Managing structural and dynamic complexity in Supply Chains: Insights from four case studies

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Complexity is regarded a major impediment to Supply Chain (SC) performance. However, very few studies aid SC managers adopt adequate practices in response to structural and dynamic complexity. This study offers a comprehensive review of the practices that four manufacturing companies employ in their SC function to manage the structural and dynamic complexity of their product portfolio, internal SC, and supplier and customer bases. Moreover, leveraging the results of the inductive in-depth case studies, a classification of complexity management practices consisting of four clusters is advanced: variety reducing, confinement and decoupling, coordination and collaboration, and decision support and knowledge generation. Each cluster's distinctive logic and limitations are discussed and propositions on their managerial scope are introduced, therefore providing managers with relevant insights to design effective complexity management approaches in their organisations.

Keywords: complexity management, case study research, supply chain management, dynamic complexity, structural complexity.

1. Introduction

The purpose of this study is to investigate how manufacturing companies can manage the influence of structural and dynamic complexity on SC performance. Using four in-depth case studies, the use of practices to manage these two complexity types is examined. The contribution of this paper is two-fold. First, it presents a comprehensive and structured review of the practices used in four manufacturing organisations from different industrial sectors to manage the structural and dynamic complexity in their SCs. Second, the study inductively adapts Galbraith's (1973, 1977) classification of complexity management methods in the information-processing theory literature to the SC domain. Thus, the paper advances an empirically and theoretically supported classification of practices that consists of four clusters or types of practices, and puts forth propositions on the managerial scope and the limitations or drawbacks of these.

Complexity is argued to be a major barrier for SC performance (Bode and Wagner, 2015; Brandon-Jones et al., 2014; Perona and Miragliotta, 2004; Bozarth et al., 2009; Manuj and Sahin, 2011; Aitken et al., 2016; Choi and Krause, 2006; Vachon and Klassen, 2002). Therefore, effective complexity management can provide companies with competitive advantage (Seth et al., 2017; Mocker et al., 2014). However, and despite the number of studies that discuss the management of complexity at SC or firm level (e.g. Caniato and Größler, 2015; Perona and Miragliotta, 2004; Collinson and Jay, 2012), the extant literature concerned with the management of complexity in the SC falls short in aiding practitioners effectively manage structural and dynamic complexity as follows.

Firstly, the complexity management literature has primarily focused on structural complexity (e.g. Perona and Miragliotta, 2004; Ashkenas, 2007; Hoole, 2005), and, in the SC domain, very few papers (Aitken et al., 2016; Serdarasan, 2013) investigate the management of dynamic as well as of structural complexity. Secondly, practices can prove more effective to handle specific categories of complexity factors, such as: product or customer complexities, and, consequently, be adopted by practitioners accordingly. While some attempts to link specific complexity factors to management practices have been made, most notably by Serdarasan's (2013) review of complexity drivers, no study offers practitioners with a structured classification of practices that can be employed for categories of structural and dynamic complexity factors. So, there is a scarcity of frameworks that can aid managers in designing overarching complexity management strategies and selecting practices that are consistent with these (Aitken et al., 2016). More recently, Turner et al. (2018) have proposed a framework for studying how managers respond to SC complexities. In this vein, this paper provides greater detail, i.e. more granularity in the analysis of the case studies presented.

Leveraging its focus on both structural and dynamic complexity and its broad examination of complexity factors, this paper aims at shedding further light onto how complexity may be managed in the SC function. So, the following research question is put forth:

RQ: How can manufacturing companies manage the influence of structural and dynamic complexity on SC operations performance?

The structure of the paper is as follows. Section 2 draws from the research strands of systems, business and, especially, SC complexity to lay the theoretical background of the study and better define the research gap. The use of inductive case studies and the data analysis processes are described in Section 3. The empirical findings of four in-depth case studies in manufacturing organisations are presented in Section 4. Section 5 discusses the findings, leading to the introduction of testable propositions. Section 6 concludes the manuscript by underlining contributions to theory and practice, as well as limitations and opportunities for future research.

2. Theoretical background

Two main complexity types are presented in the literature: structural and dynamic complexity (Serdarasan, 2013; Bozarth et al., 2009; Huaccho Huatuco et al., 2010; Frizelle, 1998; Sivadasan et al., 2002; Smart et al., 2013), which are interrelated (Casti, 1979; Bode and Wagner, 2015; Serdarasan, 2013). According to Bozarth et al. (2009, 79), detail (i.e. structural) complexity arises from 'the distinct number of components or parts that make up a system', while dynamic complexity is defined as 'the unpredictability of system's response to a given set up inputs'. A somewhat more comprehensive definition is provided by Serdarasan (2013, 533), who states that structural complexity 'describes the structure of the supply chain, the number and the variety of its components and strengths of interactions between these', while dynamic complexity 'represents the uncertainty in the supply chain and involves the aspects of time and randomness'. Similarly, the distinction between these two complexity types is reinforced in the systems complexity literature (e.g. Waldrop, 1992; Casti, 1979; Senge, 2006; Sterman, 2000). Specifically, straightforward definitions are offered by Casti (1979), who describes structural complexity as the complexity which stems from the components being 'put together in an intricate, difficult-to-understand fashion' (p. 98); and dynamic complexity as 'complexity issues that arise in connection with a system's dynamical motion or behavio[u]r' (p. 102). Therefore, structural complexity stems from the number, variety and interconnections between system components; thus, in a SC context, is driven by the diversity of elements involved (products, processes, customers, suppliers, etc.) and by the dependencies and relationships between them. Dynamic complexity stems from the system's dynamical motion and involves issues of time and uncertainty (Huaccho Huatuco et al., 2010; Bozarth et al., 2009; Casti, 1979). Hence, in a SC context, dynamic complexity is driven by the dynamics of SC operations (Sivadasan et al., 2002) and by the pace of change of SC elements or of the relationships between these (Collinson and Jay, 2012; Maylor et al., 2008).

Complexity is associated to a range of topics and outcomes in the SC literature including increased inventory costs (Wu et al., 2007), hindered decision making (Manuj and Sahin, 2011), the frequency and severity of disruptions (Bode and Wagner, 2015; Brandon-Jones et al., 2014), and supplier innovation, risk, responsiveness and transaction costs (Choi and Krause, 2006). In particular, with regards to performance, the literature has underlined the potential adverse effects of complexity on delivery performance (Vachon and Klassen, 2002), manufacturing plant performance (Bozarth et al., 2009) and SC performance (Perona and Miragliotta, 2004). Thus, complexity is generally regarded 'as a key impediment to performance' and one of the most pressing SC issues for practitioners and academics alike (Bode and Wagner, 2015, 215).

However, a growing number of researchers argue that embracing certain complexities can enhance the competitiveness of companies by, for example, allowing it to sell its products in additional market segments (Perona and Miragliotta, 2004; Brandon-Jones et al., 2014; Choi and Krause, 2006; Bozarth et al., 2009). Thus, the complexity that may be detrimental for the SC function, may, however, play a notable role in underpinning the organisation's or business unit's strategy (Manuj and Sahin, 2011; Bozarth et al., 2009; Birkie and Trucco, 2016). In this manner, Aitken et al. (2016) and Turner et al. (2018) propose the distinction between *strategic* (or *beneficial*) and *dysfunctional* (or *deleterious*) complexity, i.e. complexity that, respectively, *is* or *is not* necessary for the business unit to carry out its strategy. Moreover, because reducing such strategy-enabling complexity might be unfeasible or detrimental to the organisation, two broad approaches to manage complexity are discussed, namely reduction and accommodation (or absorption) (Serdarasan, 2013; Bozarth et al., 2009; Perona and Miragliotta, 2004; Ashmos et al., 2000), which refer to the act of physically reducing the amount of complexity in the SC function or rather of mitigating the negative effects of complexity on SC performance. Hence, prior research has broadly argued for reduction approaches to be adopted for non-strategic complexity, whereas accommodation approaches can be leveraged to reduce the performance impacts of strategic complexity (Aitken et al., 2016; Serdarasan, 2013; Bozarth et al., 2009; Manuj and Sahin, 2011). Nonetheless, further qualitative empirical research is necessary to understand the relation between the firm's strategy and the complexity management approaches adopted in the SC function.

There is a large amount of research that discusses the management of complexity (Aitken et al., 2016; Perona and Miragliotta, 2004; Serdarasan, 2013; Manuj and Sahin, 2011; Bozarth et al., 2009; Gottfredson and Aspinall, 2005; Mocker et al., 2014; Ashkenas, 2007; Mariotti, 2007). However, prior efforts in the SC literature have mostly covered a few managerial practices, approaches or solutions to cope with complexity (e.g. Perona and Miragliotta, 2004; Caniato and Größler, 2015; Huaccho Huatuco et al., 2010; Vachon and Klassen, 2002; Aitken et al., 2016; Manuj and Sahin, 2011) and very few works offer a comprehensive review of complexity management practices (Aitken et al., 2016; Turner et al., 2018). A notable exception in this respect is Serdarasan's (2013) review of complexity management solutions, that draws from a review of the literature and an analysis of company secondary data to identify 23 solutions. Moreover, the literature has focused on 'structural aspects of complexity' (Manuj and Sahin, 2011, 512), and only a few papers (e.g. Aitken et al., 2016; Serdarasan, 2013) investigate the management of dynamic as well as of structural complexity.

Additionally, there is no consensus in the literature about how to classify the discussed managerial approaches. Specifically, prior studies have focused on the discussion of the two aforementioned approaches of complexity reduction and accommodation. Nonetheless, while these two generic approaches provide with a valid theoretical foundation to root the complexity management discussion, managers require of richer and more detailed frameworks to manage complexity in their SCs (Aitken et al., 2016; Turner et al., 2018). More precisely, they need frameworks or insights that can aid them in selecting practices that are adequate for the specific complexity types and factors the SC faces and that are of a more explanatory nature, allowing managers to understand how each type of practice can aid the SC to manage complexity. A less generic and more insightful classification that has been adopted to study complexity in manufacturing systems and SCs is that proposed by Galbraith (1973, 1977). According to Galbraith's work in the information processing domain, complexity management methods are of five types: environmental management strategies, self-contained tasks, creation of slack resources, investments in information systems and lateral relations. The first three of these, aim to reduce the amount of information to be processed by the organisation (i.e. complexity reduction), whereas the remaining two increase its information processing capacity (i.e. accommodation). This theoretical framework was empirically tested in a manufacturing environment by Flynn and Flynn (1999). However, the study did not examine the connection between complexity types and factors and management practices, and is limited to manufacturing activities only. It is also used in Aitken et al. (2016) to classify the few practices encountered in an illustrative case study. Turner et al. (2018) used an ambidexterity lens approach (exploration vs. exploitation) then based on the results from interviews with SC managers in six companies operating in the context of project management, found that a third of practices can be classified as accommodation whereas two thirds can be classified as reduction. This paper contributes to advancing this line of research by refining Galbraith's classification to enhance its practical applicability in a SC context.

3. Study design

This section draws from the review of the extant literature to present the adopted definitions of the key constructs as well as the design of the research methodology.

3.1 Definition and conceptualisation of the main constructs

In line with prior studies (Birkie and Trucco, 2016; Perona and Miragliotta, 2004; Serdarasan, 2013; Bozarth et al., 2009), structural complexity is defined as the static complexity associated to the numerousness, variety, and interconnections, interactions or dependencies within SC elements (e.g. products, processes, facilities, suppliers, etc.). Dynamic complexity is the complexity stemming from the 'dynamical motion' of the SC, which is associated to the evolution of its uncertain operations and to that of the SC's structure; i.e. to the rate of changes to SC elements or to their interconnections. This conceptualisation is equally consistent with the views of several authors, such as Casti (1979), Serdarasan (2013), Maylor et al. (2008), and Collinson and Jay (2012).

In addition, the analysis of complexity factors distinguishes between three main areas of relevance, referred to as complexity categories in the study: Product portfolio and design; Internal SC design; and External SC complexity (i.e. customer and supplier bases). The introduction of this further dimensionality of complexity and the choice of the three adopted categories is consistent with the distinction between internal and external, upstream and downstream complexities often encountered in the SC literature (e.g. Aitken et al. 2016; Bozarth et al., 2009; Huaccho Huatuco et al., 2010; Serdarasan, 2013; Vachon and Klassen, 2002).

Managerial practices broadly refer to consolidated single or sets of activities that managers perform systematically toward a common purpose (Reckwitz et al., 2002; Chia et al., 2004). In this study, however, we adopt a somewhat broader definition of complexity management practices and consider the methods, techniques and tools managers implement to reduce the adverse effects of complexity in their organisations or accommodate the strategically beneficial complexity that allows for innovative exploration (Turner et al., 2018). In this sense, the term ‘management practices’ in this study is considered to encompass other similar terminologies encountered in the SC complexity literature, such as ‘tactics and tools’ in Aitken et al. (2016), ‘management levers’ in Perona and Miragliotta (2004) and ‘solution strategies’ in Serdarasan (2013).

3.2 Research approach and data sample

The explorative nature of the study’s research question calls for the adoption of a qualitative methodology. Indeed, the study investigates *what* practices can be used to manage both complexity types and *how* do these practices together address the effects of the range of structural and dynamic complexities examined in the study. The case study methodology can be used to obtain a rich understanding of the nature and complexity of the phenomena in their natural context (Yin, 2003). Hence, inductive case studies allow for a rich understanding of the aim, scope and purpose of practices in responding to complexity, thus allowing for a detailed exploration of the field in the development of new theory (Eisenhardt, 1989; Meredith, 1998).

A multiple case study design is adopted, as this facilitates the creation of testable and more robust theory (Yin, 2003; Barratt et al., 2011). In this regard, Eisenhardt (1989) warns that the use of multiple cases can raise a challenge for researchers to cognitively process the collected information and suggests that a number of between four and ten cases can set an adequate balance between depth and breadth of observation. Taking these considerations into account, a sample of four in-depth cases was designed for the study. The unit of analysis of the cases is the SC function, defined as the subset within the organisation that directly takes part in SC activities, i.e. planning, sourcing, making and delivering (Hoole, 2005; Stewart, 1995). From a SC network standpoint, the unit of analysis includes all SC facilities (i.e. warehousing, manufacturing, etc.) where the prior activities take place and that are specifically owned by the company. Hence, this portion of the SC network that is internal to the organisation is equally referred to as the internal SC. This unit of analysis offers a more comprehensive view on SC complexity than earlier works that have focused solely on, for example, manufacturing or logistics (e.g. Bozarth et al., 2009; Flynn and Flynn, 1999. Supply- and customer-base complexity factors are considered in the analysis, although from the perspective of the case company.

Given the paper's theory building nature, theoretical sampling was employed to increase the validity, breadth and relevance of results (Miles and Huberman, 1994; Yin, 2003). A first preliminary assessment of each candidate case was made relying on available secondary documentation, which served to ensure an adequate distribution of the sample along multiple relevant parameters, e.g. position within the SC, industry, strategic orientation: efficiency or responsiveness (Fisher, 1997), areas of complexity factors, etc. This initial assessment was subsequently supported by preliminary interviews with the organisation before commencing the data collection process. Table 1 summarises the key characteristics of the case companies in the study.

Table 1. Sample characteristics.

Characteristic	Drinks	Percomp	Auto	Defence
Industry	Drinks/Spirits	Personal Computers	Automobile	Defence Electronics
No. employees	4000	50000	1500	45000
Revenue (€M)	1500	42000	200	12000
SC position	Focal company	Focal company	First tier supplier	Various (on a project basis)
Operations model	MTS	MTS	MTS	ETO/MTO
Strategic orientation	Responsiveness	Efficiency	Efficiency	Responsiveness

3.3 Data collection

Data from multiple sources was triangulated to strengthen its reliability and the study's internal validity (Voss et al., 2002; Benbasat et al., 1987), including interviews, company documents and archival sources, informant's notes, and secondary data collected for the preliminary assessment of the case. Nonetheless, interviews to key informants constituted the primary source of data in the study. Multiple respondents in different areas within the SC function were interviewed in each case company (e.g. purchasing director, SC chief of staff, plant manager), covering a variety of roles at different levels in the SC. Respondents were experienced members of the targeted areas within the SC, who had faced and managed complexity in the SC function on a daily basis for a number of years. A total of nineteen semi-structured interviews were performed. The duration of these was not less than 60 minutes and approximately 75 minutes in average. The protocol consisted of about six to eight broad questions, with detailed questions on these general issues arising during the interview (see Appendix).

3.4 Data analysis

The content analysis process was designed based on the recommendations and methods in Saldaña (2009) and its first steps were performed in parallel to the collection of the data, hence guiding collection efforts to ensure that a rich perspective on the complexity management issue was gathered. Detailed descriptive and structural coding were both used to capture the complex characteristics of the phenomena in the data (Coffey and Atkinson, 1996), leading to two spreadsheets respectively containing (1) emerging themes on the relations between complexity and practices; (2) a classification of the empirical data in each case according to the key construct discussed. The analysis was then carried out following a within-case and cross-case structure, and tables and visual displays were employed to summarise and illustrate the empirical evidence (Miles and Huberman, 1994; Voss et al., 2002).

Additionally, a clarification is due regarding the process followed to classify and group practices together. To this end, an abductive process was followed in which initial classifications were gathered from the SC complexity literature and were then adapted and refined to better fit the research objectives. Classifications were sought to (1) convey a clear understanding of the practice's underlying logic (i.e. how it is that the practice reduces the impact of complexity on performance) and (2) allow for practical applicability (i.e. adequate level of detail and terminology to guide practitioners adopt relevant practices). The classification proposed by Galbraith (1973, 1977) was used in this paper. This classification offers considerable more detail than the previously discussed distinction between accommodation and reduction responses, and a clearer understanding of practice's logic; thus, it is better fitted for the purposes of this study. Nonetheless, it does not fully meet the study's requirements as, for example, some clusters are defined in relation to the type of resource that is leveraged (e.g. information systems) and not its actual logic or aim. Consequently, and in line with the adopted abductive approach, it was adapted and refined during the analysis of the explored practices and the empirical observations (as discussed in presenting the empirical findings).

4. Empirical results

Table 2 offers an overview of the encountered complexity factors in the case studies.

Table 2. Key structural and dynamic complexity factors.

Company	Structural complexity	Dynamic complexity
Drinks	The product portfolio consists of more than 100 products organised into 50 brands. The need to adapt products to local legal requirements, customer preferences and promotional activities can result in thousands of variants per product. The variety of teams and functions involved in the SC and process fragmentation and scarce formalisation render the interactions between functions a critical source of complexity. The diversity of customer segments influences the physical and organisational design of the network. The large number of suppliers employed results in higher procurement costs.	M&A are a cornerstone of the firm's strategy, yet the initial stage of the subsequent integration process poses as a critical source of dynamism and uncertainty for SC managers. The company introduces changes to its internal SC network and flows on a daily basis to take advantage of market opportunities. Operational dynamics related to customers and front-end functions are a major concern for the SC. Product launches further accentuate this dynamism (e.g. uncertain demand).
Percomp	The size of the firm's product portfolio plus the introduction of technology-, regulation- and marketing-driven product variants result in a vast number of SKUs. Complex network of facilities comprised of three tiers and a hundred locations, compromising optimisation and efficiency. Differences between local partners and regulation lead to differences between SC country-networks and procedures.	Frequent product lifecycle events are a challenging source of uncertainty and dynamics in the SC. Their management is further complicated by the different lifecycle curves and characteristics of product segments. A 'SC transformation' initiative encompasses various innovation projects that alter the SC network and processes to reduce costs and improve performance. Uncertain customer demand and the introduction of premium and standard delivery options result in complex operational dynamics (e.g. bullwhip effect).
Auto	Product specificities (e.g. aesthetic design, tolerances, flow-formation) increase structural complexity beyond the size and breadth of the portfolio. The variety of packaging options per product drastically increases the number of SKUs. Customer requirements (especially OEMs') are diverse and regard a range of non-product-related aspects (e.g. management procedures, suppliers, etc.). In addition, OEM customers hinder the development of product standards. SC facilities differ in terms of their equipment, organisational design (e.g. teams' responsibilities) and managerial processes.	The introduction of new products and of a new product lines demands upgrading production lines and embracing new technologies Continuous improvement, which is primarily cost-oriented and may be influenced by customer suggestions, results in frequent changes to production equipment and procedures. Customer demand variability, raw material delays, breakdowns and quality issues underpin operational dynamics and hinder SC performance.

Defence	Products push the state-of-the-art of technology and the product portfolio consists of six large product segments (e.g. micro-electronics, optics, radar). Customers are of a variety of types (e.g. military, customer integrator, platform developer). In addition, their requirements are not only diverse but broad, as they span a range of aspects beyond product features (e.g. delivery, support, sourcing). Supplier complexity does not stem from the size of the supply base but from its critical dependencies with the SC, that are accentuated by the technological nature of products and the extensive use of outsourcing.	The development and introduction of new products is a critical dynamic complexity factor that entails iteration and involves suppliers and, often, customers. The irregular pace of operations, driven by supplier, customer and internal instabilities, is a major dynamic complexity factor. Supplier obsolescence is a frequent, yet hard to predict dynamic complexity factor that is underpinned by the length of product service and support lives.

More than 40 practices used to manage complexity factors in their internal supply chain were identified. See Table 3.

Moreover, the cross-case analysis compares and identifies similar aims of different practices and organise them into clusters. Thus, in the context of this study, complexity management clusters can be defined as bundles of practices (i.e. managerial, technological, design-related, etc.) that rely on the same principle or logic to manage complexity. The presented classification resulted from adapting the classification of complexity management methods by Galbraith (1973, 1977) to the empirical findings and setting of this study following the process described in the methodology section. In this sense, three types of refinements were made:

- *Clusters that relate to specific types of resources:* to facilitate the understanding of the complexity management issue, the adopted classification is set to divide practices based on their logic or aim, rather than the type of resource employed (e.g. Galbraith's 'investing in information systems').
- *Dependency-focused practices:* practices that relate to the use of slack resources and those that instead define self-contained tasks are separated in Galbraith's classification, but share a unique logic for the purpose of this study, as they seek to act upon the dependencies and constraints that define the relations between SC elements at the expense of a less optimal exploitation of shared resources (Flynn and Flynn, 1999). Thus, a single confinement and decoupling practices cluster is employed.
- *Theoretically-rooted terminology:* Galbraith's clusters whose names stem from information processing theory and are not clear indicators of their logic and purpose are given labels that reflect their logic (e.g. practices that aim to reduce diversity in the SC are simply referred to as 'variety reducing practices', instead of 'environmental management strategies').

The resulting classification of practices consists of four clusters: variety reducing, confinement and decoupling, decision support and knowledge generation, and coordination and collaboration. Firms can leverage on these four clusters for jointly managing structural and dynamic complexity factors and their interplay. It should be noted that while most practices adhere well to single clusters, some of them do not. For instance, product-centric organisational design reduces the number of layers that need to interact to manage unexpected demand changes, and fosters the generation of product-specific knowledge and the reduction of differences between countries and regions. Thus, in principle, product-centric organisational design could have been mentioned under three clusters, namely variety reducing, knowledge generation and coordination. In these instances, practices have been classified according to the contribution that was most significantly mentioned by SC managers (see supplementary file).

Table 3. Aim and scope of complexity management practices in the case studies.

Type of complexity / Cluster of Practices	Structural			Dynamic		
	Prod.	**Int.**	**Ext.**	**Prod.**	**Int.**	**Ext.**
Variety reducing (No. tally)	**5**	**5**	**2**	**1**	**0**	**1**
Accessory-based customisation	b					
Product platforms and standards	c					
Product portfolio rationalisation	a,d					
Product-centric organisational design	b,d	b,d		b,d		b,d
Rationalisation of SC facilities		b				
Platform teams		b				
Process standardisation		a,c				
Unification of customer requirements			b,c,d			
Centralisation of purchasing	a,c	c	a,c			
Confinement and decoupling	**6**	**1**	**6**	**3**	**2**	**6**
Outsourcing	b,d	b	b			
Customised distribution channels			a			
Modular design and software customisation	d		d			
Category management	a,d		a,d			

Localisation of activities	a		a,c			a,c
Additive manufacturing postponement	b		b			b
Split of sourcing activities	d			d		d
Flexible workforce				d	d	d
Stocks				c	a,b,c	a,b,c
Intermediate interface teams						a
Coordination and collaboration	**1**	**5**	**5**	**5**	**5**	**8**
Decentralisation of procurement			d			d
Global SC forums		b		b		
Integrated product teams	d	d		d		d
Strategic relations with partners and suppliers		b	a,d		d	b,d
Integrated ERP systems		a,c			c,d	c
Benchmarking		c			c	
Coll. with product design and front-end teams				b		
Project management			d	All	a,b,c	
Cross-functional KPIs						b
Multi-level supply-demand reconciliations						a,d
Unique customer interfaces			c			c
Supplier development			d	d	d	b,c,d
Decision support and Knowledge generation	**7**	**2**	**2**	**6**	**2**	**4**
Cellular manufacturing and product tech. groups	d					
Forward-looking forecasting	b			b		
Product segmentation and specialised teams	a			a		
Automation	b,c					
Traceability and anti-mixing systems	a,c,d				a,d	a,c,d
Multi-Echelon ERPs and optimisation IT tools	a,b	a,b				b
Product lifecycle management processes and tools	d	d	d	c,d		d
Vendor rating tools			c			
Specific training				a,c	a,c,d	
Product design carry-over				c,d		
Simulation				c		b

Note: Numbers indicate usage in case study. a=Drinks, b=Percomp, c=Auto, d=Defence.

Next, a description of the clusters, of how each enables the SC to better cope with complexity, and of their scope and limitations or drawbacks follows.

4.1 Variety reducing management practices

Variety reducing management practices are adopted to physically reduce the level of structural complexity that SC managers must cope with in two ways. The first is by aiding the firm focus on a narrower range of elements (e.g. products, customers, geographies, etc.) via rationalisation exercises. In Drinks, for example, the rationalisation of SKUs has become a standard part of every project concerned with the launch of a new product or product variant, thus helping the firm reduce and contain the complexity of its portfolio. The second is by establishing commonalities among these elements, thus reducing internal diversity while minimising the effect of this on the breadth of the firms' businesses (for instance, by deploying platform teams that seek to define a common internal architecture of processes and tools for SC activities across businesses and geographies). This is the option undertaken by Auto, which rather than rationalising, aims to define standards and platforms that can then be leveraged by multiple products.

The adoption of these practices can be limited for different reasons. On one hand, these practices relate to the design of products, of the internal SC and the firm; and their focus on variety makes them suitable to directly address structural complexity only. On the other hand, while rationalisation can bring focus to the firm and reduce complexity costs in the SC, trimming down variety in the SC beyond a certain point can stand in the way of the firm's objectives. For example, the high diversity of product formats and sizes in Drinks is presented as a consequence of the sales function's efforts to continuously drive firm revenues. In this vein, some of the structural complexity that hinders SC performance may be the basis for company-level competitive advantage. Similarly, Defence employs reusable packaging, increasing packaging variety and adding further complexity in the form of dependencies between SC activities, because 'at the end of the day, saving a couple of hundred pounds in packaging in a half a million pounds sale is nonsense' (Head of SC in Defence). This is similar to the situation encountered in Auto, where some products where delivered in more than ten different packaging types to the same customer because this is hard to negotiate out of customer's requests. Hence, in these companies, forcing customers to rely on standardised packaging to reduce variety is perceived as an action that can get in the way of both customer satisfaction and sales (i.e. responsiveness and revenues).

4.2 Confinement and decoupling practices

Confinement and decoupling practices focus on the dependencies and relations between elements in the system. Confinement practices (e.g. outsourcing, customised distribution channels) aim to contain complexity within a reduced domain, where specialised resources can be leveraged. For example, by defining bespoke distribution channels for each of its core customer segments, Drinks can employ specific infrastructure and tools to meet the differing needs of customer segments. Decoupling seeks to lessen the relations and constraints between elements and to render certain parts of the system more independent from others (e.g. postponement, stocks). For instance, planning teams in Drinks are placed to act as an intermediate interface between front-end functions and production, and planning managers are responsible for protecting manufacturing teams from customer-related dynamics and requirements as much as possible. By doing this, the firm can better meet the contrasting performance goals of front-end and back-end functions (i.e. responsiveness vs. efficiency), as 'the more [Drinks] succeeds in dealing with complexity locally, the more manufacturing plants can focus on producing' (SC Director in Drinks).

These practices can narrow the range of activities that must bear with complexity in the SC, and because they do not incur in the loss of revenue-driving variety, they can be used to reduce complexity while preserving firm responsiveness, hence surpassing some of the limitations of variety reducing practices. Furthermore, by making groups of activities independent to others, decoupling can aid in managing dynamic complexity (e.g. stocks, flexible workforce, etc.). Therefore, practices in this cluster can be leveraged to reduce structural and dynamic complexity, especially that related to the customer and supply basis and, to a somewhat lesser degree, the product portfolio. For instance, the localisation of promotional activities close to the end-market in Drinks allows the firm to contain the effect of local regulation and customer preferences affecting these activities within local teams in each individual market, reduces the variety of SKUs in manufacturing activities and enhances the SC's ability to cope with the demand uncertainty that comes with promotional activities by shortening lead-times and enhancing responsiveness.

4.3 Coordination and collaboration practices

Coordination and collaboration practices are those managerial techniques or systems that foster sharing knowledge and solutions in the SC, as well as the synchronisation and alignment between teams and functions inside and outside the internal SC. Thus, these practices do not reduce extant complexity, but rather make the SC more capable of coping with it by allowing managers to understand the effects of their actions outside their domain and facilitating for complexity to be managed more holistically rather than from within silos.

These practices focus on the management of dynamic complexity factors, as the establishment of these information flows are critical in managing dynamic complexity. As put by a Planning Manager in Percomp: 'From the dynamics related to products, related to transformation, related to network design, it all arrives at complex processes involving other functions beyond SC. None of these can be managed purely from within a SC silo'. Hence, the company defines cross-functional KPIs that allow both front-end functions and SC managers to jointly minimise the effect of operational customer dynamics on SC performance. In the same vein, the product lifecycle communication tool and the definition of unique customer interfaces in Auto allows the SC to better cope with the dynamics of customers and the development and introduction of new products. Defence is, as highlighted by Table 3, the company that most strongly relies on these practices, as this is fostered by both its operations model and the technological edge and complexity of its products. In this respect, the firm employs integrated product teams, project management and integrated ERP systems to achieve the necessary coordination and collaboration across functions that is critical in an ETO firm, while additionally investing in supplier development initiatives, decentralising procurement and establishing strategic relationships with suppliers and partners to create the collaboration and coordination required for the design and procurement of its products.

Nonetheless, these practices cover a wide range of complexity factors and can be also used to address structural complexity. This is partly due to an often-encountered positive side-effect of collaboration and coordination practices, which is that they drive homogenisation within the internal SC. Indeed, practices such as benchmarking and process platforms facilitate the escalation of best practices and the definition of shared processes and solutions throughout the SC. In Percomp, global SC forums are hold 'putting together regional and global SC teams to discuss common topics and define common decision making processes' (Planning Manager in Percomp). Therefore, in doing this, these practices can help reduce structural complexity. Likewise, the implementation of integrated systems in Auto (e.g. ERPs) drive plants to homogenise organisational designs and team responsibilities across SC regions.

4.4 Decision support and knowledge generation practices

Decision support and knowledge generation practices are equally employed to accommodate complexity. These practices increase the SC's ability to cope with extant complexity by enhancing decision making at (generally) the individual manager level. In order to do so, they aid managers partially surpass their cognitive limitations in dealing with complexity in various ways. Some practices allow managers to filter out and focus on a reduced number of decisions and elements (e.g. automation, vendor rating tools, anti-mixing systems). For example, to deal with the large portfolio in Percomp, 'part of the [planning] decisions are automatized, allowing planners to focus on those that entail higher risk. Otherwise, the excess of information and of decisions to be made does not allow managers to assess these properly' (SC Planning Architect in Percomp). Similarly, bespoke anti-mixing containers are used to pick up components in Defence, reducing the need for careful attention driven by the diversity of product parts and materials. Other practices provide managers with more valuable information to base their decisions (e.g. optimisations tools, simulation, forward-looking forecasting). For example, Percomp has developed in-house simulation solutions that allow planning managers to explore the consequences of rare events (e.g. a strike interrupting certain material flows into a country) on the performance of the network, and adjust decisions accordingly. Lastly, some practices help managers build and maintain relevant skills and knowledge (e.g. specific training, product-centric organisational design, product-design carry over).

5. Discussion

This study explores how structural and dynamic complexity are managed in the SC function of four manufacturing organisations. In this respect, the empirically and theoretically grounded classification of complexity management practices put forth and the grouping of complexity factors into three complexity categories allows to gather a clearer view of the practice-complexity link than prior SC works (e.g. Serdarasan, 2013). This is especially important as very few studies have adopted such structured approaches to investigate the adoption of complexity management practices (e.g. Aitken et al., 2016, Turner et al., 2018). In addition, the findings underline different specific approaches to both reduce and accommodate complexity, thus serving to expand the results of studies that have proposed reduction and accommodation as the two main generic responses to complexity in the SC function (Turner et al., 2018; Aitken et al., 2016; Perona and Miragliotta, 2004; Bozarth et al., 2009).

The proposed classification underlines the existence of four distinct logics that companies can follow to manage complexity. In the light of the findings, complexity can be reduced using variety reduction or confinement and decoupling practices; and may be accommodated by employing either coordination and collaboration or decision support and knowledge generation practices. Similarly, the offered classification is fully in line with Galbraith's (1973, 1977) theoretical classification of complexity management methods, but provides with a refined and more practically fitted alternative to this to manage complexity in the context of SCs. In this respect, the study advances beyond prior empirical works that have equally drawn from Galbraith's work, such as Flynn and Flynn (1999), Aitken et al., (2016) and Turner et al. (2018), since these have offered very reduced visibility over the link between clusters and complexity categories or factors.

As anticipated, each of the proposed clusters lessens complexity's negative outcomes in a distinctive manner, and thus has a particular scope and limitations that have been reviewed in section 4. Drawing from this discussion and from the analysis of the qualitative evidence summarised in Table 3, Table 4 synthesises the range of complexity factors that are predominantly addressed with each cluster.

Table 4. Overview of the scope of complexity management clusters.

Type of complexity / **Cluster of Practices**	**Structural**			**Dynamic**		
	Prod.	**Int.**	**Ext.**	**Prod.**	**Int.**	**Ext.**
Variety reducing	**	**				
Confinement and decoupling	**		**	*		**
Coordination and collaboration		*	*	*	*	**
Decision support and Knowledge generation	**			**		*

**: a few of the cluster's practices are used to manage the category of complexity factors.*
***: the majority of the cluster's practices are used to manage the category of complexity factors.*

There is a large body of research that has discussed variety reduction and, specifically, the role of pruning and of defining commonalities as a means to cope with complexity (Aitken et al., 2016; Serdarasan, 2013; Flynn and Flynn, 1999; Mariotti, 2007; Ashkenas, 2007; Gottfredson and Aspinall, 2005). On one hand, Robertson and Ulrich (1998) focus on the use of product platforms and argue for the need to establish a balance between commonality and distinctiveness (i.e. specificities) to bind the complexity in the product portfolio. Similarly, Mocker et al. (2014) propose the use of process digital platforms to establish commonalities and reduce the complexity that stems from the diversity and specificities of internal processes. On the other hand, Aitken et al. (2016) and Serdarasan (2013) underline the rationalisation of the number of product, product variants and of distributions centres as complexity reduction practices focused on structural complexity factors. Mariotti (2007) advices the combination of both pruning and platforms to address product complexity, which is in line with the proposition of Turner et al. (2018) on the use of ambidexterity as a lens to understand responses by managers to SC complexities. Hence, and in line with our findings, while some examples of the use of these practices to address external SC complexity are found both in this study and in the literature (e.g. Serdarasan, 2013), these are less relevant and numerous and prior literature especially relates these practices to product portfolio and design and internal SC design structural complexity factors.

Therefore, we propose,

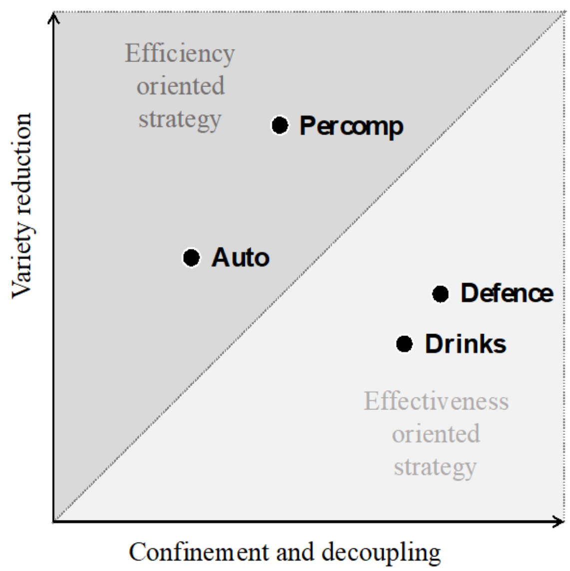
Proposition 1: *Variety reducing practices mitigate the negative impact of product portfolio and design, and internal SC design structural complexity on SC performance.*

Confinement and decoupling practices are in line with Galbraith's (1973, 1977) discussion of the use of self-contained practices and of slack resources to alleviate the amount of information necessary for the organisation to cope with complexity. In the business complexity literature, Mocker et al. (2014) argue for the use of digital technologies such as digital process platforms to decouple product portfolio complexity from the complexity of internal processes to allow the firm to leverage on a diversified customer-oriented offering while minimising internal complexity costs. In the SC literature, the use of modular product designs to reduce complexity has received especial attention (Perona and Miragliotta, 2004; Choi et al., 2001; Pero et al., 2015). In this regard, Pero et al. (2015) found an inverted relation between the use of product modularity and the level of complexity within the SC. Similarly, and in line with our definition of the cluster, Choi et al. (2001) proposes the use of modularisation to decrease the density of dependencies within the SC network. Other studies have noted the usefulness of this approach to cope with uncertainties and dynamic complexity related to the external SC such as demand variability, supplier constraints or changing currency exchange rates (Aitken et al., 2016; Manuj and Sahin, 2011). In particular, Perona and Miragliotta (2004) discuss product modularisation as a critical lever to improve new product development and introduction performances, hence also supporting our finding of the scope of these practices. Therefore, we propose,

Proposition 2: *Confinement and decoupling practices mitigate the negative impact of product portfolio and design and external SC structural and dynamic complexities on SC performance.*

Moreover, our analysis of the use of these two clusters of practices suggests that the firm's ability to implement complexity reduction practices is influenced (i.e. contingent) on specific factors. Drawing from these findings and from the empirical evidence summarised in Table 3, Figure 1 represents the adoption of complexity reduction practices in each cluster and the influence of these factors. In particular, the findings suggest that the strategic orientation of the firm (i.e. efficiency or responsiveness) is a central factor in influencing firm's implementation of either variety reduction or confinement and decoupling practices. In this vein, firms with a strategy based on responsiveness and customer-orientation tend to rely on confinement and decoupling practices and to leverage variety to achieve higher levels of customisation of their offerings (i.e. Drinks and Defence). On the contrary, companies with efficiency and cost-reduction strategies employ variety reduction practices to a higher extent (i.e. Auto and Percomp). Additionally, other factors can influence cluster adoption. In this vein, despite both being primarily cost-oriented companies, the different position of Percomp and Auto (i.e. focal vs. first tier supplier) and the impact this has on the type of relationship with customers, allows Percomp to leverage on variety reduction practices more extensively than its counterpart (i.e. number and aim of practices). Similarly, it can be noted that, among the companies with a similar strategic orientation, those with more complex products, in terms of the number of components, make more use of decoupling practices than those that do not (i.e. Defence vs. Drinks, Percomp vs. Auto).

Figure 1. Use of complexity reduction practices in the case companies



Prior research has argued that variety can play a substantial role in implementing a customer-centric strategy (Perona and Miragliotta, 2004), and that, consequently, firms pursuing responsiveness should employ accommodation rather than reduction practices (i.e. Turner et al., 208; Aitken et al., 2016; Perona and Miragliotta, 2004). In this respect, while our findings do support that firms leverage variety to better fulfil customer requirements, they show that these companies may still employ some types of complexity reduction practices, which reduce complexity even if preserving the range of elements offered to external customers. Therefore, this suggests that such firms are not bound to leveraging accommodation practices as suggested by Perona and Miragliotta (2004) and Aitken et al. (2016), but to rather minimise the use of variety reduction practices that prune customer-oriented variety. Ultimately, this implies that firms may, in fact, reduce strategically beneficial (Turner et al., 2018) employing such alternative reduction approaches. This is, for example, the case of confinement and decoupling practices (e.g. modular product designs, localisation of activities) or of variety reduction practices that rely on establishing commonalities rather than on pure rationalisation (e.g. product or process platforms), which are also leveraged by efficiency focused companies in our sample (i.e. Auto and Percomp) as reported in Table 3. In addition, the findings suggest that, despite the critical influence of the firm's strategic orientation, other factors may help understand the adoption of complexity reduction practices by companies. These findings expand current understanding of the role of context in complexity management, as prior studies have focused on the influence of factors on complexity (e.g. Manuj and Sahin, 2011; Perona and Miragliotta, 2004) and not on that on complexity management practices (e.g. discussed in Vachon and Klassen, 2002). Therefore, we propose,

Proposition 3: *The efficiency (or responsiveness) strategic orientation of a company fosters the adoption of variety reduction (or confinement and decoupling) practices to reduce complexity.*

The relevance of coordination and collaboration to accommodate complexity is well established in the literature (Caniato et al., 2015; Caniato and Größler, 2015; Serdarasan, 2013; Cicmil and Marshall, 2005; Vachon and Klassen, 2002; Flynn and Flynn, 1999; Perona and Miragliotta, 2004). First, the results show that coordination and collaboration are indeed the cluster with a broader scope, as these are used to manage all complexity categories except for product portfolio and design structural complexity. Second, the analysis suggests that these practices are needed to support the usefulness and offset the drawbacks of, respectively, confinement and decoupling, and of decisions support practices.

Moreover, other researchers have provided evidence of the broad scope of these practices. Manuj and Sahin (2011) underline collaboration and alignment as moderators of structural and dynamic complexity factors such as the numerousness of SC facilities and organisational restructuring. Perona and Miragliotta (2004) also highlight the use of partnerships with suppliers and integrated information systems with suppliers and customers to accommodate complexity, and Aitken et al. (2016) observe that collaboration and coordination between production and marketing can aid firms cope with demand variability. This resonates with Serdarasan (2013) who links collaboration practices to dynamic complexity factors and argues that these are the best practices to address demand uncertainties that may be difficult to address with forecasting (i.e. decision support) practices. Hence, in line with our findings, these latter works suggest that these practices are especially effective to address external SC complexity. Therefore, we propose,

Proposition 4: *Coordination and collaboration practices mitigate the negative impact of internal SC design and external SC structural complexity, as well as of product portfolio and design, internal SC design and external SC dynamic complexity on SC performance.*

The decision support and knowledge generation cluster resonates with another pillar in the complexity management literature: information systems (Galbraith, 1973, 1977; Manuj and Sahin, 2011; Perona and Miragliotta, 2004; Vachon and Klassen, 2002; Guimaraes et al., 1999). Yet, the study's definition of this cluster makes it broader than investing in IT systems in two ways: First, this cluster encompasses not only decision-making tools but also practices that can facilitate and foster the development of new relevant knowledge in the internal SC (e.g. product technology groups or specific training). This aspect is along the lines of Manuj and Sahin's (2011) discussion of 'human cognitive ability moderators'. Second, it does not only focus on information systems and technological tools but also includes managerial and design-based practices that result in similar benefits (e.g. product lifecycle management processes and specialised product teams). Our findings show that these practices are predominantly leveraged against product structural and dynamic complexity as well as against external dynamic complexity. In this sense, the findings support those of Serdarasan (2013), in which the use of IT-based decision support technologies is presented as a key strategy to accommodate product design and portfolio structural complexity. Likewise, the works of Aitken et al. (2016) and Perona and Miragliotta (2004) offer some empirical evidence of their use against external SC complexity. On the contrary, our results are misaligned with the arguments that these practices play a significant role in the management of internal SC complexity factors found in Manuj and Sahin (2011), as we find that these factors are predominantly managed through coordination and collaboration practices instead. In this vein, we propose,

Proposition 5: *Decision support and knowledge generation practices mitigate the negative impact of product portfolio and design structural and dynamic complexity as well as of external SC dynamic complexity on SC performance.*

6. Conclusions and implications

6.1 Contributions to theory and practice

This paper offers a comprehensive review of the practices employed in four manufacturing companies to manage complexity, and makes a number of relevant contributions to the literature. Complexity reduction and accommodation are presented as the prevailing approaches to manage complexity (Bozarth et al., 2009, Perona and Miragliotta, 2004; Aitken et al., 2016; Turner et al., 2018). However, these two approaches are too generic to guide managers in deciding which practices to adopt in their organisations, and there is a need for developing more detailed frameworks that can be leveraged to this end (Aitken et al., 2016; Turner et al., 2018). Although there is not a clear-cut relationship between the propositions and the empirical evidence provided in this paper and that carried out by Turner et al. (2018), it is possible to see the similarities with their proposed three complexities (structural, socio-political and emergent) mapping out on to three management responses (planning and control, relationship development and flexibility). In their paper, the predominant managerial responses were of ‘planning and control’, whereas in this paper, the predominant managerial responses are ‘confinement and decoupling’ and ‘coordination and collaboration’.

This study puts forth an empirically and theoretically supported classification of complexity management practices that adapts Galbraith’s (1973, 1977) theoretical framework to the SC complexity domain. The classification consists of four clusters of practices: (1) variety reduction, (2) confinement and decoupling, (3) coordination and collaboration, and (4) decision support and knowledge generation. The first two clusters can be employed to reduce complexity, while the remaining two encompass complexity accommodating practices. Hence, the study makes a theoretical contribution to this stream of studies by presenting with detailed ways in which companies can implement the generic management approaches of reduction and accommodation.

Moreover, leveraging on the advanced classification, the study provides a much clearer view of the link between complexity management practices and factors than prior works, which have paired complexity factors and solutions or strategies in a much less structured manner (e.g. Serdarsan, 2013; Manuj and Sahin, 2011). The scope of each cluster and its limitations or drawbacks is reviewed and the discussion of this analysis has led to the introduction of propositions. Coordination and collaboration are found to have the broadest managerial scope, but all clusters except for variety reducing practices are employed to address both structural and dynamic complexity factors in the cases. In doing this, the study offers precise empirical findings that can aid practitioners make better practice adoption decisions, hence addressing the call of Aitken et al. (2016). Additionally, the study has found that factors that are external to the SC function may influence its choice of complexity reduction practices. The company's strategic orientation is found to be the most influential of these, as it drives firms to predominantly rely on either variety reducing or confinement and decoupling practices, but other factors such as the type of relationships with customers may facilitate or hinder the use of these practices. Therefore, the findings suggest contextual characteristics may not only influence complexity (Manuj and Sahin, 2011; Perona and Miragliotta, 2004) but also complexity management.

The study's findings provide practitioners and academics with key insights to better manage the impact of complexity on SC performance. In particular, while the extent and type of practices available for organisations to reduce complexity varies in relation to contextual factors and to the nature of the complexity faced by the SC, the empirical evidence shows that companies can in fact reduce strategy-enabling complexity (e.g. with confinement and decoupling practices), and not only complexity that does not underpin the business's strategy as suggested in prior literature (e.g. Turner et al., 2018; Aitken et al., 2016; Bozarth et al., 2009).

6.2 Limitations and future research

This study has a number of limitations. The use of case study is regarded as an appropriate first step in the theory-building process (Meredith, 1998), but one that demands from further research. In this sense, the paper provides practitioners and academics with valuable insights to analyse and respond to complexity in SCs, but further research is called for to ensure the generalisability and expand these findings. In particular, a quantitative method could be employed to test the propositions put forth by this research. Additionally, by defining the unit of analysis as the SC function (i.e. internal SC), this paper offers a comprehensive description of how complexity is managed in the four manufacturing companies from a SC viewpoint. Nonetheless, the understanding of the implementation of practices that involve other functions could benefit from a broader cross-functional perspective.

With regards to the findings of the study, the large and wide-ranged review of complexity management practices offered in the study allows the identification of key practices (Table 3). Some of these have received relative little attention in the SC complexity literature (e.g. product lifecycle processes or solutions) and further qualitative or mixed-method studies could examine their implementation and effect in more detail and in a broader set of contexts. The study is equally limited on the analysis of factors on which the adoption of practices might be contingent (an aspect that indeed lies outside its focus). While a few prior works have suggested that contextual factors may influence complexity management (e.g. Vachon and Klassen, 2002), the literature has focused on the influence of context on complexity (e.g. Manuj and

Sahin, 2011) or on the role of complexity as contingent factor (Pero et al., 2015). Hence, in the light of its findings, this study calls for further research to investigate which and how contextual factors might influence the management of complexity.

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Appendix. Interview protocol example

- Brief description of role and core responsibilities.
- What are the key aspects that contribute to the complexity of your tasks as part of CompanyA's SC? What is the most complex regular activity under your responsibility?
- In addition to the prior aspects, which of the following factors (i.e. complexity sources) do you find to more directly influence the design and performance of CompanyA's planning activities?

Table 5. Sample structural and dynamic complexity factors.

Static Complexity	**Dynamic Complexity**
Variety of customer needs and requirements	New product introduction and rate of change of the product portfolio
Number or diversity of suppliers	Component obsolescence (suppliers)
Variety and breadth of the product portfolio	Modifications to main processes
Variety of distribution channels	Switching between partners
Diversity or number of SC facilities	Continuous improvement practices
Complex processes involving other functions	Innovation projects
Variety of KPIs and performance reporting metrics	Changes to the network design and flows
Number of organizational functions or layers involved in SC activities	Rationalisations of the portfolio or supply/customer base

- How do the factors discussed in the prior two questions positively and negatively influence the performance of the internal SC activities (i.e. cost, speed, flexibility and quality)?
- Could you discuss the tools or practices (such as IT systems, techniques, processes, standards) that are adopted to handle the sources of complexity you have highlighted (dynamic and structural)? What are the major benefits and drawbacks of these approaches?

- Which of the main SC areas (i.e. planning, purchasing, production and logistics) are influenced the most by the complexity factors you have selected? How do the adopted practices facilitate addressing the complexity factors in these specific areas?