Aligning supply chain complexity with product demand and design characteristics

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ABSTRACT

This study models the alignment of supply chain complexity with product demand and design characteristics and formulates appropriate strategies to enhance supply chain alignment. An integrated theoretical framework linking all the three main constructs of supply chain complexity, namely coordination, collaboration and configuration, with product demand and design complexities is developed and empirically tested. Data were collected from a cross-industry sample of 273 Australian manufacturing firms and analysed using structural equation modelling. The results show that volatility of demand, product life cycle, and innovativeness directly impact on the complexity of supply chain collaboration. Product modularity, on the other hand, is more likely to indirectly influence supply chain collaboration through the mediating role of coordination. Higher complexity in product demand and design characteristics increases complexity in supply chain coordination and configuration while reducing complexity in supply chain collaboration. Based on the findings, a taxonomy is proposed to provide a reference frame for practitioners to formulate appropriate alignment strategies to manage or mitigate risk associated with growing supply chain complexity.

KEYWORDS Product attributes; supply chain management; complexity; collaboration; coordination; alignment

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1. Introduction

Globalisation of production systems has significantly increased the complexity of global supply chains. It enables an access to cheaper resources and extends opportunities in previously restricted markets for companies (Roh *et al*., 2014), while simultaneously increasing business uncertainties and supply chain risks. The rapid transformation of supply chains from local to global supply networks necessitates an alignment strategy to tackle the growing complexity of supply chains arising from spatially fragmented production, distribution and consumption networks. In a globalised marketplace, manufacturing firms are increasingly required to produce a variety of products in the same production period, leading to shortened product life cycles. Rapid technological improvements, together with intense competition, have also resulted in more pressure on manufacturing firms to innovate in product development as a key feature of value propositions (Oke, 2013). Chand *et al*. (2018) identify the supply chain complexity drivers for Indian mining equipment manufacturing companies including number of suppliers and layers/tiers in the upstream, number of parts and product variety during operations in the mid-stream, and the changing needs and number/variety of customers in the downstream. Greater the number of components and operations in the supply chain, the higher the supply chain complexity (Dittfeld *et al.*, 2018). Increased diversity and volatility of customer demand, compressed lead time and complex supply chain networks (Connelly *et al*., 2013; Serdarasan, 2013) have significant impact on service quality provisions, operational efficiency and supply chain performance (Wilding, 1998).

A firm's capability to alter its products at a short notice to fulfil uncertain and highly diverse customer demand depends on the agility of its supply chain. A seamless alignment of product design and development to meet rapidly changing customer demand is needed to manage the effect of growing supply chain complexity. Highly responsive, transparent, and structurally aligned supply chains require an optimised configuration of supply chain, an efficient coordination of logistics operations and an effective collaboration among suppliers. Joint product and supply chain configuration/designs that integrate product development and supply chain decisions by suppliers can lead to better decision outcome Yao and Askin (2019). Hence, product design, product demand and supply chain complexity are more likely to be connected and interdependent. The need to improve the understanding of the relationship between supply chain complexity, product demand and product design characteristics is widely expressed in numerous studies (Boon-itt and Wong, 2011; Christopher and Ryals, 2014;

ElMaraghy and Mahmoudi, 2009; Hashemi *et al*., 2013; Khan *et al*., 2012; Marsillac and Roh, 2014; Nepal *et al*., 2012). Most studies, however, have either focussed on examining the relationships between supply chain and product demand (Boon-itt and Wong, 2011; Christopher and Ryals, 2014) or between supply chain and design characteristics of product (Khan *et al*., 2012; Marsillac and Roh, 2014). The former argues for the necessity of matching the characteristics of a supply chain with that of product demand, while the latter places greater emphasis on aligning a supply chain with product design characteristics to improve supply chain performance. There is limited research that simultaneously examined the alignment of a supply chain with both product demand and design characteristics.

Misalignment between what and how goods or services are produced (upstream of supply chain) and what being demanded (downstream of supply chain) and the way goods are consumed can increase the risk of supply chain disruption. As such, one way to mitigate the risk of supply chain disruption and eventual failure is to better understand the relationship between aspects of supply chain complexity and product demand as well as design characteristics. Since the investigation of supply chain complexity from these two perspectives is currently lacking, arguably an examination of the extent to which supply chains are aligned with products, considering simultaneously the roles of product demand and design characteristics, is urgently needed.

This study thus examines the extent of alignment of supply chain complexity with product demand and design characteristics by modelling the effect of key characteristics of product demand and product design on supply chain complexity. To achieve this, a theoretical framework that integrates both product demand and design characteristics as the key drivers of supply chain complexity is proposed. Following the argument of Pero *et al*. (2010), it is assumed that an alignment between product demand and design characteristics determines the levels of supply chain complexity. To assess the level of alignment, the three dimensions in Hieber's (2002, p. 80) model of supply chain complexity, namely collaboration, coordination and configuration, are integrated in the theoretical framework. Pero (2010) argues that supply chain in general entails planning, management and design. Supply chain design represents the structural aspects of collaboration across the supply chain, whilst supply chain management and planning relate to the methodology, systems and processes to operate the supply chain. The model developed by Hieber (2002) covers all three dimensions of configuration, collaboration and coordination, which contextualises the complexity of planning, management and design of supply chain.

Given the general disagreement on the theoretical perspective, a modelling framework that is grounded in theory, yet driven by robust modelling approach is needed to conceptualise and quantify supply chain complexity. The use of Hieber's model (2002) to measure supply chain complexity in this study is justified for three key reasons. First is the "transcorporate" perspective of the model to represent process, structure and design of inter-firm interactions, illustrated by a three-dimensional concept of supply chain complexity. Second is the multi-theoretic approach to capture both operative and structural aspects of supply chain complexity. Hieber's model integrates both the operative complexity (*e.g.*, type, quality and length of relationship) (Choi *et al.*, 2001; Perona and Miragliotta, 2004) and structural complexity amongst supply chains (Bozarth *et al.*, 2009; Pathak *et al.*, 2007) to formulate a multi-theoretic approach to framing supply chain complexity. Third is the morphological scheme proposed by Hieber's (2002) model that encompasses three groups of features that are closely linked to supply chain complexity. Key 'features', 'possible values', and increasing complexity of supply chain collaboration, of supply chain coordination, and of supply chain configuration provides the foundation for formulating theoretical constructs and associated survey items that are needed to implement a survey-based approach. This is also deemed appropriate for data modelling that needs self-reported measures to adequately represent multidimensionality of supply chain complexity constructs, whilst producing reliable results.

From a theoretical perspective, this study argues for a new mode of enquiry that conceives supply chain complexity as a multi-dimensional construct as well as holistically integrates its drivers from both upstream and downstream ends of a supply chain. This is achieved by generating a comprehensive supply chain alignment theoretical framework, which integrates characteristics of product demand (Fisher, 1997) and product design (Pero *et al.*, 2010). Earlier studies (Stock, 1997; Holweg and Pil, 2008) were largely driven by single-theory approaches to separately explore supply chain complexity and its causes according to their origins. This study has integrated two schools of thought, which separately examines supply-side and demand-side characteristics that impact on supply chain complexity.

From a methodological perspective, this study develops a comprehensive measurement model to estimate the impact of product design (*e.g.*, product innovativeness, product structure complexity and modularity) and product demand (*e.g.*, demand volatility, product variety and product lifecycle) on various aspects of supply chain complexity. It is the only study that empirically models the interrelatedness and interdependencies among dimensions of supply chain complexity as reflected in configuration, collaboration and coordination. Based on the findings, a taxonomy of supply chain complexity is developed to assist in the strategic alignment of product design and product demand with supply chain to better manage uncertainty and risk in our increasingly volatile world.

The paper is structured as follows. A literature review on product characteristics and supply chain alignment, together with a theoretical framework developed for the study, are presented in the next section. This is followed by a detailed description of the method used in the research. Research findings are then presented and discussed, followed by a discussion on the key contributions, limitations of the study and directions for future research.

2. Literature review

The concept of supply chain complexity has recently drawn the attention of several scholars. For example, Schuh *et al.* (2008) use the complexity approach to develop a Generic Model of Complexity (GeMoC) for establishing industrial collaborations based on problem and system complexity. In their study, collaborations are viewed as complex adaptive systems with environment/market, product and production system design as three interacting layers. Medini and Rabénasolo (2014) analyse the performance of supply chains configurations using agent-based simulation. The proposed agents are based on the Supply Chain Operations Reference (SCOR) model. The study discusses different effects of supply chain configurations and the competitive environment on SCOR performance indicators from a global point of view. Gattorna (1998) presents the alignment as a strategy to improve coordination between internal and external supply chain partners. Alignment of supply chain in a dynamic market with increased uncertainties in both demand and supply is challenging (Lee, 2002). Christopher (2000), Fisher *et al*. (1994) and Hoole (2005) have highlighted the need to align supply chain strategy with market forces; whilst Grussenmeyer and Blecker (2013) and Pero *et al.*, (2010) consider an alignment of supply chain design with product characteristics critical to managing complexity arising from increased dynamics of the market.

2.1 Product demand characteristics and supply chain complexity

A clear and comprehensive understanding of customer demand characteristics can help design optimal supply chains to reduce unnecessary complexity (Heikkilä, 2002; Jüttner *et al*., 2007;

Walters & Rainbird, 2004). With the view that everything is demand-driven, some argue that supply chains should be designed from a "customer backward" rather than "the company outward" perspective (Aitken *et al*., 2005). Previous studies have identified three key characteristics of product demand, which underpin supply chain decisions. They include product volatility (Hilletofth and Eriksson, 2011; Wagner *et al*., 2012), product variety (Pero *et al*., 2010; Pil and Holweg, 2004), and product life cycle (Kaipia and Holmström, 2007; Olhager 2010).

The implications of demand volatility or uncertainty on supply chain choices are long debated in the extant literature, both in terms of supply chain strategy and supply chain design. From a perspective of supply chain strategy, Fisher (1997) states that products based on their demand characteristics fit into two main categories: "functional" and "innovative". Functional products need an efficient supply chain where the main objective of operational management is to reduce supply chain costs. On the other hand, innovative products require responsive supply chains that focus on flexibility and reduce lead time to fulfil customer demand. In line with Fisher (1997), Lee (2002) divides products into functional and innovative types based on demand uncertainty (Low/High) and separates supply into stable and evolving types based on supply chain uncertainty (Low/High). To deal with different levels of demand and supply chain uncertainties, three key supply chain strategies are proposed: "efficient", "risk hedging", "responsive" or "agile". Heikkilä (2002) argues that Fisher's (1997) structuring of the supply chains based on demand characteristics is overly simplistic. Separating the products into two categories is not feasible and seems to be problematic as many companies consider their products to be hybrid types (Lo and Power, 2010).

Demand uncertainty is considered by many as the main factor in supply chain design (Amin and Zhang, 2013). For example, Mason-Jones, Naylor and Towill (2000) argue that the lengths of the push and the pull segments of a supply chain depend on how certain the demand is which impacts on the position of the order decoupling point or the push/pull boundary. Volatility of demand can further impact on supply chain strategies in terms of setting optimum number or strategic location of facilities, *i.e.*, production plants, distribution centres and warehouses, to respond to the demand. ElMaraghy and Mahmoudi (2009) also claim that supply chain configuration in certain geographical locations should match demand requirements. Xiao and Qi (2008) emphasise that information sharing and good communication between multiple tiers and channels constitute a key strategy for avoiding disruption in supply chains due to demand volatility. D'Avolio *et al*. (2015) also reveal that companies in the fashion industry could leverage supply chain collaboration to cope with uncertain demand with high volatility.

Product variety is another driver of supply chain complexity as an optimal supply chain design for one type of product may not be optimal for another. For example, a large volume of low-value products requires an efficient supply chain design to achieve economies of scale. In constrast, small volume of high-value products may require a responsive supply chain to provide flexibility to meet customer needs. As such, a one-size-fits all design is inadequate and a hybrid or parallel design would be necessary when the product variety increases. Brun and Pero (2012) state that supply chain choices should be aligned to product variety and higher supply chain coordination is needed when there is high product variety (Arshinder *et al*., 2008). In other words, the higher the product variety, the greater the supply chain complexity.

Product life cycle is another key factor in shaping the complexity of supply chain design. A shorter product life cycle implies more rapid changes in supply chain design to align with different levels of demand uncertainty at different stages. It also requires faster production and reduced delivery lead time (Olhager, 2010), thereby requiring manufacturing plants or distribution centres to be closer to the final consumers. With the growing demand for new products from the global market, the frequency of new product development is likely to increase. This adds to the complexity of withdrawing obsolete products at the end of their now shorter life cycles. These challenges generate a need for greater alignment between product demand characteristics and supply chain complexity (Fisher, 1997; Mason-Jones *et al*., 2000).

2.2 Product design characteristics and supply chain complexity

Product design is essentially the process of designing new products from the generation and development of ideas through a product development stage. It involves the process of specifying materials, configurations, tolerances, modularity and the like. Product design and development have a significant impact on supply chain configuration and complexity (Caridi *et al*., 2010; Ernst and Kamrad, 2000; Fixson, 2005; Novak and Eppinger, 2001; Petersen *et al*., 2005; Salvador *et al*., 2002). Lee and Billington (1992) reveal that product-process design, without supply chain alignment, can result in higher costs and poorer product quality. Key product design characteristics include product modularity (Chiu and Okudan, 2014; Roh *et al*., 2014), product innovativeness (Danneels and Kleinschmidtb, 2001; Garcia and Calantone, 2002), and product structural complexity (Ramdas, 2003; Stock and Tatikonda, 2004).

Product modularity is a technique for product design that decomposes products into independent loosely coupled modules connected by standard interfaces (Ulrich, 1995). The degree of product modularity determines the number of suppliers required, collaboration levels, information exchange, and levels of vertical integration (Fine, 1998; Fixson, 2005; Novak and Eppinger, 2001; Pero *et al.*, 2015). Multi-dimensional collaborations with high product modularity can enhance existing values and create new ones (Ramanathan, 2013). Such collaborations are critical to improving the accuracy of demand forecasts, thereby impacting on supply chain design and complexity.

Some researchers (Howard and Squire, 2007; Jacobs *et al*., 2007; Lau *et al.*, 2010; Swink *et al*., 2007) argue that product modularity is a key enabler of outsourcing. Modularity can be leveraged to satisfy customer needs in different markets, thus impacting on the supply chain configuration choices (Kumar and Chatterjee, 2013). As product modularity can increase outsourcing and offshore manufacturing, it wields an important influence on integration strategies. *Build-to-order* strategies, for instance, are enabled by product modularity to complement outsourcing decisions. Chiu and Okudan (2014) observe that increased modularity is critical for design and integration of supply chain, due to its effect on assembly sequence and selection of components and suppliers. In other words, product modularity is related to supply chain complexity.

Product innovativeness with respect to different degrees of mass customisation necessitates different approaches to configuring a supply chain, which depends primarily on the variations in customer specifications (Salvador *et al*., 2014). Pero *et al.* (2010) suggest that highly innovative products call for deeper changes in product architecture and, as a result, various suppliers need to be engaged. In particular, Pero *et al.* (2010) include product variety, product modularity and product innovativeness as the parameters of product alignment with supply chain. Caridi *et al.* (2012) empirically investigate the impact of modularity and innovativeness on supply chains. The results show that both features must be considered when designing the supply chain implying that product innovativeness is another driver for supply chain complexity.

Product structure complexity refers to the number of different parts composing a product. Greater product complexity calls for a larger number of suppliers (Cooper *et al*., 1997) and higher complexity in coordinating them (Helo and Szekely, 2005), *e.g.*, the need for more complex information systems. As supply chain coordiantion is one of the dimensions in

Hieber's (2002) model of supply chain complexity on which the conceptual framework of the current study is developed, product structure complexity is included as a driver of supply chain complexity accordingly.

In this study, product structure complexity is defined based on the number of technical components and the level of sophistication in product whilst product innovativeness is defined based on the degree to which a firm is familiar with the technological aspects of its product. Although both of these components relate to the design characteristics of the products, they may not necessarily correlate. Thus, this hypothesis needs to be empirically validated.

3. Conceptual model

A conceptual model, which extends from the work of Pero *et al*. (2010), is used to theorise the relationships between product demand, product design and supply chain complexity (Figure 1). Product demand represents demand characteristics, which are often measured through key constructs such as product demand volatility, product variety and product life cycle. Product design denotes the design characteristics, which are measured through the constructs of product innovativeness, product structure complexity and product modularity. Supply chain complexity is measured through three constructs, namely coordination, collaboration, and configuration, which are adopted from Hieber's model (2002). Table 1 defines these nine constructs and lists the key seminal studies that examined these constructs.

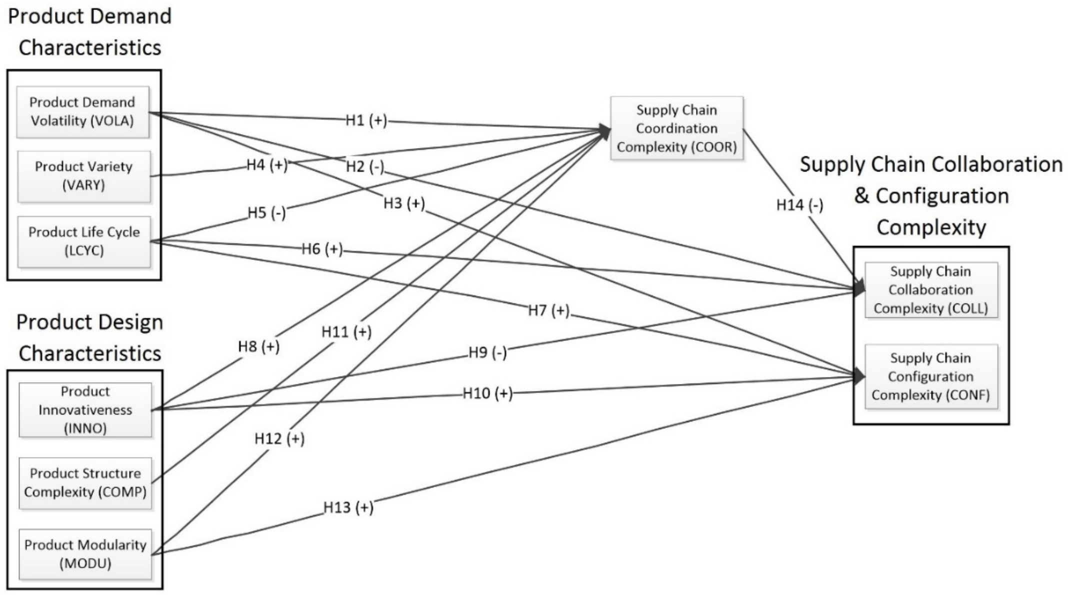

Figure 1. Conceptual model and hypotheses

Table 1. Model constructs

Dimension	Construct	Definition	Seminal studies
Product Demand Characteristics	Product Demand Volatility (VOLA)	Degree of fluctuation or variability in demand	Celly and Frazier (1996), Fisher (1997), Hilletofth and Eriksson (2011), Mason-Jones, Naylor and Towill (2000), Pagh and Cooper (1998), Wagner, Grosse-Ruyken and Erhun (2012)
	Product Life Cycle (LCYC)	Duration from when a product is introduced to market until when it is withdrawn as a commodity by the firm	Appelqvist, Lehtonen and Kokkonen (2004), Huang, Uppal and Shi (2002), Kaipia and Holmström (2007), Lee (2002), Olhager (2010), Wong and Ellis (2007)
	Product Variety (VARY)	Number of different versions of a product offered by a firm at a single point in time	Lee (2002), Salvador, Forza and Rungtusanatham (2002), Pero *et al.* (2010), Pil and Holweg (2004), Randall and Ulrich (2001)
Product Design Characteristics	Product Structure Complexity (COMP)	Number of technical components and level of sophistication involved in product	Griffin (1997), Kaski and Heikkila (2002), Novak and Eppinger (2001), Ramdas (2003), Stock and Tatikonda (2004)
	Product Innovativeness (INNO)	Degree of newness of a new product to the firm or market	Danneels and Kleinschmidtb (2001), Garcia and Calantone (2002), Roh, Hong and Min (2014)
	Product Modularity (MODU)	Extent to which a product either contains a larger percentage of components or subassemblies that are modular (*i.e.*, designed and built separately but put together as one unit)	Baldwin and Clark (1997), Chiu and Okudan (2014), Doran and Hill (2009), Gershenson, Prasad and Allamneni (1999), Parker (2010), Pero *et al.* (2010), Ulrich and Tung (1991)
Supply Chain Complexity	Supply Chain Collaboration Complexity (COLL)	Degree of alignment of strategy and interest, orientation of business culture (from highly competitive to highly collaborative), substitutability of suppliers and level of trust and openness between supply chain partners	Chiu and Okudan (2014), Hieber (2002), Khan, Christopher and Creazza (2012)
	Supply Chain Configuration Complexity (CONF)	Number of value adding tiers, number of logistics channels in supply chain and levels of partnerships	Chiu and Okudan (2014), Hieber (2002), Khan, Christopher and Creazza (2012)
	Supply Chain Coordination Complexity (COOR)	Level of information sharing, independence on logistics decisions, degree of communication and extent of information technology usage involved in daily operations of trans-corporate processes and methods	Amin and Zhang (2013), Hieber (2002), Nepal, Monplaisir and Famuyiwa (2012)

Volatile demand requires higher levels of information sharing and more advanced integrated planning and forecasting. This environment increases the inter-dependence of suppliers and buyers in terms of commitment and strategic decisions. Sahin and Robinson (2005) discuss the importance of smooth information flow for supply chain coordination, especially when demand is highly volatile. Their findings lead to the conclusion that higher product demand volatility can be a potential source of higher supply chain coordination complexity. This argument forms the basis for the first hypothesis of this study which states that product demand volatility positively impacts on supply chain coordination complexity.

Similarly, supply chains of products with a more volatile demand require greater collaboration and information sharing across the supply chain. Christopher and Towill (2002) suggest that agile supply chains are needed to cope with rapid and volatile demand conditions. Muckstadt *et al*. (2001) also note that collaborative supply chain relationships that deal with demand uncertainties need to use improved information systems to respond efficiently to market changes. Therefore, under highly volatile demand conditions, special efforts are required to ensure a high level of supply chain collaboration. In other words, higher product demand volatility can potentially create less supply chain collaboration complexity. This view constitutes the basis for the second hypothesis of this study which states that product demand volatility negatively impacts on supply chain collaboration complexity.

Justification for the hypotheses about the relationships between product demand, design characteristics and supply chain complexity and the directions of impact to be tested in the model are discussed in the previous literature review section. Table 2 lists the developed hypotheses and the supporting studies that laid the foundation for the development of the theoretical framework for this study.

Table 2. Model hypotheses

Number	Hypothesis	Key studies
H1	Product demand volatility positively impacts on supply chain coordination complexity	Bray and Mendelson (2012), Sahin and Robinson Jr. (2005), Xiao and Qi (2008)
H2	Product demand volatility negatively impacts on supply chain collaboration complexity	Christopher and Towill (2002), Gunasekaran, Lai and Cheng (2008), Muckstadt, Murray and Rappold (2001)
H3	Product demand volatility positively impacts on supply chain configuration complexity	Amin and Zhang (2013), ElMaraghy and Mahmoudi (2009), Wadhwa, Saxena and Chan (2008)
H4	Product variety positively impacts on supply chain coordination complexity	Arshinder, Kanda and Deshmukh (2008), Sahin and Robinson Jr. (2005), Simatupang and Srihharan (2002)
H5	Product life cycle negatively impacts on supply chain coordination complexity	Fisher (1997), Liu *et al*. (2006)
H6	Product life cycle positively impacts on supply chain collaboration complexity	Christopher and Towill (2002), Fisher (1997), Olhager (2003), Seuring (2009)
H7	Product life cycle positively impacts on supply chain configuration complexity	Christopher and Towill (2002), Fisher (1997), Olhager (2003), Seuring (2009)
H8	Product innovativeness positively impacts on supply chain coordination complexity	Caridi *et al*. (2010), Petersen, Handfield and Ragatz (2005), Wong, Wong and Boon-itt (2013)
H9	Product innovativeness negatively impacts on supply chain collaboration complexity	Cassivi (2006), Petersen, Handfield and Ragatz (2005), Soosay, Hyland and Ferrer (2008)
H10	Product innovativeness positively impacts on supply chain configuration complexity	Salvador, Chandrasekaranb and Sohail (2014)
H11	Product structure complexity positively impacts on supply chain coordination complexity	Cooper, Lambert and Pagh (1997), Helo and Szekely (2005), Hobday (1998), Novak and Eppinger (2001), Fixson (2005)
H12	Product modularity positively impacts on supply chain coordination complexity	Chiu and Okudan (2014), Hong, Pearson and Carr (2009), Pero *et al.* (2010), Ro, Liker and Fixson (2007)
H13	Product modularity positively impacts on supply chain configuration complexity	Chiu and Okudan (2014), Howard and Squire (2007), Jacobs, Vickery and Droge (2007), Kumar and Chatterjee (2013), Lau *et al.* (2010), Swink, Narasimhan and Wang (2007)
H14	Supply chain coordination negatively impacts on supply chain collaboration complexity	Lee and Fernando (2015), Singh and Benyoucef (2013)

4. Research methodology

4.1 Survey design and sample

A questionnaire survey was conducted to collect data from supply chain professionals and practitioners for analysis. The survey respondents targeted were members of key industry associations in Australia, including Australian Industry Defence Network, Furniture Association of Australian, Australian Manufacturing Technology Institute Limited, Association of Manufacturing Excellence, Australian Industry group, Supply Chain and Logistics Association of Australia, and Australian division of the American Production and Inventory Control Society. By administering the survey to members of multiple manufacturing associations including Defence Network and Furniture Association enabled procuring the sample that represents the diversified nature of the manufacturing industry in Australia. The hypotheses in the model thus are tested across the larger sample and there are sufficient data points to ensure the results are reliable. A total of 2,600 prospective participants from these associations were approached. In addition, 850 supply chain and operations managers in a list of Australian manufacturing companies acquired through Mint Global database were also invited to participate in the survey. In view of the large and diverse sample to be surveyed, a Web-based survey approach was adopted. Online survey has the advantages of reduced cost, simplified collection procedure, improved confidentiality, convenience in participation, and minimised data entry error (Pasveer and Ellard, 1998).

4.2 Survey instrument

The survey questionnaire comprises five sections. For product demand characteristics, volatility, variety and life cycle are measured with six, two and one measurement item respectively. For product design characteristics, innovativeness, structure complexity and modularity are measured with three, four and six items respectively. For supply chain complexity, coordination, collaboration and configuration are measured by seven, six and six items respectively. Five-point Likert scale with anchors is used in the survey questionnaire. Table 3 lists the measurement items and the Likert-scale anchors used for the constructs of product demand and design characteristics. Table 4 shows the items and anchors for the constructs of coordination, collaboration and configuration.

Table 3. Measurement items for product demand and product design characteristics

Construct	Measurement item	Likert-scale anchor
Product Demand Volatility (VOLA) Adopted and customised from Celly and Frazier (1996) and Olhager (2003)	▪ Sales are predictable (VOLA1) ▪ Market trends are easy to monitor (VOLA2) ▪ Sales forecasts are easy to monitor (VOLA3) ▪ Sales volumes are stable (VOLA4) ▪ Sales volumes change rarely (VOLA5) ▪ Range of sales volume variation is small (VOLA6)	1 - Strongly agree 2 - Agree 3 - Neither agree nor disagree 4 - Disagree 5 - Strongly disagree
Product Variety (VARY) Adopted and customised from Fisher (1997)	▪ How many versions of this product are offered at the market by your company at this point of time (Make-to-Stock)? (VARY1) ▪ How many versions of this product can be offered to customers by your company based on order at this point of time (Make-to-Order)? (VARY2)	1 – Less than 10 2 - 10 to 20 3 - 20 to 50 4 - 50 to 100 5 - More than 100
Product Life Cycle (LCYC) Adopted and customised from Fisher (1997)	▪ How long is the life cycle for this product? (LCYC)	1 - Less than 3 months 2 - 3 to 12 months 3 - 1 to 2 years 4 - 2 to 5 years 5 - More than 5 years
Product Innovativeness (INNO) Adopted and customised from Danneels and Kleinschmidtb (2001)	▪ Indicate to what extent your company was familiar with the following aspects involved in the development of this product: o Technology (INNO1) o Engineering and design (INNO2) o Production technology and process (INNO3)	1 - Totally disagree 2 - Disagree 3 - Neither agree nor disagree 4 - Agree 5 - Totally agree
Product Structure Complexity (COMP) Adopted and customised from Kaski and Heikkila (2002)	▪ Level of technical component (COMP1) ▪ Level of sophistication (COMP2) ▪ Level of engineering component (COMP3) ▪ Level of complexity (COMP4)	1 - Very low 2 - Low 3 - Neither low nor high 4 - High 5 - Very high
Product Modularity (MODU) Adopted and customised from Parker (2010)	▪ Product is designed to enable the swapping of components (MODU1) ▪ Product functions can be directly added or deleted by adding or removing components (MODU2) ▪ Product has interchangeable features and options (MODU3) ▪ The interfaces of product components are designed to accept a variety of components (MODU4) ▪ Product components are able to accept a wide range of components (MODU15 ▪ Product is designed to be easily reconfigured ((MODU6)	1 - Very low 2 - Low 3 - Neither low nor high 4 - High 5 - Very high

Table 4. Measurement items for supply chain coordination, collaboration and configuration complexities

Construct	Measurement item	Likert-scale anchor
Supply Chain Coordination Complexity (COOR) Adopted and customised from Hieber (2002)	▪ What is the level of information sharing between you and your key suppliers? (COOR1)	1 - Very low (limited to the needs of order execution) 2 - Low (forecast exchange) 3 - Moderate (order tracking and tracing) 4 – High (sharing inventory/capacity levels) 5 - Very high (as required for planning and execution)
	▪ What is the integration level of logistics processes between your company and your key suppliers? (COOR2)	1 - Very low (mere order execution) 2 - Low (integrated execution) 3 - Moderate (vendor management inventory) 4 - High (collaborative planning) 5 - Very high (integrated planning and execution)
	▪ How independent are you and your key suppliers in making logistics decisions? (COOR3)	1 - Highly independent (self-directed decisions) 2 - Independent 3 - Moderate (local decision with central coordination guidelines) 4 - Dependent 5 - Highly dependent (led by strategic centre)
	▪ How often does consumption amount of products requested from your key suppliers vary? (COOR4)	1 - Very rarely 2 - Rarely 3 - Sometimes 4 - Often 5 - Very often
	▪ What is the extent of long-term orders with your key suppliers? (COOR5)	1 - Very low (regular purchase orders) 2 - Low 3 - Moderate 4 - High 5 - Very high (long-term blanket orders)
	▪ What is the level of communication between your multiple tiers and channels? (COOR6)	1 - Very low (single contact for the transaction)2 2 - Low 3 - Moderate (supply chain manager) 4 - High 5 - Very high (multiple contacts between levels and channels)
	▪ What is the extent of information technology used between you and your key suppliers? (COOR7)	1 - Very low (to support internal processes) 2 - Low 3 - Moderate (EDI) 4 - High 5 - Very high (SCM software)
Supply Chain Collaboration Complexity (COLL) Adopted and customised from Hieber (2002)	▪ To what extent you and your key suppliers' network interest and strategy are aligned? (COLL1)	1 - Very high (common strategy and interest) 2 - High 3 - Moderate (common network analysis) 4 - Low 5 - Very low (divergence of strategy and interest)
	▪ What is the type (or orientation) of business relations between you and your key suppliers? (COLL2)	1 - High cooperation 2 - Cooperation 3 - Coopetition (Opportunistic) 4 - Competition 5 - High competition

	▪ To what extent can you replace your key suppliers? (COLL3)	1 - Extremely low (sole sourcing) 2 - Low 3 - Moderate 4 - High 5 - Extremely high (highly substitutable)
	▪ What is the level of trust and openness between your company and your key suppliers? (COLL4)	1 - Extremely high 2 - High 3 - Moderate 4 - Low 5 - Extremely low
	▪ How similar is the business culture of your key suppliers to your company? (in terms of corporate culture, size and structure) (COLL5)	1 - Highly similar 2 - Similar 3 - Moderate 4 - Different 5 - Highly different
	▪ To what extent do you or your main suppliers influence each other's supply chain (logistics) decisions? (COLL6)	1 - Very significant influence 2 - High influence 3 - Moderate influence 4 - Low influence 5 - Very low influence
Supply Chain Configuration Complexity (CONF) Adopted and customised from Hieber (2002)	▪ How many value-adding tiers are there in your supply chain network? (CONF1)	1 - Two 2 - Three 3 - Four 4 - Five 5 - More than five
	▪ How many logistics channels are there in your supply chain network? (CONF2)	1 - One to two 2 - Three 3 - Four 4 - Five 5 - More than five
	▪ How complex are the linkages of your key suppliers (based on number of tiers and channels they are connected with)? Are they connected to many other partners through many channels? (CONF3)	1 - Not complex at all (connected to a few other partners through a few channels) 2 - Slightly complex 3 - Moderately complex 4 - Highly complex 5 - Extremely complex (connected to many other partners through many channels)
	▪ What is the geographical spread of this supply network? (CONF4)	1 - Local 2 - Regional (intrastate) 3 - National (interstate) 4 - International
	▪ How long do you intend to source from these key suppliers? (CONF5)	1 - More than four years 2 - Three to four years 3 - Two to three years 4 - One to two years 5 - Less than one year
	▪ What is your type of partnership with these key suppliers? (CONF6)	1 - Group 2 - Alliance 3 - Independent business partners 4 - Others

To pre-test the survey instruments, the questionnaire was reviewed by a panel of six experts comprising three supply chain managers and three academics. Through this triangulation process (Lynn, 1986), two items, COLL5 and COOR4, were removed due to duplication. Some questions that were poorly worded were also rewritten to eliminate ambiguity. The study was then piloted through an online survey sent to the members of Supply Chain and Logistics Association of Australia. Based on the outcome of the pilot study, three more items – COOR2, CONF3, and CONF4 – were removed due to ambiguity. The final questionnaire comprises primarily 41 questions: eight on product volatility, one on product life cycle, six on product modularity, three on product innovativeness, four on product structure complexity, five on supply chain coordination complexity, five on supply chain collaboration complexity, four on supply chain configuration complexity, and five on other responses.

4.3 Data collection

Data were collected in two streams running in parallel. With the help of the industry associations, a survey Web link was sent via e-mail with a covering letter to the 2,600 members of eight professional associations in Australia to solicit participation in the survey. The survey Web link and the covering letter were also sent via e-mail to the 850 managers of supply chain and operations working in the industry sector. In both cases, a reminder e-mail was sent one month after the first email to increase the response rate. In the end, 273 valid responses were received from the two streams of data collection representing a response rate of 8% from 3,450 invitations.

4.4 Data analysis and modelling

Upon screening and cleaning of data, a series of tests were conducted on the data set to ensure that the various assumptions of parametric statistics are met. Kolmogorov-Smirnov (K-S) test was used to check the statistical significance of the normal distribution of data variables and the results found the data deviate from normality. Since the normality was not established, so bootstrapping was used to adjust distributional misspecification. Mahalanobis distance test was used to identify outliers and Spearman's correlation analysis for multicollinearity. There was no significant issue detected in these tests. Then, *t*-test for non-response bias was conducted. Cronbach's alpha and item-scale correlation were calculated for internal consistency reliability. Four items with low values of item-scale correlation – MODU4, CONF5, COLL6, and COOR5 – were removed. Finally, exploratory factor analysis was used to determine factorial validity.

A measurement model was then developed using confirmatory factor analysis. As shown in Table 5, the comparative fit index (CFI) of 0.97 exceeds the threshold value of 0.92, which indicates an acceptable model fit. The root mean square error of approximation (RMSEA) value of 0.05 is below the recommended limit of 0.08. This indicates that there is no discrepancy and a good fit between the hypothesised model and the data, with optimally chosen parameter estimates. Furthermore, the p of close fit (PCLOSE) value is above 0.05, which also indicates that the model is an acceptable fit.

Table 5. Full CFA measurement model statistics

Model identification			**Model fit statistics**					
Observed variables	=	29	χ^2	=	580.176	CFI	=	0.97
Estimated parameters	=	80	χ^2 / df	=	1.634	RMSEA	=	0.048
df	=	355	p	=	0.00			
Model is identified			RMR	=	0.04	PCLOSE	=	0.648

Discriminant validity of the constructs was assessed through correlations between constructs and the average variance of the constructs (Fornell and Larcker, 1981). The results show that correlation between product structure complexity and product modularity exceeds the acceptable value of 0.85. In addition, the average variance between product structure complexity and product modularity constructs is less than the correlation's square. Also, the average variance of product structure complexity is less than the maximum shared variance. These results suggest that product structure complexity and product modularity are highly correlated. Product structure complexity was thus removed from the measurement model and the model was re-estimated.

The statistics for the re-estimated model show that the model is an acceptable fit. The CFI is 0.975 (threshold value of 0.92), The RMSEA is 0.05 (0.08 limit) and the PCLOSE value is over 0.05 showing a good model fit. Discriminant validity holds for the re-estimated model. None of the correlations between the constructs has exceeded the threshold of 0.85. Furthermore, the average variance calculated for all the constructs is more than the maximum shared variance in all instances. In other words, the re-estimated model also indicates a good model fit. It thus forms the foundation for evaluation of the structural model proposed. Results of the full structural equation model are shown in Figure 2 and the model fit statistics are given in Table 6.

Table 6. Full structural equation model fit statistics

Model fit statistics											
			Acceptance level						Result		
χ^2	=	492.32	χ^2 / df	>	1.00	and	<	2.00	χ^2 / df	=	1.63
df	=	320	CFI	≥	0.95				CFI	=	0.97
p	=	0	RMSEA	≤	0.08				RMSEA	=	0.048
Items	=	27	PCLOSE	≥	0.50				PCLOSE	=	0.65

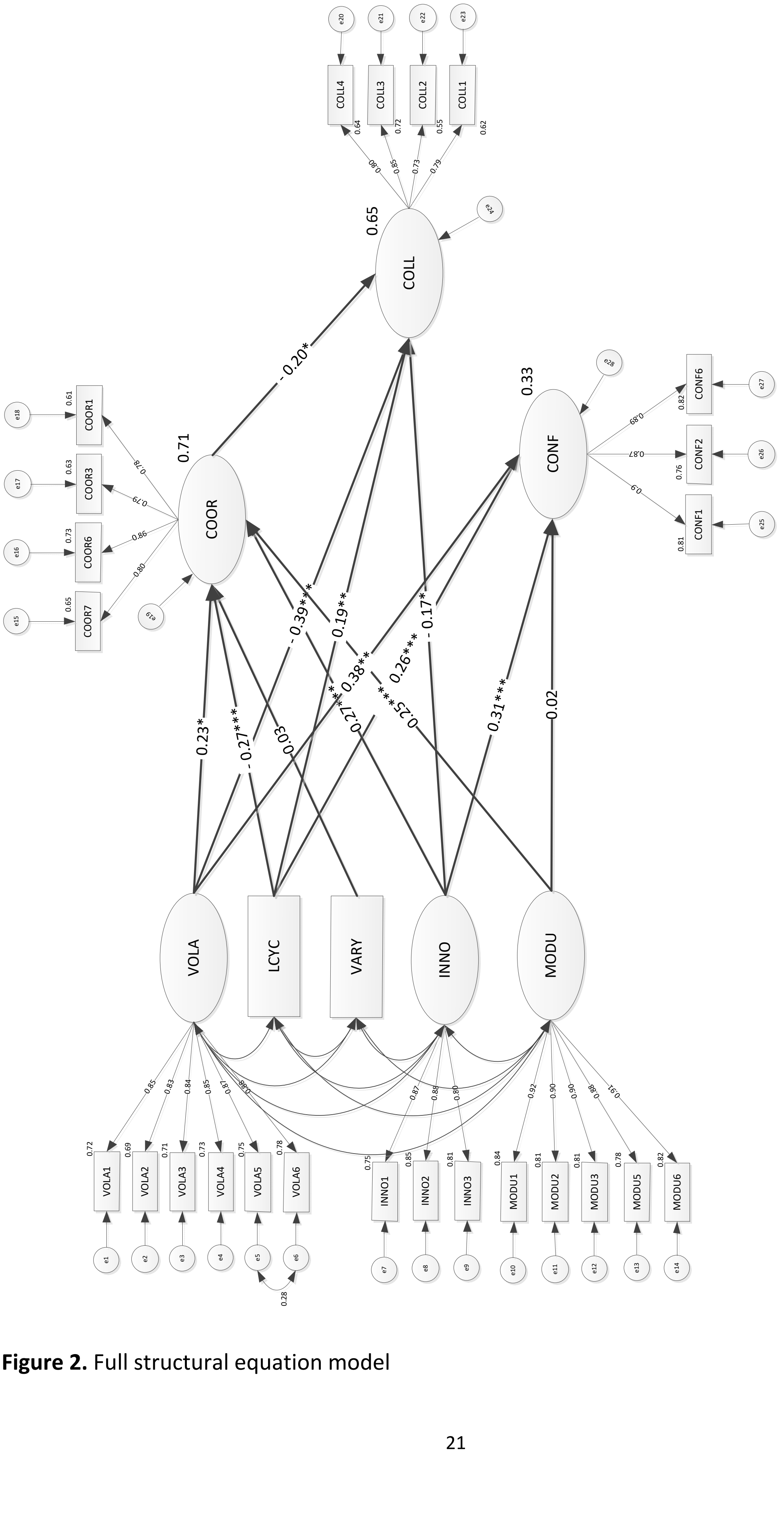

Figure 2. Full structural equation model

Table 7 shows the correlation coefficients and associated significance levels of the hypotheses. Of the 13 theorised structural paths in the structural model, 11 are significant with a confidence interval of 95 per cent, *i.e.*, $p < 0.05$.

Table 7. Strengths of the structural paths and outcome of hypothesis testing

Construct			Correlation coefficient	*p*-value	Significance	Hypothesis	Outcome
Product Demand Volatility	→	Coordination Complexity	0.23	0.01	*	H1	Supported
Product Demand Volatility	→	Collaboration Complexity	-0.39	< 0.001	***	H2	Supported
Product Demand Volatility	→	Configuration Complexity	0.38	0.00	**	H3	Supported
Product Variety	→	Coordination Complexity	0.03	0.53	Not Significant	H4	Not Supported
Product Life Cycle	→	Coordination Complexity	-0.27	< 0.001	***	H5	Supported
Product Life Cycle	→	Collaboration Complexity	0.19	0.00	**	H6	Supported
Product Life Cycle	→	Configuration Complexity	0.26	< 0.001	***	H7	Supported
Product Innovativenes s	→	Coordination Complexity	0.27	< 0.001	***	H8	Supported
Product Innovativenes s	→	Collaboration Complexity	-0.17	0.01	*	H9	Supported
Product Innovativenes s	→	Configuration Complexity	0.31	< 0.001	***	H10	Supported
Product Modularity	→	Coordination Complexity	0.25	< 0.001	***	H12	Supported
Product Modularity	→	Configuration Complexity	0.02	0.87	Not Significant	H13	Not Supported
Supply Chain Coordination Complexity	→	Configuration Complexity	-0.20	0.03	*	H14	Supported

*** ⇒ $p < 0.001$, ** ⇒ $p < 0.01$, * ⇒ $p < 0.05$

Table 8 summarises the direct and indirect standardised effects of product demand and design characteristics on the three dimensions of supply chain complexity.

Table 8. Standardised effects of product demand and design on supply chain complexity

Construct	**Supply Chain Coordination Complexity**		**Supply Chain Collaboration Complexity**						**Supply Chain Configuration Complexity**	
	Direct		Direct		Indirect		Total		Direct	
	S.E.	*p*-value	S.E.	*p*-value	S.E.	*p*-value	S.E.	*p*-value	S.E.	*p*-value
Product Demand Volatility	0.235	0.030	-0.392	0.008	-0.046	0.017	-0.438	0.002	0.375	0.005
Product Life Cycle	-0.267	0.005	0.192	0.110	0.053	0.007	0.246	0.015	0.259	0.004
Product Variety	0.029	0.546	-	-	-	-	-	-	-	-
Product Innovativeness	0.268	0.001	-0.172	0.005	-0.053	0.007	-0.225	0.007	0.313	0.004
Product Modularity	0.254	0.006	-	-	-0.080	0.007	-0.080	0.007	0.016	0.886
Supply Chain Coordination Complexity	-	-	-0.198	0.009	-	-	-0.198	0.009	-	-

5. Results and findings

The findings of the SEM establish that product demand and product characteristics are significant explanatory predictors of supply chain complexity of manufacturing firms in Australia. In particular, product demand volatility, product life cycle, product innovativeness and product modularity explain 71% of variance in supply chain coordination complexity. The model explains 65% variance of supply chain collaboration complexity through product demand volatility, product life cycle, product innovativeness, product modularity and supply chain coordination complexity. Product demand volatility, product life cycle and product innovativeness, however, only explain 33% of variance in supply chain configuration complexity. The details of the findings of this study are presented in the following sub-sections.

5.1 Demand volatility and supply chain complexity

The standardised effect of product demand volatility on supply chain coordination complexity is 0.235. This finding supports *H1* which hypothesises that greater demand volatility, reflected in lower stability of sales volume (factor loading 0.88) and predictability of market trend (0.85), increases complexity in supply chain coordination. Previous studies, such as Lee (2002) and Xiao and Qi (2008), concur with this finding which highlights that products with highly volatile demand may have stronger information sharing requirement between the manufacturer and its suppliers. High factor loadings of the measurement items of supply chain coordination complexity (0.78, 0.79, 0.86, and 0.80) suggest that a high degree of communication and coordination across multiple tiers and channels facilitates supply chain coordination. Companies often prove to be very reliant on their key suppliers in making operational and strategic decisions to efficiently manage the variability and volatility of demand and to reduce bull-whip effects. Therefore, information sharing and good communication across multiple tiers and channels to facilitate supply chain coordination constitute a key strategy for managing demand volatility collaboratively (Dwaikat, 2016).

Product demand volatility, with a standardised total effect -0.438, has a significant negative impact on supply chain collaboration complexity. This finding supports *H2* which hypothesises that greater demand volatility reduces complexity in supply chain collaboration, as reflected in the substitutability of the collaborating partners (0.85) and the level of trust and openness between the parties (0.80). Most of this impact is explained through a direct relationship (standardised effect -0.392) between product demand and supply chain collaboration. Apart from this direct effect, product demand has a -0.046 standardised indirect effect via supply chain coordination on supply chain collaboration. The finding suggests that firms in Australia which experience high volatility in their demand may need to leverage information sharing in a collaborative supply chain to consolidate relationships, make joint decisions, enable system coupling and align interest and strategy with their key suppliers. These collaborative efforts reduce supply chain collaboration complexity.

Product demand volatility also has a significant impact on supply chain configuration complexity with a standardised effect of 0.375. This finding supports *H3* which hypothesises that greater demand volatility increases complexity in supply chain configuration. Such linkage emphasises the necessity to standardise communication and practices sharing to align supply chain configuration with product demand volatility. Under high demand volatility conditions, supply chain configuration *e.g.*, the distance between nodes and the number of levels of the supply chain network, spatial and strategic positioning of production plants, distribution centres and warehouses, need to be more agile and responsive to tackle the uncertainty and variability of demand. This view is supported by the high loadings (0.90, 0.87 and 0.89) of the measurement items. High complexity of supply chain configuration enables customer-driven requirements to be recorded on the order and design/engineering to be finalised as part of the execution of the order. Product demand volatility thus produces customer-driven requirements which are unknown at the time of product design or are variations that are not designed into the product or offering (at the time of product engineering).

5.2 Product life cycle and supply chain complexity

The standardised effect of product life cycle on supply chain coordination complexity is -0.267. The finding supports *H4* which hypothesises that a shorter product life cycle increases supply chain coordination complexity. This might be due to the need for a higher level of marketing, managerial ability and sophistication as well as investment in resources in the supply chain. Products with short life cycles also require higher levels of information sharing to manage a short life on the market, a steep decline stage and the shortened maturity period. Short product life cycle requires coordination that is more efficient across the supply chain to reduce risks and uncertainty resulting in higher coordination complexity. Thus, some firms are deploying strategies to adapt to uncertainties in demand through process standardisation or delayed differentiation to deal with shorter product life cycles.

Product life cycle, however, has an insignificant direct standardised effect on supply chain collaboration yet a significant indirect standardised effect of 0.053. The total standardised effect is 0.246 which is significant. As such, *H6* is supported which hypothesises that longer product life cycle results in greater supply chain collaboration complexity. This indirect relationship between product life cycle and supply chain collaboration via supply chain coordination suggests that information sharing and coordination can facilitate collaboration and reduce complexity. Firms producing products with shorter life cycles may require a more aligned strategy across the supply chain. Due to time compression for production and distribution of these products in the market, a high level of trust and openness among supply chain partners in their operations would be required.

Product life cycle also has a significant relationship with supply chain configuration complexity with a standardised effect of 0.259. This finding supports *H7* which hypothesises that products with shorter life cycles reduces complexity in supply chain configuration. This is in line with the arguments made by Fisher (1997), Mason-Jones *et al*. (2000) and Olhager (2010). Short product life cycle imposes time pressure on firms and their product design. As a result, procurement, production, distribution and delivery operations have all to be executed in a more agile and time efficient way. For instance, the number of intermediaries in the distribution channel structure might have to be reduced in order to move closer to the end consumers.

5.3 Product variety and supply chain complexity

Product variety has an insignificant relationship with supply chain coordination complexity. As such, *H4* is not supported. This finding contradicts the argument of Arshinder *et al*., (2008) that there is a greater need for supply chain coordination when product variety is high. The plausible explanation is that manufacturers offering highly varied products might require information sharing and coordination among functional departments and between supply chain partners, which could be better managed with supply chain integration, system coupling and information platforms to promote production coordination and to achieve distribution objectives. This finding however confirms the result of the study by Pero *et al.* (2010), which found a weak relationship between product variety and supply chain coordination complexity.

5.4 Product innovativeness and supply chain complexity

Product innovativeness, as reflected in the familiarity of the firm in product development technology (0.87) as well as engineering and design (0.88), has a significant effect on supply chain coordination complexity. Therefore, *H8* is supported. With a standardised effect of 0.268, it exerts the highest positive direct effect on supply chain coordination complexity. The finding aligns with the fact that companies manufacturing innovative products often require higher information sharing, greater inter-firm dependence and closer contact with multiple tiers and channels (Caridi *et al.*, 2010; Pero *et al.*, 2010). This in turn results in higher levels of coordination complexity.

Similarly, product innovativeness has a significant direct effect of -0.172 on supply chain collaboration complexity. There is also a significant indirect effect of -0.053 through supply chain coordination. This finding suggests that supply chain coordination complexity, when aligned with level of product innovativeness, could reduce complexity in supply chain collaboration. With a significant total effect of -0.225, *H9* is supported. In other words, product innovation requires higher levels of inter-firm coordination across the supply chain supported by strong information exchange, which can then help reduce complexity in collaboration.

Impact of product innovativeness on supply chain configuration complexity is also significant with a standardised effect of 0.313. Therefore, *H10* is supported. Higher product innovativeness results in new product or new market development projects, which consequently increases the level of supply chain configuration complexity. Product innovativeness requires supply chains to be more globally distributed and fragmented in multiple locations so that new innovative technologies can be developed, and new markets can be created. The finding suggests that aligning supply chain configuration with product innovativeness is paramount to gaining competitive advantage and sustaining supply chain performance.

5.5 Product modularity with supply chain complexity

Product modularity, as reflected in changeability of components (0.92), ease of configuration (0.91), and flexibility in functionality (0.90), has a significant impact on supply chain coordination complexity. The standardised effect of product modularity on supply chain coordination is 0.254. Therefore, *H12* is supported. The debate about the implication of product modularity for supply chains is still open (Caridi *et al.*, 2012). In contrast to that of Fine (1998), the finding of this study contends that products with greater modular design require more information sharing and a higher level of communication with key suppliers.

Product modularity also has a negative indirect impact on supply chain collaboration complexity through supply chain coordination complexity. The standardised indirect effect of product modularity on supply chain collaboration complexity is -0.080. It is argued that product modularity reduces supply chain collaboration complexity by enabling many firms producing the modules to collaborate better and in a more aligned environment. This outcome suggests that supply chain coordination can be the facilitator of this collaboration. Interestingly, the finding aligns with Pero *et al.*'s (2010) proposition that product modularity reduces supply chain collaboration complexity suggesting that supply chain collaboration and the level of product modularity should be aligned.

In contrast, product modularity has insignificant effect on supply chain configuration complexity. *H13* is thus not supported. Product modularity has been regarded as a key enabler of outsourcing, leading to an increase in the number of supply chain tiers (Howard and Squire, 2007; Jacobs *et al.*, 2007; Lau *et al.*, 2010; Swink *et al.*, 2007). The argument is based on the observation that as the number of suppliers and value-adding tiers increases due to higher product modularity, the time horizon of business relationships decreases while the geographical spread of the network increases, thereby increasing supply chain configuration complexity.

5.6 Supply chain coordination and supply chain collaboration complexities

Supply chain coordination complexity has a significant negative relationship with supply chain collaboration complexity. The standardised effect is -0.198. Therefore, *H14* is supported. It is evident that a higher level of supply chain coordination decreases the level of supply chain collaboration complexity. This is in line with the argument of Singh and Benyoucef (2013) who postulated that higher levels of coordination in the supply chain results in a better collaboration, hence lower complexity. Basically, this result reiterates the significant role of supply chain coordination in enhancing collaboration complexity across the supply chain.

Overall, the findings of this study support the theoretical argument that supply chain needs to be aligned with product demand and product characteristics to help manage or mitigate the risk of growing supply chain complexity. Demand volatility, product life cycle, product innovativeness and product modularity were found as critical drivers shaping the scale and intensity of supply chain complexity reflected in terms of configuration, coordination and collaboration. In particular, companies delivering highly innovative products with highly volatile demand and short life cycle should develop a robust collaborative supply chain, leveraging on communication and information sharing tactics among supply chain partners. Highly volatile and highly innovative products are generally associated with highly complex supply chains. For products with short life cycles, the situation is not necessarily the same as the short time may demand simpler coordination in operations. Companies which are manufacturing volatile and innovative products with short life cycle therefore needs to be more prudent in designing their supply chain configuration to ascertain the right balance between the needs for simpler coordination and complex collaboration. As for product modularity, the findings of this study add to the debate about the implications of modularity on supply chains (Caridi *et al.*, 2012). In particular, the results suggest that highly modular products call for higher information sharing and collaborative relationships among supply chain partners.

6. Discussions

Supply chain complexity is neither chaos nor complicatedness. It is an ordered and structured state of inter-connectedness and inter-dependencies of supply chain network where a change in one component affects the functioning of other elements. Supply chain denotes a complex and dynamic network of a system as an intricate whole, composed by businesses with different objectives, needs and cost parameters, which transcend into different levels of supply chain complexity. To make an effective decision, supply chain managers needs to be cognizant of the key constructs that define and measure the levels of supply chain complexity and devise strategies to mitigate risk emanated from globalised production networks and variegated demand structures. This notion is well recognised by researchers and various frameworks have been proposed to deal with supply chain complexity from different perspectives. For example, Kaluza *et al*. (2006, p. 3) acknowledge that "the complexity of a supply chain is related to the numerousness, the variety of business processes in the supply chain, as well as the number of interacting partners." To integrate complexity management into supply chain management, they introduce a complexity strategy matrix comprising four domains representing four basic strategies to manage complexity. Depending on the potential impact of integrated complexity management on supply chain performance and the effort for realisation of integrated supply chain management, four distinct management strategies including accepting, controlling, reducing and avoiding complexity can be adopted. Successful implementation of any strategy depends on the effective controlling of the parameters of the strategy and the resulting measures.

Realising the significance of managing supply chain complexity, a supply chain complexity taxonomy (Figure 3) is developed to help managers comprehend and mitigate the likely challenges associated with interconnectedness and interwoven interactions between product demand and design complexity (*i.e.*, demand volatility, product life cycle, innovativeness and modularity) and supply chain complexity (*i.e.*, coordination, collaboration and coordination). Guided by the findings of this study, especially the validity of the hypotheses, the proposed two-dimensional taxonomy depicts the high and low levels of product demand complexity on the x-axis and product design complexity on the y-axis. Using a segmented bar chart showing the percentage of high and low level, the taxonomy succinctly dissects different combinations of complexity in supply chain coordination, collaboration and configuration upon the impacts of product demand and product design complexity. Four quadrants are identified, and they reflect the unique framework that businesses can deploy to tackle the challenges under various plausible situations. The taxonomy can thus serve as a reference for practitioners to formulate appropriate strategies to manage or mitigate risk associated with growing supply chain complexity.

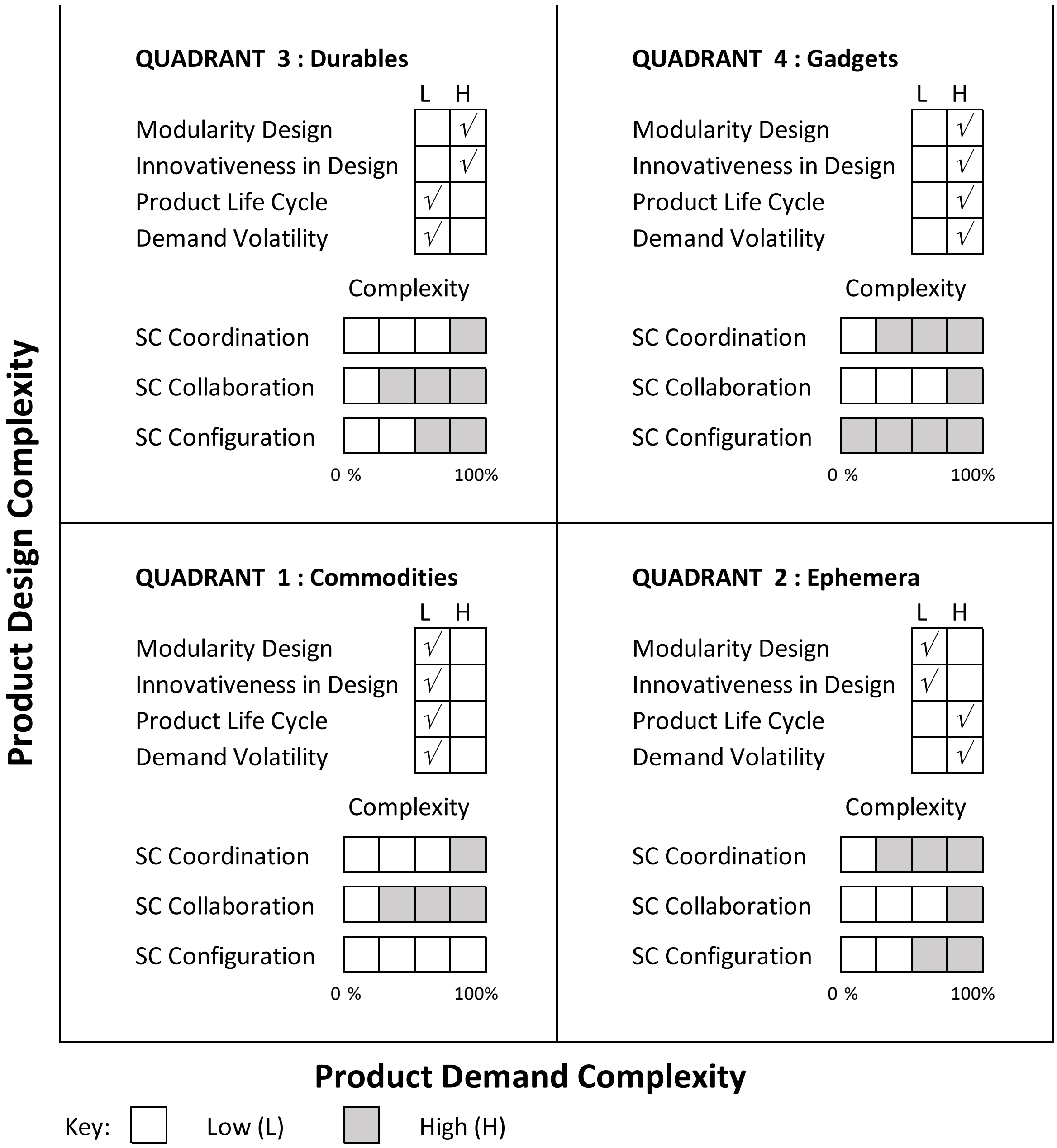

Figure 3. Supply chain complexity taxonomy

Quadrant 1 shows low coordination and configuration complexity due to lower levels of product demand and product design complexities. Products in this category are commodities, such as copper and coffee. Structure of the supply chain is relatively simple. Information sharing in the supply chain can be limited to merely satisfying customer orders. Decision making is usually independent and autonomous within individual firms. Contacts between supply chain partners are limited to individual transactions. As such, simple information technologies should suffice and there is no need to use complex SCM software for planning and execution. Collaboration complexity, on the other hand, is high as supply chain network strategies and interests of various partners can differ significantly. Owing to the stable demand and low level of integration, supply chain partners can have a competition-oriented relationship. As mutual need in the network is weak and suppliers are highly substitutable, there is no immediate incentive for a high level of trust and openness in the business relationships, thereby making collaboration a complicated matter. To manage supply chain complexity in this situation, practitioners can formulate strategies to strengthen supply chain collaboration by standardising supply chain operations to improve efficiency, planning jointly with customers and suppliers to better match supply and demand, sharing knowledge with supply chain partners to build trust, and synchronising and interfacing with supply chain partners to remove barriers to communication and learning (Simatupang and Sridharan, 2004, 2005; Soosay *et al.*, 2008).

Quadrant 2 indicates high coordination and low collaboration complexities due to high product demand complexity and low product design complexity. Products in this category are ephemera such as fast fashion and trendy toys. High demand complexity requires greater sharing of information, such as demand forecast and inventory levels, between supply chain partners. Supply chain planning also needs to follow certain mutually agreed coordination guidelines instead of relying on autonomous decisions. As such, more coordination is required. High demand complexity implies a need for greater responsiveness. The change in supply chain structure increases complexity in supply chain configuration. Variability in demand warrants a more structured communication pattern with regular meetings and reviews among firms. As a result of the structured coordination, a relatively lower level of collaboration is needed to maintain a common interest in the network to address demand volatility issues. To manage risk arising from high demand volatility and short product life cycle, practitioner can adopt multiple sourcing to ensure supply (Blome and Henke, 2009). To facilitate and strengthen supply chain coordination, strategies can be formulated to leverage IT for information sharing, promote process integration to smoothen operation, and relationship commitment to build trust through joint investment (Ghosh *et al.*, 2014; Huo *et al.*, 2015).

Quadrant 3 denotes low coordination and high collaboration complexities due to the lower level of product demand complexity (similar to that of Quadrant 1) and high level of product design complexity. Product in this category are durables such as panel TV and household appliances. For products that are highly modular and innovative but stable in demand with a reasonably long life cycle, a medium level of information sharing, such as order tracking and tracing, should suffice. Use of inter-organisational information technology, such as electronic data interchange, to support supply chain coordination is suitable (Hill and Scudder, 2002; Sanchez and Pérez, 2003). The linkage can help build to a more aligned network with a certain level of trust required for smooth coordination and collaboration. As a result of increased modularity and innovativeness in product design, more parties are involved in the supply chain making supply chain configuration relatively more complex. Since highly modular and innovative products are best developed and delivered by collaboration-based networks with effective communication across module teams (Caridi *et al.*, 2012; Lau *et al.*, 2011), practitioners can formulate strategies to strengthen supply chain collaboration and communication using the approaches suggested for the situation as depicted in Quadrant 1.

Quadrant 4 signifies high coordination and low collaboration complexities due to high levels of product demand and product design complexities. Products in this category are gadgets such as mobile phones and other gizmos. For firms making products with high demand and design complexities, such as high-end consumer electronic devices, intensive information sharing with their suppliers is required and a high level of communication between multiple tiers and channels is usually maintained. Such arrangement can help minimise disruptions in the supply chain due to demand complexity and respond quickly to changes in customer preferences. Businesses with products having a more volatile demand and short life cycle usually require more coordination with suppliers to reduce risk and uncertainty, thereby increasing coordination complexity (similar to that of Quadrant 2). Centralised strategic decision making, and collaborative planning, forecasting and replenishment are commonly used approaches to eliminate bullwhip effects in the downstream and assist in reducing overall supply chain cost. To ensure success, a high level of collaboration among supply chain partners with trust and common need in the network to deal with product demand and design uncertainties is naturally developed. This helps reduce supply chain collaboration complexity. Owing to the increased number of parties, facilities and operational procedures in the supply chain to handle high product demand and design complexity, supply chain configuration can be quite complex and need to be carefully managed. Apart from integrating demand planning with product design to align with supply chain complexity, practitioners can also formulate strategies to ensure flexibility in machine utilisation, product modularization, production scheduling practices, organisational capabilities, mass customisation capability, and distribution capability to enhance operational performance and responsiveness (Salvador *et al.* 2004; Trattner *et al.*, 2017).

7. Conclusions

6.1 A summary of findings

This paper investigates the relationships between product demand and design characteristics and supply chain complexity. Building on the works of Pero *et al.* (2010) and Hieber (2002), a supply chain complexity alignment model was proposed to depict the relationship among the various constructs. Using questionnaire survey for data collection and SEM for analysis, this study validated the proposed model thereby extending the work of previous research (*e.g.*, Fisher, 1997; Gattorna and Walters, 1996; Lee, 2004; Pero *et al.*, 2010).

Through SEM, the relationships between the key constructs of product demand and product design and the measurement dimensions of supply chain complexity, namely coordination, collaboration and configuration, were empirically examined. Taking the Australian manufacturing firms as a sample, the study finds that the identified constructs are highly relevant in capturing the different levels of supply chain complexity. The findings show that product demand and design characteristics can be seen as underlying drivers of the different dimensions of supply chain complexity. The model reveals that there is indirect impact of product design characteristics on supply chain collaboration through supply chain coordination. It also shows that product demand volatility, life cycle, innovativeness and modularity are the key factors affecting supply chain complexity. Furthermore, product demand volatility has the highest statistically significant impact on supply chain collaboration complexity whilst product innovativeness has the highest significant effect on supply chain coordination complexity. Also, it is found that product modularity has insignificant direct impact on the complexity of supply chain collaboration. However, it influences indirectly a firm's supply chain collaboration through the mediating role of supply chain coordination. Finally, product variety has no impact on supply chain complexity, which contradicts the findings of previous research.

The findings of this study also suggest that complexity is not necessarily a negative feature of global supply chains. It can be seen as an outcome of the complexity of product demand and product design. As such, some products would lead to more complex supply chains while others would result in much simpler supply chain structure. A complex product creates a relatively more complex supply chain as it requires a higher level of coordination, collaboration and configuration. Complexity, therefore, is an inherent characteristic of the supply chain which, as this study contends, can be managed through aligning supply chain with product characteristics. An appropriate level of alignment can reduce supply chain costs, enhance efficiency and help improve supply chain performance.

6.2 Contributions of study

This study significantly contributes to the current knowledge of supply chain complexity by empirically validating the key constructs involved, namely product demand volatility, product life cycle, product design innovativeness and product modularity, and how they are interwoven and interconnected to supply chain complexity in coordination, collaboration and configuration. Hence, this study extends the scope of supply chain complexity research beyond merely reducing the product complexity through standardisation and modularisation. Deeper knowledge is created to improve the understanding of the impact of product demand volatility on supply chain collaboration complexity and that of product design innovativeness on supply chain coordination complexity. Further, a taxonomy is designed as a complexity management tool to enhance decision-making and strategic thinking to help manage the complexity and mitigate the associated risk. Different strategies to deal with supply chain complexity resulting from the various combinations of product demand and design complexity are proposed for the consideration of practitioners and supply chain professionals. Finally, the current study consolidates the extant work on this highly fragmented and disjointed research on supply chain complexity and set out the direction for further research.

6.3 Limitations and future research

Like other studies of this nature, there are limitations and scope for further research. Firstly, supply chain complexity in this study was measured using only three key concepts—collaboration, configuration and coordination. As there can be other theoretical approaches and constructs, such as production and delivery lead time, to conceptualising and measuring the supply chain complexity, using alternative approaches or different measurement items can be a direction for further research. Secondly, the constructs of supply chain complexity were measured using a questionnaire survey, which was based on individual perceptions rather than objective measures. Despite stringent validity and reliability checks of the surveyed data, there might still be bias due in personal interpretation and judgement of the respondents. Use of more objective measures, such as supply chain performance indicators and supply network metrics, can be considered in future research. Thirdly, the study investigates the relationship between supply chain complexity and the characteristics of product demand and product design mainly from the manufacturer's point of view. It would be desirable to complete the picture by examining the relationship from the perspective of other supply chain partners such as suppliers and distributors in future studies.

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