Int. J. Production Economics 169 (2015) 215–232

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Assessment of static complexity in design and manufacturing of a product family and its impact on manufacturing performance

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ARTICLE INFO

Article history:
Received 10 September 2014
Accepted 30 July 2015
Available online 7 August 2015

Keywords:
Static complexity
Design and manufacturing complexity
Complexity metrics
Product family
Manufacturing performance

ABSTRACT

As products and their manufacturing systems have become more sophisticated and complex, both industry and academia have widely discussed complexity in product design and manufacturing to understand its impact. However, the impact of complexity on manufacturing performance has not been clearly articulated in the previous empirical studies despite the widely expected negative relationship between them. As a response, this paper considers static complexity, which is due to inherent structural characteristics in product design and manufacturing, to elucidate the impact of design and manufacturing complexity on manufacturing performance. Metrics to properly capture design and manufacturing complexity in a product family are proposed and applied to a screwdriver product family case. Then, regression analysis is performed to identify the impact of complexity on manufacturing performance under different demand levels and manufacturing strategies. As a result, the negative impacts of design and manufacturing complexity on lead time and total production cost and their changes commensurate to the increase in demand are observed under the make-to-order policy. On the other hand, similar negative impacts are not statistically significant under the make-to-stock policy. These results indicate that static complexity negatively affects manufacturing performance only in the make-to-order system; and the inventory held of common parts in the make-to-stock system decreases the influence of static complexity on manufacturing performance.

1. Introduction

Nowadays the term "complexity" is frequently used in the manufacturing domain to represent modern manufacturing systems where many uncertainties (e.g., demand and supply variation) and various inter-related components in products and production are considered (Wu et al., 2007). Growing complexity is indeed inevitable for modern companies due to numerous market and business conditions causing an increase in uncertainty (Wiendahl and Scholtissek, 1994; Perona and Miragliotta, 2004). Wiendahl and Scholtissek (1994) observed that the individual departments within a company that used to be hierarchically or sequentially connected have been restructured to functionally integrate and decentralize individual processes to be flexible and responsive to customer demands. This restructuring trend should have reduced the complexity of an entire system, but it resulted in organizational complexity due to the integrated and interactive links. They further mentioned that the coordination between order-related (e.g., make-to-order) and customer-independent (e.g., make-to-stock) manufacturing strategies causes complexity in production. Complicating the matter further, most companies are now required to produce multiple product variants to satisfy diverse and frequently changing customer needs, which generally lead to manufacturing additional part variants and assemblies (Schleich et al., 2007).

Under the internal and external factors that increase complexity in a manufacturing system, complexity has become an important issue a company must tackle. Despite this fact, there are many obstacles in understanding and measuring complexity. First of all, there is no widely accepted common definition of complexity due to the ambiguity that the term itself has (Klir, 1985; Flood, 1987; Perona and Miragliotta, 2004; Wu et al., 2007; Crespo-Varela et al., 2012). Not surprisingly, complexity concepts introduced in previous literature are also varied depending on the context of their applications (Rodríguez-Toro et al., 2002; Crespo-Varela et al., 2012). Most existing complexity metrics are shown for simple cases, or are very specialized for a certain application area; it is very hard for general manufacturing companies to practically identify their current complexity levels at which they operate. In addition, complexity metrics have been developed mostly from a single perspective, either product design or manufacturing, and with no regard to the relation of complexity in product design and its manufacturing to manufacturing outcomes.

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http://dx.doi.org/10.1016/j.ijpe.2015.07.036
0925-5273/

Complexity in product designs and manufacturing systems has been investigated to demonstrate its negative impact on manufacturing performance: productivity (Stalk, 1988; MacDuffie et al., 1996; Guimaraes et al., 1999), operational cost (Stalk, 1988; Guimaraes et al., 1999; Wu et al., 2007), profitability (Kekre and Srinivasan, 1990; George and Wilson, 2004), and quality (MacDuffie et al., 1996; Guimaraes et al., 1999). Although the negative impact of complexity on manufacturing performance seems to be expected from a managerial perspective, dynamics between complexity and manufacturing performance under various manufacturing conditions has not been clearly articulated in the literature. For example, MacDuffie et al. (1996) employed different complexity measures associated with products and production systems to statistically justify the negative impact of complexity on manufacturing performance, but not all measures show statistically significant results for the impact of complexity.

This paper focuses on static complexity, occurring from the structural configuration of a system, from the perspectives of both product design and manufacturing and scrutinizes the impact of complexity on manufacturing performance under the change in manufacturing policies (make-to-order vs. make-to-stock) and the increase in demand level. This paper firstly proposes information-theoretic metrics representing static complexity in product design and manufacturing to measure static complexity at a product family level. This is to reflect today's variant-rich manufacturing environments. Manufacturing different products with all different raw materials and subassemblies is a very rare case nowadays; most companies configure product platforms for product families to decrease complexity resulting from the increase in product variety (Ulrich and Eppinger, 2000; Simpson, 2004). Furthermore, analyzing complexity for product variants within the same product family is more appropriate than that for products from different product categories since the sources and changes of complexity can be easily tracked under the same environment. Also, complexity analysis based on each product family not only facilitates comparison of complexity among multiple product families but also informs complexity changes from a product family level to a product portfolio level.

The complexity metrics are applied to a screwdriver product family case, adopted from Park (2005) and Artar and Okudan (2008), to observe a relationship between complexity and constituents of a product order. The relationships between the manufacturing performance of the screwdriver product family and the complexity levels derived from the proposed design and manufacturing complexity metrics are statistically analyzed to confirm the impact of complexity on manufacturing performance. The manufacturing performance variables in the case study are average order lead time and total production cost under a total of six manufacturing conditions, which are obtained from the combinations of manufacturing policies (make-to-order and make-to-stock) and demand levels (80,000, 100,000, 120,000 units).

2. A summary of prior research on design and manufacturing complexity

In this section, the literature addressing complexity in design and manufacturing contexts is reviewed. Complexity in operations management is generally defined as how the members of a system are varied and interacted (Choi and Krause, 2006). Complexity in industrial manufacturing can be found in both products themselves and their production, and the level of complexity in each of these varies depending on industry, product type, and operational strategies (Wiendahl and Scholtissek, 1994). Complexity for manufacturing systems can be categorized into two broad main areas corresponding to application or focus areas: design complexity (i.e., product design and engineering design process) and manufacturing complexity (i.e., manufacturing and assembly). Each focus area of complexity can be further characterized by its properties: static and dynamic complexity. It should be noted that uncertainty can be seen as a function or outcome of complexity; indeed, following definitions attest to this relationship. Static complexity is the time-independent complexity associated with the structure or physical configuration, and reflects uncertainty resulting from the structural characteristics of a system (Orfi et al., 2011; Park and Kremer, 2013). On the other hand, dynamic complexity is defined as uncertainty caused by the amount of state changes of a system and related to time-dependent activities increasing complexity and unexpected events in a system (Frizelle, 1996; Wu et al., 2007; Park and Kremer, 2013). This section discusses how these types of complexity have been defined beyond ambiguous or ad hoc definitions of complexity and quantified through different approaches. Table 1 shows the literature corresponding to each type of complexity.

2.1. Approaches to design complexity

Complexity is a popular term used in many scientific domains such as computer science, biology, and physics (Mitchell, 2009); however, there is no one unique definition to describe complexity

Table 1
Categorization of Complexity Research in Design and Manufacturing.

Complexity Focus Areas		Complexity Property: Static Complexity	Complexity Property: Dynamic Complexity
Design Complexity	Satisfaction of Design Requirements	Suh (1999), Braha and Maimon (1998), El-Haik and Yang (1999)	Suh (1999) El-Haik and Yang (1999)
	Product Intra-Variety	Pahl and Beitz (1996), Griffin (1997), Bashir and Thomson (1999), Gupta and Krishnan (1999), Kaski and Heikkila (2002), Ramdas (2003), Ameri et al. (2008), Crespo-Varela et al. (2012), Orfi et al. (2012), Jacobs (2013)	-
	Product Inter-Variety	Collier (1981), Wacker and Treleven (1986), Johnson and Kirchain (2010), Roy et al. (2011), Closs et al. (2008), Jacobs and Swink (2011), Orfi et al. (2012), Jacobs (2013)	-
Manufacturing Complexity	Queuing Information	Frizelle and Woodcock (1995)	Frizelle and Woodcock (1995) Wu et al. (2007)
	Process & Assembly Information	Deshmukh et al. (1998), Fujimoto et al. (2003), Zhu et al. (2008), Hu et al. (2008)	-
	Scheduling	Zhang (2012)	Sivadasan et al. (2006), Zhang (2012)
	Supply Chain Operations & Management	Vachon and Klassen (2002), Choi and Krause (2006), Bozarth et al. (2009), Serdarasan (2013)	Vachon and Klassen (2002), Bozarth et al. (2009), Serdarasan (2013)