty. The results show the ENPV of flexible platform performs better than the inflexible platform when the degree of uncertainty increases. Hu and Cardin (2015) also simulate the ENPV of the flexible design schemes and benchmark design, and then help designers to evaluate the value of flexible modules and determines whether flexibility is worth the additional cost and design effort. The results show more than 10% ENPV improvement compared with a fixed and rigid system when flexibility is embedded in the selected system modules. Similarly, Deng et al. (2013) and Cardin, de Neufville, and Geltner (2015) use the DCF analysis to calculate the Value of Flexibility (VoF) of design schemes under the planned scenarios. Obviously, the results of platform evaluation considering uncertain scenarios will help the enterprises make a better choice in the development and update of product platform.

Based on the analysis of emerging product platforms under uncertainty, this paper presents a generic development process of UOPP, and summarizes the related techniques of each step. However, UOPP is a complex design process that still faces many challenges. Next, we will discuss the future research framework, opportunities and challenges of UOPP.

5 Prospects for future research

5.1 *Future research framework*

As witnessed in this comprehensive review, product platform under uncertainty has emerged in the past decade, such as flexible product platform, adaptable product platform, market-driven product platform, and sustainable product platform, and achieved promising results. At present, the emerging product platforms under uncertainty mainly focus on random uncertainty. This paper also only summarizes the product platform development process and related technologies under random uncertainty. However, it is clear that the roughs and fuzzy uncertainty is worth studying in the future. In addition, platform strategy is not only addressing the narrow users' requirements but also pays full attention to the much wider stakeholders' requirements with uncertainties through the product life-cycle. The extension of the product platform concept is along two principal directions: (i) extending user requirements to all stakeholders' requirements, and (ii) extending product design into through-life product service systems. We believe the future research will follow the research framework as shown in Figure 5.

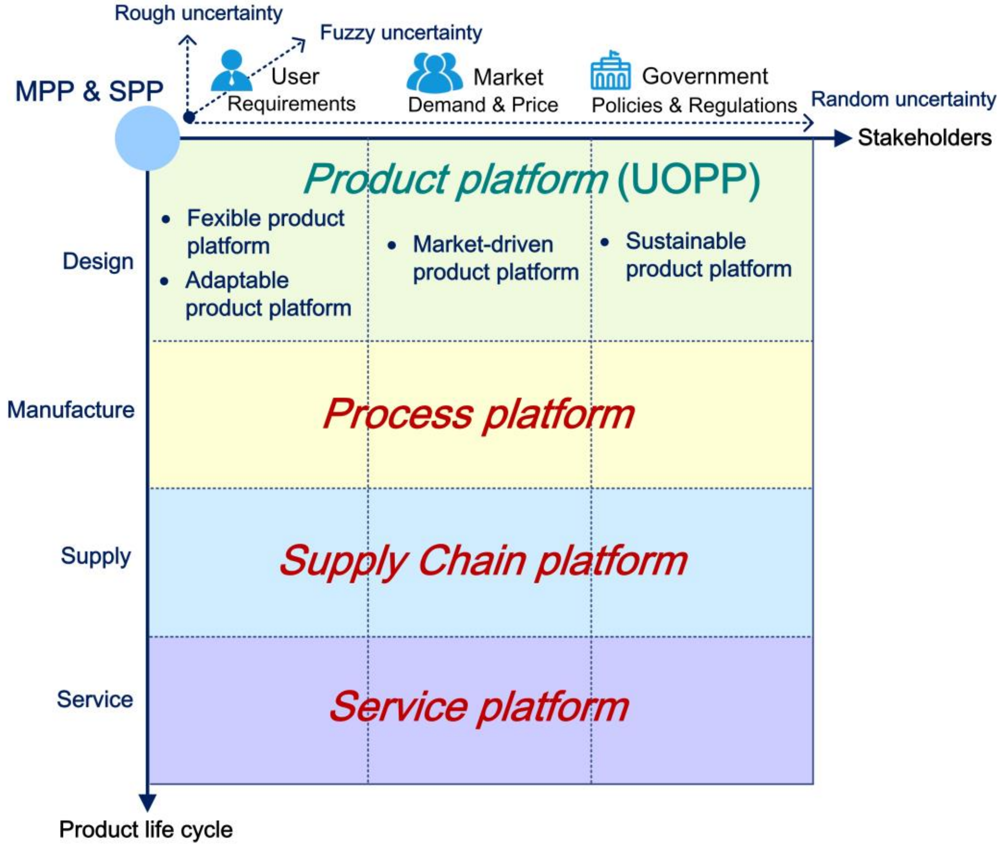

Figure 5. The future research framework of platform development.

5.2 *Future opportunities and challenges*

As can be seen from Figure 5, in today's market, the concept of traditional product platforms (including MPP and SPP) has changed to meet uncertain stakeholders' requirements. In addition, the process platform (Jiao, Zhang, and Pokharel 2007), supply chain platform (Pashaei and Olhager 2015), and service platform (Moon, Simpson, and Kumara 2011) concepts have been proposed. The future research opportunities and challenges of UOPP include the following five aspects:

(i) **Comprehensive analysis of all stakeholders' requirements.** Traditional product platforms generally only consider user requirements, and lack sufficient analysis of markets, technologies, policies and regulations, which may lead to platform development failure. At present, the academia has proposed flexible and adaptable product platforms to handle uncertain user requirements, market-driven product platform to deal with uncertain demand and price, and sustainable product platform to accommodate environmental sustainability requirements. However, a product platform that comprehensively addresses all stakeholders' requirements has not yet been formed. In the future, we should identify the requirements of all stakeholders to support product platform design. The first challenge is how to automatically identify stakeholders' requirements based on data-driven techniques. In addition, how to balance the conflicts between stakeholders' requirements is also a challenge.

(ii) **Addressing random, rough, and fuzzy uncertainty**. As mentioned earlier, uncertainty in product platform shows three characteristics of randomness, roughness, and fuzziness. Random uncertainty is one of the most concerned in the product platform design. The key to addressing it is prediction. For example, using time-series approach predicts product demand, and using grey theory predicts future customer preferences. These forecast results will help enterprises to reduce the risk of platform strategy. In fact, in addition to the random uncertainty considered in this paper, the impact of rough and fuzzy uncertainty on product platform should be investigated in the future. At present, the academia has proposed some methods for dealing with random, rough and fuzzy uncertainty, but these methods have not been effectively integrated into product platform design. Identifying and mitigating the three types of uncertainty in the product platform development will be a challenge.

(iii) **Dynamic update mechanism of product platform**. Markets, customer requirements, technologies, etc. keep evolving and cannot be frozen during the development and use process of product platform. Obviously, product platform dynamic update is necessary. Furthermore, to improve the platform's continuous adaptability to accommodate uncertain factors, the update mechanism should be an automatic and dynamic way based on big data analysis techniques. Therefore, the challenge of this research is how to continuously identify the exogenous and endogenous uncertain factors and assess the risk of platform update under uncertainty, and how to help enterprises make a right decision to dynamically update the product platform.

(iv) **Product family modeling and reasoning under uncertainty.** Product family information model consists of platform modules, non-platform modules, and configuration mechanisms, which is the basis and key to supporting requirements-driven product design. At present, the academia has many researches on product family information modeling, such as Generic Bill-Of-Materials (GBOM)-based, rules-based, constraint-based, and ontology-based. But these methods seldom consider uncertain factors in the product family modeling. To obtain better scale and scope economies, product family information modeling under uncertainty needs to be considered. Furthermore, the product family reasoning methods under uncertainty should be studied to achieve continuous product variants that meet uncertain stakeholders' requirements. The challenge of this research is how to model dynamic information, reflecting in: 1) the presence or absence of modules, 2) changes in module types, 3) changes in module boundary, and 4) changes in the relationships among modules.

(v) **Establishing an integrated platform that merges product, process, supply chain and service platform.** In general, products go through multiple phases involving design, manufacturing, operation and maintenance, and recycling, etc. Obviously, establishing a platform for only one phase cannot make the platform-based products to achieve optimal performance. Therefore, in the future, we should construct an integrated platform that merges product, process, supply chain and service platform. The challenge of this research is how to extract the features of each phase and construct the relationships between these features, thereby building an optimization model for the product life cycle to support integrated planform design.

6 Conclusions

Product platform is an effective strategy for addressing mass customization. In recent years, as the customization scale has leaned toward medium and small batch sizes, and the manufacturers change their product-centered strategy to customer-centered strategy, the academia and industries have begun to investigate the product platform under uncertainty for improving the adaptability of enterprises to meet uncertain markets, customer requirements, technologies, policies, and regulations, etc. This study systematically presents a review of product platform development under uncertainty, including the connotation of uncertainty and UOPP, the development process and key technologies of UOPP, and the future research framework, opportunities and challenges. Compared with MPP and SPP, the proposed UOPP has the following theoretical innovations:

(i) UOPP is a product platform that considers the requirements of multiple stakeholders, such as users' requirements, technologies, markets, policies, and regulations, etc. Obviously, it is more competitive and less risky than a product platform that considers the requirements of individual stakeholder.

(ii) UOPP is a dynamic and adaptable product platform. The "dynamic" shows that the platform is able to update or upgrade under exogenous uncertain drivers. The "adaptable" shows that the platform has the ability to dynamically accommodate uncertain customer requirements and technologies, etc. at lower additional investment.

(iii) UOPP is a data-driven product platform. To ensure continuous adaptability of product platform to accommodate uncertain factors, it needs to establish quantifiable mathematical models (e.g. classification, optimization, probability, and decision, etc.) and knowledge models based on historical data, and then using dynamic data to modify these models to continuously guide product platform development and update.

Consequently, customer requirements, technologies, and markets, etc. keep evolving during the development and use process of product platform. UOPP, a data-driven product platform that has continuous adaptability and considers the requirements of multiple stakeholders, will have significant theoretical and practical implications for the future. This literature review lays the foundation for future research of product platform design under uncertainty. However, this paper highlights the product platform design under uncertainty, while the process, supply chain, and service platform under uncertainty have not been fully investigated. Although we focus on studying the impact of random uncertainty on product platform design, rough and fuzzy uncertainty are worth studying intensively. It is expected that this research will provide a reference and will spur more research to explore this important and interesting field.

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