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Citation: Zhang, Haizhu, Qin, Sheng-feng, Li, Rong, Zou, Yisheng and Ding, Guofu (2020) Progressive modelling of feature-centred product family development. International Journal of Production Research, 58 (12). pp. 3701-3723. ISSN 0020-7543

Published by: Taylor & Francis

URL: https://doi.org/10.1080/00207543.2019.1634295 <https://doi.org/10.1080/00207543.2019.1634295>

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International Journal of Production Research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tprs20

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To cite this article: Haizhu Zhang , Shengfeng Qin , Rong Li , Yisheng Zou & Guofu Ding (2020) Progressive modelling of feature-centred product family development, International Journal of Production Research, 58:12, 3701-3723, DOI: 10.1080/00207543.2019.1634295

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International Journal of Production Research, 2020
Vol. 58, No. 12, 3701–3723, https://doi.org/10.1080/00207543.2019.1634295

Progressive modelling of feature-centred product family development

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(*Received 24 July 2018; accepted 17 June 2019*)

Modelling a product family is critical for understanding the evolution of key design and manufacturing features associated with products in the product through-life development. This research aims to establish a model for the holistic description of the evolution process of a product family to support rapid development of new products with hybrid innovations. In this study, a new broader definition of the product family is proposed for products on cross-platforms but in the same class or category, called feature-centred product family. A progressive modelling of feature-centred product family is developed for progressively addressing the evolution of products and achieving the dynamic expression of a product family. A prototype system has been developed and tested with an industrial case study, which indicates that the proposed new feature-centred product family concept and progressive modelling method are not only supportive to realise the common and adaptive analysis of key design features but also helpful to improve the design and production efficiency of innovative products with knowledge and feature reuse.

Keywords: product family; progressive modelling; feature-centred; hybrid innovations; knowledge and feature reuse

1. Introduction

Product family design is a cost-effective design strategy that can bring a variety of products to different market segments at a competitive price (Zamirowski and Otto 1999). Applying product family design has a significant impact on the sales and production benefits (Thevenot and Simpson 2004; Agard and Bassetto 2013), such as satisfying customer needs/wants, improving product performance, managing their production cost, etc. Since the market conditions and customer preferences are rapidly changing, this dynamic exogenous influences along with its uncertainties shall be taken into new product development considerations(Matsui et al. 2007; Pirmoradi and Wang 2011). The product main structure and its derived customised product structure in the life cycle of the product family are constantly and dynamically evolving along with the changes of customer requirements as time goes on (ElMaraghy et al. 2013). Product family modelling is helpful for product development teams to rapidly develop a new product with holistic product development knowledge in response to changes in customer demands and market conditions. There is a fundamental requirement for understanding complex decision-making during the product family development, capturing and storing design context and knowledge properly, and incorporating them into a new product development of a product family (Krishnan and Ulrich 2001). However, how to model a product family to effectively meet these requirements is challenging (Liu, Lim, and Lee 2013).

The typical product family model is an architecture-and-units model describing which modules (Erens and Verhulst 1997) or units (Pan et al. 2014) are part of the product family model and how they can be combined in the product family architecture. Thus, most studies focus on the product family architecture and unit information. A module or unit is defined typically as a 3D substructure, which is equivalent to a part or component or subsystem in an assembled product. This is good for rapidly (re)configuring a product from existing modules or units on the product family platform with necessary newly developed parts (or modules/units) (Wu et al. 2016).

The limitations of module-/unit-based representations of product families are two-fold. First, the module/unit-based representation of a product family limits its exploration space from core product design to tangible and intangible product design with both tangible and intangible design features such as styling, after-sale service, information and knowledge driven interaction and user-experience design features (Thoben, Eschenbächer, and Jagdev 2001; Zhang, Chu, and Xue 2019). While intangible design features are important for marketing complex technical products (Shaw, Giglierano, and Kallis 1989). Therefore, it is important for a product family design platform to be able to create new design features and

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transfer or transform all design features associated with products on its own family and other product families into a new product design in the current product family via hybrid innovation. Second, this product family architecture-and-units model provides incomplete design evolution and decision-making information, which is a key part of design knowledge for sharing and reuse. Information on product family evolution plays such a key role in sustaining profit and growth, which enables marketers to predict more accurately which attributes of a product's performance will be most highly valued in the next generation.

Above all, mostly existing product family models are module-/unit-based modelling representations of product families by a top-down approach (Alizon et al. 2007), which mainly focuses on design for variety and upgradability in the global markets and support the design reuse in a new product development (Ulrich and Eppinger 2016). However, there is lack of feature level modelling which is the core of enabling the technique to support all variability and evolution management, and traceability in the evolution design of product family, which provides important insights into the new product development. In the existing feature modelling approaches, research is mainly from the field of software product line focusing on feature-based parametric product family (Ranta et al. 1996), multi-level feature trees to manage product families (Reiser and Weber 2007), and feature evolution in a family of product variants (Xue, Xing, and Jarzabek 2010). To our knowledge, little research has addressed feature-based product family design. It enables enterprises to have a full customer and market understanding of related products on the market (including the products from various market competitors on the other platforms) (Goswami, Daultani, and Tiwari 2017). When innovating new products, enterprises can make right choices and decisions with both internal design information and knowledge from itself own product platform and some external information and knowledge from other product platforms with its competitors to win competitions. This is a very important hybrid innovation strategy by learning from the past and the competitors.

The hybrid innovation here is defined as a concept that a product innovation is enabled by (1) combining/mixing the new, disruptive or other emerging technologies with the old technologies, and (2) adapting/transforming/integrating design features from other product families (outside of current product family). The hybrid innovation represents a sustaining innovation supported by blended learning from the past to the emerging technologies and from the inside product family development knowledge to the outside world (Christensen, Horn, and Staker 2013). Hybrid electric vehicles (Pohl and Yarime 2012), gives an example of hybrid innovation.

In this research, we propose a novel progressive modelling approach to product family centred on design and manufacturing features and product evolution. It is a dynamic and time-dependent expression of a product family. This new type of product family modelling can enable rapid product developments with hybrid innovations in a new product development. It can improve the research and development efficiency of a product family to adapt to the complex and changeable customer demands and market conditions by conducting longitudinal studies and investigating cross-sectional relationship of the product family. The main contributions of this paper are:

1. We introduce a new product family concept centred on design and manufacturing features as an extension to existing definition of product family to enable hybrid innovation and the capturing of design evolution. It synthesises the information of a product family to support features-based knowledge modelling, hybrid innovation and time-dependent holistic product development. Feature-Centred Product Family (FCPF) has capacity of accurately capturing full knowledge of design reasoning and evolution, which is not only helpful to full understanding of the relationships of products in the product family, but also important from the standpoint of improving quality and maintainability and plays such a key role in sustaining profit and growth.
2. We propose a new progressive modelling method for describing a product family. This method can graphically show the progressive pattern of a complex product family, and model progression rules for positioning and defining the new product node in the family tree. It can help to track and predict the trajectories of performance improvement and market demands as well.
3. We develop a prototype system to demonstrate the new FCPF concept, operational methods to dynamically construct a product family model as a pedigree graph and application tools to analyse common and adaptive features.

The rest of this paper is structured as follows. In Section 2, a brief literature review of product family design and modelling is presented. The proposed method of progressive modelling a product family is described in Section 3. The development of a prototype system and its application in the development of a high speed train's bogie are presented in the Section 4. Section 5 discusses the application results and implications. The conclusions are drawn in Section 6.

2. Related work

The product family is defined as *a set of similar products that share common technology platform but have specific functionality/features to address a related set of market segmentations and meet particular customer requirements* (Erens and Verhulst 1997; Meyer and Utterback 1993; Meyer and Lehnerd 1997). Based on the typical definition of the structural product family, a top-down or bottom-up approach for product family design has been developed (Simpson, Jiao, and Siddique 2014). The concept of product family has been extended from multiple viewpoints to support the development of new product families such as a service family (Ki Moon et al. 2009), an evolving family (ElMaraghy 2009), a modular product family (Liu, Wong, and Lee 2010), a meta-product family (Schönsleben 2012), an universal product family (Moon and McAdams 2012), a sustainable product family (Tao and Yu 2012) and an eco-product family (Yang, Yu, and Jiang 2014). The researches related to product family can be summarised into three categories.

2.1. Global markets driven product family design

With the increasingly intensified market competition, designing products for multiple global markets (Wiersema and Bowen 2008) is essential to satisfy the variation of users, business and regulatory requirements across the nations and market segments of the world (Wang and Zhou 2008), although it is difficult to practise (Eppinger and Chitkara 2006). Maier and Fadel (2007) proposed three product family design strategies including concurrent, evolving and some typical mixed evolving/mutating product family designs to meet the different market niches. Nadadur et al. (2012) proposed three broad top-down design strategies to satisfy varying requirements across the globe, namely, non-platform design (to lower degrees of variations, such as Adidas Jabulani), static platform design(to medium degrees of variations, such as global automotive) and flexible platform design (to larger variations, such as Apple's IOS). An integrated approach was proposed to product family redesign using commonality and variety metrics for increasing company global presence (Jung and Simpson 2016).

In general, the market-driven design focuses on the market-reconfigurable design and supports top-down design strategies.

2.2. Variety and upgradability driven product family design

As the changing of market from manufacturers' to buyers' market, the demand for product variety are constantly increasing (McKay, Erens, and Susan Bloor 1996). Therefore, product family design needs to focus on not only market-reconfigurable design as detailed in the previous section but also user (buyer)-reconfigurable design. The latter includes design for variety (DFV) and design for upgradability (DFU). The DFV method was proposed (Martin and Ishii 2002). It offers a quality function deployment (QFD) based structured approach by introducing a Generational Variety Index (GVI) and a coupling index with guiding rules to reduce the amount of redesign effort for future generations of the product, and to help companies identify how their products may evolve as customer needs change (Martin and Ishii 2002). The drivers of generational changes are the external drivers such as customers' requirements, technologies, standards, and so on, but the products' main functions remain the same or similar. ElMaraghy (2009) identified eight distinguishable variety levels in the hierarchy: (1) part features, (2) parts/components, (3) parts family, (4) product modules or sub-assemblies, (5) products, (6) products families, (7) products platform, and (8) products portfolios. The GVI analysis was applied in evaluating the multigenerational evolving design of the Apple iPhone (Nadadur, Parkinson, and Simpson 2012). Different approaches of achieving product variety are discussed in (ElMaraghy et al. 2013), including product architecture, product modularity, commonality, integration, differentiation, mass customisation and personalisation. To eliminate the negative effects of increased variety, clustering derivative product components is helpful to ease manufacturability and reduce planning complexity (Aydin and Ulutas 2016).

Shimomura, Umeda, and Tomiyama (1999) proposed a functional upgradable design methodology to maximise functional flexibility with minimal structural changes for upgradable products, which can be regarded as a variant of platform design. DFU is a feasible approach to extend product's value life by upgrading functions and parameters among multiple generations by adding, replacing or removing modules (Ishigami et al. 2003). An upgrade plan for several generations of a product should be made to against the uncertainty for future requirements by delayed selection of components and expanding and shrinking platform replaceable components (Umemori et al. 2001). Umeda et al. (2005) developed a design methodology based on Function–Behaviour–State (FBS) modelling to support a designer for finding out candidates of function structure changes and configurations of a platform. The product upgradability index is proposed to evaluate the overall upgradeability of a product including compatibility to generational variety (CGV), fitness for extended utilisation (FEU), and life cycle oriented modularity (LOM) (Xing et al. 2007). The analogy-based upgrade method is proposed to support both functional upgrading and performance upgrading for a product family to sustain its market competitiveness (Tu et al. 2018). Lermen et al. (2018) applied lean principles to improve new product development performance in sustainable product innovation.

In summary, the market-reconfigurable design and the user-reconfigurable design are focusing on market conditions and regulations, reconfigurable product functions and performances based on either QFD or FBS design modelling. They pay a little attention to hybrid innovation of a product family in terms of organically borrowing new design and manufacturing features from other reference products just like bring new bloods (or genes) into a family by marriage with other family members.

2.3. Product family modelling

The product family modelling is a key to powerful and successful product family design (Nomaguchi, Taguchi, and Fujita 2006). The existing product family modelling technologies mainly include Product Family Architecture (PFA) modelling (architectural aspect), Product Family Knowledge (PFK) modelling (static aspect) and Product Family Evolution (PFE) modelling and mapping (dynamic aspect).

2.3.1. PFA modelling

To establish a powerful PFA model, market, design and production domains must be encompassed from the viewpoints of customers, designers and manufacturers (Meyer and Utterback 1993; Du, Jiao, and Tseng 2001; Jiao, Simpson, and Siddique 2007). Erens and Verhulst (1997) defined an architecture of product family in functional, technological and physical domains to deal with the conflict between modularity and integration; Jiao and Tseng (2000b) described a PFA from the functional, behavioural and structural perspectives to organise product varieties in design for mass customisation. Pavlic, Pulkkinen, and Riitahuhta (2006) divided the description of PFA into three levels including domains concepts, the notation used to define the elements of domains and the design rules. Based on a top-down platform development paradigm, Liu, Wong, and Lee (2010) proposed a modularised PFA to generate variety and optimise a product family with rationalised commonality configuration. Bonev et al. (2015) presented a formal computer-assisted approach that identifies the design requirements of PFA to support the architecture documentation, communication and synthesis. Liu, Du, and Jiao (2017) took make-or-buy (MOB) decisions into account in PFA for the manufacturer and suppliers in the distributed environment. The product family modelling approaches are proposed to achieve the expression of PFA including a product family modelling of multiple abstraction levels (Jørgensen and Petersen 2005), a dynamic structure-based product family modelling (Brière-Côté, Rivest, and Desrochers 2010), a semantically annotated multi-faceted ontology for product family modelling (Lim, Liu, and Lee 2011), etc.

From the above review, it is clear that the existing PFA models are used to (1) indicate the structure of a product family, (2) serve as a backbone for systematic analysis of the development of a product family, and (3) store embedded implicit and/or explicit design knowledge. The key concept of a typical product family is based on and limited to a product platform normally belonging to a manufacturing company. Thus, traditional product family models provide little support of the sharing and evolution of key design and manufacturing features among relevant products on different platforms.

2.3.2. PFK modelling

Product family provides an architecture foundation for the management, sharing and re-use of knowledge, in turn knowledge modelling supports to deal with the diverse and rapidly changing customer requirements and to reduce product cost and environmental impacts for product family (Giovannini et al. 2016; Luo, Sun, and Pan 2005). With the increasing number of product offerings targeted at different market segments, it is more complicated and challenging than knowledge management in product family (Lim, Liu, and Lee 2011). Therefore, a flexible information model is crucial for the systematic development and deployment of product families during all life phases of product (Nanda et al. 2007). To capture, manage, share, reuse and integrate product family knowledge, Xu, Ong, and Nee (2007) initiated a product family design reuse (PFDR) process model; Nanda et al. (2007) proposed a flexible knowledge management framework which is called a networked bill of material (NBOM) using formal concept analysis (FCA); Ki Moon et al. (2009) presented a methodology to develop a service ontology for capturing and reusing design knowledge in a service family; Moon, Simpson, and Kumara (2010) proposed a methodology of integrating an ontology and data mining for knowledge discovery of product family; Lim, Liu, and Lee (2011) proposed a multi-facet product family ontology framework to search and retrieve information of product family; Pan et al. (2014) put forward an information integration modelling architecture for product family life cycle (I^2MAfPFL);

Giovannini et al. (2016) applied an anti-logicist approach for the unambiguous design-knowledge representation during a product family design stage; Lundin et al. (2017) explored the computer-aided technologies (CAX) to capture and represent reuse knowledge of product families.

The above PFK models can show the characteristics of product variety and multiple generations, however, they lack information and knowledge about key design features either derived from the product family or hybridised (married) with ones from other product families in current practice of PFK. Thus, it is necessary to have a new PFA model which can capture, manipulate, share and reuse this type of design information and knowledge to show a big picture of new product developments possibly crossing/linking to multiple product families and their knowledge.

2.3.3. PFE modelling and mapping

Modelling the evolution of a product family is critical for satisfying customer, improving performance, reducing manufacturing cost and minimising risk (ElMaraghy et al. 2013). With the time changes, the main driver of PFE is adaptation such as the new requirements, the new regulations, and/or the availability of new technology (Pan et al. 2014; Martin 2000), and the family redefinition, restructuring and perfective maintenance have an important effect on the change of product family (Lam 1999).

Developing a new generation of products (including enhanced, customised, cost reduced and hybrid products) needs a generational relationship map to show how the product offering in one generation may be related each other, allowing designers to track the evolution of product families from one generation to another (Wheelwright and Sasser Jr 1989). The products in the family are functionally related with traceable changes crossing generations due to new features, functions, and available technologies, thus a general model was proposed to describe such relationships for multicycle product families (Sanderson 1991). Product family maps as a legend can show the chronology of a product family and convey organisational information, which can be created by using recollections of product histories (Meyer and Utterback 1993; Meyer and Lehnerd 1997).

Wang et al. (2003) proposed a product family evolution model as an extension of the core product model (CPM), which consists of family, evolution and rationale. Le, Sha, and Panchal (2014) developed a generative network computational model for product evolution based on different mechanisms of networks evolution. Kim, Lee, and Jung (2016) used an agent-based model (ABM) to identify that the velocity of product evolution increases. Dou, Zhang, and Nan (2017) developed a dynamic model based on the Hegselmann–Krause model for analysing the changing trends of group opinions and the evolution regularity. Li et al. (2018) proposed a quantitative product evolution design model that is based on Bayesian networks to model the dynamic relationship between customer needs and product structure design. Because product changes have often triggered a change or a series of changes in its manufacturing system, a biological analogy is utilised to establish a co-evolution model. It can help understanding of the changes occurring within manufacturing and predicting co-evolution trends of new products/features and manufacturing systems based on available historical information and dual cladograms (ElMaraghy, AlGeddawy, and Azab 2008; AlGeddawy and ElMaraghy 2011, 2012; ElMaraghy and AlGeddawy 2012).

The existing studies above on the longitudinal and cross-sectional evolution of demands, products and manufacturing take snapshots of the states at different time steps and conduct predictive analyses in the field of PFE. Such approaches are subject to the capacity of their prior PFA and PFK models so that they might miss a big picture of underlying product evolution. Commercial product lifecycle management (PLM) systems can provide limited support to this PFE area, however they focus on data and process management during the lifecycle development of a single product, rather than on entire families' derivation history (Sudarsan et al. 2005). Thus, it is demanding to model a product family in a new way centring on the design and manufacturing features and to develop a set of operational tools to record, track, analyse and predict dynamic product evolution in a broader product family, and to effectively support the design context knowledge and feature reuse.

To sum up, existing studies on product family modelling in terms of the architecture, knowledge and evolution modelling are limited to a specific product platform belonging to a manufacturing company. An appropriate method, which can build the evolutionary relationship of a set of related products and reuse product evolution knowledge, is much needed so as to make new product developments in a holistic way of sustaining production profit and growth. This new type of product family modelling can enable rapid product developments with hybrid innovations in new product development, but this has yet been well developed.

Here, we propose a new progressive modelling method for describing a product family and demonstrate its effectiveness with a prototype system - information system illustrating the new conceptual model based on a new product family concept-FCPF. This method not only facilitates the solution to the above problems but also helps progressively construct newly defined product family models.

3. Progressive modelling of product family

3.1. A new broader definition of product family

With the development of global economic integration, the customer demands (i.e. personalised and diversified demand) and market conditions (i.e. economical, technical, ecological, social and ergonomic) are rapidly changing, leading to form a huge product pedigree of horizontal diversities and vertical generations (Jørgensen 2009; Dou, Zhang, and Nan 2017; Pirmoradi and Wang 2011). The issue of knowledge management in product family design, that is related to an effective storage, sharing and timely retrieval of design reasoning and evolution information, has become more complicated and challenging (Lim, Liu, and Lee 2011). At the same time, the main structure of a product family is dynamically and constantly evolving along with the changes of market conditions and customer demands as time goes on, which is a spiral process (Pan et al. 2014). The time-dependent product family evolution caused by dynamic environments is shown in Figure 1.

Each square represents a product. At time t_0, a set of original base products (PF_0 or G_0 products) are developed with a set of base design features. At time t_1, new products can be developed by combining the base design features differently and become new members; Meanwhile, some new products need to be developed with some new features (newly created or borrowed from other products) to meet some requirements by new driving factors, so this set of products will create a new generation of products in the product family. In such a way of progression, a product family will be developed in an evolutionary fashion.

From a global environmental perspective, a range of factors including both internal and external factors of a firm contribute to the innovation development of products, which is the inherently international nature of the industry based on historical data (Pohl and Yarime 2012). From a knowledge reuse perspective, a feature is regarded as an information unit (element) that is described by an aggregation of properties of a product including their values and relations with respect to the classes of properties and to the phases of the product life-cycle, which is the vehicle to bring this information to the downstream applications for embodiment, analysis, detail part design, and assembly (Brunetti and Golob 2000).

However, the typical definition of a product family is difficult to support its exploration space in product innovation at the design feature level, for example, transferring or transforming design features associated with other product families into hybrid innovation. Therefore, it is necessary to consider time-dependent, globalised and feature-centred product family evolution into the definition of product family. We proposed a new broader definition based on the typical definition of product family. With reference to the original concept of product family, here we emphasise that *a product family is a set of time-dependent pedigree related products that share common feature-centred key knowledge yet targeting a variety of*

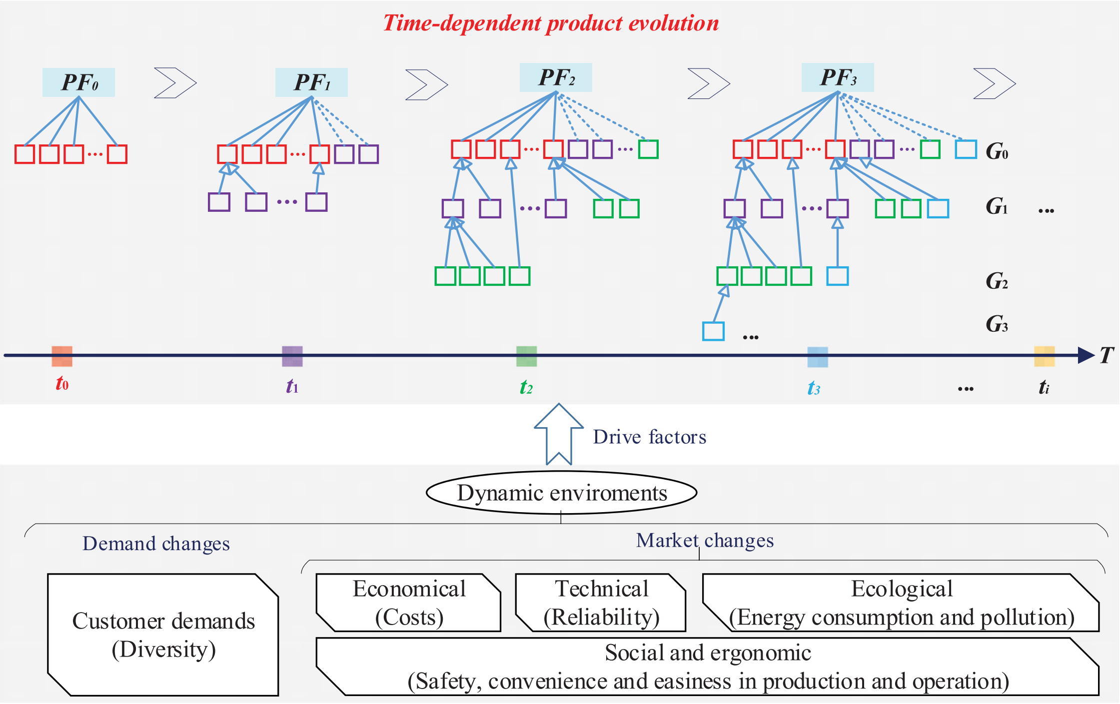


Figure 1. Time-dependent product family evolution caused by dynamic environments.

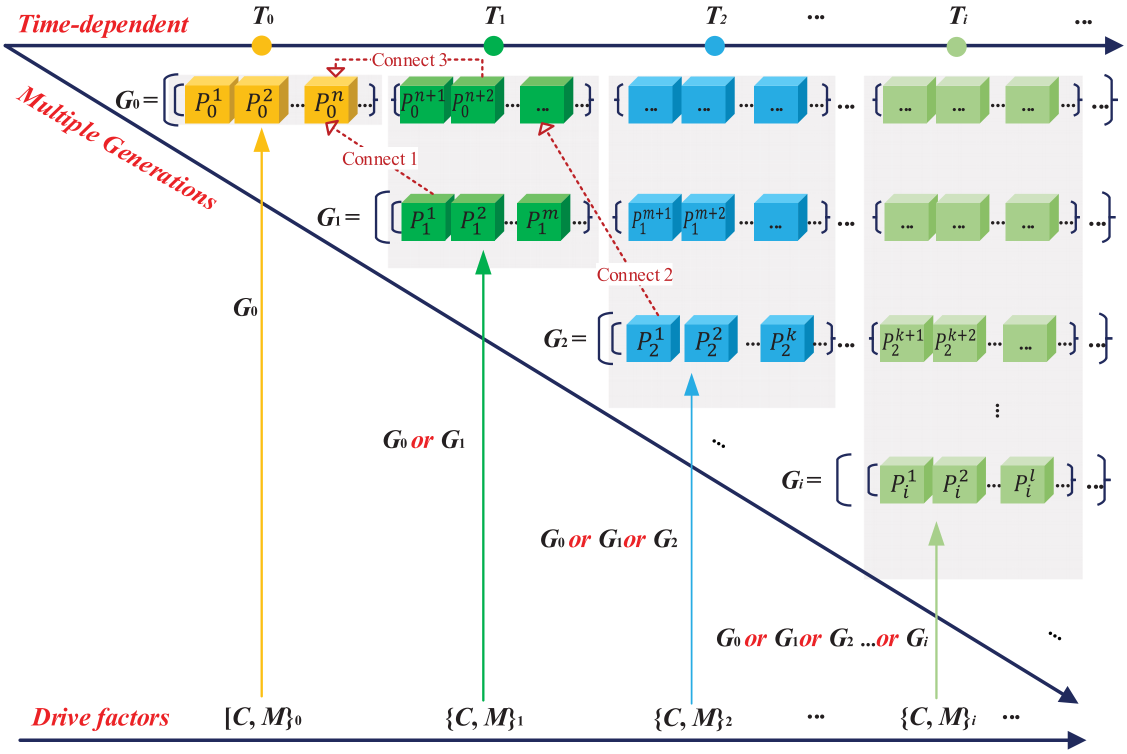


Figure 2. The progressive pattern of FCPF.

market conditions and customer demands within the global business horizon, which is called as FCPF (Feature-Centred Product Family).

Due to the demands of products, new products are normally developed based on an FCPF, there is an update and retrieval mechanism of features and knowledge in the development progress of FCPF. In our research, we take a broader view of a product family modelling, not centred on a product development platform typically belonging to an individual firm but on the sharing and evolution of key design features among relevant products. When developing a new product, both design (artefacts) and design knowledge reuse are based on not only products in the same product platform but also products on other platforms but in the same class or category. FCPF is capable of capturing a full set of knowledge of design reasoning and evolution rules, which is not only helpful to full understanding of the original base design and the design of their predecessors, but also important from the standpoint of improving quality and maintainability, and can play such a key role in sustaining profit and growth (Wang et al. 2003). In the next section, we will explain how an FCPF is progressively developed and modelled.

3.2. Progressive modelling of FCPF -(PMfFCPF) development

3.2.1. The progressive pattern of FCPF

Such dynamically and constantly changeable environment of market conditions (M) and customer demands (C) urges the need for developing a new evolving modelling paradigm for FCPF. Progressive modelling (PM) is a forward-looking multi-disciplinary modelling approach (Ismail 2013) that can address and represent time-dependent (t) product (P) developments in multiple generations (G) driven by dynamic development environment (Figure 1) such as changing C, M and their combinations$\{C, M\}$ (see Figure 2). Note that the driving factors for developing new products are many (Dou, Zhang, and Nan 2017). In this paper, the progressive pattern of FCPF is proposed as shown in Figure 2, for simplifying the representation in which only C and M are indicated.

As shown in Figure 2, progressively constructing a product family graph (or tree) is from the beginning (or time 0). Each node on the product family graph contains some design-context, rationales and feature statements. Along the time line, new generational products are developed by inheriting some features from products in previous generations.

At time t_0, the first generation product set G_0 is produced under the influence of the driving factor $[C, M\}_0$, however, G_0 is an open set which may be expanded constantly along the time. At time t_1, the requirements driven by factors $\{C, M\}_1$

can be resulted from two sets of products via two development paths. The first path is to generate the second generation product set G_1 with new features and G_1 is also open set. The second path is to reconfigure previous features to generate the previous generation products such as G_0. The parents' node of products of G_1 at time t_1 is the products of G_0 at time t_0, and the products of G_0 at time t_1 become the brothers of the products of G_0 at time t_0 and can be added to the open set G_0. Both brothers and parents relationships are time-dependent. Similarly, at time t_2, as a result of new requirements driven by $\{C, M\}_2$, three sets of products belonging to G_0, G_1 and G_3 respectively can be developed. At each subsequent time, FCPF continues to evolve in accordance with this progressive pattern. With the changes in customer demands and market conditions, the FCPF constantly update with new generational products and enhanced previous generational products. Each generation of products can be expanded along the time.

3.2.2. The progressive modelling construction method of FCPF

The PM*f*FCPF is a structural construction method that describes the relationships between the inheritance and variation of the essential characteristics (features) of design elements (things). Its visual representation is shown in Figure 3 for constructing a graph. For example, a family pedigree describes the inheritance and variation relationship of a family from the beginning of ancestors of a certain generation to descendants at a certain time. With reference to the progressive pattern of FCPF (see Figure 2), the progressive modelling (or construction) method of FCPF or PM*f*FCPF can be described as in Figure 3 by two-step operations. The first step construction is operated at time t_0 and the second step is operated at time t_i ($i = 1, 2 \ldots$) progressively and repeatedly with reference back to existing construction generated from time t_0 to t_{i-1}. At any time, we take two driving factors: C and M as exemplars. The combinations of $\{C\}$ and $\{M\}$ is represented as $\{C, M\}$, C and M together with product design specification (PDS), product (P), key design features (f) and development time (t) are represented in Figure 3.

Figure 3 shows the mappings among $\{C, M\}$, $\{PDS\}$, $\{f\}$ and the same generational product $\{P\}$ in the horizontal direction with time signatures and the progressive development of products with new feature elements $\{f\}^i$ in the vertical direction with generation signatures. There are four core problems should be solved in the construction process of this model, which are (1) how to define the mappings for the first generation product, which mainly focuses on the mappings from PDS to f; (2) at time t_i, how to expand the previous generational products (in the sense of refashion, old features but new combinations at a new time) with previous generational features or produce products for a new generation with new features, which mainly focuses on the progressive development of new products, (3) at time t_i, how to position the newly designed product on the pedigree graph of a FCPF and present their relations with others, and (4) how to graphically present the new product's relations with others. Therefore, the progressive modelling method aims to resolve these four core problems.

The PM*f*FCPF for a known product category can be detailed as follows:

Step 1: Create the market segment, *PDS* vector and *f* vector

It is necessary to create market segments (S) that extracting the driving information from C and M *of* a certain product. The S is formed by combining comprehensive evaluation with clustering analysis, as follows:

$$\mathrm{S} = \{\mathrm{C_i}, \mathrm{M_j}\} = \{\mathrm{C_1}, \mathrm{C_2}, \cdots, \mathrm{C_i}\} \cup \{\mathrm{M_1}, \mathrm{M_2}, \cdots, \mathrm{M_j}\} \tag{1}$$

From a PDS for the conceptual design of a product, construct a requirement space. All requirement (specification) elements (or variables) of market segments (E) are listed as an initial input vector. Each element is assigned a weight value to describe its degree of importance (W). PDS is called as the driving impactor of the progressive modelling, then at time t_i, PDS is described as follows:

$$\mathrm{PDS}^i = E \times W^T \tag{2}$$

where $E = [e_1, e_2, \ldots, e_n]$ and $W = [w_1, w_2, \ldots, w_n]$, then $PDS^i = \{PDS_1, \ldots, PDS_m, \ldots\}$.

In this paper, we use the f instead of the general terms to describe the product and part design information that significantly influences on product functions, performances, and quality. The f can better support adaptive design that is the most important pattern of complex product design, which helps designers focus on a small set of critical design features to rapidly develop an adaptive design scheme by reusing f-based design knowledge. Therefore, how to build an f-vector becomes an important issue in the complex product adaptive design. Previous design knowledge, case studies, and data usages are main sources for the construction of f. The f is called as genetic impactors of progressive modelling, then at time t_i, f is presented as follows:

$$f^i = \{f_1, f_2, \cdots, f_\mathrm{u}, \cdots\} \tag{3}$$

Figure 3. The construction method of PM*f*FCPF.

Step 2: Develop the mapping from *PDS* to *f*

At the end of step 1, the *PDS* and *f* are listed and distributed in a vector, then analyse the relationships between the vector *f* and the vector *PDS* and establish the mapping M_1. M_1 can be structurally viewed and established from design knowledge and experience (Zhang et al. 2016). Its element a_{ij} ($i = 1$ to n; $j = 1$ to u) describes the correlation relationship (the value is between 0 and 1) between the element S_i in S and the element f_j in f.

$$M_1 = \begin{bmatrix} a_{11} & \cdots & a_{1\mathrm{u}} \\ \vdots & \ddots & \vdots \\ a_{\mathrm{n}1} & \cdots & a_{\mathrm{nu}} \end{bmatrix} \tag{4}$$

The accuracy of correlation matrix is important because they affect design scheme selections and evaluations, but it is difficult to guarantee because it is established based on the accuracy of design knowledge and experience expression. However, there are some methods, which can help avoid false correlation. For example, the grey relational analysis method (Kuo, Yang, and Huang 2008) can describe the strength of relations between factors by the grey relational degree, which is a kind of order relation model. It can be used to deal with factor analysis problems and is suitable for dealing with poor, incomplete, and uncertain information systems.

The mapping M_1 between *PDS*-vector and *f*-vector can be then used for the key design features scheme (f_{scheme}) generation and evaluation. The element f_j^w is the value to reflect on relative correlations to the weighted design requirement space.

$$f_{\text{scheme}} = W \times M_1 = [w_1, w_2, \cdots, w_n] \times \begin{bmatrix} a_{11} & \cdots & a_{1\text{u}} \\ \vdots & \ddots & \vdots \\ a_{\text{n}1} & \cdots & a_{\text{nu}} \end{bmatrix} = [f_1^w, f_2^w, \cdots f_u^w] \tag{5}$$

The element f_j^w with the biggest value in f_{scheme} suggests that the feature scheme f_j can possibly support the key functional requirements and have the best overall support to other design requirements.

A group of f_j should be combined to a product (P), at time t_i, $FCPF^i$ is described as follows:

$$\text{FCPF}^i = \{P_1, P_2, \cdots, P_n, \cdots\}^i \tag{6}$$

where $P = [f_1, f_2, \cdots, f_i]$.

Step 3: Positioning and defining the new product node in the family tree

The goal of this step is to position and define a new product node in the family tree. This is based on a generic mapping relation analysis on how the product offerings in one generation or next generation, and focuses on identification of either a brother relationship (with a horizontal positioning) among the same generational products and a parent relationship between the offspring and its prior generational products (with a vertical positioning), respectively. The relationships can be graphically represented (detailed in step 4), allowing us to track the evolution of product families from one generation to another (vertically) and refashioning of previous products to the newly design product (horizontally). The features referenced to other product families are treated as new ones in the product family while this reference information will be recorded in the node information and displayable.

Features are regarded as the core of all variation and evolution management (Reiser and Weber 2007). The positioning starts from evaluating what makes the new design. If new design and manufacturing features have been brought in the new design, it will progress into a new generation. If the new design is only resulted from a new combination of existing features on the previous generations, it will be progressed as a member of one of previous generations.

The FCPF progresses in both horizontal and vertical directions. Due to the change of PDS, a new product design is needed. With reference to the product family modelling, if the new design can be realised by a new combination of a set of design features $\boldsymbol{f}$ from a previous generation, the model progression direction is horizontal along the time dimension, and a new product node on the previous generation will be generated (See Figure 2). If the new design needs to be realised with new features, which could be combined with some of the previous generation $\boldsymbol{f}$, then the model progression direction is vertical and a product node should be created as a new next generation node generated (See Figure 2).

In this process, $\boldsymbol{PDS}$, $\boldsymbol{f}$ and $\boldsymbol{P}$ are changing time-dependently, the model progression rules can be summarised as follows:

- Horizontal Rule: If $\forall \text{PDS}^i \oplus f^0$ or $\text{PDS}^i \oplus (f^0 + f^1)$ or $\cdots$ or $\text{PDS}^i \oplus (f^0 + \cdots + f^{i-1})$, generate $\{P_u\}$ or $\cdots$ or $\{P_v\}$; then $\text{FCPF}^0 = (P_1, \cdots, P_n, P_{n+1}, \cdots, P_{n+u}, \cdots)$ or $\cdots$ or $\text{FCPF}^{i-1} = (P_1, \cdots, P_k, P_{k+1}, \cdots, P_{k+v}, \cdots)$.

$$\text{Vertical Rule: if } \forall \text{PDS}^i \oplus (f^0 + \cdots + f^i), \text{ generate } \{P_1\}; \text{ then } \text{FCPF}^i = (P_1, P_2, \cdots, P_1, \cdots).$$

Step 4: Construct the pedigree graph of FCPF

Based on the above positioning rules, a pedigree graph of FCPF can be constructed and presented graphically. Firstly, cluster several or more products in the first generation to generate a root node at t_0 (See Figure 3). Secondly, at t_i, if a new product is positioned by the horizontal rule, then the node of the new product will be put into the corresponding set of $FCPF(G_k)$ $(k < i)$; if the new product is positioned by the vertical rule, then the node of new product will be put into the new set of $FCPF(G_i)$. Finally, according to the similarity of the key design features set $P = [f_1, f_2, \ldots, f_i]$ between the new and old products, the parent or brother connection will be described.

The f can be classified into two categories: symbolic and numerical. The similarity between the features of the symbol metrics and Boolean metrics is measured using Jaccard's similarity coefficient (Niwattanakul et al. 2013). For the numerical features, one-dimensional relative distance is used to calculate the similarity between the two feature sets. The similarity of design features between the new and old products can be calculated by Equation (7).

$$S(P_{\text{new}}, P_{\text{old}}) = \sum_{i=1}^{m} w_i g \frac{f{b_{\text{P}_{\text{new}}}^i} \cap f{b_{\text{P}_{\text{old}}}^i}}{f{b_{\text{P}_{\text{new}}}^i} \cup f{b_{\text{P}_{\text{old}}}^i}} + \sum_{j=1}^{n} w_j g \left(1 - \frac{|f{d_{\text{P}_{\text{new}}}^j} - f{d_{\text{P}_{\text{old}}}^j}|}{\max(f{d_{\text{P}_{\text{new}}}^j}, f{d_{\text{P}_{\text{old}}}^j})} \right) \tag{7}$$

In (7), w_i, w_j – the weight of the symbol and numerical features, $\sum_{i=1}^{m} w_i + \sum_{j=1}^{n} w_j = 1$; $fb^i_{P_{\mathrm{new}}}, fb^i_{P_{\mathrm{old}}}$ – the i-th symbolic parameter value in the object P_{new}, P_{old}; $fd^j_{\mathrm{P}_{new}}$, $fd^j_{\mathrm{P}_{old}}$ - the j-th numeric parameter value of the object P_{new}, P_{old}.

The Max$\{S\ (P_{new}, P_{old})\}$ will indicate either a parent or a brother connection between P_{new} and P_{old}. The parent connection can be to the adjacent generation or inter-generation such as connect 1 or 2 in Figure 2. The brother connection can be to the same generation such as connect 3 in Figure 2.

Every one connection in the product family graph implies the information of features evolution along either vertical or horizontal direction. These information is not only useful in the identification of common and adaptive features in longitudinal of a product's evolution, but also the max features set and value domain of features in cross-sectional. It is helpful to support the generation of new products. Currently, our research is focusing on the analysis and visualisation of the information of connections in the pedigree graph of FCPF to show a big picture and information of underlying product evolution on entire families' derivation history. The detail analysis as follows:

(1) Cross-sectional analysis

The horizontal direction of same generation products describes a number of products derived from the configuration/variant design of same generation feature set, as follows:

$$\{f_1, f_2, \dots f_v\}^i \xrightarrow{\text{configuration design}} \begin{cases} \{f_1, f_3, f_5 \dots f_k\} = P_1 \\ \{f_1, f_2, f_5 \dots f_l\} = P_2 \\ \{f_2, f_3, f_6 \dots f_m\} = P_n \end{cases} \xrightarrow{\text{variant design}} \begin{cases} \{\Delta f_1, f_3, \Delta f_5 \dots \Delta f_k\} = P'_1 \\ \{f_1, \Delta f_2, f_5 \dots \Delta f_l\} = P'_2 \\ \{\Delta f_2, \Delta f_3, \Delta f_6 \dots f_m\} = P'_n \end{cases} \tag{8}$$

For each generation, there is a corresponding max set of design features $\{f_1, f_2 \ \dots, f_v\}$, which can serve as a generational referring model together with default properties of each feature and their ranges of property values. Each configuration design product such as $P_1 = \{f_1, f_3, f_5, \dots, f_k\}$ in the same generation is resulted from a different configuration of those key design features. Furthermore, each configuration design can be further fine turned into several variant design products such as $P_1{}' = \{\Delta f_1, f_3, \Delta f_5, \dots, \Delta f_k\}$ by changing the attribute values of each feature. Thus, the referring model that is the max set of design features needs to be obtained, which is the basis for product progression, configuration and variant design.

Based on the PM*f*FCPF providing the feature information of product nodes, we can obtain the max-*f* set of anyone generation *Gi* and the value domain of features in the pedigree graph of FCPF, as follows:

$$\text{Max-}f\,(\mathrm{G}_i) = \cup_{j=0}^{n}(P_i^j) = \{f_1, f_2, \cdots, f_v\}^i \tag{9}$$

According to the max-*f* set, furthermore differentiation of the products is formed by using basic variety generation methods such as attaching/removing, swapping and scaling (Du, Jiao, and Tseng 2001). Actual, through this analysis, the unused space in either feature combinations or feature value variations can also be obtained. This unused space information can guide a new variant design direction and space information to meet the diversity and personality customers' requirements.

(2) Longitudinal analysis

The vertical direction of different generation products describes a number of products derived from the inherit/upgrade/innovation design of a previous generation feature set, as follows:

$$P_i^j = \{f_1, f_3, f_5, \dots f_k\} \begin{matrix} \xrightarrow{\text{inherit}} \\ \xrightarrow{\text{upgrade}} \\ \xrightarrow{\text{innovation}} \end{matrix} \left. \begin{matrix} \{f_1, f_5, \dots f_s\} \\ \{\uparrow f_3, \uparrow f_6, \dots \uparrow f_l\} \\ \{f_{k+1}, f_{k+2}, \dots f_s\} \end{matrix} \right\} \xrightarrow{\text{hybrid}} P_m^n\{f_1, \uparrow f_3, f_{k+1} \dots f_u\} \tag{10}$$

For different generation, each new product such as $P_m^n = \{f_1, \uparrow f_3, \cdots f_{k+1}, \cdots f_u\}$ in the next generation is resulted from an evolution design of those products $P_i^j = \{f_1, f_3, f_5, \cdots, f_k\} (i < m)$ in the previous generation, such as inherit design features $\{f_1, f_5, \cdots f_s\}$, upgrade design features $\{\uparrow f_3, \uparrow f_6, \cdots, \uparrow f_l\}$, and innovation design features $\{f_{k+1}, f_{k+2}, \cdots f_u\}$. Furthermore, each design can be further hybrid into new products such as $P_m^n = \{f_1, \uparrow f_3, \cdots f_{k+1}, \cdots f_u\}$ in the next generation. The three mechanisms to support feature changes are to add features, delete features, inherit features and improve features, which provide different insights into how the products grow in variety and complexity and allow feature level hybrid innovation. However, it is possible to define other types of mechanisms to support feature changes. Our approach can be easily extended to handle the new types of feature changes.

Thus, the parent connection information that is sets of common and adaptive features should be obtained to detect feature changes in a family between different generations, which is the basis for product progression and evolution design. Based

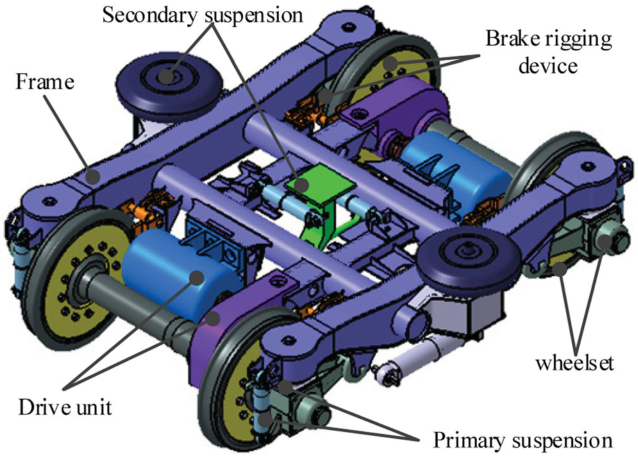


Figure 4. High-speed train's bogie.

on feature information, the common technology features(C-*f*) and adaptive technology features (A-*f*) can be refined and accumulated with each generation of product updates, as Equation (11) and (12), respectively:

$$\mathrm{C\text{-}f} = \cap_{i=0}^{n} \mathrm{FCPF}(\mathrm{G}_i) = \{f_1, f_2, \cdots, f_u\}^{\mathrm{C}} \tag{11}$$

$$\mathrm{A\text{-}f} = \cup_{i=0}^{n} \mathrm{FCPF}(\mathrm{G}_i) - \cap_{i=0}^{n} \mathrm{FCPF}(\mathrm{G}_i) = \{f_1, f_2, \cdots, f_v\}^{\mathrm{A}} \tag{12}$$

In the future, C-*f* is helpful to improve the performance and maintenance of a product, and A-*f* is helpful to capture and predict the evolution rules and accelerate the development of the evolving product.

4. Case study – high speed train's Bogie

4.1. Case background

With the operation of high-speed railways in various countries around the world, high-speed train as a typical complex product system, which have a large number of demands throughout the world, and its demands are characterised by high completeness and openness, including differences in operating conditions, geographical environments, climates, scales, cultural and religious environments, standards, etc. Bogie is the most important component of the high-speed train connecting the train coach body to the rail tracks since the rationality of its design directly affects the operation quality and safety of high-speed train, as shown in Figure 4 (Zhang et al. 2017).

With the development of personalised and diversified demands and technology level of high-speed train's bogie, the bogie not only shows a vertical generational relationship but also becomes diverse horizontally, which will form a product family pedigree and challenge for the existing research and development model of bogie. Meanwhile, the knowledge accumulation and reuse of the bogie is not enough, resulting in a large number of repetitive work in the process of repeated design and modification. To solve the above problems, we need to improve the research and development efficiency of bogie to adapt to the complex and changeable global market demand.

4.2. Architecture of the PMfFCPF-based information system

The traditional commercial Product Lifecycle Management (PLM) and Product Data Management (PDM) provide limited support in this area, which mainly focus on data and process management during the development lifecycle of a single product, rather than on entire families' derivation history (Sudarsan et al. 2005). However, such information is important for improving the performance and maintenance of the product and aiding making decision. There is a need to establish an information system for FCPF. Based on the PM*f*FCPF and combined with the knowledge management and visualisation technologies, the system architecture is built as shown in Figure 5.

In this architecture, the data layer is regarded as a foundation in the information system and supports the function layer. All products related data including system knowledge, target knowledge and transformation knowledge are called as the innovation knowledge. In the construction and analysis process of PM*f*FCPF, the knowledge needs to be captured and reused including PDS, features, products, mapping rules, progressive rules, product relationships, etc. This layer provides the functions with data capture, sharing, reuse and storage. Function layer consists of functions such as creating product

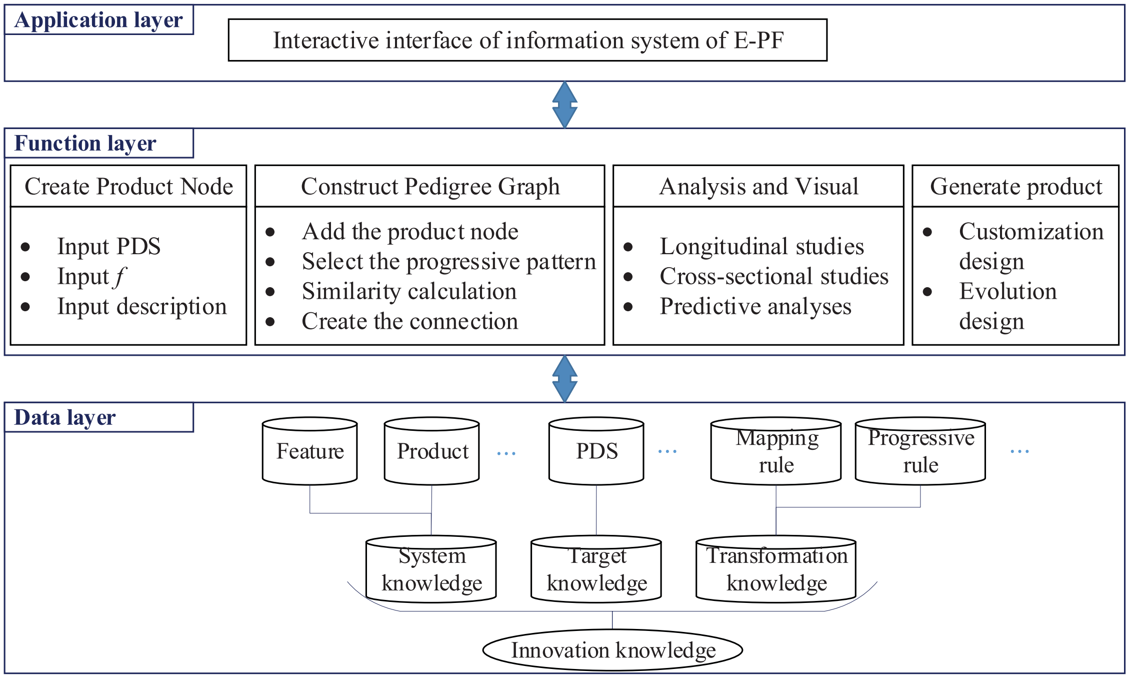


Figure 5. The architecture of information system based on PM*f*FCPF.

nodes, constructing a pedigree graph, conducting analysis and visualisation, and generating products, which are supported by the construction, visualisation and application tools of PM*f*FCPF. In this paper, we mainly focus on three function modules, which are explained and developed during the case study.

4.3. Illustration examples

On the basis of the analysis of the characteristics of common and adaptive technology of high-speed train products, the PMfFCPF is constructed as follows:

(1) Create product node

In this module, the product node which should be integrated is identified in association with the PDS, related features and description, the interactive interface is shown in Figure 6.

Firstly, we need to create the product node information, including product node name, creator, creation time, and description. To build the progressive context of the high-speed train' bogie by analysing the information specific product models, years of use, and speed grades, which includes the Japan Shinkansen series, the German ICE series, the French TGV series, and the China CRH series. The product node information is drawn from several countries and is shown in Table 1 as follows:

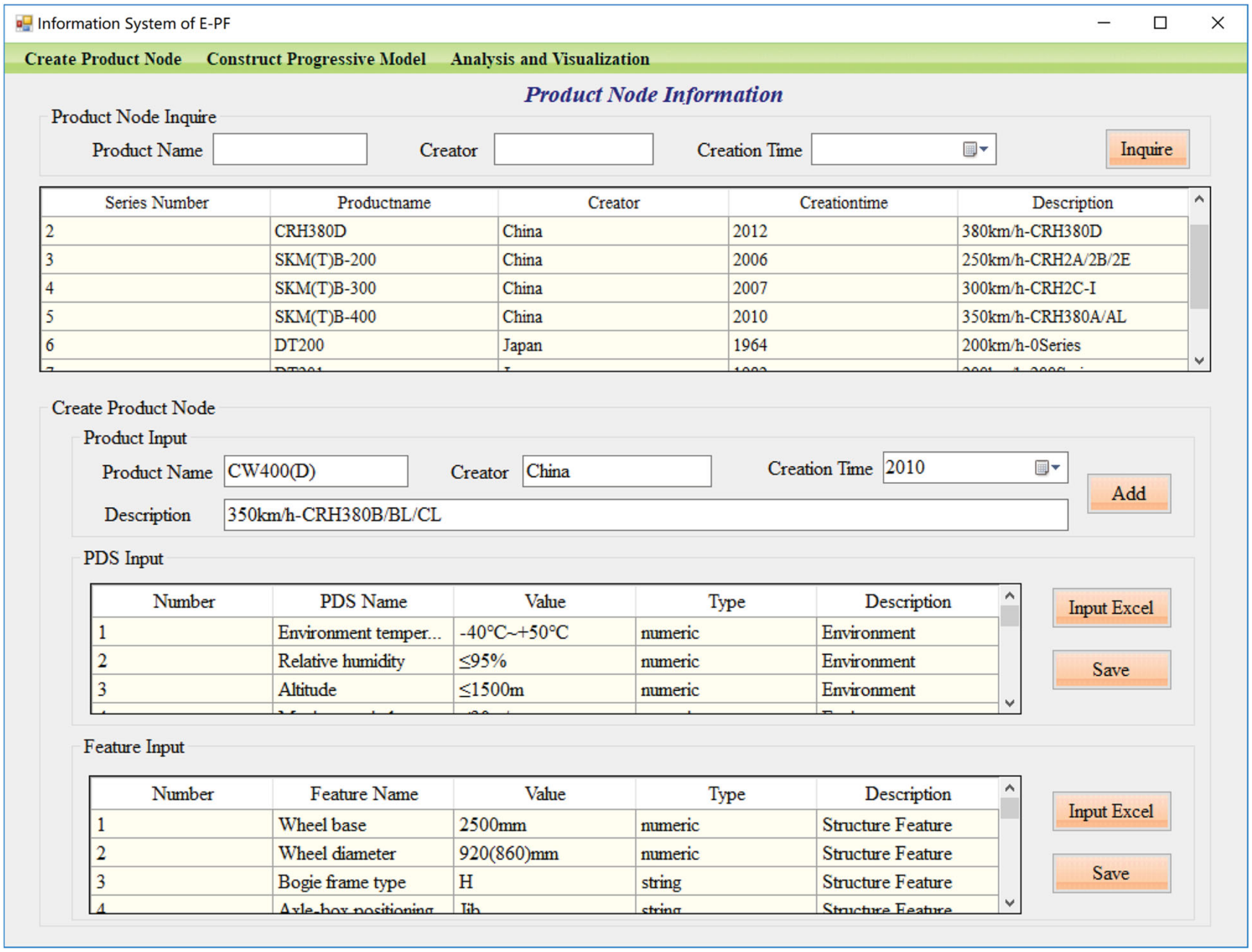
Secondly, we need to create the PDS of high-speed train's bogie. The market segments are formed by extracting the driving information of C and M of high-speed train's bogie, including environment type, speed level, line gauge, running distance, standard requirement, etc. The core and necessary demand features of products are extracted from the complex and diversified demands of high-speed train's bogies. An example of bogie's PDS is shown in Table 2 as follows:

Thirdly, we need to create the features of high-speed train's bogie. The key design features set should obtain the functional features, behaviour features, structural features, performance features, material features, interface features, etc. An example of key design features of bogies is shown in Table 3 as follows:

(2) Construct pedigree graph

Firstly, the product node information is added by selecting the time interval and creator, which shows the number of product node. According to the model progression rules, the new products will be continuously joined in the FCPF depending on the creating time, and the connection relationships of products are created based on the similarity calculation of feature between new product and old products. The interactive interface of constructing the progressive modelling graph of FCPF is shown in Figure 7.

High-speed train's bogies from 1960 to 2015 in Japan are divided into three generations based on the vertical rule. The first product-DT200 was designed in 1964, then based on the horizontal rule, DT201 and DT202 were designed to improve



Product Node Information

Product Node Inquire

Product Name:
Creator:
Creation Time:

Series Number	Productname	Creator	Creationtime	Description
2	CRH380D	China	2012	380km/h-CRH380D
3	SKM(T)B-200	China	2006	250km/h-CRH2A/2B/2E
4	SKM(T)B-300	China	2007	300km/h-CRH2C-I
5	SKM(T)B-400	China	2010	350km/h-CRH380A/AL
6	DT200	Japan	1964	200km/h-0Series

Create Product Node

Product Input

Product Name: CW400(D)
Creator: China
Creation Time: 2010
Description: 350km/h-CRH380B/BL/CL

PDS Input

Number	PDS Name	Value	Type	Description
1	Environment temper...	-40°C~+50°C	numeric	Environment
2	Relative humidity	≤95%	numeric	Environment
3	Altitude	≤1500m	numeric	Environment

Feature Input

Number	Feature Name	Value	Type	Description
1	Wheel base	2500mm	numeric	Structure Feature
2	Wheel diameter	920(860)mm	numeric	Structure Feature
3	Bogie frame type	H	string	Structure Feature
4	Axle-box positioning	Jib	string	Structure Feature

Figure 6. The interactive interface of creating product node.

the performance and adapt to the new environment, which constituted the first generation. Based on the first generation products, the second generation products are generated by adding the new features, then according to the time, the product are listed including TDT203, DT204, DT205, DT206, WDT205, DT207A, TDT204 and DT208. In the same way, the third-generation products were designed including TDT205, DT209, and DT210A. Finally, these products are connected between the different generations by the similarity calculation of features between new and old products. The product node information, longitudinal and cross-sectional relationship will be visually analysed in the next section.

(3) Analysis and visualisation

Based on the progressive modelling graph of FCPF, we can analyse the longitudinal generation relationship of a product's evolution, and the cross-sectional constitute relationship and value domain of features. According to Figure 7, the progressive modelling graph of high speed train's bogie from 1960 to 2015 in Japan, we get the result of longitudinal and cross-sectional analysis as shown in Figure 8.

In Figure 8, in the cross-sectional analysis, we can obtain the key design features set of any one generation and the value domain of features, for example, the max key design features set of first generation is the features union of DT200, DT201 and DT202, the value domain of tread is 1/40 taper and curve due to the value of tread DT200 is 1/40 taper and DT201 and DT202 are curve, and the value domain of wheel base is same as 2500 mm.

In product variant design, for example, the different values of the axle weight feature generate various product variants such as DT200 (16t), DT201 (16.4t) and DT202 (15t), and the different combinations of brake features generate various configuration designs such as DT200 (split wheel brake disc and air unit brake cylinder) and DT 202 (wheel brake disc and eddy brake disc).

In the longitudinal analysis, we can obtain the common features and added or deleted features between the different generations, for example, the central suspension structure G1 has the bolster feature, while, G2 deletes the bolster feature

Table 1. The product node information of high-speed train’s bogie (Zhang 2017).

Number	Product name	Creator	Creation time	Description
1	DT200	Japan	1964	200 km/h-0 Series
2	DT201	Japan	1982	200 km/h-200 Series
3	DT202	Japan	1985	200 km/h-100 Series
4	TDT203	Japan	1992	270 km/h-200 Series
5	DT204	Japan	1992	240 km/h-400 Series
6	TDT204	Japan	1999	350 km/h-700 Series
7	WDT205	Japan	1997	350 km/h-500 Series
8	DT205	Japan	1996	240 km/h-E1 Series
9	DT206	Japan	1996	275 km/h-E2 Series
10	DT207A	Japan	1997	275 km/h-E3 Series
11	TDT205	Japan	2007	350 km/h-N700 Series
12	DT209A	Japan	2016	320 km/h-E5 Series
13	DT210A	Japan	2013	320 km/h-E6 Series
14	MD52	Germany	1974	200 km/h
15	MD530	Germany	1982	250 km/h-ICE1
16	SF400	Germany	1997	280 km/h-ICE2
17	SF500	Germany	2002	330 km/h-ICE3
18	Y230	French	1981	270 km/h-TGV-PSE
19	Y230	French	1989	300 km/h-TGV-A
20	Y237-A	French	1996	300 km/h-TGV-2N
21	CRH1	China	2007	250 km/h-CRH1A/1B/1E
22	CRH380D	China	2012	380 km/h-CRH380D
23	SKM(T)B-200	China	2006	250 km/h-CRH2A/2B/2E
24	SKM(T)B-300	China	2007	300 km/h-CRH2C-I
25	SKM(T)B-350	China	2010	350 km/h-CRH2C-II
26	SKM(T)B-400	China	2010	350 km/h-CRH380A/AL
27	CW250(D)	China	2006	250 km/h-CRH5A
28	CW300(D)	China	2007	300 km/h-CRH3C
29	CW400(D)	China	2010	350 km/h-CRH380B/BL/CL
...	...	...	...	...

Table 2. An PDS example of high-speed train’s bogie (Zhang 2017).

Number	PDS name	Value	Type	Description
1	Environment temperature	$-40°C$ to $+50°C$	numeric	Environment
2	Relative humidity	$\leq 95\%$	numeric	Environment
3	Altitude	≤ 1500 m	numeric	Environment
4	Maximum wind speed	≤ 30 m/s	numeric	Environment
5	Salt fog intensity	0.01 g/m^3	numeric	Environment
6	Ice and snow intensity	1000 mm	numeric	Environment
7	Wind and sand strength	0.01 to 4 g/m^3	numeric	Environment
8	Running distance	Main line	string	Route
9	gauge	1435 mm	numeric	Route
10	Limit	GB 146.1	string	Route
11	slope	30‰	numeric	Route
12	Minimum curve radius	2200 m	numeric	Route
13	Maximum height	180 mm	numeric	Route
14	Line spacing	4.2 m	numeric	Route
15	The distance between the platform and the centre of the track	1750 mm	numeric	Route
16	Design speed	200–250 km/h	numeric	Performance
17	Axle weight	17 t	numeric	Performance
18	Braking deceleration	≥ 0.96 m/s^2	numeric	Performance
19	Braking distance	≤ 3200 m	numeric	Performance
20	Acceleration performance	0.5 m/s^2	numeric	Performance
21	Dynamic performance standards	GB/T 5599	string	Performance
22	Design life	20 years	string	Performance

Table 3. An example of key design features of high-speed train's bogie (Zhang 2017).

Number	Feature name	Value	Type	Description
1	Wheel base	2500mm	numeric	Structure
2	Wheel diameter	920(860)	numeric	Structure
3	Bogie frame type	H	string	Structure
4	Axle-box positioning	Jib	string	Structure
5	Braking device	2WMD/3AMD	string	Structure
6	Gearing device	Parallel cardan shaft /gear transmission	string	Structure
7	Traction device	Double lever	string	Structure
8	Tread	S1002	string	Structure
9	...	...	...	...
10	Carrying	—	—	Function
11	Transmission	—	—	Function
12	Direct	—	—	Function
13	...	...	...	...
14	Design principle	Independent non-pendulum bogie	string	Behavior
15	...	...	...	...
16	Design Speed	350 km/h	numeric	Performance
17	Life	30 years	numeric	Performance
18	Dynamics	GB5599	string	Performance
19	Comfort	≤ 2	numeric	Performance
20	...	...	...	...
21	Frame material	Weathering steel	string	Material
22	Axle material	EA4T	string	Material
23	Wheel material	ER9	string	Material
24	...	...	...	...
25	Bogie – Body	2500 mm	numeric	Interface
26	Bogie – Track	1363 mm	numeric	Interface
27	Axles – Axle boxes	130 mm	numeric	Interface
...	...	...	...	...

and adds the traction rods and centre pins feature. We can also find the inheritance or improvement of common features, for example, the design speed features are improved from the 200 km/h in the G1 to the 270 km/h in the G2.

Given an initial family of instantiated product feature sets, development of an evolving product then iteratively selects a product feature set from this family, evolves it by applying up to four types of feature changes, and adds the evolved product features set back to the FCPF. This process is helpful to accelerate the development of evolving products (Le, Sha, and Panchal 2014).

4.4. *Qualitative validation of the proposed modelling approach*

According to above case study, the qualitative validation of the proposed modelling approach is shown as Figure 9, including validation of concept, modelling method and key model progression rules, as follows:

(1) Validation of concept by product node information

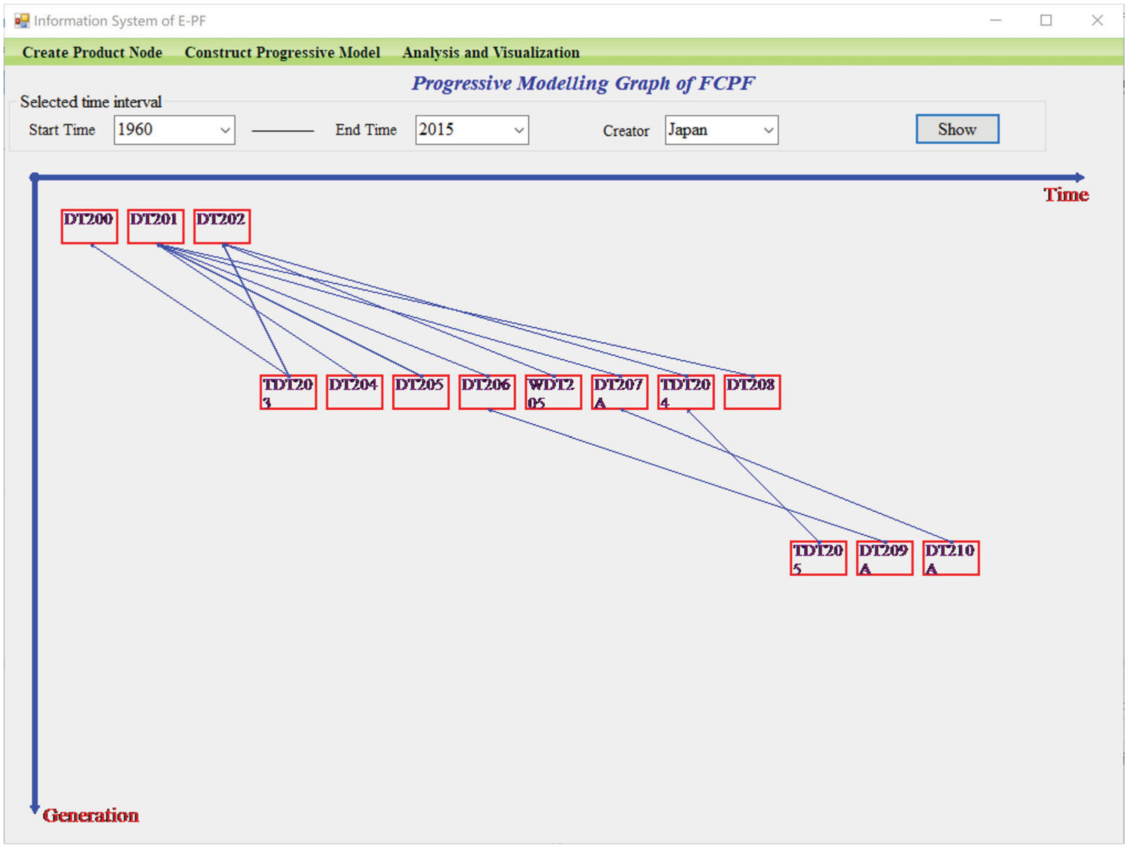
The creation of product node information as illustrated in Figure 6 shows that the FCPF can provide insight feature-level information between this product and other products on the other product families, such as bogie frame type feature.

(2) Validation of the progressive modelling method by generating pedigree graph of FCPF

Constructing the pedigree graph in Figure 7 follows four modelling steps to position and define the new product node in the family tree. Compared the progressive pattern of FCPF in Figure 2 with the pedigree graph in Figure 7 of high-speed train's bogie from 1960 to 2015 in Japan, we can see that the generated pedigree graph of FCPF is consistent with the progressive pattern, and that the brother and parent relationships of products in a whole product family are in the agreement with design experts' opinion.

(3) Validation of key rules by longitudinal and cross-sectional analysis

As described in the analysis and visualisation section (see Figure 8), after constructing a product family model, we can identify a full set of key design features in one generation and associated feature value domain by the cross-sectional analysis. Both the feature names and their value ranges are utilised in the following the longitudinal analysis. The core common and



Start Time 1960

End Time 2015

Creator Japan

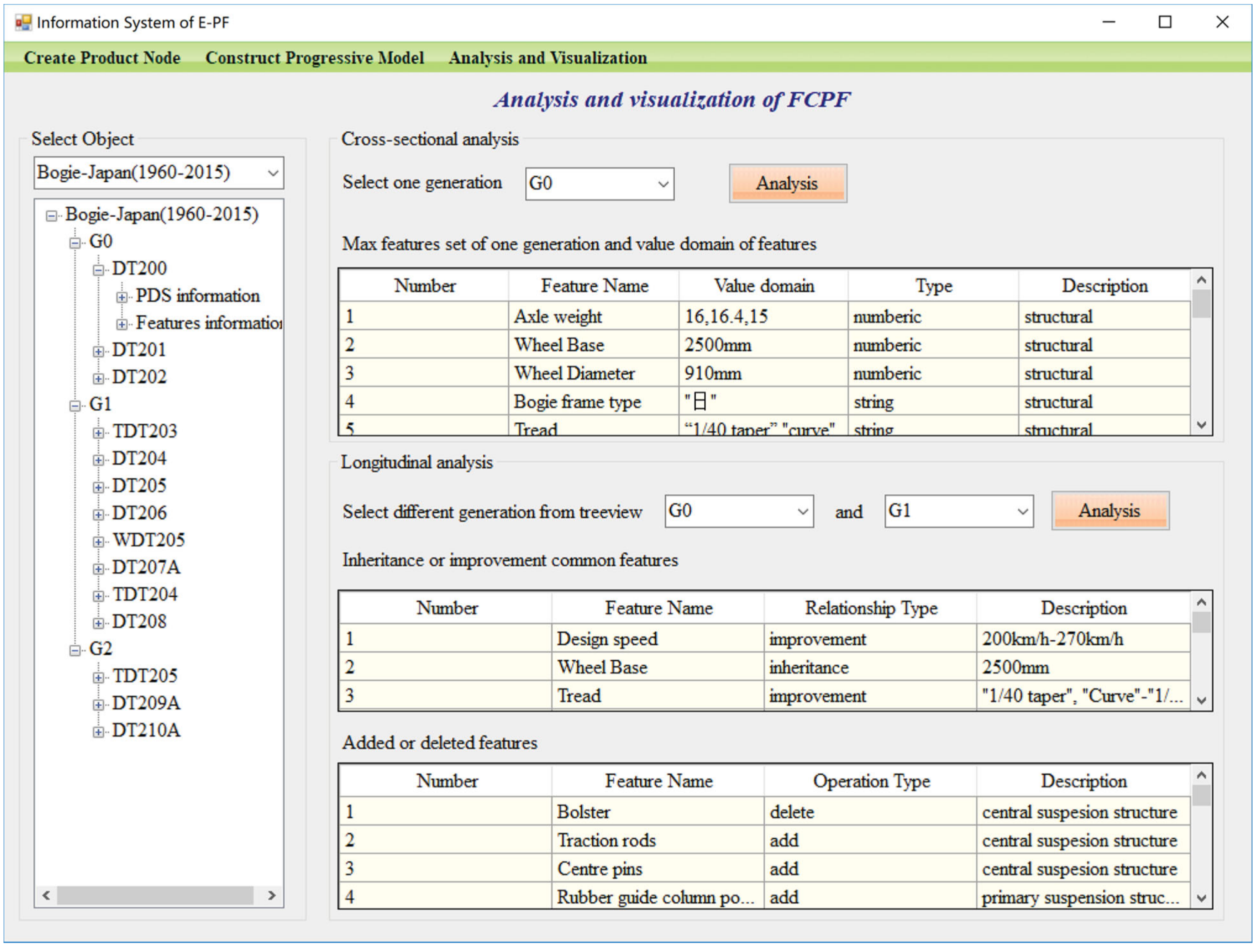
Figure 7. The interactive interface of construct progressive model.

adaptive features in different generations identified by the longitudinal analysis are used to indicate generational differences and describe evolution mechanism. For example, DT 201 and DT 202 are realised by adopting new feature values from the key design features in DT200, thus the model progression direction is horizontal along the time dimension. While TDT 203 is created with new added features such as central suspension structure and combined most features from DT202 and some from DT200. Thus the model progression direction is vertical and a new product node on the next generation is generated. This result shows that both the horizontal and vertical progression rules is workable.

5. Discussion

As demonstrated in the case study, we have obtained a progressive model graph and its graphical representation supported by progressive rules, cross-sectional and longitudinal analysis of the product family node with feature information. According to the development history of bogies for multiple units on Shinkansen in Japan (Yu 2012), the result is of coincident indicating that it is a feasible method and its prototype system is useful. It is worth noting that the accuracy of feature expression and the weighting of feature are important because they affect the similarity calculation, but it is difficult to guarantee. In general, if feature information is available or even triable, this method is feasible to get the accurate result. In fact, the similarity threshold for identifying a parent node can lead to multi inheritance relationships crossing generations, for example, a father node and a mother node. As shown in Figure 7, DT200 and DT 202 are identified as the father node and mother node or vice versa respective for TDT203. This happens because the DT200 and DT202 were developed independently during the same time period by two companies in two countries. They are grouped together as t_0 time products in the first generation and thus they don't have a brother relationship. We can summarise our observations as follows:

Firstly, this case study shows that our modelling method can progressively describe the evolution of products with a dynamic expression of a product family along the development time. It can also realises the common and adaptive analysis of key design features based on the concept of FCPF, which provides a new insight about this product family and this analysis could not be done before. The previous product family model schemes tend to organise product varieties at the modular/unit level of granularity in design such as functions, behaviours and structures (Jiao and Tseng 2000a; Meyer and Lehnerd 1997) which is based on a product platform normally belonging to a manufacturing company (Martin 2000).



Select Object: Bogie-Japan(1960-2015)

- Bogie-Japan(1960-2015)
  - G0
    - DT200
      - PDS information
      - Features informatio
    - DT201
    - DT202
  - G1
    - TDT203
    - DT204
    - DT205
    - DT206
    - WDT205
    - DT207A
    - TDT204
    - DT208
  - G2
    - TDT205
    - DT209A
    - DT210A

Cross-sectional analysis

Select one generation: G0

Max features set of one generation and value domain of features

Number	Feature Name	Value domain	Type	Description
1	Axle weight	16,16.4,15	numberic	structural
2	Wheel Base	2500mm	numberic	structural
3	Wheel Diameter	910mm	numberic	structural
4	Bogie frame type	"日"	string	structural
5	Tread	"1/40 taper" "curve"	string	structural

Longitudinal analysis

Select different generation from treeview: G0 and G1

Inheritance or improvement common features

Number	Feature Name	Relationship Type	Description
1	Design speed	improvement	200km/h-270km/h
2	Wheel Base	inheritance	2500mm
3	Tread	improvement	"1/40 taper", "Curve"-"1/...

Added or deleted features

Number	Feature Name	Operation Type	Description
1	Bolster	delete	central suspesion structure
2	Traction rods	add	central suspesion structure
3	Centre pins	add	central suspesion structure
4	Rubber guide column po...	add	primary suspension struc...

Figure 8. The interactive interface of analysis and visualisation.

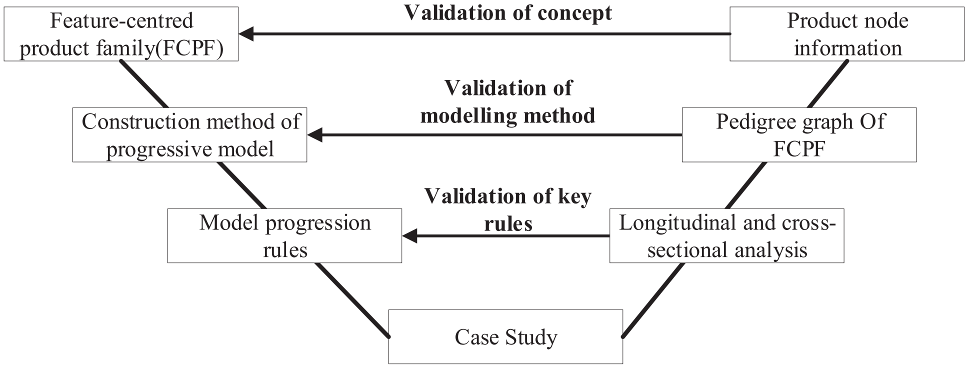


Figure 9. The qualitative validation of the proposed modelling approach.

Secondly, as shown in Reiser and Weber (2007), feature-based modelling has become a popular technique for domain analysis and variability management and allows local innovations. Our research follows this trend and promotes global innovations with new features from other reference products in a hybrid innovation process for a product family development. For example, the development of China standard high-speed train is by organically integrating the technology features of trains developed in Japan, Germany and French, into new product innovation.

Thirdly, existing studies on product family evolution design (ElMaraghy 2009; Meyer and Utterback 1993; Wang et al. 2003) and upgradable design (Umeda et al. 2005), can only provide product evolution information inside the product family. In contrast, our progressive product family modelling can also provide insight feature-level information between this product and other products on the other product families. The progressive product family model can be visualised based on different terms such as a development period (1960–2015) and feature origins (Japan) as shown in Figure 7. Therefore, using this model can help obtain a big picture of underlying product evolution within this product family and connections to other products in other families. In addition, based on our model, we can also analyse the core common and adaptive features among the products. This is important to evaluate the product family's ability by analysing commonality (Kota, Sethuraman, and Miller 2000) and generational variety (Martin 2000).

Finally, the advantage of organising the existing product family nodes in the progressive model graph is to realise the analysis of longitudinal and cross-sectional and prediction in the future and, finally, to further generate new products based on the knowledge reuse, and formalised information system of PMfFCPF. However, this perspective is not implemented in our current research yet and it will remain in one of our future work.

The limitation of this progressive modelling method is its ability to graphically illustration of product evolution relationships with a product belonging to the other product families. Although the method can support hybrid innovation by borrowing design features from products on the other product families, our product family tree (or graph) construction method can only graphically show the design feature evolution relationships to the products on its own product family. This feature inheritance information is current stored in the product node information but it is not able to graphically show its connection to a product from other families. This limitation in the future can be overcome by using three- or multi-dimensional modelling representation techniques.

6. Conclusions and future work

In this paper, a new progressive modelling method for a feature-centred product family architecture with a prototype system modelling tool has been proposed, which is significant for the automation of product family evolution analysis and consistent management of knowledge and feature information in the field of engineering design. Based on the proposed FCPF concept, the progressive pattern and construction methods of FCPF are presented as a framework to gain the progressive model graph, guide the longitudinal and cross-sectional analysis. This method can be used in engineering design of products or complex product systems with some domain knowledge support.

Our case study of high-speed train's bogie shows that (1) the proposed FCPF concept and PM*f*FCPF model are feasible and applicable in engineering design of complex product systems and (2) the development of information system based on PM*f*FCPF is a tool to realise the effective modelling and analysis.

As demonstrated in the case study, the implementation of the proposed modelling method requires more verified product instances and continues to complete the model. In the future, the progressive rules and similarity calculation method could be improved and a design knowledge base could be established to support AI-based generation of new products. The model could be able to recommend a set of features for a new product design based on the product design requirements and their automatic mappings to possible design features. Therefore, how to predict/determine future evolution and generate new products based on the proposed feature-centred modelling approach is one of our future work.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Dowell Company Project [grant number RCR00820]: modular design techniques for product family development of high-speed train Project; National Natural Science Foundation of China [grant number 51575461]; and National Key Research and Development Program of China [grant number 2017YFB1201102].

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