POLITECNICO DI MILANO

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

MASTER OF SCIENCE IN MANAGEMENT ENGINEERING

COMPLEXITY MANAGEMENT FROM THE RESILIENCE PERSPECTIVE: AN EXPLORATORY STUDY ON SUPPLY CHAINS

Supervisor: Prof. Paolo Trucco

Co-Supervisors: Prof. Seyoum Eshetu Birkie

Dr. Pablo Fernandez Campos

Master thesis by:

Alessandra Negri, ID 852402

Academic Year 2016/2017

Table of contents

List of tables

List of figures

Abstract

Purpose: The study seeks to contribute to a better understanding of the relationship between supply chain complexity and resilience, considering the influence of complexity management practices on the resilience properties of a supply chain.

Knowledge background: Despite the presence of literature discussing the link between supply chain complexity and resilience, the relation can be further investigated, as empirical evidence is needed. Moreover, a gap still exists about dynamic complexity drivers and complexity management practices.

Research questions: The study aims at investigating how supply chain structural and dynamic complexity, as well as the corresponding management practices, influence supply chain resilience.

Design/Methodology/Approach: The study is articulated in two main phases, characterized by two different research methods: Critical Incident Technique and inductive case studies. While the former was adopted to analyse the relationship between supply chain complexity and resilience, conceptualized through constituents (i.e. flexibility, visibility, velocity and collaboration), the latter was used to investigate the role of complexity management practices. Finally, results were triangulated and collected in a comprehensive summary matrix, and the five most relevant complexity management practices were deeply discussed in their contribution to supply chain resilience.

Main findings: Main results qualitatively demonstrate the different impacts of different complexity drivers on the four resilience constituents: while dynamic ones only positively affect them, static ones can present also negative effects (e.g. differences between facilities in different territories decreases flexibility, velocity and collaboration). Moreover, findings assess the multiple positive and negative impacts of complexity management practices on supply chain resilience, as well as the kind of interplay of complexity drivers. Considering the five most critical practices, while *centralisation of purchasing* and *project management* increase resilience, *product-centric organisational design*, *strategic relations with partners and suppliers*, and *multi-echelon ERPs and optimisation IT tools* are ambivalent, showing, both positive and negative effects.

Practical implications: Managers are informed of the interactions existing between the three dimensions, thus they can consider them in making supply chain design decisions and when evaluating management practices to adopt.

Limitations and future developments: Main limitations are due to the adopted methodology: the qualitative inductive and exploratory approach is appropriate for theory building, without quantitatively supporting findings, opening to future theory testing. Moreover, in both Critical Incident Technique and inductive case studies, the subjectivity of the researcher or key informants may affect the analysis and its conclusions. Then, the adopted unit of analysis, i.e. the manufacturing firm’s internal supply chain, limits the study at the level of the single organisation. Finally, there are three content limitations: first, secondary-data collection did not allow to equally investigate all the supply chain complexity drivers at the same level of detail; secondly, the study does not empirically analyse the role of complexity management practices under disruption; third, the focus of discussion was limited to five dominant practices, which calls for further research on the remaining set of practices.

Keywords: supply chain, structural complexity, dynamic complexity, resilience, practices, Critical Incident Technique, case study

Sommario

Scopo: Lo scopo dello studio è quello di approfondire e comprendere meglio il legame che esiste tra la complessità della supply chain e la resilienza, considerando l'influenza che le pratiche di gestione della complessità hanno sulle proprietà di resilienza di una supply chain.

Background letterario: Nonostante l'esistenza di letteratura che discute la relazione tra la complessità della supply chain e la resilienza, il legame può essere approfondito in quanto manca l'evidenza empirica. Inoltre, ci sono grosse lacune riguardo alla complessità dinamica e alle pratiche di gestione della complessità.

Domande di ricerca: Lo studio mira a definire come la complessità statica e dinamica della supply chain e le rispettive pratiche di gestione influenzino la resilienza della filiera produttiva.

Design/Metodologia/Approccio: Lo studio si articola in due fasi principali, caratterizzate da due diverse metodologie di ricerca: la Critical Incident Technique e i case study induttivi. Mentre la prima è stata utilizzata per analizzare il legame tra complessità e resilienza, concettualizzata tramite i quattro elementi formativi (flessibilità, visibilità, velocità e collaborazione), la seconda è stata adottata per definire il ruolo delle pratiche di gestione della complessità. Infine, i risultati sono stati triangolati e raccolti in una matrice riassuntiva, e le cinque pratiche più rilevanti sono state approfondite e il loro contributo alla resilienza della supply chain è stato discusso.

Risultati principali: I risultati principali dimostrano qualitativamente i diversi effetti dei diversi driver di complessità sui quattro elementi formativi della resilienza: mentre quelli dinamici hanno soltanto un impatto positivo, quelli statici presentano anche legami negativi (es. le differenze tra gli impianti produttivi in diverse zone geografiche diminuiscono la flessibilità, la velocità e la collaborazione). Inoltre, emergono gli effetti, sia positivi che negativi, delle pratiche di gestione della complessità sulla resilienza, così come pure la relativa intermediazione dei driver di complessità. Considerando le cinque pratiche più rilevanti, mentre la *centralizzazione degli acquisti* e la *gestione per progetti* aumentano la resilienza, il *design organizzativo centralizzato sul prodotto*, le *relazioni strategiche con i fornitori*, e gli *strumenti informativi integrati di gestione e ottimizzazione* sono ambivalenti, mostrando effetti sia positivi che negativi.

Implicazioni pratiche: I manager sono informati e resi consapevoli delle interazioni che esistono tra le tre dimensioni analizzate, e possono quindi considerarle nel prendere decisioni riguardo al design della supply chain e nel valutare le pratiche di gestione da adottare.

Limitazioni e sviluppi futuri: Le maggiori limitazioni dello studio sono dovute alla metodologia utilizzata: l'approccio qualitativo, induttivo ed esplorativo è appropriato per

la definizione di una nuova teoria, ma non fornisce una dimostrazione quantitativa dei risultati, lasciando quindi spazio per ricerche future che li testino. Inoltre, sia nella Critical Incident Technique che nei case study induttivi, la soggettività del ricercatore o degli informatori chiave potrebbe pregiudicare l'analisi e le conclusioni. Per quanto riguarda l'unità di analisi adottata, cioè la supply chain interna di un'azienda manifatturiera, limita lo studio al livello di una singola organizzazione. Infine, tre limitazioni di contenuto sono presenti: innanzitutto, la raccolta di informazioni attraverso dati secondari non ha permesso di discutere equamente tutti i driver di complessità con lo stesso livello di dettaglio; in secondo luogo, lo studio non analizza empiricamente il ruolo delle pratiche di gestione della complessità in caso di disruption; in aggiunta, la discussione approfondita è stata limitata alle cinque pratiche più rilevanti, richiedendo quindi ulteriori studi futuri.

Parole chiave: supply chain, complessità statica, complessità dinamica, resilienza, pratiche, Critical Incident Technique, case study

Executive summary

Introduction

Nowadays companies must compete in more complex global markets, thus they are requested to grow, fostering proliferation of products, customers, markets, suppliers, services and locations. Complexity represents the root cause of the actual companies' crisis, as they exhibit problems in managing it. Even though it enables firms to grow nicely in sales, it also increases management costs, hindering profit growth. Consequently, most companies focus on tactical complexity reduction, for instance eliminating slow-moving SKUs or reducing the customers base. However, in many cases complexity represents a competitive source of advantages and cannot simply be removed, hence accommodating practices to cope with it are required. For instance, in its study on supply chain complexity, Fernandez Campos (2018) states that complexity mastering capabilities of Amazon and Dell Computers are essential to their competitiveness. Therefore, it is fundamental to recognize unnecessary complexity to drive it out of the business, distinguishing it from the value-adding one, in order to achieve and maintain profitable growth by only adding it where it counts (e.g. providing customers with the right product variety). Apart from reducing those unnecessary complexities that destroy value for the firm, managers need to introduce management approaches and tools to mitigate and lessen the negative effects of inevitable value-adding ones (Bozarth et al., 2009).

Although it can represent a major impediment to performances, complexity could reveal a value-adding element in case of disruption, positively contributing to supply chain resilience. Resilience is a concept discussed in several different domains and can be defined as the "adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" (Ponomarov and Holcomb, 2009). Being able to return to normal operating performance within an acceptable period of time after a disruption nowadays is more important than the simply traditional risk management. Among the wide range of studies investigating different issues concerning supply chain resilience, a relevant but not much deepened vein regards its link with supply chain complexity. Resiliently facing supply chain disruptions in the current global business environment requires to consider supply chain complexity, not only as it could trigger unexpected events, but also due to its positive influence on adaptive capabilities (Birkie et al., 2017).

While the positive implications of supply chain complexity on business performance have been deeply investigated by prior studies (Bozarth et al., 2009; Brandon-Jones et al., 2014; Fernandez Campos, 2018; Perona and Miragliotta, 2014), companies still need to fully understand its influence on supply chain resilience. Through a systematic literature review performed independently in two different online databases, many existing gaps about the topic are evident, and need to be addressed. Despite a general consensus on the enabling role of complexity drivers on resilience (Arkhipov and Ivanov, 2011; Birkie et al., 2014; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca and Zobel, 2008; Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Hosseini et al., 2016; Mari et al., 2015; Skilton and Robinson, 2009; Sokolov et al., 2016; Statsenko et al., 2016), negative influence has been identified too (Adenso-Diaz et al., 2012; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca and Zobel, 2008; Hearnshaw and Wilson, 2013; Skilton and Robinson, 2009). Moreover, no empirical evidence of the link between the two dimensions has been provided, and the relation should be deployed in detail. Indeed, there is a gap in the extant knowledge on how structural and dynamic complexity drivers influence the capability of an organisation to maintain continuity of operations under disruption, preparing for, responding to and recovering from unexpected events.

Research purpose and framework

Drawing from previous arguments, the study seeks to contribute to supply chain management science by systematically analysing the relationship between supply chain complexity and resilience, which are relevant issues from both theoretical and practical point of view. The link is investigated considering not only the direct connection between them, but also whether complexity management practices can be regarded as resilience contributing practices and to what extent. On the one hand, it aims to better prove that the level of complexity, both structural and dynamic, affects flexibility, visibility, velocity and collaboration, as theoretically analysed so far. Particularly, in the current state-of-the-art a large gap concerning dynamic complexity emerges, while the understanding of the role of static complexity requires more empirical evidence. On the other hand, the research aims to demonstrate that some specific complexity management practices can be (easily) exploited by companies to mitigate disruptions and return to normal operating performances. To manage supply chain structural and dynamic complexity, indeed, companies develop specific management practices and tools, either reducing or accommodating it. These practices could aid operational resilience in case of unexpected incidents. Leveraging studies already supporting the linkage between structural and dynamic complexity and management practices (Fernandez Campos, 2018), the research wants to make a further step ahead, linking approaches and tools to resilience.

In this vein, the key constructs forming the research framework are supply chain complexity, both structural and dynamic, complexity management practices and supply chain resilience, as shown in Figure 1. The former is conceptualized through a list of static and dynamic complexity drivers: *portfolio breadth*, *product variety and specificities*, *variety of/interaction between teams and functions, number and layers of supply chain facilities, differences between facilities in different territories, number/variety of partners and suppliers, variety and breadth of customer requirements, product introduction and lifecycle events, reconfiguration of supply chain activities and facilities, improvements to equipment, procedures and systems, restructuring and M&A, internal operational dynamics, demand/supply sides operational dynamics, new customers or suppliers*. Then, resilience is conceptualised through four constituents, i.e. flexibility, visibility, velocity and collaboration, while complexity management practices are grouped in four clusters, namely: variety reducing practices, confinement and decoupling practices, coordination and collaboration practices, and decision support and knowledge generation practices.

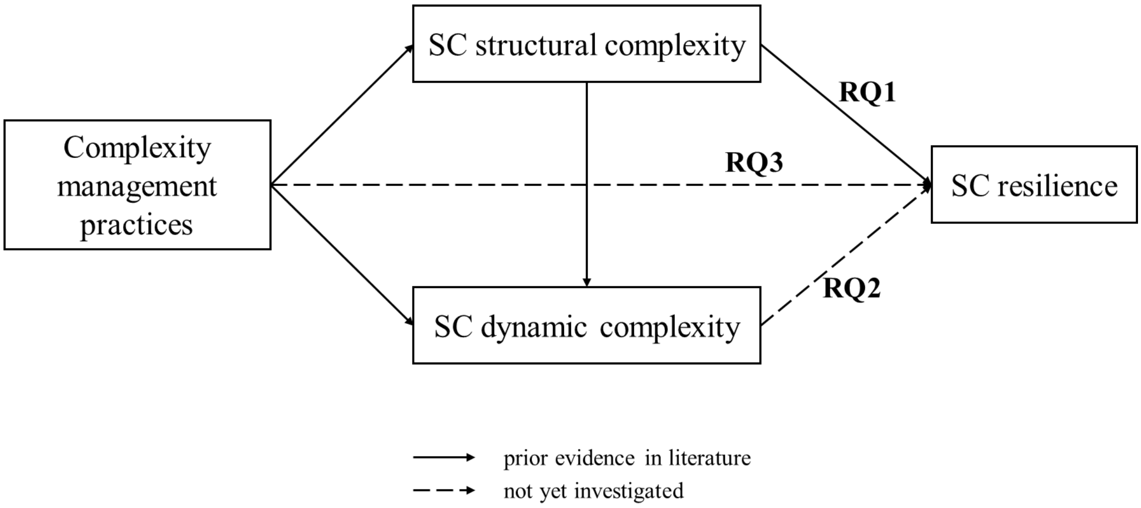

Figure 1: *Research framework and questions.*

Although there is prior evidence in literature about some links between the key constructs, as shown by solid lines (i.e. between complexity management practices and supply chain complexity, between structural supply chain complexity and dynamic complexity, and between structural complexity and supply chain resilience), other relationships have not yet been discussed in the knowledge background, indicated by dashed lines. The latter ones are the subject matter of the study and determine the research questions:

RQ1: How does supply chain structural complexity influence supply chain resilience?
RQ2: How does supply chain dynamic complexity influence supply chain resilience?
RQ3: How does the management of supply chain complexity influence supply chain resilience?

On the one hand, research question RQ1 aims at further analysing already investigated links, by providing empirical evidence. On the other hand, RQ2 and RQ3's goal is to fill extant gaps present in the prior literature. The explorative study to answer the research questions is structured in two main phases. The first part is dedicated to the relationship between supply chain complexity and resilience, thus to the research questions RQ1 and RQ2, while the second one focuses on supply chain complexity management practices, analysing their direct link to supply chain resilience and answering to research question RQ3. Finally, the findings are unified and triangulated in a comprehensive framework linking all the key constructs.

Research methodology

Aiming at exploring the not well understood interplay mechanisms between supply chain complexity, resilience and management practices, the adopted approach is a qualitative one, coherently with the goal to address a gap in extant literature (Benbasat et al., 1987; Meredith, 1998). In this vein, the study leverages two different methodologies. First, through Critical Incident Technique (CIT; Flanagan, 1954) the direct link between supply chain complexity and resilience is empirically proved and deployed. The analysed sample includes 16 multinational companies characterised by a complex supply chain and recently impacted by different supply chain disruptions, including environmental events, such as earthquakes or floods, destroying incidents, such as fires, chemical contaminations of materials, faulty products distribution, social media attacks etc. Furthermore, the considered sample is heterogeneous not only for what concerns the kind of disruption, but also in the different industries considered and the different severity of the consequences, as reported in Table 1. The CIT was developed through secondary data collection and analysis. Data and information were collected from corporate websites, annual reports and corporate presentations, as well as from newspapers' websites for what concerns incidents chronicles, since multiple sources enables to strengthen data reliability.

Table 1: *Critical incidents' characteristics.*

Case number	Company	Industry	Incident	Time of incident	Disruption type
1	Takata Corporation	Automotive	Recall of cars due to faulty airbags following deaths in US	April 2013, until today	III

(continue)

Case number	Company	Industry	Incident	Time of incident	Disruption type
2	Dell Inc.	Computer technology	US west coast lock out due to longshoremen strike	December 2002	II
3	Evonik Industries	Chemical	Fire at German plant, affecting supply of CDT for global automakers	March 2012	III
4	Boeing	Airplanes	Potential parts delay due to Japan earthquake	March 2011	I
5	Sanofi Genzyme	Pharmaceutical, biotechnology	Virus contamination of 3 drugs at a plant in Massachusetts	June 2009	III
6	Mitsubishi Motors Corporation	Automotive	Damage at local part suppliers, due to Thailand flood	October 2011	II
7	Nestle S.A.	Food and drink	Social media attack on KitKat, due to unsustainable forest clearing in production of palm oil	March 2010	II
8	SK Hynix Inc.	Semiconductor (Electronics)	Fire in a plant in China	September 2013	III
9	PSA Peugeot Citroën	Automotive	Air flow sensor and other parts shortage due to Japan earthquake	March 2011	I
10	Mattel Inc.	Toy manufacturing	Unauthorized second-tier supplier using the lead-based paint exceeding limits for the production of a specific toy	August 2007	I
11	Honda Motor Co. Ltd.	Automotive	Production disruption due to Thailand flood	October 2011	III

(continue)

Case number	Company	Industry	Incident	Time of incident	Disruption type
12	Sapporo Group	Alcoholic beverage, food and soft drinks	Facilities damages due to Japan earthquake	March 2011	III
13	Goodyear Tire and Rubber Company	Tire manufacturing	Facilities damages due to Thailand flood	October 2011	III
14	Procter and Gamble Co.	Consumer goods	Coffee flooding due to hurricane Katrina	August 2005	III
15	Johnson & Johnson	Personal and health care	Quality and safety violations	April, May 2010	III
16	Volkswagen Group	Automotive	Diesel issue: scandals relating to the emissions from diesel engines	September 2015	I

Secondly, analysing a sample of four in-depth inductive case studies, the influence of complexity management practices on resilience is highlighted. Case studies were selected through convenience sampling (Barrat et al., 2011), leveraging on the same sample analysed by Fernandez Campos (2018) in his study on supply chain complexity. Although they are all large global organisations (i.e. global footprint and operations), the four focused cases are characterised by different contexts and complexity features, as reported in Table 2, increasing the validity of conclusions, and the sample incorporates differing positions within the supply chain, operations models and industries. To further enhance the reliability of the study, structured data collection and analysis processes were adopted (Fernandez Campos, 2018). Data were collected from multiple sources: semi-structured interviews, company documents and archival sources, and informant's notes during and prior to the interview, as well as secondary data from corporate website, financial reports, corporate presentations, etc. However, interviews to key informants constituted the primary source.

Table 2: *Case companies' characteristics.*

Characteristic	Percomp	Auto	Drinks	Defence
Industry	Personal Computers	Automobile	Drinks/Spirits	Defence Electronics
No. employees	50,000	1,500	4,000	45,000
Revenue (M€)	42,000	200	1,500	12,000
SC position	Focal company	First tier supplier	Focal company	Various (on a project basis)
Operations model	MTS	MTS	MTS	ETO/MTO

For both the adopted methodologies the considered unit of analysis was the manufacturing firm's internal supply chain, including planning, sourcing, making and delivering activities (Hoole, 2005). The internal supply chain perspective is more comprehensive than previous studies, but it is still limited at the level of the single organisation, and does not consider a cross-functional point of view.

Key findings

Through CIT, static and dynamic supply chain complexity drivers and their influence on resilience constituents have been analysed, answering to the first two research questions. Investigating the incidents affecting the different companies, most of the drivers played a significant role and there is evidence that each driver affects at least two constituents, demonstrating the relationship between supply chain complexity and resilience. Particularly it emerges that flexibility and collaboration are the most impacted, while structural drivers are more relevant than dynamic ones. Although for most drivers the link is positive, thus the higher the complexity the higher the resilience, there are also inverse proportional relationships attesting that not always complexity is a strength. Flexibility is the most affected constituent: *differences between facilities in different territories* has a negative impact on it, while all the other complexity drivers mainly positively affect it. In most cases, the higher the supply chain complexity, the higher the flexibility due to the redundancies and different alternatives exploitable by the company. Differently, the other constituents are not influenced by all the complexity drivers. Collaboration is strongly impacted too, mainly by structural drivers, which play a twofold role. On the one hand, the internal structure of the supply chain ensures higher collaboration among different facilities if they are many, but not much different between different territories. On the other hand, even though a higher number of customers and suppliers allows a wider set of collaborative actors, collaboration with them is better if their number is low, due to the stronger partnerships. Considering velocity, the highest positive role determining it is played by dynamic complexity drivers: all of them, except *new customers or suppliers*, increase it, since they allow the company to be already used to change its operations and adopt new solutions. As a matter of fact, being used to dynamicity, the affected companies can rapidly develop technical solutions, identify substitutes, rebuild facilities, ramp up production, change the manufacturing process and introduce new procedures. Finally, visibility is affected by the supply chain structure and its evolution in time: the more complex is the set of actors the company relates to, the less is the visibility on them, but the greater is the dynamicity characterizing the supply chain, the higher is the visibility on new and innovative alternatives in case of disruption. Therefore, static complexity drivers play a negative role, while dynamic ones increase visibility.

Through inductive case studies, instead, the influence of complexity management practices on resilience constituents is investigated to answer the third research question. Only 6 out of 45 practices seem not to have any impact on resilience, while all the others affect at least one resilience constituent, and many links' evidence emerges from more than one case. The strongest relationship is between *integrated ERP systems* and visibility, proved in three case studies. Moreover, all the constituents are impacted by more than 20 practices, around half of the total list. The most affected one is collaboration (60% of practices), while the less one is velocity (47% of practices). The former is only increased by complexity management practices of all the clusters, except decision support and knowledge generation, which, however, has a positive influence stronger than the negative one. Flexibility is mainly positively impacted by variety reducing, and confinement and decoupling practices. Coordination and collaboration practices, instead, play uniquely a negative role, while the last cluster has a both positive and negative contribute. Velocity is purely increased by practices belonging to cluster confinement and decoupling and decision support and knowledge generation, while the other two clusters present also a little negative influence. Finally, visibility is impacted both positively and negatively by all the clusters. On the one hand variety reducing and coordination and collaboration practices have mainly a positive role, on the other hand the other two clusters have a high evidence of negative linkages.

Finally, the last step of the study consists in a comprehensive discussion of the results emerging from the previous analyses, collected in a summary matrix of findings matching supply chain complexity management practices and resilience constituents. It highlights the relationships between the two dimensions that are disclosed by the present study, considering the mediating role of static and dynamic complexity drivers. Findings are strongly supported through the triangulation of results evident from the previous CIT and case studies, also leveraging on the Fernandez Campos' study (2018) assessing the link between complexity management practices and complexity drivers. However, since resulting information is inconveniently fragmented and could impair the quality of a truly in-depth analysis of the phenomena, discussion focuses on dominant practices only, i.e. those with the widest set of mechanism of influence on resilience, namely: *product-centric organisational design*, *centralisation of purchasing*, *strategic relations with partners and suppliers*, *project management*, and *multi-echelon ERPs and optimisation IT tools*. Table 3 matches the five complexity management practices and their positive or negative influence on resilience constituents, reporting in each cell the supply chain complexity drivers mediating the linkage. It emerges that, when combining the five complexity management practices, it is possible to obtain a positive effect on all the resilience constituents.

Table 3: *The influence of complexity management practices on resilience constituents, mediated by supply chain complexity drivers.*

	Flexibility		**Visibility**		**Velocity**		**Collaboration**	
	Increase (+)	**Decrease (-)**	**Increase (+)**	**Decrease (-)**	**Increase (+)**	**Decrease (-)**	**Increase (+)**	**Decrease (-)**
Product-centric organisational design	Portfolio breadth Product var. and spec. Variety customer requires Product LC events Demand/supply dynamics Differences between facilities	Product var. and spec. Variety customer requires		Variety customer requires	Product LC events Demand/supply dynamics Differences between facilities	Product var. and spec. Variety customer requires	Portfolio breadth Product var. and spec. Variety customer requires Demand/supply dynamics Differences between facilities	
Centralisation of purchasing	Differences between facilities		N./var. of partners				Differences between facilities N./var. of partners	
Strategic relations with partners and suppliers		N./var. of partners New customers/suppliers Product var. and spec.	N./var. of partners		N./var. of partners Product LC events Demand/supply dynamics	Product var. and spec.	N./var. of partners Product var. and spec. Demand/supply dynamics	
Project management			Reconfig. SC Improvements M&A		Product LC events Reconfig. SC Improvements M&A		Portfolio breadth Product var. and spec. Variety customer requires M&A	
Multi-Echelon ERPs and optimisation IT tools	Portfolio breadth Product var. and spec. N. and layers of SC	Product var. and spec.	N. and layers of SC		N. and layers SC Demand/supply dynamics		Portfolio breadth Product var. and spec. N. and layers of SC Demand/supply dynamics	

Product-centric organisational design plays a dual role, as it positively influences flexibility, velocity and collaboration, but at the same time it could impair flexibility, visibility and velocity. As a matter of fact, on the one hand, it enables a simpler and more effective management of certain complexity drivers (e.g. *portfolio breadth*, *difference between facilities in different territories*, and *product introduction and lifecycle event*), on the other hand, it fosters the increasing of other complexity drivers that hinder resilience constituents (e.g. *product variety and specificities* and *variety and breadth of customer requirements*). On the contrary, *centralisation of purchasing* only positively influences resilience constituents, increasing flexibility, visibility and collaboration. Indeed, it decreases two structural complexity drivers (i.e. *number and variety of partners* and *differences between facilities in different territories*) which in turn play a negative role in terms of resilience, hence the final effect is positive. *Strategic relations with partners and suppliers* plays a twofold role, because, on the one hand, it positively influences visibility and collaboration, on the other hand, it could impair flexibility and shows an ambivalent influence on velocity. For instance, the positive influence on resilience is given by the better management of *product introduction and lifecycle events* and *supply sides operational dynamics*, while the negative one by the reduction of *new suppliers*. Facilitating the management of both structural and dynamic complexity drivers, *project management* foster their presence among the main supply chain characteristics, increasing complexity, but in turn also resilience. Finally, *multi-echelon ERPs and optimisation IT tools* mainly positively affects supply chain resilience, thanks to the interplay of some complexity drivers.

Conclusions

Being the first study deeply considering supply chain dynamic complexity drivers and their impact on resilience, as well as the influence of complexity management practices, this research not only reveals original and relevant theoretical contributions, but also provides important practical implications to managers.

First, the study provides empirical evidence to further prove the relationship between the level of supply chain complexity and resilience. Although the impact of structural complexity drivers on the supply chain capability to proactively respond to unexpected events and recover from disruptions has been assessed by many authors, the study provides relevant findings. On the one hand, new relationships are introduced. For instance, in the literature there is a gap concerning product structural complexity drivers, i.e. *portfolio breadth* and *product variety and specificities*. On the other hand, extant knowledge is expanded, offering empirical evidence to what some authors previously discussed at theoretical level only. For example, the positive impact of *the number and layers of supply chain facilities* on visibility, velocity and collaboration has been only theoretically investigated by Durach et al. (2015) and Thome et al. (2016), thus this study consistently provide evidence to their argument.

Secondly, few prior papers cover supply chain dynamic complexity, regarding both resilience constituents and resilience core functions. The extant knowledge background is mainly theoretical (Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Thome et al., 2016; Durach et al., 2015; Hosseini et al., 2016) and dynamic complexity is not well conceptualized. Consequently, this study covers the gap and provide a new relevant contribute to the extant body of knowledge, empirically proving the positive influence of all dynamic complexity drivers on the four resilience constituents.

Third, considering complexity management practices, listed and described by Fernandez Campos (2018), this research explores their influence on resilience; first by identifying the direct relationship between the two dimensions in four different case studies, then triangulating results considering the interplay of supply chain complexity drivers. Since no prior author has assessed the role of management practices under supply chain disruption, this study offers a completely new contribute, posing the basis for future investigation.

For what concerns practical implications, managers are informed of the interactions existing between supply chain complexity drivers and resilience constituents. Therefore, companies undergoing significant structural and dynamic supply chain complexity should consider its impact not only on business performances (e.g. costs or quality), but also on resilience constituents, i.e. flexibility, velocity, visibility and collaboration. In this respect, supply chain could be designed aiming at reaching adaptive capabilities to prepare for, respond to and recover from unexpected incidents. Moreover, the emerging results improve the knowledge body regarding supply chain management practices. This study, analysing their impact on supply chain resilience, allows managers to identify which practices could reveal a fundamental weapon under disruption. For instance, complexity accommodation practices could be positively leveraged, while complexity reduction ones could decrease resilience enablers. In addition, they could also be combined to maximise the positive effect, covering all the resilience constituents and offsetting negative influences. In conclusion, the main practical implication is the managers' awareness that supply chain complexity embraced by the focal company could help under disruption, fostering supply chain resilience, both directly and indirectly through complexity management practices.

Despite the theoretical and practical contributions, the study presents limitations too, mainly due to the adopted methodology. These represent opportunities for future research and further developments. First, the qualitative inductive and exploratory approach, demanded by the limited extant knowledge about the investigated issues, is appropriate for theory building (Meredith, 1998), without quantitatively supporting findings, thus leaving space for future developments in theory testing. Therefore, although it provides practitioners and academics with valuable insights, it does not allow to fully generalise results, calling for a further quantitative analysis.

The second limitation is determined by the data collecting approach for CIT. Indeed, not all the supply chain complexity drivers are covered in the same way, as information is difficult to collect through secondary-data, and variety of/interaction between teams and functions and internal operational dynamics cannot be well documented due to the scarce disclosure of companies about them. Moreover, leveraging secondary-data, the empirical evidence of links between complexity drivers and resilience constituents is more difficult to prove, and the subjectivity of the researcher may affect the analysis and its conclusions. The quality of information collected, hence, could be enriched establishing direct connections with the affected companies, performing direct interviews, in order to demonstrate findings consistency and to cover undisclosed complexity drivers, such as variety of/interaction between teams and functions and internal operational dynamics.

The second part of the study, is based on inductive case studies analysis. The adopted sample consists of four in-depth cases, focused on manufacturing companies operating in different industries. These have been selected through convenience sampling (Barrat et al., 2011), leveraging a first level analysis performed by Fernandez Campos (2018) in his study on supply chain complexity. Thus, it cannot be claimed that these are exhaustive and comprehensive of all the possible mechanisms ruling the relationships between supply chain complexity, resilience and management practices. Then, the study does not empirically analyse the role of complexity management practices under disruption, but it only indirectly proves it, triangulating the relationship between supply chain complexity drivers and resilience constituents and the linkage between supply chain complexity practices and resilience constituents. Consequently, one or more case studies could be set aiming at theory testing. Particularly, a tailored semi-structured interview protocol could aid in focusing data collection.

In both the methodologies, the adopted unit of analysis is the manufacturing firm’s internal supply chain, limiting the study to the management of complexity and its impact on supply chain resilience at the level of the single organisation and not of the chain or network. Therefore, despite considering collaboration with upstream and downstream supply chain actors, multi-tier or cross-functional aspects are not fully captured. Therefore, the research can be further developed investigating the validity of findings with respect to a wider unit of analysis. Indeed, similar considerations could be extended to a multi-tier or cross-functional perspective. For instance, a whole supply chain, considering all the involved companies from raw material suppliers to end consumers, could be analysed.

Finally, since the high fragmentation of findings could hinder the quality of a truly in-depth analysis of the phenomena, results discussion focuses on five dominant complexity management practices only, calling for further research with respect to the others, extending the analysis to the whole list. In general, considering the results, there are some linkages between supply chain complexity, resilience and management practices that present both positive and negative correlations. In this respect, they should be further investigated, in order to clarify it and distinguish among them. In addition, since practices could be mixed to maximize the positive influence on resilience, the possible synergies brought by multiple practices should be considered. Finally, an analysis about how to prioritize practices according to the expected contribution to resilience constituents could be relevant from the practical point of view.

In conclusion, the main aims of future research are two: on the one hand, to test and strengthen the theoretical findings emerging from this study, generalising results through quantitative methodologies; on the other hand, to extend the scope considering still existing gaps and widening the unit of analysis.

Ringraziamenti

Ringrazio innanzitutto il mio correlatore, il prof. Paolo Trucco, che mi ha guidato in tutto il lavoro, trasmettendomi passione per la materia analizzata ed entusiasmo per la ricerca. Fin da subito, egli si è dimostrato sempre disponibile, offrendomi un indispensabile supporto e permettendo alla mia tesi di prendere forma, passo dopo passo.

Ringrazio inoltre il prof. Seyoum Eshetu Birkie del KTH di Stoccolma, la cui esperienza nell'ambito della Supply Chain Resilience ha dato il via al mio studio, e il dott. Pablo Fernandez Campos del Politecnico di Milano, la cui tesi di dottorato ha rappresentato un tassello fondamentale per la mia ricerca. Il loro contributo è stato significativo soprattutto nella fase di raccolta e analisi dei dati, ma anche nella stesura finale della tesi.

Un ringraziamento speciale va ai miei genitori, Doris e Stefano, che mi hanno insegnato e continuano ad insegnarmi ogni giorno il mestiere della vita. Sempre al mio fianco, mi hanno sostenuto durante l'intero percorso accademico, condividendo fatiche e soddisfazioni.

Ringrazio mia sorella, Elisabetta, che mi ha supportato (e sopportato) in questi mesi, confermandosi amica preziosa e compagna di studio da sempre.

Un altro ringraziamento speciale lo devo a Mattia, con cui ho condiviso pienamente questa avventura. Compagni di studi fin dal liceo, abbiamo tagliato insieme diversi traguardi, aiutandoci a vicenda, e così è stato anche per la tesi.

Ringrazio le mie coinquiline Marica e Cecilia, con cui ho condiviso la quotidianità della vita universitaria, e le mie amiche Arianna, Valentina e Sara, compagne fondamentali di vita.

Un ringraziamento va anche a tutta la mia famiglia, nonni, zii e cugini, che mi hanno da sempre sostenuto e che rappresentano un pezzo fondamentale di me. E a tutti i miei amici, siano essi Ruote, compagne di allenamento o altro, perché danno colore a ciò che faccio.

Ringrazio infine "l'amor che move il sole e l'altre stelle", perché senza di Lui tutto ciò non sarebbe stato possibile.

Chapter 1
Introduction

1.1 The supply chain complexity dilemma

As stated by Tom Blackstock, Vice President Supply Chain Operations Coca-Cola North America: “If you are in Supply Chain Management today, then complexity is a cancer you have to fight” (Gilmore, 2008). As a matter of fact, nowadays companies must compete in more complex global markets, thus they are requested to grow, fostering proliferation of products, customers, markets, suppliers, services and locations. For instance, large retail store and supermarket are characterised by an explosion in the variety of SKUs. Consumer product manufacturers have added brands, extended lines and altered pack sizes, shapes and colours to encourage purchasing. In 2003 alone, nearly 27,000 new food and household products were introduced, including 115 deodorants, 187 breakfast cereals and 303 women’s fragrances (AT Kearney, 2004). Another example is given by automakers, such as Ford and GM, which have to cope with a higher and higher level of complexity: too many brands, too many models, too many dealers, too many plants, too many union work restrictions, etc. (Mariotti, 2008).

Complexity represents the root cause of companies’ crisis, as they exhibit problems in managing it. Even though it enables firms to grow nicely in sales, it also increases management costs, hindering profit growth. A wide range of SKUs requires more effort to manage, as well as an overload of customers and locations determines a reduction in speed of response. Many are the elements adversely affecting profit: inventory excess and obsolescence, closeout pricing, premium freight charges, but also raising overhead for operations management and selling, general and administrative expenses. Consequently, since it hinders business performance, representing a competitive disadvantage, new rules and metrics are needed to deal with the increasing challenge of complexity.

Most companies focus on tactical complexity reduction, for instance eliminating slow-moving SKUs or reducing the customers base. Quoting Alan Perlis, computer scientists and Yale University professor, “Fools ignore complexity. Pragmatists suffer it. Some can avoid it. Geniuses remove it” (Mariotti, 2008). However, in many cases complexity represents a competitive source of advantages and cannot simply be removed, hence accommodating practices to cope with it are required. For example, companies often rely on product proliferation to enter a new market segment. In its study on supply chain complexity, Fernandez Campos (2018) states that complexity mastering capabilities of Amazon and Dell Computers are essential to their competitiveness. Therefore, it is fundamental to recognize unnecessary complexity to drive it out of the business, distinguishing it from the value-adding one, in order to achieve and maintain profitable growth by only adding it where it counts (e.g. providing customers with the right product variety). How many products and how they are developed, introduced and managed, as well as whether entering new markets or opening new facilities, are strategic decisions to be considered. In this vein, managers adopt both complexity reduction and complexity accommodation practices. Apart from reducing those unnecessary complexities that destroy value for the firm, they need to introduce management approaches and tools to mitigate and lessen the negative effects of inevitable value-adding ones (Bozarth et al., 2009). For instance, to cope with the dynamic complexity related to product design, cross-functional reporting metrics and KPIs can be introduced, enabling mangers to better understand customer behaviours (Fernandez Campos, 2018).

1.2 The importance of supply chain resilience

Clayton M. Christensen, Harvard Business School professor, stated that "Disruption is continuously afoot in every industry" (Scott, 2017). Indeed, in the current turbulent and uncertain environment, every company is susceptible to unexpected events that disrupt the normal flow of goods or services in a supply chain, exposing firms to operational and financial risks (Craighead et al., 2007). Supply-chain problems result from natural disaster, labour disputes, supplier bankruptcy, acts of war and terrorism, and more others, entailing dramatic negative repercussions on companies. For example, many supply lines in US were affected by critical shortages due to the closing of country's borders and the shutting down of incoming and outgoing flights following the September 11, 2001, terrorist attack. Since suppliers' trucks from Canada and Mexico were delayed, Ford Motor Co. had to shut down several assembly lines, downing its output of 13% comparing with its production plan. Negative consequences of the event affected Toyota Motors Corp. too, as its just-in-time inventory discipline suffered of shortages affecting upstream actors in the supply chain (Sheffi and Rice, 2005).

Although for many companies the only thing standing between them and a disruption is luck, luck eventually runs out and they need comprehensive security management approaches to recover from incidents (Rice and Caniato, 2003). Therefore, it is more and more important to develop proactive and reactive capabilities to manage unanticipated happenings, developing resilience capabilities "to prepare for and respond to disruptions, by maintaining continuity of operations at the desired level of connectedness and control over structure and function" (Ponomarov and Holcomb, 2009). For instance, an organisation's ability to recover can be improved by building redundancy and flexibility (Sheffi and Rice, 2005).

According to a World Economic Forum and Accenture's study, 80% of analysed firms reported that resilience to supply chain disruptions has become a top priority (Ambulkar et al., 2015), hence it is critical to improve it. As a matter of fact, capabilities to proactively manage supply chain risks can make the difference in operational outcomes and performances of companies affected by unexpected events. A clear example is given by the different reactions of two companies, i.e. Nokia Corp. and Telefon AB L.M. Ericsson, to the same supply chain disruption: a microchips supply shortage due to a fire in Royal Philips Electronics' plant in Albuquerque, New Mexico. While the former, thanks to its multiple-supplier strategy, immediately began switching its chip orders to other Philips' facilities or other Japanese and American suppliers, the latter could not leverage any other source of microchips, due to its single-sourcing policy. Consequently, while Nokia's production little suffered during the crisis, Ericsson had to halt production for months, losing $400 million in sales (Chopra and Sodhi, 2004).

In this vein, several recent studies have focused on supply chain resilience, as it is a concept of growing interest for academics and practitioners (Thome et al., 2016). For instance, Jüttner and Maklan (2011) conceptualise resilience through flexibility, visibility, velocity and collaboration, and explore its relationship with supply chain vulnerability and risk management. A different perspective is adopted by Birkie et al. (2014), who conceptualise operational resilience through five core functions: build, reconfigure, sustain and re-enhance. In addition, Birkie et al. (2017) identify resilience through capabilities that can be developed prior to or after a disruptive event, classifiable in four bundles, i.e. proactive-internal, proactive-external, reactive-internal and reactive-external practices. Finally, Tukamuhabwa et al. (2015) present a review of the extant literature on supply chain resilience, from which the main strategies aiming at improving it are identified, i.e. increasing flexibility, creating redundancy (spare capacity and inventory, multiple suppliers and extra facilities), forming collaborative relationships, and improving agility.

1.3 The link between supply chain complexity and resilience

As emerging from the previous two sections, supply chain complexity and resilience are two critical issues that today's companies need to consider when making strategic or tactical decisions. Among the wide range of studies investigating different issues concerning supply chain resilience, a relevant but not much deepened vein regards its link with supply chain complexity. Resiliently facing supply chain disruptions in the current global business environment requires to consider supply chain complexity, not only as it could trigger unexpected events, but also due to its positive influence on adaptive capabilities (Birkie et al., 2017). Although it can represent a major impediment to performances, for instance increasing the frequency of disruptions (Bode and Wagner, 2015), complexity could reveal a value-adding element, positively contributing to supply chain resilience. For example, a supply chain characterised by a high number of manufacturing facilities available to manufacture the same products can effectively absorb unexpected demand spikes and increase resilience to natural disasters or other supply-side disruptions. Considering the severe Thailand flooding in 2011, which forced more than 1,000 factories to close leading to global shortages, Honda Motor Co. flexibly shift production in other plants located around the world, keeping lines running and supporting a smooth recovery. Similarly, SK Hynix could leverage the support from other business sites to making up for lost production due to a fire in a Chinese plant in 2003.

While the positive implications of supply chain complexity on business performance have been deeply investigated by prior studies (Bozarth et al., 2009; Brandon-Jones et al., 2014; Fernandez Campos, 2018; Perona and Miragliotta, 2014), companies still need to fully understand its influence on supply chain resilience. Despite a general consensus on the enabling role of complexity drivers on resilience (Arkhipov and Ivanov, 2011; Birkie et al., 2014; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca and Zobel, 2008; Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Hosseini et al., 2016; Mari et al., 2015; Skilton and Robinson, 2009; Sokolov et al., 2016; Statsenko et al., 2016), negative influence has been identified too (Adenso-Diaz et al., 2012; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca and Zobel, 2008; Hearnshaw and Wilson, 2013; Skilton and Robinson, 2009). Moreover, no empirical evidence of the link between the two dimensions has been provided, and the relation should be deployed in detail. Indeed, there is a gap in the extant knowledge on how structural and dynamic complexity drivers influence the capability of an organisation to maintain continuity of operations under disruption, preparing for, responding to and recovering from unexpected events.

1.4 Research purpose and methodological approach

Drawing from previous arguments, the study seeks to contribute to supply chain management science by systematically analysing the relationship between supply chain complexity and resilience, which are relevant issues from both theoretical and practical point of view. The link is investigated considering not only the direct connection between them, but also whether complexity management practices can be regarded as resilience contributing practices and to what extent. On the one hand, it aims to better prove that the level of complexity, both structural and dynamic, affects flexibility, visibility, velocity and collaboration, as theoretically analysed so far. Particularly, in the current state-of-the-art a large gap concerning dynamic complexity emerges, while the understanding of the role of static complexity requires more empirical evidence. On the other hand, the research aims to demonstrate that some specific complexity management practices can be (easily) exploited by companies to mitigate disruptions and return to normal operating performances. To manage supply chain structural and dynamic complexity, indeed, companies develop specific management practices and tools, either reducing or accommodating it. These practices could aid operational resilience in case of unexpected incidents. Leveraging studies already supporting the linkage between structural and dynamic complexity and management practices (Fernandez Campos, 2018), the research wants to make a further step ahead, linking approaches and tools to resilience.

Being the first study deeply considering supply chain dynamic complexity drivers and their impact on resilience, as well as the influence of complexity management practices, this research not only reveals original and relevant theoretical contributions, but also provides important practical implications to managers. Moreover, it empirically investigates mechanisms already assessed regarding supply chain static complexity, proving their consistency.

Aiming at exploring the not well understood interplay mechanisms between supply chain complexity, resilience and management practices, the adopted approach is a qualitative one, coherently with the goal to address a gap in extant literature (Benbasat et al., 1987; Meredith, 1998). In this vein, the study leverages two different methodologies. First, through Critical Incident Technique (CIT) the direct link between supply chain complexity and resilience is empirically proved and deployed. Secondly, analysing a sample of four in-depth case studies, the influence of complexity management practices on resilience is highlighted. Finally, triangulation of results via complexity drivers enables to further discuss the evidence of the interrelationships between the three dimensions.

1.5 Outline of the thesis

The dissertation is structured into eight chapters, as shown in Figure 1.1. Chapter 2 reviews the extant literature on supply chain complexity and resilience, setting the theoretical background for the study and highlighting existing gap. Chapter 3 presents research framework, defining key constructs and relationships among them. Moreover, it introduces the three research questions. The methodology adopted to address them is described in Chapter 4, where Critical Incident Technique and inductive case study are introduced, as well as the considered unit of analysis and data collection and analysis are described. Then, Chapter 5 illustrates the Critical Incident Technique (CIT) adopted to analyse the influence of supply chain complexity on resilience in case of disruption, answering the first two research questions. Chapter 6 assesses how complexity management practices influence supply chain resilience, leveraging four in-depth case studies to answer the third research question. Findings of both these chapters are collected and discussed in Chapter 7, which presents a summary matrix and further discusses the five more critical complexity management practices, comparing results with prior literature. Finally, Chapter 8 remarks the theoretical contributions and the practical implications of the study, as well as limitations and opportunities for future research.

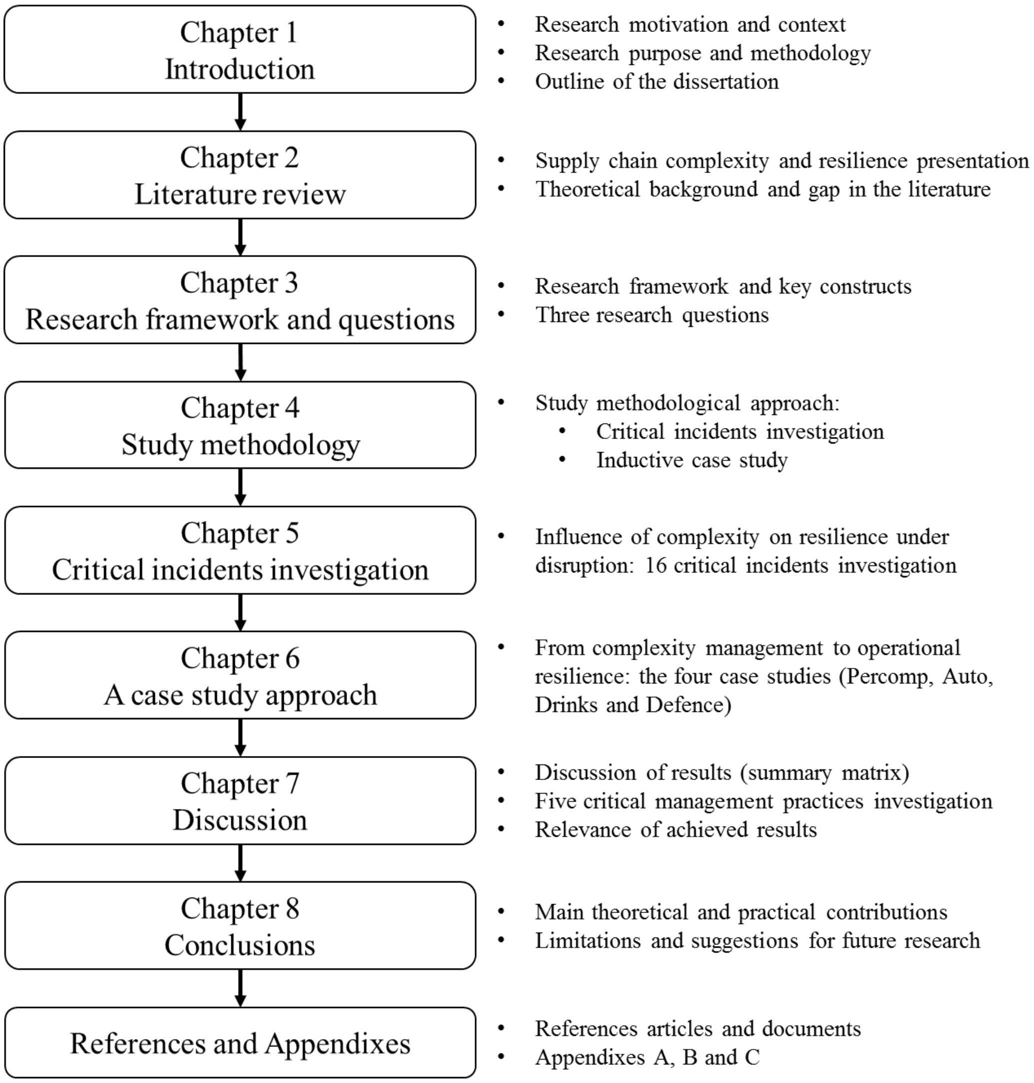

Figure 1.1: *Outline of the dissertation.*

Chapter 2
Literature review

The chapter explores the state-of-the-art of the existing knowledge on supply chain complexity and resilience, setting the theoretical background for the study. After a first section presenting the main purpose of the literature review and the adopted methodology, concepts of supply chain complexity and resilience are introduced, and the relationship between them investigated. Finally, considered papers are mapped according to these two dimensions, highlighting the existing gap in literature that this study seeks to fill. In general, despite the consensus that complexity drivers are enablers of supply chain resilience, empirical evidence is needed to demonstrate what theoretically sustained and the relation should be further investigated and deeper defined.

2.1 Literature review purpose and methodology

The literature review analyses the existing body of knowledge with a dual purpose: on the one hand, it defines the context and set the theoretical background, providing the reader with a comprehensive understanding of it. On the other hand, it serves to identify possible existing gaps that could be addressed and thus filled by the contribution of this study.

In order to ensure an adequate coverage of pertinent literature, relevant academic and practitioners' contributions were searched and selected through a systematic approach. Mainly focusing on publications in peer-reviewed journals and scientific papers, the search was performed independently in two different online databases, Scopus and Web of Science, using the following three keywords, separated by the Boolean operator AND. According to the topics of this dissertation, the exact search keyword combination was: "supply chain" AND "complexity" AND "resilience". This systematic approach allowed to define the boundaries of the theoretical setting, avoiding the early convergence that could result instead from snowballing, as smaller subsets of works sharing common references tend to be formed inside larger literature reviews, thus giving a false sense of convergence. Nevertheless, the snowballing approach was leveraged to better define concepts of supply chain complexity and resilience present in the selected articles.

As result, considering the overlapping outcomes from the two databases, 26 papers were selected, temporally distributed as represented in Figure 2.1. It is evident that in the last years the topic has been growing in importance, showing an increasing trend of papers published between 2010 and 2016.

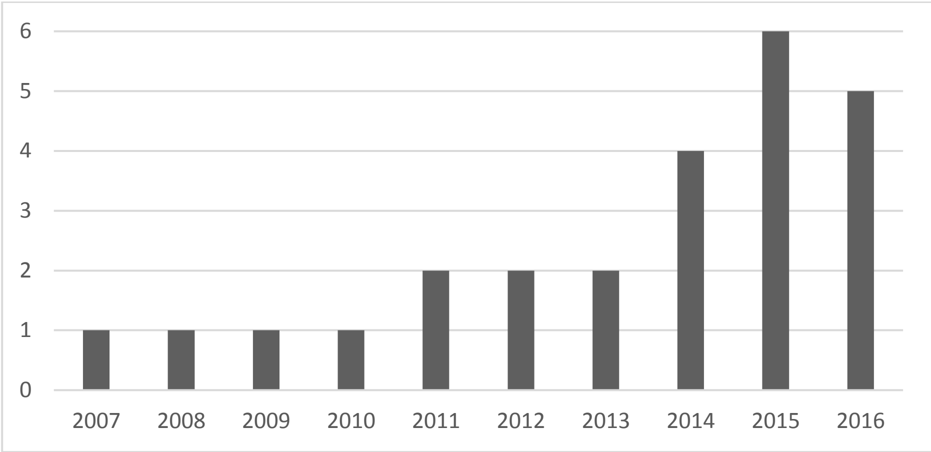

Figure 2.1: *Temporally increasing trend of selected papers from the literature review.*

The selected 26 documents were then analysed and systematically classified, not only according to articles' information, such as the adopted methodology, the year of publication and the number of citations, but also considering the discussed contents, i.e. supply chain structural and dynamic complexity, industry, analysis boundaries (i.e. focus company or whole supply chain), disruption type, resilience capabilities, and operative performances. Two main dimensions were identified: supply chain complexity, articulated in static and dynamic complexity, and supply chain resilience, which can be conceptualised either through constituents or core functions. The following two sections present these concepts, while another section provides an in-depth understanding of the knowledge background of the existing relationship among them. Thus, the theoretical foundations of the study are set.

Finally, drawing from it, in order to identify possible existing gaps in literature, articles were mapped in a matrix, set by matching supply chain complexity and resilience, as shown in Figure 2.2. In it, static and dynamic complexity factors were put on the rows, while resilience constituents and core functions on the columns. If an article links row *x* with column *y*, or vice versa, the relative cell was filled with the following information:

- the presence of a demonstration of the complexity-resilience link in the article;
- the study methodology strengthening the evidence, distinguishing between case study, regression analysis, simulation, scenario analysis, and theoretical study or framework;
- the kind of link, either positive or negative;
- the direction of link, i.e. if the considered complexity factor impacts on a specific resilience element or, vice versa, if a resilience element increases a certain complexity driver.

The grade of coverage of the different areas of the table allowed to visually understand where the existing body of knowledge is concentrated and where, instead, there is space for investigation. The evidence emerging from this analysis, discussed in the last section of this chapter, delineated the presence of gaps in literature, highlighting where the contribution of this study can be of higher value.

		Resilience constituents				**Resilience functions**		
		Flex.	Vel.	Visib.	Collab.	Robustness	Adaptability	Absorptive capacity
Static	N. nodes							
	N. flows							
	Density							
	…							
Dynamic	Uncertainty							
	Randomness							
	…							

Figure 2.2: *Matrix used for articles mapping.*

2.2 Supply chain complexity

The first of the two considered dimensions is the supply chain complexity. Due to its elusive nature, the concept of complexity has long been deeply discussed in many academic disciplines, adopting a variety of different measurements and conceptualisations (Bode and Wagner, 2015).

Considering supply chains, they are regarded as complex systems, since they comprise numerous elements that richly interact with each other, often in non-linear ways, exchanging information, products and services (Choi et al., 2001). Therefore, supply chain complexity is the level of complexity exhibited by products, processes and relationships that make up a supply chain (Bozarth et al., 2009). It can be described in terms of product portfolio (number and variety of product lines, and brands), supply base dispersion (number and geographical dispersion of production facilities and legal entities), size (turnover and number of employees) and restructuring (mergers, acquisitions and sellouts) (Birkie et al., 2017).

Supply chain complexity can be distinguished in two main categories: on the one hand, static complexity, which states structural characteristics of the network, including the number and variety of elements and the strength of interactions among them; on the other hand, dynamic complexity, which represents uncertainty and evolutionary events altering the supply chain, considering both strategic and operational perspectives (Bozarth et al., 2009; Serdarasan, 2013). While the former includes number of nodes, flows and tiers, density of network, criticality of elements, geographic dispersion and characteristic path length, the latter concerns uncertain operational dynamics, organisational restructuring, production relocation, mergers and acquisitions, and supply chain reconfiguration. In addition to this classification, supply chain complexity factors can be classified in three categories according to their origin: internal, supply/demand interface and external complexity drivers (Serdarasan, 2013). The first ones are generated by decisions and factors within the organisation, such as products or processes design. The second ones, instead, are related to the material and information flows between the company and upstream and downstream actors. Finally, external drivers are determined by environmental elements, such as market trends and regulations, thus the company has little control on them.

Considering company performance, supply chain complexity can be a major impediment to them and one of the most pressing issues for practitioners and academics (Bode and Wagner, 2015). In the literature, a list of outcomes has been analysed, including hindered decision making (Manuj and Sahin, 2011), the frequency and severity of disruptions (Bode and Wagner, 2015; Brandon-Jones et al., 2014; Craighead et al., 2007), supplier innovation, risk, responsiveness and transaction costs (Choi and Krause, 2006), as well as the impact on supply chain performance (Perona and Miragliotta, 2004), more specifically on costs, speed, flexibility and quality (Fernandez Campos, 2018). Furthermore, due to supply chain's complex nature, small changes or disturbances propagate through the system and result in unexpected and unintended consequences (Bode and Wagner, 2015).

Despite its potential hindering impact on performance, it is argued that, since companies pursue business growth, complexity increase is inevitable, and nowadays it is becoming more and more important to leverage it as a source of competitive advantage, instead of reducing it (AT Kearney, 2004). For instance, to differentiate their business from their peers, managers leverage accelerated product introductions and reduced product lifecycles, as well as expansion of markets and channels, which often translate into greater supply chain complexity. Therefore, the relationship between complexity and performance has a dual nature, as underlined by many authors (Bozarth et al., 2009; Brandon-Jones et al., 2014; Perona and Miragliotta, 2014). Perona and Miragliotta (2014) note that, although enhancing the competitive strength of the company, structural complexity increases coordination and management costs. Similarly, Brandon-Jones et al. (2014) argue that, on the one hand, complexity allows to enter in new markets and to offer customer greater product variety, on the other hand, it negatively affects performance and risk. Bozarth et al. (2009) acknowledge the trade-off too, reporting that companies could choose to embrace the dynamic complexity of dealing with customers whose demand is less predictable but who purchase high-margin products. Furthermore, there are some studies in the literature which suggest that it could reveal a value-adding element, representing an incentive for companies to develop new practices and techniques and aiding effectiveness of resilience in mitigating disruption, as better described in the last section of the chapter.

To manage supply chain complexity, companies have to develop effective complexity management capabilities. Due to the previously discussed twofold nature of complexity, which could reveal both a liability and an opportunity, reduction complexity management practices are insufficient, as firms cannot eliminate value-adding elements. As consequence, it is necessary to develop tools and approaches enabling organisations to mitigate the adverse effects on performance. Bozarth et al. (2009) in addition to the reduction practices, which physically reduce the amount of complexity in the supply chain, introduce accommodation practices, which absorb its negative consequences. Manuj and Sahin (2011) support the arguments too, discussing the companies’ necessity to combine both these approaches in order to generate profit of complexity. Similarly, Perona and Miragliotta (2014) distinguish between reduction and management levers, and Serdarasan (2013) does the same. The latter introduces complexity prevention approach too, stating that companies should first reduce non-strategic complexity, then accommodate strategic one, and finally prevent non-strategic complexity from coming into the system.

Particularly, firms can leverage four clusters of practices to lessen complexity’s hindering effects on their internal supply chain’s performance, i.e. variety reducing, confinement and decoupling, coordination and collaboration, and decision support and knowledge generation (Fernandez Campos, 2018). First, variety reducing practices physically reduce complexity, both tightening the managed range of elements and establishing commonalities among them. Confinement and decoupling practices, instead, reduce the domain where specialised resource can be leveraged or make some parts of the system more independent. Then, coordination and collaboration not only foster knowledge and solution sharing, but also synchronise and align teams, both inside and outside the company’s supply chain. Therefore, they do not reduce complexity, but rather accommodate it. Finally, decision support and knowledge generation cluster contains practices adopted to overcome cognitive limitations, enhance decision making and build and maintain relevant skills and know-how. Since each cluster has its own scope and limitations, companies can combine them to cover a specific range of structural and dynamic complexity factors, as empirically proved by Fernandez Campos’ case study (2018).

2.3 Supply chain resilience

Resilience is a concept discussed in several different domains and can be defined as the “adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function” (Ponomarov and Holcomb, 2009). It implies anticipating and flexibly addressing the environmental events, in order to keep the business delivering value and remain viable in the competitive business environment. Being able to return to normal operating performance within an acceptable period of time after a disruption nowadays is more important than the simply traditional risk management.

Although resilience has been investigated from different perspectives, it can be conceptualised in two main forms: on the one hand, considering the core functions characterising the disruption profile: sense, build, reconfigure, sustain and re-enhance (Birkie et al., 2014); on the other hand, focusing on constituents, formative elements such as flexibility, velocity, visibility and collaboration (Johnson et al., 2013; Jüttner and Maklan, 2011; Tukamuhabwa et al., 2015).

Considering the core functions, sense refers to the ability of firms of early detecting unanticipated events, while build is related to a set of activities executed prior to facing incidents or starting immediately after it. Reconfigure means to adapt in responding to unanticipated events that have a relevant impact on firm's business operations. Then, sustain core function refers to the continuity of delivering business operations, reducing lingering consequences and attaining objectives. Finally, the re-enhance function is concerned with retaining competitive performance levels after the disruption, recovering and enhancing success (Birkie et al., 2014).

For what concerns resilience constituents, instead, they have been defined by different authors. Jüttner and Maklan (2011) identify flexibility with the ability of a company to absorb changes caused by risk events, encountering, resolving and exploiting unexpected emergencies. They include redundancy in it, as duplication of capacity so that operations can continue following failure, although some other authors propose it as a separate resilience formative element. This approach is adopted by Johnson et al. (2013) too. Later, Tukamuhabwa et al. (2015) define flexibility as the ability of an enterprise to adapt to the changing requirements of its environment and stakeholders with minimum time and effort. In other words, it represents the easiness with which a supply chain can change its range number (i.e. number of possible options) and range heterogeneity (i.e. degree of difference between options), to cope with a range of market changes and events while performing comparably well.

Although Tukamuhabwa et al. (2015) identify velocity and visibility as a unique constituent called agility (i.e. the ability to respond quickly to unpredictable changes in demand or supply), the most authors separate them. Velocity is the speed with which a supply chain can react to and recover from market changes, thus it places a stronger emphasis on the efficiency rather than effectiveness of response (Jüttner and Maklan, 2011). Visibility is the ability to see through the entire supply chain (Tukamuhabwa et al., 2015), helping in timely detecting signals. It is the extent to which actors within the supply chain have access to or timely share information about identity, location and status of entities within the network, as well as events and their planned and actual dates and times (e.g. events regarding end-to-end orders, inventory, transportation and distribution, but also environment) (Jüttner and Maklan, 2011).

Finally, collaboration is the ability to work effectively with other entities for mutual benefit in areas such as forecasting, postponement and risk sharing (Tukamuhabwa et al., 2015). It represents the level of joint decision making and working together at a tactical, operational or strategic level between two or more supply chain members. It is scalable through the magnitude of relationship strength, quality and closeness. Since supply chain resilience is a interorganisational concept, involving the whole network, its constituents include the attitudinal predisposition of the actors to align forces in case of disruption (Jüttner and Maklan, 2011). Moreover, as it involves knowledge exchange and parties' willingness to share risk information, collaboration is strictly related to visibility.

Resilience can be differently influenced by supply chain complexity, and analysing it both the described conceptualisations are adopted in literature. Even though most authors investigate the linkages between complexity drivers and resilience constituents (e.g. Brandon-Jones et al., 2014; Cardoso et al., 2015; Falasca and Zobel, 2008; Hearnshaw and Wilson, 2013; Skilton et al., 2009), some papers consider resilience core functions, recognising links mainly with robustness and adaptability, respectively identifiable with sustain and reconfigure functions (Durach et al., 2015; Hosseini et al., 2016; Mari et al., 2015; Sokolov et al., 2016; Statsenko et al., 2016). The next section aims at deeply investigate these studies.

2.4 Relationship between supply chain complexity and resilience

Supply chain complexity plays a twofold role in terms of risk management: on the one hand, it increases the frequency of disruptions, on the other hand, it positively affects company's resilience. For instance, as stated by Bode and Wagner (2015), since no supplier is perfectly reliable, multi-sourcing arrangements increase incident probability, but can mitigate the severity of the experienced disruption. Another example is given by spatial complexity: although a geographically dispersed supply chain allows to diversify the risk, it implies a physically elongated flow of goods with longer paths and longer and more variable lead times, decreasing the network's robustness (Bode and Wagner, 2015). Since disentangling this dual relationship is the main aim of the study, a systematic literature review on this topic is conducted, as explained in Section 2.1.

Even though Craighead et al. (2007) are the first authors discussing about both supply chain complexity and resilience capabilities, they do not consider the possible link between the two dimensions. As a matter of fact, their study limits to separately describing them: first, they prove that the supply chain design characteristics, i.e. density, complexity and node criticality, increase the severity of supply chain disruptions; secondly, that recovery and warning, that are the two supply chain mitigation capabilities, reduce it. The link is first analysed by Falasca et al. (2008), who define density, complexity and node criticality as three determinants of supply chain resilience and assess their relationship not only with the occurrence of disruptions, but also with the impact of them on performances and with time needed for recovery. Therefore, they link static complexity drivers (i.e. number and criticality of nodes and number of flows) to flexibility. Similarly, Arkhipov and Ivanov (2011) provide a theoretical discussion on how the number of elements, as well as their variety and interrelations, increase this supply chain resilience constituent.

The positive linear relation between number of entities, both nodes and flows, and flexibility is also empirically supported thanks to case studies and scenario analysis (Cardoso et al., 2014; Cardoso et al., 2015). Through a Mixed Integer Linear Programming approach, a design and planning model that integrates demand uncertainty is applied to five different network structures submitted to different types of disruptions. Furthermore, a case study of a European supply chain is used to illustrate the methodology. Monitoring eleven indicators defined to assess resilience, the positive influence of node complexity, node criticality and flow complexity on resilience is proved. Moreover, evidence of a negative impact of density also emerges.

Still considering resilience constituents, relationship with structural complexity is theoretically sustained by Skilton and Robinson (2009) too: they prove how supply network complexity influences the traceability of adverse events, considered as the ability to identify and verify components and chronology of disruptions at all the stages of a process chain. Moreover, they also consider transparency, i.e. the extent to which information about sources, processes and relationships is readily accessible to counterparties in an exchange, and to outside observers. Drawing on examples from food supply networks, they demonstrate that numerousness of nodes negatively affects both traceability and transparency, while their degree of coupling increases the former and decreases the latter.

On the contrary, empirically investigating the linkage between static complexity and visibility through confirmatory factor analysis and multiple regression, Brandon-Jones et al. (2014) positively link number of nodes with the constituent, proving that scale complexity positively moderates the relationships between visibility and supply chain resilience (i.e. the higher the complexity, the greater the beneficial effects of visibility on resilience). If a company has to manage a greater number of suppliers, relationships will most likely become more transactional in nature, therefore connectivity and information sharing will enable to better understand the inherent strengths and weaknesses in the system and thereby increase supply chain resilience. However, the model also demonstrates that none of other dimensions of complexity, including geographic dispersion, differentiation and delivery complexity, have the same interaction impact. Visibility positively impacts supply chain resilience regardless of the geographic dispersion or concentration of suppliers, their reliability and lead-time length, as well as their level of differentiation or similarity.

Considering instead the opposite link going from supply chain resilience capacities to structural complexity, Elleuch et al. (2016) discuss to what extent the formers mitigates the severity of vulnerability factors, including static complexity drivers, such as dependency to foreign suppliers. Results show that visibility, sharing of information and close collaboration with commercial service are a good instrument to manage structural complexity, reducing the severity of its impact on business performance.

Thome et al. (2016) theoretically discuss the link with flexibility, collaboration and agility, through tertiary research and bibliometric analysis. Since agility comprehends visibility and velocity (Tukamuhabwa et al., 2015), their study considers all the four resilience formative elements. Moreover, they do not consider only static complexity drivers (number of nodes and flows), but also dynamic ones (uncertainty of time and randomness). According to their framework, they are both related to resilience, mediated by risk factors and management. As a matter of fact, complexity drives toward organisational, network, industry and environmental risks, which in turn require a higher level of resilience. In addition, risk management, is a driver to build resilience, increasing flexibility, redundancy, collaboration and agility, allowing the company to constantly be ready and prepared to respond to unforeseen disruptions. Finally, resilience loops back to complexity, as strengthened resilience may lead to more complex networks.

Another study considering both structural and dynamic supply chain complexity is by Hearnshaw and Wilson (2013), who apply theoretical and empirical developments in complex network literature to the context of supply chains. The authors identify short characteristic path length, high clustering coefficient and power law connectivity distribution (i.e. a heterogeneous connectivity distribution indicating the presence of a small number of highly connected nodes, and a large number of nodes with a low number of connections) as key properties of efficient supply chains, and theoretically assess their positive links with resilience constituents. Particularly, higher the clustering coefficient, higher is the collaboration among nodes and the reduction of opportunistic behaviour, while shorter the characteristic path length, higher is the supply chain velocity of materials and information flow. Then, considering power law connectivity distribution, it increases flexibility, due to the high coordination enabling adaptability to change. Furthermore, Hearnshaw and Wilson adopt a mixed approach for resilience conceptualisation, as they considered not only constituents, but also a core function, i.e. reconfigure. Indeed, according to them, the number of nodes constituting a supply chain negatively affects adaptability, which is identifiable with reconfigure function because it is defined as the capacity to adapt, and not just resist, to unexpected changes, self-organizing and reconfiguration the system structure. The same perspective is applied in assessing dynamic complexity role: networks are considered more adaptable when characterised by continuously entering and exiting nodes.

Hosseini et al. (2016) consider both static and dynamic drivers too, as well as they conceptualize resilience with two key features: absorptive and adaptive capability. Employing Bayesian network and investigating an Iranian sulfuric acid manufacturer's supply chain, they design a framework in which the causal relationships between supply chain attributes and its resilience contributors are reported. On the one hand, the number of redundant suppliers in the network, due to multiple sourcing approach, supplier reliability and geographic dispersion are positively linked to the absorptive capacity of a company, defined as the level to which a system is capable of withstanding and absorbing shocks from perturbations and minimising the corresponding impacts. On the other hand, dynamics drivers, such as replacing raw materials, utilizing alternative modes of transportation and contracting with new suppliers, increase adaptability, i.e. the ability to adapt with disruption using non-standard operating practices to avoid discontinuity of system's performance. These drivers are respectively defined flexible manufacturing configuration, flexible transportation modes and flexible supply contracting, due to their tight connection with flexibility.

An inverse relationship between complexity and resilience is stated by Gunasekaran et al. (2015), who identify a two-way linkage is identified: not only the structural absence of transparency and continuous monitoring reduce end-to-end visibility, but also visibility and collaboration negatively affects uncertainty. For instance, sourcing dynamic complexity arises in case of miscommunication among companies. However, the authors also identify a positive link: multiple sourcing increases supply chain velocity, as a higher number of redundant suppliers allows to avoid supply shortages.

Durach et al. (2015) theoretically discuss a negative impact of complexity on resilience too. In their study, they apply a systematic literature review approach to provide groundwork for an emerging theory of supply chain robustness. This is conceptualised as a dimension of resilience (i.e. the ability to resist or avoid change), and is identifiable with sustain core function. It is mainly reduced by structural drivers, including the number of nodes, their relative individual criticality and the network length, but also uncertainty negatively affects it. The only positive impact on resilience is given by density (i.e. the number of nodes in each cluster), which increases collaboration.

On the contrary, considering robustness, an increase proportional to static complexity is proved through agent-based simulation analysis by Mari et al. (2015). According to complex networks theory, it is positively related to supply availability rate, as it offers more chances of survivability during disruptions. Moreover, scale-free supply chains, characterised by few significant nodes with many connections and many nodes with very few connections (power law connectivity), are more robust supply chains. The authors consider resilience constituents too, assessing that higher the clustering coefficient, higher is the flexibility, as well as shorter the characteristic path length, more the velocity.

According to Statsenko et al. (2016), supply chains are systems of systems, complex networks exhibiting self-organising properties and characterized by distinctive structural patterns, such as power law connectivity distribution, scale-free and nearly decomposable modular structure. A case study of the mining industry supply network in South Australia enables them to identify patterns in real world. In addition, the findings provide insights about such operational characteristics as robustness, responsiveness, flexibility and resilience. Particularly, referring to structural drivers (e.g. size of the largest connected component of a network, and hierarchical modularity or decomposability) a positive linkage between complexity and robustness is proved.

Sokolov et al. (2016), in their analysis on the ripple effect in the supply chain, define a positive relationship between connectivity coefficient (i.e. the ratio between the total number of arcs and the minimal number of arcs when a connected graph with the same number of nodes is still possible) and supply chain robustness, as well as between reachability coefficient (i.e. the ability to achieve all the nodes) and flexibility.

Differently from all the previous mentioned authors, Adenso-Diaz et al. (2012) identify supply chain resilience with reliability, used to measure the ability of a supply network to withstand disruption risks. As a matter of fact, they adapt the classical definition, according to which reliability is the ability of a system to perform under specific conditions, to the context of their research. Performing a full factorial experimental design and an analysis of variance, the study provides empirical findings assessing the role of many supply chain factors that affect reliability. Particularly, it proves the positive impact of number of flows, percentage of critical nodes, nodes reliability and flows reliability, but also the negative one characterising number of nodes, network density (i.e. the number of nodes in each cluster) and percentage of supplier nodes. Finally, from a dynamic perspective, it demonstrates the lack of relationship with density variance, node reliability variance, flow reliability variance and cluster reliability variance.

The most recent study concerning the influence of supply chain complexity on the effectiveness of resilience capabilities in mitigating supply chain disruptions is by Birkie et al. (2017), who demonstrate not only the positive impact that the former has on performance improvement after incidents, but also its positive moderating effect on the relationship between resilience and performance. Due to the structural equation modelling, based on secondary data collection from companies that have faced at least one supply chain disruption between the years 2002 and 2015, the analysis represents the first research empirically proving the benefits of supply chain complexity for a better recovery of operational performance after a disruption. Indeed, more resources and interconnections could provide opportunities to keep up performances. Moreover, the size of business organisations and the supply base dispersion strongly moderate the resilience-performance link. For instance, higher the firm size, higher the financial and human capital to be employed in rebuilding capabilities, thus determining a more effective sustain to performance upon disruption with the same resilience capabilities. Similarly, more diversified the supply base and wider the network of facilities, more are the opportunities in leveraging resilience capabilities. Even though it focuses on structural complexity drivers (i.e. product portfolio, size and supply dispersion), due to the nature of data collected, organisational restructuring is considered: it is the factor with the weakest contribution in the model, as merger, acquisition and sell-out processes could coincide with disruption, distracting from mitigation efforts. In conclusion, despite the attempt to manage and limit supply chain complexity, some level of it is required in dealing with unexpected events, to better recover operational performance.

In addition to the mentioned studies, other ones are among the results of the systematic search through key words described in Section 2.1: Barroso et al. (2010; 2011), Braziotis et al. (2013), Carvalho et al. (2014), Gunasekaran et al. (2014), Heckmann et al. (2015), and Li and Gulati (2015). Although they do not explicitly consider the relationship between supply chain complexity and resilience, resulting out of scope with respect to this study, they are important to set the theoretical background.

Barroso et al. (2010; 2011) discuss proactive and reactive management strategies that can be adopted by the supply chain to make it resilient to disturbances at the supply side. They set the context describing how supply chain entities exhibit ever increasing levels of complexity, thus increasing the likelihood of disturbances, but they do not link the two dimensions. Furthermore, through a case study related to a Portuguese automotive supply chain, they analyse multi-sourcing and other resilience strategies, not directly connected with complexity (Barroso et al., 2010). Then, they deepen the study, focusing on multi-supply and buffer stocks as resilience strategies and assessing their impact on cost performance (Barroso et al., 2011).

Similarly, the study by Carvalho et al. (2014) presents a supply chain simulation study for a real case concerned with a Portuguese automotive company, evaluating alternative supply chain designs in order to improve resilience. The impact of mitigation strategies on performance is assessed, particularly the role of flexibility and redundancy on costs and lead time performance. Consequently, this study is focused on the linkage between resilience and performance, considering complexity only to set the context, like the previous two.

Li and Gulati (2015) investigate how to mitigate supply chain risk, considering the increasing complexity and vulnerability of supply chains. They propose a framework for identifying, prioritising and mapping risks and related mitigation policies. Particularly, identification, ranking, matching, evaluation and implementation are the five major steps of the model. Furthermore, they categorize mitigation policies into major types based on the risk issues, distinguishing among structure, visibility, resilience and buffer. Resilience is specified to be a more and more important strategy due to the growing complexities of supply chain networks, but specific link between the two dimensions is not analysed.

Braziotis et al. (2013) theoretically clarify the distinction between supply chains and supply networks, reviewing the literature and integrating it with inputs from academic experts during relevant supply chain workshops. On the one hand, a supply chain is a set of primarily collaborative activities and relationships linking firms in the value-creation process; on the other hand, a supply network is a set of active members within a company's supply chain, as well as inactive members to which a company is related, that can be called upon to actively contribute if a need arises. Therefore, despite the higher complexity and the multiple interdependencies, the supply network is also significant for inactive members, who can exploit the contribute of core companies in case necessity, hence enhancing supply chain resilience.

Gunasekaran et al. (2014) provide a detailed literature review concerning sustainable supply chain capabilities building in the age of global complexity, highlighting emerging theories and practices. The paper examines the nature of complexity challenges (i.e. regulatory requirements, global market opportunities, multi-faceted products/services, rapid technology changes, global market and competitive pressures), which require to design specific dynamic supply chain configurations, including flexible usage of physical and knowledge resources. However, since complexity conceptualisation does not consider internal drivers and resilience is not deeply investigated, it cannot be included in the literature relevant for the scope of this study.

Heckmann et al. (2015) provide a literature review too, focusing on definition, measurement and modelling of supply chain risk. Since economic systems are increasingly prone to complexity and uncertainty, interest in risk management is more and more important, leading to the adoption of the risk concepts, terminologies and methods from other fields. Moreover, the affected supply chain, exposed to a certain degree of risk, has underlying characteristics identifiable as vulnerability and resilience, which determine the reaction of the network to a disruption.

In conclusion, almost all the studies identified through the structured literature review can be mapped according to supply chain complexity and resilience dimensions, as explained in Section 2.1. The findings emerging from it are discussed in the next section.

2.5 Selected literature mapping

After having searched and selected through the aforementioned systematic approach the relevant academic and practitioners' contributions, these are mapped, in order to identify possible existing gaps in literature, following the procedure described in section 2.1. According to the two main identified dimensions, i.e. supply chain complexity and resilience, each article is placed in a matrix, graphically showing its contribute in the discussion about the existing relationship between the two, as deeply described in section 2.4. Figure 2.3 represents the detailed matrix, in which the kind and the direction of the links are reported, as well as the study methodology adopted to prove the evidence (i.e. CS = case study, TH = theoretical study or framework, REG = regression, SA = scenario analysis, SIM = simulation).

First, it emerges that both conceptualisations of resilience are covered: on the one hand, most authors assess the relationship between complexity drivers and resilience constituents (Adenso-Diaz et al., 2012; Arkhipov and Ivanov, 2011; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Elleuch et al., 2016; Falasca and Zobel, 2008; Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Mari et al., 2015; Sokolov et al., 2016; Skilton and Robinson, 2009; Thome et al., 2016); on the other hand, some studies focus on resilience core functions, more specifically robustness, adaptability and absorptive capacity (Durach et al., 2015; Hosseini et al., 2016; Mari et al., 2015; Sokolov et al., 2016; Statsenko et al., 2016). In addition, Adenso-Diaz et al. (2012) identify resilience with supply chain reliability, while Birkie et al. (2017) consider proactive and reactive capabilities.

The positive linear relation between number of elements (both nodes and flows) and supply chain flexibility has been not only theoretically sustained (Falasca and Zobel, 2008; Skilton and Robinson, 2009), but also empirically supported thanks to case studies and scenario analysis (Cardoso et al., 2014; Cardoso et al., 2015). Differently, links with collaboration and visibility have been mainly theoretically discussed (Skilton and Robinson, 2009; Thome et al., 2016). Regarding core functions, the positive relation between structural complexity and robustness is proved through simulation (Mari et al., 2015) and case study (Statsenko et al., 2016). Moving to dynamic complexity, few papers cover it, with regard to both resilience constituents and resilience functions, and a gap is still present concerning it. Moreover, literature covering dynamic complexity is mainly theoretical (Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Thome et al., 2016; Durach et al., 2015; Hosseini et al., 2016; Adenso-Diaz et al., 2012).

Complexity drivers		Resilience constituents					Resilience functions			Reliability	Proactive/reactive capabilities	Authors
		Flexibilty	Velocity	Visibility	Collaboration	Agility	Robustness	Adaptability	Absorptive capacity			
Static	# nodes	+, ←, ↑, CS-SA +, ↑, TH (pSIM) +, ←, TH		+, ↑, REG -, ↑, TH	+, ←, TH	+, ←, TH	-, ↑, TH (LR)	- , ↑, TH		-, ↑, SIM		Adenso-Diaz et al., 2012 Brandon-Jones et al., 2014 Cardoso et al., 2014; 2015 Durach et al., 2015 Falasca et al., 2008 Hearnshaw and Wilson, 2013 Thome et al., 2016 Skilton and Robinson, 2009
	# flows	+, ←, ↑, CS-SA +, ↑, TH (pSIM) +, ←, TH			+, ←, TH	+, ←, TH				+, ↑, SIM		Adenso-Diaz et al., 2012 Cardoso et al., 2014; 2015 Falasca et al., 2008 Thome et al., 2016
	density (# nodes in each cluster)	-, ←, ↑, CS-SA			+, ↑, TH (LR)					-, ↑, SIM		Adenso-Diaz et al., 2012 Cardoso et al., 2014; 2015 Durach et al., 2015
	% critical nodes	+, ←, ↑, CS-SA -, ↑, TH (pSIM)								+, ↑, SIM		Adenso-Diaz et al., 2012 Cardoso et al., 2014; 2015 Falasca et al., 2008
	relative criticality individual nodes						-, ↑, TH (LR)					Durach et al., 2015
	% supplier nodes									-, ↑, SIM		Adenso-Diaz et al., 2012
	# redundant suppliers (multiple sourcing)	+/-, ↑, CS-SA +, ↑, TH (pSIM)	+ , ↑, TH						+, ↑, TH-CS	+, ↑, SIM		Adenso-Diaz et al., 2012 Cardoso et al., 2014; 2015 Falasca et al., 2008 Gunasekaran et al., 2015 Hosseini et al., 2016
	node reliability									+, ↑, SIM		Adenso-Diaz et al., 2012
	flow reliability			no, REG						+, ↑, SIM		Adenso-Diaz et al., 2012 Brandon-Jones et al., 2014
	cluster reliability									no, SIM		Adenso-Diaz et al., 2012
	supplier reliability								+, ↑, TH-CS			Hosseini et al., 2016

(continue)

Complexity drivers		Resilience constituents					Resilience functions			Reliability	Proactive/reactive capabilities	Authors
		Flexibilty	Velocity	Visibility	Collaboration	Agility	Robustness	Adaptability	Absorptive capacity			
Static	entropy: elements, variety, interrel.	+, ↑, TH										Arkhipov and Ivanov, 2011
	geographic dispersion			no, REG					+, ↑, TH-CS			Brandon-Jones et al., 2014 Hosseini et al., 2016
	differentiation of nodes			no, REG +/-, ↑, TH								Brandon-Jones et al., 2014 Skilton et al., 2009
	out/in-degree centrality - # arcs											Cardoso et al., 2014; 2015
	out/in-degree centrality - flow											Cardoso et al., 2014; 2015
	network lenght						-, ↑, TH (LR)					Durach et al., 2015
	dependency to imports			-, ←, CS	-, ←, CS							Elleuch et al., 2016
	not continuous monitoring			- , ↑, TH								Gunasekaran et al., 2015
	no transparency			- , ↑, TH								Gunasekaran et al., 2015
	high clustering coefficient	+, ↑, SIM			+ , ↑, TH							Hearnshaw and Wilson, 2013 Mari et al., 2015
	short characteristic path lenght		+ , ↑, TH +, ↑, SIM									Hearnshaw and Wilson, 2013 Mari et al., 2015
	power law connectivity (scale-free network)	+ , ↑, TH					+, ↑, SIM					Hearnshaw and Wilson, 2013 Mari et al., 2015
	power law distribution multi-sourcing	+ , ↑, TH										Hearnshaw and Wilson, 2013
	supply availability rate						+, ↑, SIM					Mari et al., 2015
	connectivity coefficient						+ , ↑, TH					Sokolov et al., 2016
	reachability coefficient	+ , ↑, TH										Sokolov et al., 2016
	degree of coupling			+/∩, ↑, TH								Skilton and Robinson, 2009
	level and types of interrelationships			-, ↑, TH								Skilton and Robinson, 209
	hierarchical modularity						+, ↑, CS					Statsenko et al., 2016
	product portfolio										+ , ↑, TH	Birkie et al., 2014
	supply dispersion										+ , ↑, TH	Birkie et al., 2014
	size (turnover, employees)						+ , ↑, CS				+ , ↑, TH	Birkie et al., 2014 Statsenko et al., 2016

(continue)

Complexity drivers		Resilience constituents					Resilience functions			Reliability	Proactive/reactive capabilities	Authors
		Flexibilty	Velocity	Visibility	Collaboration	Agility	Robustness	Adaptability	Absorptive capacity			
Dynamic	uncertainty			-, ←, TH	-, ←, TH		-, ↑, TH (LR)					Durach et al., 2015 Gunasekaran et al., 2015
	continuous entering/exiting nodes							+ , ↑, TH		+ , ↑, TH		Hearnshaw and Wilson, 2013
	flexible manufacturing configuration	+, ←, TH-CS						+, ↑, TH-CS				Hosseini et al., 2016
	flexible transportation modes	+, ←, TH-CS						+, ↑, TH-CS				Hosseini et al., 2016
	flexible supply contracting	+, ←, TH-CS						+, ↑, TH-CS				Hosseini et al., 2016
	uncertainty of time	+, ←, TH			+, ←, TH	+, ←, TH						Thome et al., 2016
	randomness	+, ←, TH			+, ←, TH	+, ←, TH						Thome et al., 2016
	organisational restructuring (M&A)										+ , ↑, TH	Birkie et al., 2014
	density variance									no, SIM		Adenso-Diaz et al., 2012
	node reliability variance									no, SIM		Adenso-Diaz et al., 2012
	flow reliability variance									no, SIM		Adenso-Diaz et al., 2012
	cluster reliability variance									no, SIM		Adenso-Diaz et al., 2012

Figure 2.3: *Detailed articles mapping, matching supply chain complexity (static and dynamic) and supply chain resilience.*

Results can be summarized in a less detailed table, represented in Figure 2.4, which reports the considered studies in the four different quadrants resulting by matching structural and dynamic complexity with resilience constituents and core functions. The summary matrix graphically indicates the grade of coverage of different areas, enabling to visually understand where the existing body of knowledge is concentrated and where, vice versa, there is space for researching. Therefore, it is possible to highlight which gaps could be covered by the contribution of this study.

	RESILIENCE CONSTITUENTS	**RESILIENCE FUNCTIONS**
STATIC COMPLEXITY	Adenso-Diaz et al., 2012 Arkhipov and Ivanov, 2011 Brandon-Jones et al., 2014 Cardoso et al., 2014 Cardoso et al., 2015 Elleuch et al., 2016 Falasca and Zobel, 2008 Gunasekaran et al., 2015 Hearnshaw and Wilson, 2013 Mari et al., 2015 Sokolov et al., 2016 Skilton et al., 2009 Thome et al., 2016	Birkie et al., 2017 Durach et al., 2015 Hosseini et al., 2016 Mari et al., 2015 Sokolov et al., 2016 Statsenko et al., 2016
DYNAMIC COMPLEXITY	Gunasekaran et al., 2015 Hearnshaw and Wilson, 2013 Thome et al., 2016	Durach, 2015 Hosseini, 2016

Figure 2.4: *Summary articles mapping, matching supply chain complexity (static and dynamic) and supply chain resilience.*

The most covered area is the intersection between static complexity and resilience constituents, where there is the contribution of many authors, both theoretically (Arkhipov and Ivanov, 2011; Falasca and Zobel, 2008; Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Skilton and Robinson, 2009; Sokolov et al., 2016; Thome et al., 2016) and empirically (Adenso-Diaz et al., 2012; Brandon-Jones et al., 2014; Cardoso et al., 2014; Cardoso et al., 2015; Elleuch et al., 2016; Mari et al., 2015; Skilton and Robinson, 2009; Thome et al., 2016). Few authors, instead, cover dynamic complexity, with regards to both resilience constituents and resilience functions, and the concerning literature is mainly theoretical (Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Thome et al., 2016; Durach et al., 2015; Hosseini et al., 2016). As a matter of fact, selected papers often mention dynamic complexity too and indicate it as an interesting future investigation topic, but do not deepen the concept and focus only to the static one.

For what concerns resilience dimensions, few authors investigate resilience core functions, considering both structural and dynamic complexity. Furthermore, only robustness, adaptability and absorptive capabilities are assessed, without taking in consideration the those theoretically defined by literature (Birkie et al., 2014), i.e. sustain, sense, build, reconfigure, sustain and re-enhance.

In conclusion, the emerging evidence delineates three main gaps in matrix in Figure 2.4: first, concerning the relationship between dynamic complexity and resilience constituents; second, about the linkage between static complexity and resilience core functions; and finally, regarding the impact of dynamic complexity on resilience core functions. Moreover, despite the amount of research discussing static complexity in relation to resilience functions, there is space for demonstrating through empirical evidence what theoretically sustained, more deeply defining the link. In particular, the contribution of this study can be of higher value in covering the first gap (i.e. between dynamic complexity and resilience constituents), as well as in empirically sustaining the impact of complexity on resilience constituents. Drawing from it, research framework and question are defined, as discussed in the next chapter.

Chapter 3
Research framework and questions

Chapter 3 presents the research framework and questions adopted in the study. First, the research framework is delineated, and the main constructs and relationships between them are introduced. Secondly, the key constructs are defined, i.e. supply chain structural and dynamic complexity, complexity management practices and supply chain resilience, according to extant literature. Then, literature providing evidence and insights on the link between supply chain complexity and resilience is recalled, as well as that related to impact of complexity management practices on supply chain complexity. Finally, the research questions at the basis of the study are presented.

3.1 Research framework

As emerged from the literature review in Chapter 2, few studies have deeply investigated the influence of supply chain complexity on resilience (e.g. Brandon-Jones et al., 2014; Cardoso et al., 2015; Falasca and Zobel, 2008; Hearnshaw and Wilson, 2013; Skilton et al., 2009). Therefore, this research seeks to contribute in further analysing this relationship, considering not only the direct link between complexity and resilience, but also investigating whether complexity management practices are resilience formative elements. Drawing from it, a preliminary research framework is designed, as represented in Figure 3.1.

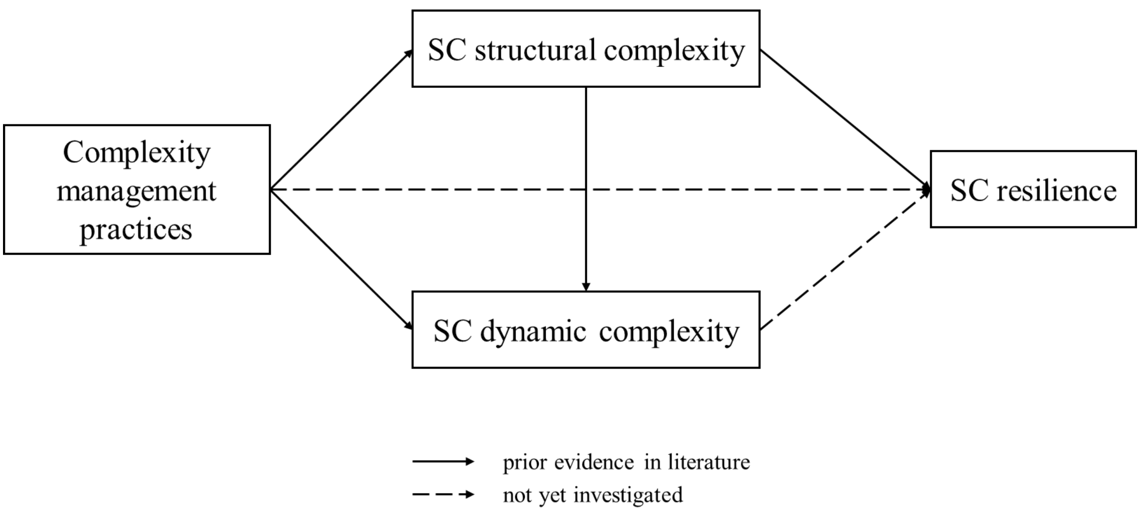

Figure 3.2: *Research framework*

The key constructs are supply chain complexity, both structural and dynamic, complexity management practices and supply chain resilience. Each one of them is deeply described in the next section. Linking them, there are two different kind of arrows in the picture: on the one hand, solid lines represent linkages with prior evidence in literature, on the other hand, dashed lines stand for relationships not yet discussed in the knowledge background. As for the formers, related evidence and insights are recalled in Section 3.3. The latter ones, instead, are subject matter of this study, therefore are representative of the research questions presented in Section 3.4.

3.2 Research constructs

This section clarifies the definition of each single key construct, leveraging extant theoretical background.

Starting with supply chain resilience, as discussed in Chapter 2, it is the "adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" (Ponomarov and Holcomb, 2009). Different authors conceptualise it in different ways, mainly classifiable in two perspectives: on the one hand, considering the core functions characterising the disruption profile, i.e. sense, build, reconfigure, sustain and re-enhance (Birkie et al., 2014); on the other hand, focusing on constituents, formative elements, i.e. flexibility, velocity, visibility and collaboration (Jüttner and Maklan, 2011). The latter is the approach considered in this study, and resilience constituents are defined as follows:

- Flexibility is defined as the ability of an enterprise to adapt to the changing requirements of its environment and stakeholders with minimum time and effort (Tukamuhabwa et at., 2015). It represents the easiness with which a supply chain can change its range number (i.e. number of possible options) and range heterogeneity (i.e. degree of difference between options), to cope with a range of market changes and events while performing comparably well. In some cases, it is identified with redundancy, i.e. the duplication of capacity so that operations can continue following failure (Johnson et al., 2013; Jüttner and Maklan, 2011)
- Velocity is the speed with which a supply chain can react to and recover from market changes (Jüttner and Maklan, 2011).
- Visibility is defined as the ability to see through the entire supply chain (Tukamuhabwa et al., 2015), helping in detecting signals and having knowledge of the status of a supply chain's assets and environment. It is the extent to which actors within the supply chain have access to or timely share information about identity, location and status of entities within the network, as well as events and their planned and actual dates and times (e.g. events regarding end-to-end orders, inventory, transportation and distribution, but also environment) (Jüttner and Maklan, 2011).

Furthermore, in this study visibility includes also the degree of knowledge that a company has on market factors, and ability to see potential alternatives to cope with unexpected events.

- Collaboration is the ability to work effectively with other entities for mutual benefit in areas such as forecasting, postponement and risk sharing (Tukamuhabwa et al., 2015). It represents the level of joint decision making and working together at a tactical, operational or strategic level between two or more supply chain members. It is scalable through the magnitude of relationship strength, quality and closeness. Since collaboration could involve information exchange, which can reduce uncertainty, increase transparency and facilitate the creation and sharing of knowledge, it is strictly related to visibility. Moreover, due to the consequent alignment of forces in case of disruption, it can have a positive effect on flexibility, allowing companies to minimise the effort to adapt. Therefore, in the study it is important to consider it only when risk sharing, reciprocal contribution and coordination are present, distinguishing it from the other resilience constituents.

The second key construct is supply chain complexity, distinguished in structural and dynamic forms. Supply chain structural complexity is defined as the static complexity associated to the main characteristics of the network, such as numerousness, variety, and interconnections, interactions or dependencies within elements (e.g. products, processes, facilities, suppliers, etc.) (Bozarth et al., 2009; Serdarasan, 2013). It includes number of nodes, flows and tiers, density of network, criticality of elements, geographic dispersion and characteristic path length. In the study, it is conceptualised through a list of seven drivers (Fernandez Campos, 2018), which are:

- Portfolio breadth,
- Product variety and specificities,
- Variety of/interaction between teams and functions,
- Number and layers of supply chain facilities,
- Differences between facilities in different territories,
- Number/variety of partners and suppliers,
- Variety and breadth of customer requirements.

It is possible to notice that these are classifiable in three main categories: product portfolio, internal supply chain and external supply chain complexity.

Supply chain dynamic complexity is the complexity stemming from uncertainty and evolutionary events altering the supply chain, associated to its operations and its structure, considering both strategic and operational perspectives (Serdarasan, 2013) It concerns uncertain operational dynamics, organisational restructuring, production relocation, M&A and supply chain reconfiguration, and it is defined through some drivers too (Fernandez Campos, 2018):

- Product introduction and lifecycle events,

- Reconfiguration of supply chain activities and facilities,
- Improvements to equipment, procedures and systems,
- Restructuring and M&A,
- Internal operational dynamics
- Demand/supply sides operational dynamics,
- New customers or suppliers.

These are classified in the same three aforementioned categories: product portfolio, internal supply chain and external supply chain complexity.

The last key construct is complexity management practices, which are the methods, techniques and tools implemented by managers to reduce the adverse effects of complexity in their organisations. They are distinguished in complexity reduction practices, physically reducing the amount of complexity in the supply chain, and complexity accommodation or absorption practices, mitigating the negative effects of complexity on performance. As a matter of fact, since complexity may serve a company's strategy and thus represent a source of competitive advantage, reduction practices are not sufficient and it is necessary to develop managerial approaches enabling organisation to leverage complexity but lessen its adverse effects (Bozarth et al., 2009; Fernandez Campos, 2018; Manuj and Sahin, 2011; Perona and Miragliotta, 2014; Serdarasan, 2013).

Complexity management practices can be classified in four clusters, defined as bundles of managerial, technological, design-related, etc. approaches and tools that rely on the same principle or logic to manage complexity (Fernandez Campos, 2018). These are:

- Variety reducing,
- Confinement and decoupling,
- Coordination and collaboration,
- Decision support and knowledge generation.

Variety reducing practices are employed to physically reduce complexity, both aiding the firm focus on a narrower range of elements (e.g. products, customers, geographies, etc.) and establishing commonalities among them, reducing internal diversity. They enable to significantly manage the interplay between structural and dynamic complexity, reducing for instance variety of products, number and layers of supply chain facilities and differences between countries. However, their applicability can be limited, as structural complexity may be at the basis for a company's competitive advantage, determining its financial growth, thus variety reducing practices are leverageable only for non-value adding complexity.

Confinement and decoupling practices aim at reducing domain where specialised resources can be leveraged or make some parts of the system more independent from others, accommodating relations and constraints between elements. For instance, defining bespoke distribution channels for each customer segment, a firm can leverage specific infrastructures and tools. These practices can be adopted to accommodate both structural and dynamic complexity, as, on the one hand, they narrow the range of activities that must bear with variety in the supply chain, on the other hand, making groups of activities independent to others, they aid in managing supply chain dynamics. Nevertheless, they also present a series of drawbacks. First, since complexity is not reduced but rather bound to a specific area, the management of it in the specific area can still demand the adoption of additional practices belonging to other clusters. Then, the independence may contaminate the alignment and coordination between actions an internal supply chain and organisation.

Coordination and collaboration practices foster knowledge and solutions sharing, and teams and functions synchronisation and alignment, both inside and outside the company's supply chain. They do not reduce complexity, but rather enable to accommodate it, facilitating a holistic management of it. They particularly cope with dynamic complexity, for which established information flows are fundamental. For example, the definition of cross-functional KPIs may allow both front-end functions and supply chain managers to jointly minimise the effect of operational customer dynamics, or a product lifecycle communication tool may aid in new products introductions. Moreover, practices such as benchmarking, global supply chain forums and process platforms drive the escalation of best practices, facilitating homogenisation within supply chain.

Finally, decision support and knowledge generation practices are adopted to overcome cognitive limitations, in order to enhance decision making or build and maintain relevant skills and know-how. For instance, they allow managers to filter out and focus on a reduced number of decisions and elements, as well as they provide them with more valuable information. They are employed to accommodate both structural and dynamic complexity drivers, but they present limitations too, as they can hinder a comprehensive understanding of the organisation, accentuating silo-thinking. In addition, decision support tools are often the most expensive complexity management practices.

Table 3.1 provides an overview of practices encompassed in each cluster, drawing from the research study by Fernandez Campos, 2018. As underlined by the author, not all the practices adhere well to single clusters, thus they are classified according to the contribution that revealed most significantly mentioned by supply chain managers.

Table 3.1: *Complexity management practices classified in four clusters.*

Clusters	**Underlying complexity management practices**
Variety reducing	Accessory-based customisation
	Product platforms and standards

(continue)

Clusters	Underlying complexity management practices
Variety reducing	Product portfolio rationalisation
	Product-centric organisational design
	Platform teams (Organisational and processes' platforms)
	Rationalisation of SC facilities
	Process standardisation
	Unification of customer requirements
	Centralisation of purchasing
Confinement and decoupling	Outsourcing
	Customised distribution channels
	Modular design and software customisation
	Category management
	Localisation of activities
	Additive manufacturing postponement
	Organisational buffers
	Split of sourcing activities
	Flexible workforce
	Stocks
	Intermediate interface teams
Coordination and collaboration	Decentralisation of procurement
	Global SC forums (and governance models)
	Integrated product teams
	Strategic relations with partners and suppliers
	Integrated ERP systems
	Benchmarking
	Coll. with prod. design/front-end teams
	Project management
	Cross-functional KPIs
	Multi-level supply-demand reconciliations
	Unique customer interfaces
	Supplier development
Decision support and knowledge generation	Forward-looking forecasting
	Cellular manufacturing and product tech. groups
	Product segmentation and specialised teams
	Automation
	Traceability and anti-mixing systems
	Multi-Echelon ERPs and optimisation IT tools
	Product lifecycle management processes and tools

(continue)

Clusters	Underlying complexity management practices
Decision support and knowledge generation	Vendor rating tools Specific training Product design carry-over Simulation

3.3 Relationships characterizing the research framework

The research framework is characterised by different links between the key constructs described in the previous section. While some of them are supported by evidence and insights in the literature, i.e. those represented with solid line arrows, others, i.e. dashed line arrows, have not yet been investigated, hence need for further investigation.

First, structural and dynamic supply chain complexities are interrelated and affect each other (Serdarasan, 2013; Fernandez Campos, 2018), thus there is a vertical arrow between them in the framework. As empirically demonstrated, the interplay between static and dynamic complexity has a synergistic aggravating effect on supply chain performance, although proved only from the structural side to the dynamic one. For instance, the structural complexity of the product portfolio and product design increases the operational dynamics, mainly due to the increase of uncertainty that this complexity brings to operations. Furthermore, the same structural factors impact on dynamic factors related to changes to the supply chain design (e.g. supply chain reconfiguration and organisational restructuring), due to the reduction of adaptability in the internal supply chain. Another example is given by the structural complexity of the internal network of facilities, which increases the uncertainty associated to various dynamic complexity factors, such as unexpected customer demand and the reallocation of supply chain activities in the network (Fernandez Campos, 2018).

In order to manage supply chain complexity, companies develop specific management practices, aiming at reducing its negative effect on performances, either by reducing or by accommodating it (Serdarasan, 2013; Fernandez Campos, 2018). Since both static and dynamic complexity are managed by these approaches and tools, in the framework they are both linked to complexity management practices.

The arrows linking supply chain complexities and supply chain resilience represent the linkages deeply discussed setting the theoretical background in Chapter 2. Indeed, even though complexity can be a major impediment to performance, increasing for instance the frequency of disruptions (Bode and Wagner, 2015), it could aid effectiveness of resilience in mitigating disruption, as it increases flexibility, visibility, velocity and collaboration (e.g. Brandon-Jones et al., 2014; Cardoso et al., 2015; Falasca and Zobel, 2008; Skilton et al., 2009), as well as it affects resilience core functions (e.g. Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Durach et al., 2015; Hosseini et al., 2016).

The positive linear relation between number of elements (both nodes and flows) and supply chain flexibility has been not only theoretically sustained (Falasca and Zobel, 2008; Skilton and Robinson, 2009), but also empirically supported thanks to case studies and scenario analysis (Cardoso et al., 2014; Cardoso et al., 2015). Differently, links with collaboration and agility have been only theoretically discussed (Thome et al., 2016).

Nevertheless, static and dynamic complexities have been differently investigated in the literature, and a lack of knowledge regarding the latter is noticeable. While many authors have contributed to the influence of structural complexity on supply chain resilience constituents, both theoretically (e.g. Falasca and Zobel, 2008; Hearnshaw and Wilson, 2013; Skilton and Robinson, 2009) and empirically (e.g. Brandon-Jones et al., 2014; Cardoso et al., 2015; Elleuch et al., 2016; Mari et al., 2015), few authors cover dynamic complexity, with regards to both resilience constituents and resilience functions, and the concerning literature is mainly theoretical (e.g. Gunasekaran et al., 2015; Thome et al., 2016; Hosseini et al., 2016). Although analysed papers often mention dynamic complexity too and indicate it as an interesting future investigation topic, they do not deepen the concept and focus only to the static one.

Supply chain complexity represents an incentive for companies to develop new practices and techniques to manage it (Fernandez Campos, 2018), which in turn could reveal resilience enablers or reducers, aiding or hindering the recovery of normal operating performance after an incident. Therefore, there is a dashed line arrow connecting complexity management practices and supply chain resilience. Since this link is not investigated in the extant literature, it represents a hypothesis that should be further assessed to cover the gap.

In conclusion, this study focuses on the direct link between supply chain complexity and resilience, as well as on the impact that complexity management practices have on supply chain resilience. First, structural and dynamic supply chain complexity affect the company's capability to prepare for, respond to e recover from unexpected disruptive events. Secondly, complexity management approaches and tools impact on it, both directly and indirectly: on the one hand, they increase resilience formative elements due to their nature, on the other hand, by modifying supply chain complexity, they in turn modify supply chain resilience too. For instance, if complexity positively influences resilience, the management practices reducing it have a hindering role in case of disruption, while accommodation approaches have a synergic role in the recovering.

3.4 Research questions

Drawing from the previously described framework, the main aim of the study is to further analyse the relationships among the key constructs, considering not only the direct link between complexity and resilience, but also investigating whether complexity management practices affect resilience formative elements. First, it seeks to better understand how complexity, both structural and dynamic, affects flexibility, visibility, velocity, collaboration and agility, as mainly theoretically analysed until now. In particular, from theoretical background a large gap concerning dynamic complexity emerges, while the static one requires deeper empirical studies supporting theoretic frameworks. Secondly, the research aims to demonstrate that some specific practices can be easily exploited by company in order to recover from disruption and return to normal operating performance. Leveraging on studies already supporting the relation between structural and dynamic complexity and management practices, the research wants to make a further step, linking approaches and tools to resilience. In this vein, three main research questions are defined to be qualitatively answered.

As aforementioned, the impact of structural supply chain complexity on resilience has been analysed by many authors, which investigated it considering either resilience constituents (e.g. Brandon-Jones et al., 2014; Cardoso et al., 2015; Falasca and Zobel, 2008; Skilton and Robinson, 2009), or resilience core functions (e.g. Hosseini et al., 2016; Mari et al., 2015). In general, despite the consensus that structural complexity drivers are enablers of supply chain resilience, the relations can be further investigated and deeper defined, through empirical evidence. Therefore, despite the extant theoretical background, the first research question aims at qualitatively analyse the way in which supply chain structural complexity affects resilience:

RQ1: How does supply chain structural complexity influence supply chain resilience?

Moving to dynamic complexity, few papers cover it, with regard to both resilience constituents and resilience functions, and a gap is still present. Moreover, literature covering dynamic complexity is mainly theoretical (Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Thome et al., 2016; Durach et al., 2015; Hosseini et al., 2016). Consequently, the second research question is:

RQ2: How does supply chain dynamic complexity influence supply chain resilience?

Finally, the third question focuses on the complexity management practices, which could play a dual role in terms of supply chain resilience. While complexity accommodation practices could be exploited by firms to recover from disruption and return to normal operating performance, complexity reduction practices could reduce resilience because they reduce complexity factors that are its enablers. However, lack of knowledge about it is evident in literature review. Therefore, the relationship among the two dimensions exist, but could be both synergic or hindering, thus the last research question aims at investigating it:

RQ3: How does the management of supply chain complexity influence supply chain resilience?

Considering the research framework set in Section 3.1, figure 3.2 shows the research questions in relation with the identified links between research key constructs. On the one hand, research question RQ1 aims at further analysing a link investigated in some studies (i.e. solid line arrow), by providing empirical evidence. On the other hand, RQ2 and RQ3's goal is to fill extant gaps present in the prior literature, hence defining the two dashed line arrows.

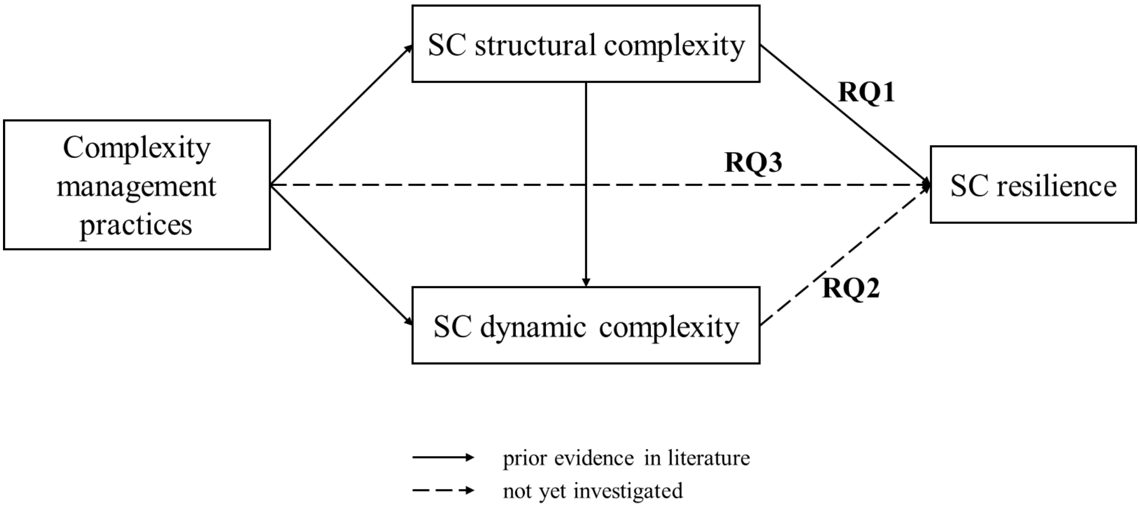

Figure 3.3: *Research framework and questions.*

As described in Chapter 4, the explorative study to answer the research questions is structured in two main phases. The first part is dedicated to the relationship between supply chain complexity and resilience, thus to the research questions RQ1 and RQ2, while the second one focuses on supply chain complexity management practices, analysing their direct link to supply chain resilience and answering to research question RQ3. Finally, the findings are unified and triangulated in a comprehensive framework linking all the key constructs.

Chapter 4
Study methodology

The chapter presents the methodology used to address the research questions. Since the study aims at investigating the interplay mechanisms between supply chain complexity, resilience and complexity management practices, the analysis is based on a qualitative approach. The research questions ask not only to understand what are the linkages between these dimensions, but also how, or in what way, they influence each other. Therefore, the study calls for a qualitative methodology adequate to address both "what" and "how" questions, examining the rules or processes that shape the relationships (Pratt, 2009; Benbasat et al., 1987). Indeed, qualitative data are useful to understand the rational underlying relationships (Eisenhardt, 1989). Furthermore, the limited extant knowledge about the issues under investigation, discussed in the literature review and theoretical background chapter, demands the adoption of an inductive and exploratory research approach, which is particularly appropriate for those problems in which research and theory are at their early, formative stages (Benbasat et al., 1987). The qualitative exploration, focusing on understanding, is preferable for new theory, while the explanation of quantitative findings and the construction of theory based on them need to be funded on qualitative understanding (Meredith, 1998). In this vein, the study's purpose is theory building, leaving space for future further developments in theory testing.

The study is articulated in two main phases, characterized by different research methods: on the one hand, the Critical Incident Technique (CIT; Flanagan, 1954; Chell, 1998), was used to investigate the relationship between supply chain complexity and resilience. On the other hand, four inductive case studies were used to analyse complexity management practices and their linkage with resilience constituents. Therefore, after a first section, illustrating the research main structure, the following discussion dedicates a section for each phase, illustrating and justifying the methodology, the unit of analysis, the data collection and analysis techniques employed, as well as the expected output and the respective answered questions. Finally, the chapter ends with a section describing the organisation of findings for the discussion. These are collected in a comprehensive matrix to match supply chain complexity management practices with resilience constituents, from which the answers to the research questions will be drawn.

4.1 Study main structure and approach

The research study structure is graphically summarised in the flowchart in Figure 4.1, which reports the four phases and the respective adopted methodologies, the expected outputs, and the respective answered research questions.

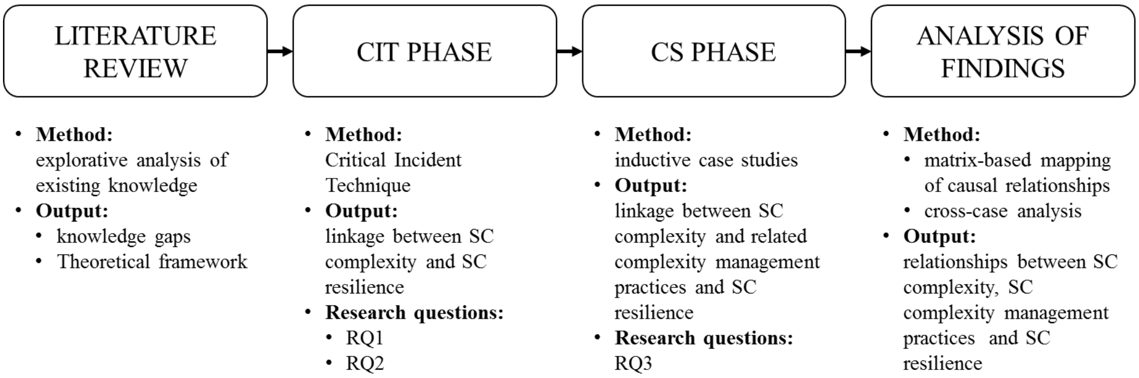

Figure 4.1: *Structure of the study.*

At the basis of the research study there is a brief explorative analysis with the aim of investigating the extant theoretical background, defining the context and identifying possible gaps in current knowledge. The literature review, discussed in Chapter 2, enabled the development of a broad understanding of complexity and resilience concepts in business organisations, as well as their relationship. Moreover, it was leveraged to build the research framework and set the research questions.

The overall study methodology is structured in two main phases. First, the CIT was used to disentangle the link between supply chain complexity drivers and resilience constituents. Analysing some cases of past disruptions and the way in which affected companies reacted, a matrix matching the two dimensions was set. Therefore, the empirical evidence demonstrates the relationship between the two, thus qualitatively answering to the first two research questions. Then, a second phase of analysis aimed at highlighting the links between supply chain complexity management practices and resilience constituents. Leveraging on four inductive case studies, management approaches and tools were clarified and their impact on resilience investigated, resulting in a matrix which matches practices and resilience constituents. Through this phase, the third research question is qualitatively answered.

The last step of the study consisted in a comprehensive analysis to merge the results of the previous phases. Drawing from the proved linkages between supply chain complexity and resilience and between the complexity management practices and resilience, a matrix crossing the three dimensions was finally set. In conclusion, it further theoretically investigates the three dimensions and the relationships between them, triangulating results of previous phases.

Figure 4.2 shows how the two different methodologies, i.e. Critical Incident Technique (CIT) and case study analysis (CS), were adopted to demonstrate different linkages between the key constructs of the research framework. While the former allows to demonstrate the relationship between supply chain complexity and resilience, the latter provide empirical evidence of the impact of complexity management practices on supply chain complexity and resilience.

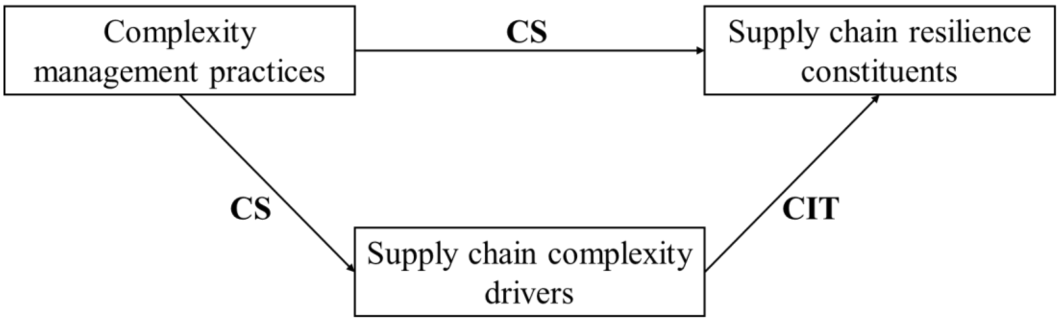

Figure 4.2: *Different methodologies adopted to investigate links between the key constructs.*

4.2 Critical Incident Technique (CIT)

The first phase of the study aims at investigating the direct relationship between supply chain complexity and resilience and answer to research questions RQ1 and RQ2. Although complexity can be a major impediment to performance, increasing for instance the frequency of disruptions (Bode and Wagner, 2015), there are studies that suggest that it could reveal a value-adding element, positively contributing to company performance. Furthermore, it represents an incentive to develop new practices and techniques and some studies have demonstrated that supply chain complexity drivers help effectiveness of resilience in mitigating disruption (e.g. Brandon-Jones et al., 2014; Cardoso et al., 2014; Falasca and Zobel, 2008; Skilton et al., 2009). However, despite the consensus that complexity drivers are enablers of supply chain resilience, the link between the two dimensions has been mainly theoretically sustained, thus the relation can be further investigated and empirical evidence is needed to demonstrate it. Particularly, from the theoretical background a large gap concerning dynamic complexity emerges, while the structural one requires deeper studies supporting theoretic frameworks.

The adopted methodology is Critical Incident Technique, analysing deviations and abnormal situations that can provide understanding about the behaviour and characteristics of supply chain systems (Dabhilkar et al., 2016). Since the aim of the first part of the study is to define reaction and performance of a company after an unexpected event, and since supply chain disruptions are considered as critical incidents, the approach is adequate. Indeed, it is particularly suitable for retrospective investigations of unusual disruptive circumstances, typical of supply chain risk and resilience studies (e.g. Craighead et al., 2007). A critical incident is characterised not only by the description of the specific event and the reason why it is considered critical (i.e. particularly interesting), as well as the environment and time in which it occurred, but also by a report of actions and behaviours associated to the event and the implications and outcomes differing from the expected routinely ones (Birkie, 2017). Investigating them, it is possible to identify the role that complexity drivers play with respect to resilience.

The analysed sample includes 16 multinational companies characterised by a complex supply chain and recently impacted by different supply chain disruptions, including environmental events, such as earthquakes or floods, destroying incidents, such as fires, chemical contaminations of materials, faulty products distribution, social media attacks etc. Data collection was stopped after the investigation of 16 incidents due to the absence of more significant nuances regarding the influence of supply chain complexity drivers on resilience. Furthermore, the considered sample is heterogeneous not only for what concerns the kind of disruption, but also in the different industries considered and the different severity of the consequences. As a matter of fact, disruption scenarios are classified in three different types: type I, II or III (Birkie, 2016). The first one is the less severe: it includes incidents damaging only few products or inputs, causing short delays in logistics or internal operations and being fairly predictable, allowing some time to preparation. Disruptions of type II cause inoperability of facilities without major damage to assets, destruction of utility assets such as communication infrastructures or power lines, damage to multiple products or inputs without processes being affected, extended delays. Moreover, they are little predictable, allowing little preparation time. Finally, type III category includes the most severe events, which destruct company's own assets or key components suppliers, affect multiple suppliers, competitors or customers, or damage people's health and well-being. They are highly unpredictable disruptions, with unexpected characteristics, and their impact is deep since multiple tiers in the supply chain are affected.

Table 4.1 summarizes the selected critical incidents, with the respective characteristics in terms of industry, incident description, time of incident and disruption type. Furthermore, each case is identified with a number.

Table 4.3: *Critical incidents' characteristics.*

Case number	Company	Industry	Incident	Time of incident	Disruption type
1	Takata Corporation	Automotive	Recall of cars due to faulty airbags following deaths in US	April 2013, until today	III
2	Dell Inc.	Computer technology	US west coast lock out due to longshoremen strike	December 2002	II

(continue)

Case number	Company	Industry	Incident	Time of incident	Disruption type
3	Evonik Industries	Chemical	Fire at German plant, affecting supply of CDT for global automakers	March 2012	III
4	Boeing	Airplanes	Potential parts delay due to Japan earthquake	March 2011	I
5	Sanofi Genzyme	Pharmaceutical, biotechnology	Virus contamination of 3 drugs at a plant in Massachusetts	June 2009	III
6	Mitsubishi Motors Corporation	Automotive	Damage at local part suppliers, due to Thailand flood	October 2011	II
7	Nestle S.A.	Food and drink	Social media attack on KitKat, due to unsustainable forest clearing in production of palm oil	March 2010	II
8	SK Hynix Inc.	Semiconductor (Electronics)	Fire in a plant in China	September 2013	III
9	PSA Peugeot Citroën	Automotive	Air flow sensor and other parts shortage due to Japan earthquake	March 2011	I
10	Mattel Inc.	Toy manufacturing	Unauthorized second-tier supplier using the lead-based paint exceeding limits for the production of a specific toy	August 2007	I
11	Honda Motor Co. Ltd.	Automotive	Production disruption due to Thailand flood	October 2011	III
12	Sapporo Group	Alcoholic beverage, food and soft drinks	Facilities damages due to Japan earthquake	March 2011	III

(continue)

Case number	Company	Industry	Incident	Time of incident	Disruption type
13	Goodyear Tire and Rubber Company	Tire manufacturing	Facilities damages due to Thailand flood	October 2011	III
14	Procter and Gamble Co.	Consumer goods	Coffee flooding due to hurricane Katrina	August 2005	III
15	Johnson & Johnson	Personal and health care	Quality and safety violations	April, May 2010	III
16	Volkswagen Group	Automotive	Diesel issue: scandals relating to the emissions from diesel engines	September 2015	I

The unit of analysis was the manufacturing firm's internal supply chain, consisting of those logistical and informational elements bounded by the market demand at one end, and by specific product/service delivery at the customer site at the other end (Stewart, 1995). Consequently, it includes planning, sourcing, making and delivering activities (Hoole, 2005). Encompassing the whole internal supply chain, the perspective is more comprehensive than earlier works (e.g. Bozarth et al., 2009), which have focused solely on, for example, manufacturing or logistics. Furthermore, the analysis considered supply- and customer-base complexity drivers too, although from the perspective of the case company. Nevertheless, adopting this unit of analysis limits the study to the management of complexity and its impact on supply chain resilience at the level of the single organisation, and not of the chain or network, despite considering collaboration with upstream and downstream supply chain actors among resilience constituents.

Even though Critical Incident Technique is a "set of procedures for collecting direct observations of human behaviour", directly interviewing involved people and observing human activities (Flanagan, 1954), in this study it was developed through secondary data collection and analysis. Data and information were collected from corporate websites, annual reports and corporate presentations, as well as from newspapers' websites for what concerns incidents chronicles. Where possible, leveraging on multiple sources enables to strengthen data reliability.

Data analysis process was supported by a MS Excel file, reporting the key information. For each investigated company, after a generic background setting, the supply chain complexity was described first, discussed through the set of static and dynamic drivers. The formers are *portfolio breadth*, *product variety and specificities*, *variety of/interaction between teams and functions*, *number and layers of supply chain facilities*, *differences between facilities in different territories*, *number/variety of partners and suppliers*, and *variety and breadth of customer requirements*, while the latter ones are *product introduction and lifecycle events*, *reconfiguration of supply chain activities and facilities*, *improvements to equipment, procedures and systems*, *restructuring and M&A*, *internal operational dynamics*, *demand/supply sides operational dynamics*, and *new customers or suppliers*. Since *variety of/interaction between teams and functions* and *internal operational dynamics* could not be well documented through secondary data due to the scarce disclosure of companies about them, they were out of scope and thus they were removed from the analysis. Then, investigating collected information about the past incident affecting the company and the way in which it reacted, the role that complexity played in the event was defined, distinguishing positive or negative influence on supply chain resilience constituents (i.e. flexibility, visibility, velocity and collaboration). In some cases, available information was not enough to assess the impact and consequently the presence of a link could not be excluded. Therefore, in each incident case for each supply chain complexity drivers four different alternatives were possible: positive role, negative role, no role, no evidence to assess the role. The linkages between complexity drivers and resilience constituents were demonstrated by empirical evidence and a final table matching the two dimensions was set, and companies were mapped in it, together with the kind of link. Drawing from it, the first two research questions can be qualitatively answered, as the relationship between supply chain complexity and resilience is demonstrated.

4.3 Inductive case studies

After having investigated the direct relationship between supply chain complexity and resilience, the second phase of the study focuses on defining the link between supply chain complexity management practices and resilience constituents. In order to manage structural and dynamic complexity and mitigate their negative impact on performances, companies develop specific management approaches and tools, which could either increase or decrease supply chain resilience. Complexity reduction practices are expected to have a hindering role when they physically reduce the amount of complexity that plays a positive role in terms of resilience, while a synergic role if they manage complexity drivers that reduce resilience. On the contrary, considering accommodation approaches and tools, which mitigate the negative effects of complexity on performance, they could be leveraged by companies to recover from disruption and return to normal operating performance.

The adopted methodology for the second phase is inductive case study, an empirical research approach that uses contextually rich data from bounded real-world settings to investigate a focused phenomenon (Barrat et al., 2011). Differently from deductive case study, employed for theory-testing purpose, inductive case study aims at understanding as fully as possible the investigated situation, building theories to fill the extant gap in literature (Meredith, 1998). Indeed, qualitative case study considers soft aspects which quantitative research cannot, thus allowing for a detailed exploration of the field in the development of new theory (Eisenhardt, 1989). Therefore, enabling exploratory and explanatory research about not well understood phenomena or unknown aspects, this tool is coherent with the goal of the study. Since case studies are more suitable for the exploration, classification and hypothesis development stages of the knowledge building process, the investigator should have a receptive attitude towards exploration, collecting data by multiple means and examining different entities (i.e. people, groups or organisations). Moreover, phenomena are examined in their natural setting, considering contemporary events and without any experimental control or manipulation, hence the method is appropriate to gain a rich understanding of them, qualitatively addressing why, what and how questions (Benbasat et al., 1987).

The adopted sample consists of four in-depth cases. This size is an adequate balance between the need to capture a rich representation of the investigated phenomena, providing external validity and reducing observer bias, gained from employing multiple cases, and the capability to manage the collected data and to deepen the observation, thanks to the reduced number of cases (Eisenhardt, 1989; Voss et al., 2002). Even though multiple cases sampling is recommended for theory building case study research, as it facilitates the creation of testable and more robust theory, the use of it can raise a challenge for researches to cognitively process the collected information. Eisenhardt (1989) suggests that a number of cases between four and ten can set an adequate balance between depth and breadth of observation.

Case studies were selected through convenience sampling (Barrat et al., 2011), leveraging on the same sample analysed by Fernandez Campos (2018) in his study on supply chain complexity. Despite the importance of adopting rigorous sampling criteria, many studies appear to use samples of convenience (Meredith, 1998). Furthermore, the four focused cases are characterised by different contexts and complexity features, increasing the validity of conclusions. The sample incorporates differing positions within the supply chain, operations models and industries, as reported in Table 4.2, which presents the key characteristics of the four case companies: industry, number of employees, revenue, supply chain position and operations model (MTS = make to stock, MTO = make to order, ETO = engineering to order). They are all large global organisations (i.e. global footprint and operations), because these are more likely to experience higher complexity in several areas (e.g. internal network of facilities, geographical product variants, different forms of regulations, international suppliers and customers, etc.) (Fernandez Campos, 2018).

Table 4.4: *Case companies' characteristics.*

Characteristic	Percomp	Auto	Drinks	Defence
Industry	Personal Computers	Automobile	Drinks/Spirits	Defence Electronics
No. employees	50,000	1,500	4,000	45,000
Revenue (M€)	42,000	200	1,500	12,000
SC position	Focal company	First tier supplier	Focal company	Various (on a project basis)
Operations model	MTS	MTS	MTS	ETO/MTO

The unit of analysis was the manufacturing firm's internal supply chain, like for the Critical Incident Technique, including planning, sourcing, making and delivering activities (Hoole, 2005). Also in this phase, the analysis considered supply- and customer-base complexity drivers too, even though from the perspective of the case company. As aforementioned, the internal supply chain perspective is more comprehensive than previous studies, but it is still limited at the level of the single organisation, and does not consider a cross-functional point of view.

To further enhance the reliability of the study, structured data collection and analysis processes were adopted (Fernandez Campos, 2018). Data were collected from multiple sources: semi-structured interviews, company documents and archival sources, and informant's notes during and prior to the interview, as well as secondary data from corporate website, financial reports, corporate presentations, etc. In this way, data reliability and study's internal validity was strengthened, through triangulation (Benbasat et al., 1987). However, interviews to key informants constituted the primary source.

Interviewed key informants were selected from different areas within the internal supply chain and covering a variety of roles at different levels (e.g. purchasing director, supply chain chief of staff, plant manager). Table 4.3 reports the respondents' role for each case study.

Table 4.5: *Case study respondents.*

Case study	Respondent's role
Percomp	Chief of Staff and planning architect
	Planning and planning platform manager
	Supply Chain program and project manager
Auto	Purchasing director
	Sales director
	Engineering director
	Logistics manager
	Plant general manager deputy
	Purchasing manager
Drinks	Supply Chain director
	Planning manager
	Supply Chain master data manager
	Innovation project manager
Defence	Supply Chain director
	Head of procurement
	Head of Supply Chain and manufacturing

After a first preparatory interview to set case's background, a focused interview was held with each respondent. The duration of these interviews were not less than 60 minutes and approximately 75 minutes on average. In order to update the protocol basing on emerging data, a semi-structured protocol was adopted (Fernandez Campos, 2018). In addition, follow-up interviews were conducted where appropriate, e.g. to gather further information on an emergent issue related to the role of an already interviewed respondent. Respondents were typically emailed the questionnaire approximately three days before the interview, to increase respondents' familiarity with the scope of the study. When necessary, clarifications on the questions were provided prior to the interview.

The protocol consists of about six to eight broad questions, with detailed questions arising during the interview. It is structured in five main areas:

- first, a description of informant's key activities and responsibilities, setting the specific context;
- key issues contributing to supply chain complexity, from both static and dynamic perspective. Particularly, two lists of structural and dynamic drivers are presented as practical examples, aiding interviewers to identify relevant aspects despite the little time for thought available in a live interview. Moreover, they help informants to understand the distinction between the two categories;
- impact of previously identified complexity drivers on supply chain performance (i.e. cost, quality, speed and flexibility), considering both positive and negative effects;
- practices leveraged to manage, cope and mitigate the highlighted complexity factors. However, in many interviews, these approaches and tools are discussed together with respective complexity drivers, in the second area;
- finally, a short section to increase the robustness and add some detail to the collected information.

An example of an adopted interview protocol is provided in Appendix A.

Drawing from it, key information was recorded into a MS Excel file, setting the basis for the subsequent analysis. For each case study, after a brief review of the background, structural and dynamic complexity characterising the company was discussed first, defined through the aforementioned complexity drivers (i.e. *portfolio breadth*, *product variety and specificities*, *variety of/interaction between teams and functions*, *number and layers of supply chain facilities*, *differences between facilities in different territories*, *number/variety of partners and suppliers*, *variety and breadth of customer requirements*, *product introduction and lifecycle events*, *reconfiguration of supply chain activities and facilities*, *improvements to equipment*, *procedures and systems*, *restructuring and M&A*, *internal operational dynamics*, *demand/supply sides operational dynamics*, and *new customers or suppliers*), leveraging Fernandez Campos' study (2018) about supply chain complexity as framework. As a matter of fact, within case analyses by this author, available in Appendix B, represented the starting point and provided a body of knowledge that, gone through with a different point of view, was the framework for the study. Similarly, adopted complexity management practices were defined, classified in the four clusters: variety reducing, confinement and decoupling, coordination and collaboration, and decision support and knowledge generation. These include both complexity reduction and accommodation approaches. Their linkages with complexity drivers were highlighted (Fernandez Campos, 2018), and their general impact on resilience constituents (i.e. flexibility, visibility, velocity and collaboration) was defined. In conclusion, the result is a matrix which matches practices and resilience constituents, thus answering to the third research question.

4.4 Findings analysis and discussion

The last step of the study consists in a comprehensive discussion of the results emerging from the previous analyses, collected in a summary matrix of findings matching supply chain complexity management practices and resilience constituents.

The summary table was set on the basis of three main relationships. First, as proved through the Critical Incident Technique, static and dynamic complexity drivers affect resilience constituents, increasing or decreasing companies' capabilities to face a disruption event. Secondly, in order to manage and mitigate complexity, companies develop specific management approaches and tools, thus specific practices can be linked to certain complexity drivers (Fernandez Campos, 2018). Finally, complexity management practices play a synergic or hindering role in terms of resilience, increasing or decreasing flexibility, visibility, velocity and collaboration, as it emerges from the four case studies. These three linkages are represented in Figure 4.2, which provides a visual understanding of the triangulation adopted for the final discussion. Drawing from it, the findings matrix unifies the direct link between complexity management practices and resilience constituents, and the indirect one, which leverages the interplay of complexity drivers. As a matter of fact, results from the two analyses were triangulated, in order to increase consistency of the relationships, and consequently the robustness of study results (Benbasat et al., 1987).

In this vein, the summary matrix presents complexity management practices on the rows and resilience constituents on the columns, and in each cell the complexity drivers linking the two dimensions are reported. To fill it, first, the respectively managed complexity drivers were identified for each practice, through the four cases analysis, supported by Fernandez Campos' study (2018). Then, evidence from Critical Incident Technique enabled to list for each resilience constituent the impacting complexity drivers. In this way, the indirect link between management practices and resilience was defined (i.e. the path below in Figure 4.2). Secondly, leveraging on case studies' results, the direct relationship between the two dimensions was proved (i.e. the path above in Figure 4.2). Matching these two information, the final table reports the linkages between complexity management practices and resilience constituents that are doubly supported by results triangulation, indicating in the respective cell the complexity drivers involved in the indirect link.

Figure 4.3 reports the template of the final summary matrix used to merge the findings obtained in the two distinct phases.

			Resilience constituents							
			Flexibility		Visibility		Velocity		Collaboration	
			+	-	+	-	+	-	+	-
Complexity management practices	**Variety reducing**	Accessory-based customisation								
		Product platforms								
		…								
	Confinement and decoupling	Outsourcing								
		Customised distribution channels								
		…								
	Coordination and collaboration	Decentralisation of procurement								
		Global SC forums								
		…								
	Decision support and knowledge generation	Forward-looking forecasting								
		Cellular manufacturing								
		…								

Figure 4.3: *Summary matrix of findings.*

Despite its comprehensiveness, this representation risks to turn out too much fragmented, hindering an in-depth understanding of the phenomena. Therefore, the following discussion focuses on few relevant complexity management practices only, selected considering their number of links, either positive or negative, with different resilience constituents. Indeed, a higher number of relationships tacked in the summary matrix points out a richer and more reliable evidence base, as they are consistently proved by triangulating different findings. This pruning approach is coherent with the overall qualitative approach adopted in the study, based on inductive exploration and hypothesis development to support a research in its early formative stages (Benbasat et al., 1987).

In conclusion, the analysis of findings and the consequent discussion allow to further strengthen the answer to the third research question, about the relationship between supply chain complexity management and supply chain resilience.

The next two chapters offers a description of the Critical Incident Technique and the inductive case studies analysis respectively. Then, in Chapter 7, findings are merged, analysed and discussed.

Chapter 5
Influence of complexity on resilience under disruption: a critical incident study

Chapter 5 describes the application of the Critical Incident Technique to analyse the influence of supply chain complexity drivers on resilience constituents in case of disruption, answering the first two research questions. As detailed in the methodology presentation (Chapter 4), the considered sample includes 16 multinational companies recently impacted by different unexpected incidents, such as environmental events or social media attacks. For each one, the supply chain complexity is described through the set of static and dynamic complexity drivers, and the role that they played with regard to resilience constituents under disruption is identified investigating the employed countermeasures, distinguishing between positive role, negative role, no role, and no evidence to assess the role. Finally, a matrix matching complexity drivers and resilience constituents is set, and companies are mapped in it to empirically prove the relationships between the two dimensions.

In the next sections, for each critical incident there is a short description of the company (industry and products, geography and foundation, sales, operating income and number of employees, vision), a table providing definition of static and dynamic supply chain complexity drivers characterizing it, a short description of the incident and the company's reaction, and, finally, the identification of the role that each complexity driver had in the incident response, with the impact on supply chain resilience constituents. Then, overall results are collected and commented in the last section of the chapter.

5.1 Takata Corporation

Takata Corporation is a specialized supplier of automotive parts, providing automobile safety components such as seat belts, airbags and child restraint systems. The company employs 50,400 employees and its yearly sales in 2016 amounted to about 5,973 million €, with an operating income of 350 million €. Based in Japan, Takata has production facilities on three continents, having plants and R&D facilities all around the world. It was founded in 1933 as textile company and later in 1950s evolved in the safety components field, driven by its dedication to save human life and embracing a pioneering spirit in developing innovative products. Takata's core mission is to provide superlative quality and services to achieve total customer satisfaction.

The most important structural and dynamic complexity drivers characterizing the company are summarized in Table 5.1.

Table 5.1: *Takata's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth The company has 8 segments: seat belts, airbags, steering wheel systems, other safety systems, electronics, textile products, child restraint systems and motors sports. ➢ Strict product specificities Safety systems are characterized by high specificities, thus verifying new designs is time-consuming and costly. Airbags are built into a car's design and cannot simply be replaced.
Internal structural complexity	➢ High number of supply chain facilities The company is present in 4 continents with many facilities: 20 production plants in Asia, 20 in America and 17 in Europe and 5 R&D facilities in Asia, 7 in America and 5 in Europe. Exchanging of parts and semi-finished goods between manufacturing plants ensures not dependency on a specific plant. ➢ First supply chain layers Takata is a business to business parts supplier at the first tiers in the automotive industry supply chain, not having a direct link to the final consumers. ➢ Not many differences between facilities in different territories Takata Production System was introduced in Japan, but with the aim to extend it to other facilities around the world in the future.
External structural complexity	➢ Limited number of suppliers Takata enhances in-house production, thus being vertically integrated and having a low number of suppliers. ➢ Medium variety of suppliers The supply system is global, but the company collaborate with local suppliers too, to develop quality products. The supply chain is streamlined. ➢ Low number of main customers Among others, Takata has 5 top customers: Honda, Ford, General Motors, Renault-Nissan and Fiat Chrysler. Moreover, there is balance between global and local customers.
Product dynamic complexity	➢ High product development As technology continues to evolve, Takata continuously pursues the development of safety technology and the design of new products, from airbag textiles to hazard detection control units and inflator technology. The company has commercialized innovative products such as the D-shape curtain airbags, which protects the head and help to prevent passenger ejection, or the far-side airbag that inflates between the left and right seats in case of side collision.
Internal dynamic complexity	➢ Reconfiguration of SC activities and facilities Pursuing further cost reduction, the company constantly reviews business and manufacturing processes, network and distribution systems to align operations with markets and ensure optimal performance. ➢ Improvement to procedures and systems Takata Production System project was launched in 2015 in Japan to achieve development of a model that continues to support JIT activities and instil a corporate culture of continual improvement.

(continue)

Internal dynamic complexity	➢	Restructuring and M&A The company actively examines opportunities for M&A and organically grows through setting up its own manufacturing and sales subsidiaries and integrating important acquisitions.
External dynamic complexity	➢	Supply side dynamics Takata is continuously developing its global supply system.
	➢	Demand side dynamics Market trend in different regions may have significant impact on performance due to changes in customer order volumes and product prices.
	➢	New customers The company is focusing on developing sales to new sales destinations in order to reduce reliance on specific customers.

Starting from April 2013, the company have recalled about 70 million cars due to faulty airbags following a series of deaths and injuries. Takata admitted their Mexican subsidiary had mishandled the manufacture of explosive propellants and improperly stored chemicals used in airbags. Therefore, auto manufacturers recalled vehicles since airbags could rupture and send flying debris inside the vehicle. Initially, only six brands were involved when Takata announced the fault, but along with new admissions from the company, more brands resulted affected. Even though the New York Times published a report suggesting that Takata knew about the airbag issues in 2004, conducting secret tests to verify the problem, the company declared the article was fundamentally inaccurate. Defective Takata airbags caused 18 victims and more than 180 injured and the recall is considered the largest of the history. The company invested significant resources to maximize recall completion rates, including launching a targeted digital advertising campaign in the USA. The event finally leaded Takata to filing for bankruptcy in June 2017.

Some of the supply chain complexity drivers previously listed played an important role in the incident, determining resilience constituents. First, severe product specificities forced carmakers to not change airbags supplier, since verifying safety of new airbag design is time-consuming and costly, requiring a high effort in case of substitution of Takata. Therefore, product technical requirements enforced the attachment to the supplier, a first element determining collaboration with automakers. Moreover, due to the low number of top customers, Takata had established deep partnerships in the past, thus it could leverage carmakers' collaboration in facing the event. In partnership with them, it investigated and analysed the cause of the problem, through collaborative testing, and they worked together to ensure stable ongoing supply of Takata's products. Furthermore, customers did not abandon the company, especially Japanese ones, which traditionally have stronger ties to their suppliers. It means that customer side complexity negatively affected resilience in terms of collaboration and visibility, because a limited range of customers determined deeper partnerships.

On the contrary, a complex internal supply chain increased the resilience. The high number of supply chain facilities and their similarity allowed to ramp up production of replacement kits. Since different plants could exchange parts and thus production was not dependent on a specific facility, increasing line capacity in Mexico, Germany, USA and China the company could manage the additional production volume required by the replacement of recalled vehicles' airbags. This enhanced the flexibility of the company, but also the collaboration among different facilities. Considering the layers constituting the automotive industry supply chain, Takata is positioned at the first tiers, thus its supply chain is streamlined and simple. This negatively contributed to visibility during the incident: being a business to business part suppliers, the company was less sophisticated in communicating to retail consumers, determining lack of communication during the whole event.

For what concerns dynamic complexity drivers, the company's continuous focus on development of safety technology facilitated a faster and deeper research on root causes of the problem. Moreover, since Takata was used to constantly review business and manufacturing processes, network and distribution systems, it was easier to ramp up production of replacement kits. Therefore, these internal dynamic complexity drivers positively affected velocity in the considered event. Finally, continuously and actively examining opportunities for mergers and acquisitions, the company had a higher visibility on other companies producing inflators, thus it could implement supply agreements with competitors to achieve the fastest possible completion of airbag replacements.

Table 5.2: *Influence of complexity drivers on resilience constituents in Takata's case.*

Complexity drivers	**Flexibility**	**Visibility**	**Velocity**	**Collaboration**
Product specificities				+
Number and layers of supply chain	+	+		+
Differences between facilities	-			-
Variety of customer requirements		-		-
Product introduction			+	
Supply chain reconfiguration	+		+	
M&A		+		+

5.2 Dell Inc.

Dell Inc. is a multinational computer technology company, manufacturing, selling and repairing personal computers, servers, data storage devices, computer software and many other electronics. It is based in USA and has yearly sales of about 49,600 million € (2016). It employs 101,800 people in different locations worldwide. Founded in 1984, it merged with EMC Corporation in 2016, to form Dell Technologies, marking the completion of the biggest tech deal in history. Dell Inc. is committed to delivering products, solutions and services to drive customers' business goals and suit their lifestyles. It is well known for its innovations in supply chain management and e-commerce, particularly for the customized individual PCs, configured to customer specifications.

The main characteristics determining Dell's supply chain complexity are in Table 5.3.

Table 5.3: *Dell's supply chain complexity drivers.*

Product structural complexity	➢ Wide portfolio range The company has 8 lines: servers, storage, networking products, workstations, notebook computers, desktop computer systems, software and peripheral products, and services. ➢ High product variety Dell is characterised by a MTO strategy, customizing products and offering tailored solution for companies through the Customer Solution Centres. Customer experience is based on customer needs and solutions are configured on customer specifications.
Internal structural complexity	➢ Worldwide presence Dell operates worldwide, having 6 different manufacturing locations. Its supply chain is characterized by the absence of warehouses. In fact, JIT production and make-to-order approach determine a no-stock policy. ➢ Differences between facilities in different territories USA and India are the only countries that have all Dell's business functions and provide support globally: research and development, manufacturing, finance, analysis, and customer care.
External structural complexity	➢ Limited number of suppliers In 2008 Dell had 53 manufacturing suppliers, all tightly integrated with the company due to the no-stock policy (JIT production). It partners with top industry technology suppliers and original development manufacturers. ➢ Global and various customer base Dell has a global customer based, serving both corporate businesses and home customers. Its products are featured in more than 60,000 retail locations around the world. Despite the many customers, the make-to-order strategy pushes close partnerships and tight connections.
Product dynamic complexity	➢ High product development Dell invests a lot in new product development and introduction.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities The company spent more than 3 billion $ annually for the last four years with diverse businesses to empower sustainable growth and innovate the supply chain. ➢ Improvements to procedures and systems Dell is characterized by continuous improvement of procurement, manufacturing and distribution processes, acquisition of new skills and capabilities and reorganisation of operations. ➢ Restructuring and M&A The company continuously acquires outstanding companies with expertise in new areas in which it wants to expand.
External dynamic complexity	➢ Supply side dynamics Dell invests in supplier development to empower sustainable growth in the supply chain.

In December 2002, a 10-days labour lockout involved 10,000 union dockworkers, shut down 29 US west coast ports and blocked hundreds of cargo ships from unloading raw materials and finished goods. Even though the longshoremen strike paralyzed global supply chains, Dell successfully recovered and adapted, leveraging its timely reaction as competitive advantage. Despite of the no-stock policy characterizing the JIT model of the company, Dell reacted quickly, fully conscious that it could not tolerate any kind of delay. It chartered plane before other companies came to realize this option and it sent teams of logistics specialists on sites to assemble a contingency plan. Moreover, it constantly communicated and collaborated with its partners and Asia-based suppliers. Therefore, Dell Inc. turned the incident into an opportunity to impress customers and win their loyalty, not delaying any customer order.

Together with other actions, Dell’s supply chain complexity features contributed to resiliently answer to the disruption. The low number of suppliers allowed a constant, round-the-clock communication with parts makers in Taiwan, China, and Malaysia, and with US-based shipping partners, who had alerted the company to the possibility of a lockout some six months before it occurred. Furthermore, the tight integration with Asia-based suppliers enabled to work together to ensure that parts were always at the Shanghai and Taipei airports in time for the returning charters to land, reload, refuel, and take off. Therefore, the low complexity determined by the stable panel of suppliers positively affected both visibility and collaboration.

Secondly, the wide breadth of customer requirements, reflected in the high product variety too, increased Dell flexibility: offering different configurations of products to answer to the labour lockout did not represent a problem for the company, which was used to customize products and tailor solutions.

The continuous reconfiguration of supply chain activities and facilities enabled the company to detect the event, as well as be flexible and timely react to the incident, accordingly changing transportation mode. As a matter of fact, Dell chartered 18 planes to cover the lack of cargo ships, even before other companies came to realize this option and the bidding for the planes grew fierce. Since the continuous improvement of procurement, manufacturing and distribution processes allowed a continuous visibility on the supply chain, the company rapidly detected the disruption and could flexibly identify an alternative transportation channel.

Finally, investing in suppliers’ development to empower sustainable growth in the supply chain, Dell had established strong relationships, increasing not only collaboration, but also flexibility in deliveries.

Table 5.4: *Influence of complexity drivers on resilience constituents in Dell's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Product variety	+			
Number of suppliers		-		-
Breadth of customer requirements	+			
Supply chain reconfiguration	+	+	+	
Procedures and systems improvements	+	+	+	
Supply side dynamics	+			+

5.3 Evonik Industries

Evonik Industries is a world's leading specialty chemicals industrial corporation. In 2016 Evonik employed about 35,000 employees, generating revenues of 12,700 million € and an operating income of 2,170 million €. It is headquartered in Germany, but has production plants in 25 different countries and carries on activities in all continents. Even though Evonik Industries was established in 2007, the businesses united under this group have historic roots, dated back to the first half of the 19th century. The company's strategy for sustained value creation is based on profitable growth, efficiency and values. Moreover, it leverages on high-growth megatrends, such as nutrition, health and resource efficiency.

Evonik's supply chain can be described by the following complexity drivers, both static and dynamic (Table 5.5).

Table 5.5: *Evonik Industries' supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth The company covers 4 segments: nutrition and care (7 business lines, 20 products), resource efficiency (9 business lines, 42 products), performance materials (business lines, 20 products) and services – technology and infrastructure (5 business lines). ➢ High product variety Given the industry in which it operates, Evonik has to take into account many different regional specificities, increasing the product variety. Moreover, it tailors products answering to customers' requests, continuously evolving due to the increasing health and sustainability awareness.
Internal structural complexity	➢ Worldwide presence Evonik has production plants in 25 different countries and activities in more than 100, doing business all around the world. It has integrated world-scale production facilities where it produces key precursors for its operations in neighbouring production facilities, offering to customers the maximum reliability of supply. ➢ Differences between different facilities Different chemical manufacturing segments operate close to markets and have a high degree of entrepreneurial independence, determining a decentralized corporate structure.
External structural complexity	➢ High number of suppliers To face the unforeseeable production outages due to the volatile procurement markets, Evonik secures supply to its sites both through a close cooperation with affected suppliers and by drawing on alternative suppliers. On the one hand, it relies on close collaboration and networking with external partners, on the other hand, it adopts a multi-sourcing strategy in order to secure availability of raw materials. In total Evonik has around 31,000 suppliers.

(continue)

External structural complexity	➢ High variety of customers Most of customers are industrial companies: food, animal feed, consumer and personal care products, automotive, construction … Customer concentration is basically low, none of the end-markets accounts for more than 20% of sales. However, some operational units have a certain dependence on key customers. ➢ High breadth of customer requirements Evonik's products are tailored to customers' specifications, thanks to a close cooperation. Moreover, usually customers rely on a single supplier and sometimes on a single plant.
Product dynamic complexity	➢ Strong innovation culture – new products introduction Evonik invests a lot to gain access to new products and applications and enter attractive future markets, filing of new patent applications. In 2016 innovation pipeline comprised a balanced mixture of well over 500 projects addressing completely new business options as well as enhancing the prospects of existing ones. The product portfolio is improved with acquisitions in new businesses too.
Internal dynamic complexity	➢ Strong innovation culture – supply chain reconfiguration The company invests in construction of new production facilities and global projects to improve capacity, continuously growing and internationally expanding. ➢ Improvements to equipment, procedures and systems Evonik continuously improve cost position through optimisation programs. Moreover, it exploits opportunities for new business models, new supply chain concepts, new channels and digitalisation. ➢ Restructuring and M&A The company makes acquisition in new businesses in order to improve the actual product portfolio, with international scope.
External dynamic complexity	➢ Supply side dynamics Evonik aims at extending strategic relationships with suppliers. ➢ Demand side dynamics Customer requirements in this industry are highly influenced by some megatrends: population growth, globalisation, and health and sustainability awareness. ➢ New suppliers and partners The company is systematically validating new suppliers and expanding network of specialized partners, to leverage external know-how.

In March 2012, a fire at a Evonik's plant in Germany seriously affected the supply of CDT for global automakers. CDT is a chemical component that serves as starting material in plastics manufacturing and it is used to produce nylon 12, qualified for automobile fuel handling system and brake lines. Other major industries of application are the sporting-goods and household-goods. At the incident time, Evonik covered a significant portion of global production capacity, satisfying about 50% of global demand. The fire started from an explosion caused by a damage due to an over-dosage of a catalyst and two employees lost their lives in the blaze. An extensive work to repair the damage caused by the fire allowed Evonik to start operating again after less than 10 months and gradually re-establishing the full product portfolio. Moreover, an independent institute was engaged to establish additional safety measures for the restore plant, in order to rule out reoccurrence of the incident.

A complexity driver that significantly contributed to face the incident was the high product variety. Evonik prove its flexibility by offering its customers various substitutes with comparable technical properties and similar processability. This was strengthened by the collaboration with its customers: since they were deeply involved in partnerships, due to their tailored breadth of requirements, they contributed to find the right substitutes. Also, it was facilitated by the fact that Evonik was used to flexibly introduce new products and applications due to its strong innovation culture.

Finally, the company's supply chain structure did not positively contribute to the resilience. The differences between production plants and their entrepreneurial independence did not allow to ramp up the production in other facilities or facilitate collaboration among them, causing a stoppage in the involved industries, since polyamide was available in smaller volumes.

Table 5.6: *Influence of complexity drivers on resilience constituents in Evonik Industries' case.*

Complexity drivers	**Flexibility**	**Visibility**	**Velocity**	**Collaboration**
Product variety	+			
Differences between facilities	-			-
Breadth of customer requirements	+			+
Product introduction	+			

5.4 Boeing

Boeing is the world's largest aerospace company, employing more than 150,000 people and having annual sales of about 85 million €, with an operating income of 5,270 million €. Headquartered in Chicago, USA, it is globally present, with locations all over the world, in more than 65 countries. Boeing products and tailored services include commercial and military aircraft, satellites, weapons, electronic and defence systems, launch systems, advanced information and communication systems, and performance-based logistics and training. Since its foundation in 1916, talented Boeing employees helped build a leading manufacturer in aerospace industry, meeting challenges and inspiring the world through innovation.

Table 5.7 collects the static and dynamic complexity drivers characterizing Boeing's supply chain.

__Table 5.7:__ Boeing's supply chain complexity drivers.

Product structural complexity	➢ High portfolio breadth The company covers 4 segments: commercial (divided in 6 families), defence, space and security, and global services (commercial and government). ➢ High product variety Boeing offers tailored solutions to meet specific needs by integrating services across the wide portfolio.
Internal structural complexity	➢ Worldwide presence Boeing has a global supply chain, operating in more than 65 countries (e.g. Boeing Commercial Airplanes has operations in more than a dozen cities and countries). Moreover, the company has 11 R&D centres, 16 consortia and 22 joint research centres. ➢ Differences between facilities in different territories In each country, the company has to be compliant with a variety of international laws, as well as US laws affecting the activities of US companies abroad. Therefore, facilities in different territories can present different activities.
External structural complexity	➢ High number of different suppliers Boeing has an extensive global supply chain, with more than 20,000 suppliers and partners worldwide, many in Japan. For instance, Boeing 737 alone relies on 367,000 parts from around the world, each part relying on hundreds of suppliers itself. Boeing 787 presents an unconventional supply chain too, relying on a high percentage of outsourcing. Production is highly dependent on the availability of essential materials, parts and subassemblies from suppliers and subcontractors. In addition, some major components and product equipment items are procured or subcontracted on a sole-sources basis. ➢ Medium variety of customers Different customers can be grouped in two categories: commercial airlines customers and US government defence spending. A significant portion revenues derives from a limited number of commercial airlines.
Product dynamic complexity	➢ Product introduction Boeing continuously transforms design and building of its solutions, expanding its product lines and services to meet emerging customer needs.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities In 2003 the company introduced an unconventional supply chain for Boeing 787, formed by a tiered structure that would allow to foster partnerships with approximately 50 tier-1 strategic partners, who assemble different parts and subsystems produced by tier-2 suppliers. ➢ Improvements to equipment, procedures and systems Boeing continuously transforms the systems to enable to work more efficiently and to improve the environmental performance of internal operations. ➢ Restructuring and M&A M&A, joint ventures and strategic alliances shape the company structure.
External dynamic complexity	➢ New suppliers or customers Boeing is expanding its international presence with new partnerships.

Since many Boeing’s suppliers are located in Japan, the company faced considerable financial risk due to uncertainty in its supply chain after the Japan earthquake in March

2011. It was the biggest earthquake to hit Japan in 140 years and it further caused a 10-meter tsunami and several explosions at the Fukushima Daiichi Nuclear Power Plant. The event disrupted many companies and three first-tier aerospace firms, Mitsubishi Heavy Industries, Kawasaki Heavy Industries and Fuji Heavy Industries, which supply key components for Boeing 787, have production facilities in affected areas, as do their subcontractors. Moreover, due to its extensive global supply chain, even if primary suppliers escaped damage, second-tier suppliers' problems could cause potential parts delay. However, even though Boeing's shares dropped 1.3%, the incident did not hurt its operations significantly. As a matter of fact, it had several weeks of inventory to buffer any deceleration in the supply chain. Moreover, suppliers were able to meet delivery schedules, despite of the encountered transportation problems.

The first complexity driver leveraged by Boeing was the portfolio breadth: it increased 737 NG production to cut down on the 787's order backlog. In fact, the latter was the most affected model, since about 35% of its components are coming from Japan. Therefore, the company tried to shift demand on another model, reacting flexibly to the incident.

Secondly, the structural configuration of partners and suppliers helped the company. Even though the single-source policy makes Boeing high dependent on its suppliers and less flexible, increasing the risk of supply chain disruption due to the absence of redundancy, it ensures collaboration with partners. They worked closely together to determine the earthquake impact on the supply chain, monitoring the availability of power, infrastructure and transportation. Moreover, through collaboration with first-tier suppliers, the company could have higher visibility on affected second-tier providers.

Finally, in case of gaps in production at the second tier of the supply chain, alternative sources were defined, leveraging the company capability to flexibly rely on new suppliers and its visibility on them, thanks to its continuous international expansion through new partnerships.

Table 5.8: *Influence of complexity drivers on resilience constituents in Boeing's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Portfolio breadth	+			
Number and variety of suppliers	+	-		-
New suppliers	+	+		

5.5 Sanofi Genzyme

Sanofi Genzyme is a pharmaceutical and biotechnology company focused on rare diseases, multiple sclerosis, immunology and oncology. It is a fully owned subsidiary of Sanofi, which acquired it in 2011. Genzyme's yearly sales in 2016 were 4,275 million € and in 2007 its workforce was about 11,000 employees. It has facilities in Massachusetts, New Jersey, Belgium, England, France and Ireland. Started in 1981, the company is characterized by a long history of developing high specialized treatments and forging relationships with physician and patient communities. In 2005, it was awarded the National Medal of Technology, a high level of honour for American leading innovators. In fact, the company is deeply dedicated to discovering and advancing new therapies, providing hope to patients and their families.

Sanofi Genzyme's supply chain is characterized by the following complexity elements (Table 5.9).

Table 5.9: *Sanofi Genzyme's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth The company has a specialized diversified product portfolio of 19 products across multiple therapeutic areas. ➢ High product specificities Approval of medicine is required at each market region for each product. Regulation is a significant factor in the pharmaceutical industry, from the development to the manufacture, from the commercialisation to the pricing and reimbursement.
Internal structural complexity	➢ Many facilities around the world Genzyme has specialized facilities located around the world, being present in approximately 65 countries, including 17 manufacturing facilities and 9 genetic-testing laboratories. Production plants are in Massachusetts, New Jersey, Belgium, England, France and Ireland. ➢ Differences between different facilities There is only one plant in the world producing a certain kind of drugs, due to uniformity requirements. As a matter of fact, since pharmaceuticals must be uniform wherever they are produced, both for quality control and regulatory reasons, processes need to be perfectly identical if done in different facilities. Moreover, foreign regulatory requirements vary by jurisdiction and may require performing additional clinical testing. Therefore, there could be different activities in different facilities.
External structural complexity	➢ Low number of suppliers In this industry, suppliers are subjected to strict regulations and some of them are the only possible sources for some materials (sole-sourcing). Genzyme also leverages third party contractor manufacturers to produce or assist the production. ➢ Breadth of customer requirements Genzyme has a large number of customers over a broad geographic area: distributors, pharmacies and hospitals. Since different patients could have different degrees of vulnerability, they have different priorities. Moreover, the company has strong relationships with patient communities and it listens to their perspectives in order to truly understand their needs.
Product dynamic complexity	➢ Product introduction Investing a lot in R&D, Genzyme launches, acquires and integrate many new products and potential new therapies are studied in clinical trials and in Sanofi's laboratories. In 2005, the company was awarded for being a leading innovator.

(continue)

Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities The company has expansion projects. ➢ Improvements to equipment, procedures and systems Genzyme is executing a plan to provide additional capacity to support the long-term growth of Cerezyme, Fabrazyme and Myozyme. Moreover, it is renewing the organisation, hiring new senior leaders and making significant management changes. ➢ Restructuring and M&A Genzyme's history is characterized by many acquisitions. Finally, it has been acquired in 2011 by Sanofi, becoming one of its business units.	

In June 2009, a virus contaminated production of three drugs at a Genzyme's plant in Massachusetts and the bulk production had to be temporarily interrupted to sanitize the facility. Due to the uniformity requirements, the involved plant was the only one in the world producing Cerezyme and Fabrazyme, approved drugs for Gaucher and Fabry diseases, genetic disorders affecting metabolism and causing extreme joint and bone pain and bodily deformities. Furthermore, the available stock was too small and held in the same facility, thus Genzyme also had to prove it had not been contaminated too. Therefore, the drugs supply suffered a global shortage, for one month the Cerezyme and two months the Fabrazyme. Even though the event represented a negative disruption for the company (one third of revenues was represented by these two drugs), it could remain profitable, thanks to the significant revenue growth in other business segments due to launch, acquisition and integration of new products.

Since the affected production plant was the only one in the world producing Cerezyme and Fabrazyme, Genzyme was not able to flexible react to the disruption because it could not leverage other facilities support. Regulatory requirements, imposing not to have more than one plant if the processes are not perfectly identical, hindered collaboration among the company's facilities in order to face the supply shortage. Because Genzyme was not able to replace the production or exploit the stockpiles, it had to prioritize patients, distributing current limited inventory to ensure that the most vulnerable ones continued to receive treatment. Therefore, leveraging on different needs of a wide breadth of customer requirements, it could ensure to serve at least some of them. It was possible also thanks to the strong relationships that the company had with patient communities. Meanwhile, Genzyme tried to introduce another experimental drug as substitute.

Table 5.10: *Influence of complexity drivers on resilience constituents in Sanofi Genzyme's case.*

Complexity drivers	**Flexibility**	**Visibility**	**Velocity**	**Collaboration**
Differences between different plants	-			-
Breadth of customer requirements	+			+
Product introduction	+			

5.6 Mitsubishi Motors Corporation

Mitsubishi Motors Corporation is a multinational automotive manufacturer belonging to the Japanese Mitsubishi Group. Even though affected by an extraordinary loss due to the issue of improper conduct in fuel economy testing, its sales reached 15,866 million € in 2016, 16% less than the previous year. In the same year, operating income was 42 million € and the number of employees was 29,604. Mitsubishi foundation dates back to 1870, but Mitsubishi Motors Corporation was officially established in 1970. The company continued to grow, developing a global network with manufacturing and R&D facilities all around the world. Focused on a customer-centric approach, Mitsubishi Motors aims at providing the utmost driving pleasure and safety, continuously developing and manufacturing new products with superior driving performance.

Table 5.11 summarized the most important structural and dynamic complexity drivers characterizing the company.

Table 5.11: *Mitsubishi's supply chain complexity drivers.*

Product structural complexity	➢ Medium portfolio breadth The main business of the company is in the automobile industry, offering 5 different families of products, with more than 26 major models. However, it also provides financial services, being engaged in sales finance and leasing services for its products.
Internal structural complexity	➢ Global network with many facilities The company has: 5 car manufacturing facilities in 3 countries, 10 car manufacturing facilities of affiliated companies and business partners in 9 countries and regions, 7 engine, transmission and parts manufacturing facilities in 5 countries and 9 R&D facilities in 5 countries.
External structural complexity	➢ High number of suppliers Mitsubishi Motors sources raw materials and parts from a large number of suppliers. The necessity to procure materials and parts characterized by higher quality or more advanced technologies at more competitive prices may bring about a situation in which orders are concentrated upon a specific supplier. There may also be only a limited number of suppliers able to supply parts for which a specific technology is required.
Product dynamic complexity	➢ Product introduction The company continuously improve its model mix, launching new and evolving existing strategic models, exploiting technology. For instance, in 2009 it launched electric vehicles.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities The company develops infrastructures to support revitalisation and growth. It builds new plants, but also discontinues operations in other ones, in order to step up production capacity. Resources are mainly concentrated in emerging markets. ➢ Improvements to equipment, procedures and systems A restructuring and streamlining of the operating structure is allowing the company to improve production efficiency globally in factories and consolidate product lines.

(continue)

Internal dynamic complexity	➢	Restructuring and M&A M&A, operational tie-ups and strategic alliances shape the company structure, reorganized in 2016.

Since Mitsubishi Motors Corporation has a subsidiary in Thailand, it suffered a supply chain disruption in 2011, due to the severe flooding hitting the country between July 2011 and January 2012. Even though plants were not directly damaged, it halted production because of difficulties in parts procurement due to flood damages at its local parts suppliers. The production suspension lasted approximately one month and caused product shortages on the sales front: 23,000 units were lost, corresponding to a profit of more than 1 billion €, also because stock allowed to cover only some days. Despite the decrease in net sales, the company reached positive results due to improvements in the model mix, together with other factors such as reductions in materials and other costs.

The high dependence of the company on auto parts makers in Thailand made it more vulnerable to the supply chain disruption. A higher geographical variety of suppliers could help to be more independent from the geography of the event. However, Mitsubishi Motors could rapidly resume the production by procuring parts through different channels, including by manufacturing them in Japan. Therefore, the high number of production facilities in different countries positively affected not only the flexibility of the company, but also its velocity, and it allowed collaboration among different plants. Moreover, it leveraged the high number of suppliers, temporarily shifting to other parts providers and collaborating with them, putting together their best efforts towards production resuming. As result Mitsubishi Motors was able to restart production earlier than expected and the production shortage lasted only one month.

Table 5.12: *Influence of complexity drivers on resilience constituents in Mitsubishi's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Global network with many facilities	+		+	+
High number of suppliers	+			

5.7 Nestlé S.A.

Nestlé S.A. is one of the world’s largest food and drink companies, including more than 2,000 brands. It produces powdered and liquid beverages, nutrition and health science products, milk products and ice cream, prepared dishes and cooking aids, pet-care goods, confectionery and water. Its revenues in 2016 were 82,061 million €, the operating income was 12,558 million € and employees amounted at around 382,000. Headquartered in Switzerland, Nestlé has more than 400 factories in 86 countries all over the world, selling in more than 190 countries. In 2016, it celebrated 150th anniversary from the foundation, as it started in 1866 as a condensed milk company. Its strategy focuses on delivering distinct benefits to people, understanding and anticipating society needs and continuously adapting in order to exploit new opportunities.

To deeply describe Nestlé's supply chain, the following complexity drivers can be identified (Table 5.13).

Table 5.13: *Nestlé's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth The company has 7 product lines: powdered and liquid beverages, nutrition and health science, milk products and ice cream, prepared dishes and cooking aids, pet-care, confectionery and water. It incorporates more than 2,000 brands, ranging from global icons to local favourites.
Internal structural complexity	➢ Huge number of SC facilities all over the world It has 418 factories in 86 different countries. ➢ No differences between facilities Facilities around the world are similar.
External structural complexity	➢ High number of different suppliers Nestlé has almost 165,000 direct suppliers and works with 695,000 individual farmers worldwide. ➢ High variety of customers Given the wide range of different products belonging to its portfolio, the company serves many different customer segments.
Product dynamic complexity	➢ Product introduction e renovation The company considers of extremely importance both the renovation of existing products and the innovation through the introduction of new ones.
Internal dynamic complexity	➢ Improvements to equipment, procedures and systems Nestlé Continuous Excellence is an approach to operational efficiency, aiming at eliminating waste and errors, increasing efficiency and effectiveness, and improving quality and safety in all operations. It represents the business model of the company, based on continuous improvement projects. ➢ Restructuring and M&A Nestlé has always been characterized by the presence of M&A, but also sell-outs and divestitures, dynamically changing during the years. In 2016 the company organically grew of 3,2%.
External dynamic complexity	➢ Supply side dynamics The company encourages its suppliers to continuously improve their operations. ➢ Demand side dynamics The wide range of consumers continuously evolves, embracing new trends, habits and lifestyles.

In March 2010, the environmental protection group Greenpeace International accused Nestlé of leading destruction of rainforests, due to the use of palm oil in products of the confectionary brand Kit Kat. As a matter of fact, the expansion of palm oil cultivation, determined by the high demand from the food companies, came at a cost of clearing of rainforests, which not only are home of orangutans, but especially contribute to greenhouse gas emission. Therefore, a social media campaign was conducted against Nestlé, including a provocative video combined with a massive online protest on the company Facebook page. At first, the company forced video's withdrawal from YouTube, citing copyright, but it appeared that it wanted to hide the facts and hinder Greenpeace's efforts against palm oil. As consequence, Nestlé was forced to address the palm oil sourcing issue, suspending purchasing from Sinar Mars and committing to use only certified sustainable palm oil by 2015. Moreover, in order to provide details of its palm oil supply chain, it partnered with Forest Trust, a non-profit organisation helping in liaising with Greenpeace and auditing suppliers. Finally, it joined the Roundtable for Sustainable Palm Oil, a partnership of companies and other parties aimed at eliminating unsustainable production. In this way, Nestlé turned the reputational risk into an opportunity. Despite of this reactions, the event severely damaged the brand image of the company, decreasing its reputation and thus sales volume. The company was forced to change its marketing and communication strategy, in order to provide a new fresh perspective through social media and digital marketing.

The structural complexity characterizing Nestlé supply chain negatively affected the velocity in reacting to the event, both on upstream and downstream tiers. Downstream, since the brand serves a wide range of different customer segments, rebuilding its reputation was hard due to the necessity to use different communication channels to reach different consumers. Upstream, required certification of suppliers was difficult and time consuming due to the large number of suppliers that the company has, hindering visibility and collaboration. However, Nestlé is used to work with suppliers and encourage them to continuously improve. Therefore, supply side dynamic complexity increased collaboration among involved actors and velocity in certification practices. Finally, the company's orientation to renovation and innovation facilitated the renovation of products eliminating palm oil.

Table 5.14: *Influence of complexity drivers on resilience constituents in Nestlé's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
High number of suppliers		-	-	-
High variety of customers			-	
Product introduction and renovation	+		+	
Supply side dynamics			+	+

5.8 SK Hynix Inc.

SK Hynix Inc. is a South Korean company operating in the electronics industry, producing memory semiconductors, such as DRAM (Dynamic Random Access Memory) and NAND flash. Hynix's sales in 2016 reached 13,392 million €, with and operating income of 2,552 million €. The company employs more than 27,813 employees all around the world. It has production facilities in Asia, sales subsidiaries in America, Europe and Asia, 18 sales offices and 4 R&D corporate bodies. Started in early 1980s as Hyundai Electronics Co., Hynix leverages a 30-year-old know-how for production and operation of semiconductor business, securing competitiveness in technology and costs and leading the global market. Believing that semiconductors are the future of the IT industry, SK Hynix continuously strengths its technological level and diversify its product portfolio.

Structural and dynamic complexity drivers characterizing the company are listed in Table 5.15.

Table 5.15: *SK Hynix's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth Hynix covers 6 segments: computing, mobile, automotive, graphics, consumer and storage. ➢ High product variety, but similar equipment specificities Even though the company offers a wide range of products, considering DRAM and NAND memory chips, their production equipment is similar. In addition, DRAMs support wide array of interfaces to meet customer needs.
Internal structural complexity	➢ Facilities all over the world The company has 2 production facilities in China and 2 domestic business sites in Korea. Moreover, it has 10 sales subsidiaries in 10 countries, including USA, UK, Germany, Singapore, Hong Kong, India, Japan, Taiwan and China, and 18 sales offices. Finally, it has 4 R&D corporate bodies in Italy, USA, Taiwan and Belarus. ➢ Differences between facilities in different territories As it emerges from the previous description, even though facilities are all over the world, the production is concentrated in Asia (China and Korea).
External structural complexity	➢ Medium number of suppliers In 2015 the company had 677 major suppliers. Since the industrial ecosystem in which Hynix operates is based on a culture of a mutual win-win growth with partners, it stipulates fair trade agreement with all subcontractors. Moreover, it supports secondary suppliers by pushing improvement of payment conditions between them and primary suppliers. ➢ Limited variety of customers Hynix is semiconductor supplier of the IT industry, in which it serves 70 major strategic customers (data of 2013).
Product dynamic complexity	➢ Product introduction Continuously investing in R&D activities, the company is developing new products, identifying and presenting specifications that meet customer needs. Being the first mover in the sector, it protects relevant technology by developing advanced patent management.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities The company is investing in new facilities. For instance, a new fabrication line was completed in 2016. ➢ Improvements to equipment, procedures and systems R&D investments aim at productivity improvements too. ➢ No M&A M&A, sell-outs or divestitures are absent in the strategy of the firm.

(continue)

External dynamic complexity	➢ Demand side dynamics Customer demands are becoming more sophisticated and diversified, as IT environments is becoming increasingly complex. ➢ Supply side dynamics The company puts many efforts in strengthening the competitiveness of supplies, aiming at a sustainable and win-win growth. It supports them in constructing a safety system and jointly develops new items with them. ➢ New suppliers Hynix continuously expand its partners base. For instance, in 2012 it added 8 new suppliers.

In September 2013, while installing a chip equipment, a fire affected a production plant in China, whose production represented around a half of Hynix's computer memory chips. The event forced the temporary facility closure, creating a significant supply chain shortage, as indicated by the nearly doubled DRAMs prices. Operations were completely resumed after a couple of months, less than the six months predicted by analysts, also thanks to the contribution of employees. Learning from the incident, the company enhanced safety measures and adopted a Business Continuity Plan to secure from various disasters and emergencies, through the preparation of business recovery plans. It systematically monitors risk factors to develop effective responses.

Considering supply chain complexity drivers, some of them played a key role in facing the incident. First, having more than one production facilities, SK Hynix could leverage the support from other business sites. Flexibly increasing output and shipments at other plants, such as the South Korea one, the company made up for lost production. Therefore, the expedite recovery was possible due to the collaboration of Icheon and Cheongiu facilities. This was possible to the detriment of NAND flash memory chips, since NAND equipment in South Korean plants was used as temporary arrangement for DRAM production, despite of the consequent inefficient use of facilities. Having similar equipment specificities for the two different products thus allowed the company to flexibly react. Furthermore, being used to invest for the improvement of the productivity not only facilitated this temporary arrangement, but also supported the conversion of the manufacturing process that the company actuated after the recovery in order to sell more profitable products, due to the production cost reduction. Hynix was able to ramp up operations in stages as soon as the damaged facilities were replaced, fully recovering normalized production level.

Table 5.16: *Influence of complexity drivers on resilience constituents in SK Hynix's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Product equipment specificities	-			
Number of supply chain facilities	+			+
Improvements to equipment etc.	+		+	

5.9 PSA Peugeot Citroën

PSA Group, known as PSA Peugeot Citroën, is a multinational manufacturer of automobiles and motorcycles, including Peugeot, Citroën, DS Automobiles, Opel and Vauxhall Motors brands. Financial results of 2016 reported sales equal to 54,676 million € and an operating income of 2,733 million €. The group has facilities all around the world, from Europe to Asia and Latin America, employing nearly 170,000 people. Although PSA was born in 1976, when Peugeot and Citroën merged, the French industrial heritage characterizing it has more than 200 years of history, since Peugeot started out in metal industry in 1810. Thanks to the ramp-up of proprietary technologies, the 2000s were marked by a significant international growth of the group. Conscious of the key changes necessary for the car of the future, the PSA Group's strategy for 2016 to 2021 aims to become a global car manufacturer and a provider of mobility services, leveraging high efficiency and customers' favour.

The most important structural and dynamic complexity drivers characterizing PSA Peugeot Citroën are summarized in Table 5.17.

Table 5.17: *PSA Peugeot Citroën's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth PSA businesses can be grouped in 4 segments: automotive, automotive equipment, finance and other businesses. The group offers a wide range of products and services with the following brands: Peugeot, Citroën, DS, Opel, Vauxhall, Free2Move (mobility services), PSA Powertrain (engines and components), Banque PSA Finance and Mister Auto (online sales of automotive spare parts). ➢ Broad range of services Many different services are available, both during and after the vehicle sale (reception, advice, getting to know the vehicle, financing and insurance options, handling, maintenance, repair, spare parts replacement). Moreover, PSA offers new mobility services, with rental and car-sharing for individual customers and companies, and connected services. ➢ Few main product platforms Streamlining of vehicle platforms is key to the group performance. The objective is to reduce the number of platforms from six at present to two platforms for global use: the EMP2, covering all global body styles for compact and family vehicles, and the CMP, for compact and city vehicles. They are compatible with different types of powertrain, including electric motors.
Internal structural complexity	➢ Many facilities all over the world The company has 16 production facilities (in China, France, Spain, Czech Republic, Slovakia, Argentina, Brazil, Italia, Portugal and Russia), 15 powertrain sites, 6 R&D centres (in France, China and Brazil) and 2 vehicle test centres (in France).

(continue)

Internal structural complexity	➢ More tiers of the supply chain and low inventory PSA activities not only include assembling of vehicles, but also manufacturing of engines and components, covering a large part of the industry supply chain. In cases in which the company relies on external subsystems and components makers, it has a tight inventory management, characterized by just-in-time deliveries. Moreover, 430 dealerships and retailers belong to the group, making up PSA Retail. ➢ Differences between facilities in different territories The group is organised into six regions: Europe, China & Southeast Asia, Latin America, Eurasia, India-Pacific and Middle East & Africa. Each region is run by an operating unit, based locally, responsible for economic profit and resources management, both for manufacturing and sales activities. Therefore, specific characteristics of each region are better considered.
External structural complexity	➢ Many suppliers, but different relationships PSA's supply chain is heterogeneous, including international groups, tier-1 suppliers and SMEs, which are often tier-2 suppliers. The group relies on many providers, divided according to their importance: 17 strategic suppliers, 52 core suppliers and more than 7,000 others. PSA has special relationships with 15 world-class suppliers, involved at early stages of strategic process in a win-win approach. Major suppliers (around 100) demonstrate capacity for innovation, desire to support the international development of the group and a solid financial position. About 50% of total suppliers are critical, meaning they are partners in innovation projects, they are single source of a component or in case of failure they can negatively affect PSA's reputation. ➢ High number of customers Around 1.7 million customers are surveyed every year worldwide. The customer is the central focus for the company: innovation is competitively priced to reach the largest number of motorists possible. The group commits to fulfilling the requirements of customers by ensuring top-level product reliability and providing them with high-quality features and services. Furthermore, PSA serves a global network of nearly 10,000 dealerships and/or approved repairers. Replacement parts are distributed by the Euro Repar Car service network and through the Mister Auto website, in addition to the Group brand service points.
Product dynamic complexity	➢ Product introduction Thanks to innovation teams focused on vehicle design and safety, the product mix is changing: 121 product launches are expected by 2021 and Peugeot and Citroën brands are being moved upmarket, increasing the sales of premium vehicle. Since the introduction of innovative solutions in the automotive industry is fundamental for PSA, it is a leading French patent filer, with 1,063 patents published in 2014.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities PSA Group continuously improve the performance of the supply chain and plants, aiming at optimising industrial processes. It is modernising and compacting its sites, leveraging connected and paperless plants, increasing flexibility to adapt to changes in demand, fully integrating suppliers in the supply chain and streamlining platforms worldwide.

(continue)

Internal dynamic complexity	➢ Improvements to equipment, procedures and systems Innovation teams are focused on environmental friendly energy sources and design methods, also partnering with leading business and engineering schools and university. The group is optimising industrial processes by consolidating the best technologies, equipment and know-how, as well as the best practices in the automotive industry. For instance, the load rate is optimised by compacting, the flexibility is increased to adapt to changes in demand and management autonomy is leveraged to maximise process improvements. ➢ M&A History of the group is characterized by mergers and acquisitions (e.g. it was born when Peugeot and Citroën merged). Moreover, it established joint ventures, for instance with Dong Feng Motor Group and Santander.
External dynamic complexity	➢ Demand side dynamics The main trend characterising the industry is the shift from ownership to experience. Even though the ownership approach is still dominating, young generations are increasingly more concerned about use and mobility. In addition, customers are giving more and more importance to safety and environment, driving innovation towards broadly affordable mobility solutions. ➢ Supply side dynamics Long-term relationships with suppliers are built in a spirit of continuous improvement, characterized by challenges involving all aspects of automobile projects (R&D, technical issues and production). ➢ New customers Expansion of customer base will come from digitisation and multi-brand offering of after-sales, leasing, used vehicle, mobility and fleet management services.

PSA Group was affected by the great Japan earthquake of March 2011 too. Since it did not have facilities in the interested area, its plants were not directly damaged. However, it suffered of air flow sensors and other parts shortage due to the supply chain disruption following the Fukushima disaster. The high proportion of electronic components made in Japan, aggravated by the tight inventory management through just-in-time policy, made the company more vulnerable, forcing PSA’s plants to shut down. The production of diesel engines was negatively affected due to the lack of a subcomponent of sensors used to regulate the flow of air, produced by Hitachi, whose plant was damaged in the event. In addition, other suppliers completely halted components deliveries. Therefore, 2011 annual report indicated the Japan disaster as one of the main causes of the recurring operating loss of 92 million € for the automotive division, versus income of 621 million € in the previous year.

Considering the structural supply chain complexity of PSA Peugeot Citroën, a key role in the event was played by the single-sourcing characteristics. Even though the company has a large supply base, most of electronic components are made by Japanese critical suppliers, which represent the unique source available. Therefore, not having alternative providers, the company could not flexibly shift to them, being forced to shut down production. Moreover, the situation was aggravated by the just-in-time management of inventory, which determined a high dependence on suppliers' operations.

Secondly, the huge and heterogeneous base of actors involved in the PSA's supply chain negatively affected the resilience of the company. Since some of the small and medium enterprises affected by the earthquake were second-tier providers, they were not directly visible to PSA Group and the company struggled to reweave its complex supply chain. As consequence, it was not able to quickly react to the disruption with resilient solutions and it was forced to slow production of thousands of vehicles in the USA and Europe.

Table 5.18: *Influence of complexity drivers on resilience constituents in PSA Peugeot Citroën's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Number of suppliers	+			
Number of actors in the SC		-	-	

5.10 Mattel Inc.

Headquartered in California, Mattel Inc. designs, manufactures, and markets a broad variety of toy products. The core product lines include Barbie fashion dolls, Hot Wheels diecast vehicles, Fisher-Price preschool toys, Disney toys and table games such as Scrabble. The company employs nearly 30,000 employees and its yearly sales in 2016 amounted to about 4,930 million €, with an operating income of 469 million €. Mattel's principal manufacturing facilities are in Canada, China, Indonesia, Thailand, Malaysia and Mexico, but it also relies on third-party manufacturers all around the world. Founded in 1944, Mattel made toy industry history, starting TV marketing and introducing some of the most popular brands, such as Barbie. Aiming at being the recognized leader in play, learning and development worldwide, the company vision is to inspire the wonder of childhood.

Table 5.19 summarizes the main complexity drivers characterizing Mattel's supply chain, from both structural and dynamic point of views.

Table 5.19: *Mattel's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth Diverse range of products for children of all ages and families are bundled in 4 main brands and products categories: Girls and Boys (including Barbie, Other Girls, Wheels and Entertainment), Fisher-Price, American Girl and Construction, Arts & Crafts. ➢ High product variety The company offers a broad variety of toy products, some developed and adapted to particular international markets.

(continue)

Internal structural complexity	➢ Facilities all over the world Principal manufacturing facilities are in Canada, China, Indonesia, Thailand, Malaysia and Mexico. To reduce risk, Mattel produces many of key products in more than one facility. ➢ Few layers in the supply chain Even though Mattel concentrates production of most of its core products in company-owned facilities, it also relies on third-party manufacturers in US, Mexico, Brazil, Asia, New Zealand and Australia. Moreover, on demand side it covers different layers: in some cases it sells directly to the final consumers, but in others it reaches them through retailers (discount and free-standing toy stores, chain stores, department stores, other retail outlets, and wholesalers), retail outlets, agents and distributors or subsidiaries selling online. ➢ Differences between facilities in different territories Apart from El Segundo facilities, used by all segments, other facilities are dedicated to different segments or different functions. For instance, New York facilities are dedicated to North America segment, Wisconsin ones to American Girl segment, Canada ones are focused on brand support and manufacturing functions …
External structural complexity	➢ High number of suppliers and third-party providers The majority of raw materials are available from numerous suppliers. Furthermore, the company outsources production of non-core products to third-party manufacturers. ➢ Limited number and variety of customers Mattel has a significant customer concentration: the most of the sales are determined by 3 large customers (Wal-Mart, Toys R Us and Target). Customer in general can be classified in: retailers, including discount and free-standing toy stores, chain stores, department stores and wholesalers; retail outlets, generally near or at corporate headquarters and distribution centres as a service to employees and as an outlet for products; agents and distributors in those countries where Mattel has no direct presence; final consumers.
Product dynamic complexity	➢ Product introduction Toy industry is characterized by trends towards shorter products life cycles and Mattel regularly refreshes, redesigns, and extends existing toy product lines and develops innovative new toy product lines for all segments. It invests in innovation by expanding relationships with inventor community, building partnerships in gaming space and making strategic investments in digital technology platforms. It also relies on independent toys designers.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities Mattel has initiatives to improve the supply chain and investment for growth by building out infrastructure in emerging markets. ➢ Improvements to equipment, procedures and systems Mattel has initiatives to reduce costs, increase efficiency, improve execution of core business, globalize and extend brands, improve productivity and simplify processes. ➢ M&A The company regularly considers and may engage in discussion and negotiations regarding acquisitions, mergers or strategic transactions.

(continue)

External dynamic complexity	➢ Demand side dynamics Toy industry is characterized by seasonal purchasing patterns: the demand is highly seasonal with large percentage during traditional holiday season. This increases the risk of under/over production and determines the need for high inventories due to the advanced production. Moreover, business is susceptible to changes in popular culture, media, fashion, and technology and customer preferences are continuously changing. Finally, often in the past the company had to face products recalls, due to non-compliant or defective products. ➢ New customers The company is increasing the portion of revenues expected to come from new and emerging markets, facing risks such as different laws, changes in governmental policies and evolution of laws, new retail trends and local customers, difficulties in products moving …	

From August to September 2007, Mattel recalled more than 1.5 million toys due to non-approved surface paint containing high quantity of lead. Since the US regulatory established that the surface coatings cannot exceed 0.06% lead by weight, the company had previously given manufacturers in China a list of paint suppliers that they could use. However, a subcontractor employed an unauthorized supplier, exceeding the limit. Lead-based paint is dangerous for children because its ingestion causes learning and behavioural problems, slow muscle and bone growth, hearing loss and brain damage. Therefore, consumers were asked to return products in turn of a voucher for a replacement toy. In addition, another recall due to faulty magnets withdrew around 18 million toys in the same period, determining the biggest recall of history. After the event, Chinese government revoked export license to the subcontractor and Mattel increased products monitoring. Thanks to its experience with recalls, the company smoothly faced all aspects of the incident, giving accurate, quick and efficient information about the recall to the public and reassuring consumers. It also created a website dedicated to the recall. Finally, the company effective communication strategy was fundamental: it placed notifications in 20 languages on its website, sent personal letters to entire customer database, sent letters and posters to retailers, manned a hotline, placed full page ads in major newspapers, and worked closely with the media.

Even though the low impact of the event on Mattel’s yearly results was determined mainly by its ability to manage a good communication plan, also some supply chain complexity drivers played an important role in the recall. First, having facilities worldwide, the company could slow down shipments out of Asia, flexibly relying on other plants. Secondly, partially covering layers of the supply chain on the demand side allowed the company to prevent affected toys from reaching end consumers, by stopping them in distribution centres and contracting retailers. Thus, high complexity of supply chain on demand side, thanks to the collaboration with actors of the distribution channels, positively contributed reducing the involvement of public on the incident. However, on the other side, covering few levels also revealed a weakness. As a matter of fact, opting for an outsourcing strategy, relying on third-party providers, decreased the Mattel's visibility on the quality of the products, reducing the possibility to quickly identify non-compliant and unauthorized raw materials suppliers. Therefore, internal structural complexity of the supply chain configuration can have both positive and negative role.

Considering Mattel's customers, the high concentration of them allowed to easily recall affected toys: the three biggest retailers collaborated with the company to prevent defective products from reaching end consumers. Thus, a low number and variety of customers positively impacted on collaboration, as well as it allows a better visibility on them.

Internal dynamic complexity drivers allowed both flexibility and velocity. Being used to invest in initiatives to improve supply chain, the company could better manage the supply reconfiguration determined by the incident, i.e. stopping of accepting goods from the guilty Chinese subcontractor and slowing down the shipments out of Asia. Furthermore, continuous improvement to procedures allowed not only to quickly and flexibly introduce procedures for the recall management, through the dedicated website, but also to review Mattel's safety procedures and extend its product testing programs. According to these, the company would control that manufacturers only use paint from certified suppliers and would test every single batch of paint from all vendors. Then, it would increase control on every level of the production process and conduct random inspections at vender facilities, testing all finished toys before they reach the consumer.

Finally, considering demand side dynamics, past history of the company is characterized by a large number of recalls, some of big size. Therefore, thanks to its experience in products withdrawing, Mattel quickly acted to face the problem and well managed all the aspects of the event, leveraging on the effective communication strategy previously described.

Table 5.20: *Influence of complexity drivers on resilience constituents in Mattel's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Facilities all over the world	+			
Many layers in SC (demand side)		-		
Many layers in SC (supply side)		+		
Number and variety of customers		-		-
Reconfiguration of supply chain	+		+	
Improvements to procedures	+		+	
Demand side dynamics			+	

5.11 Honda Motor Co. Ltd.

Honda Motor Co. Ltd. is among the largest automobile manufacturers in the world and it is the world's largest motorcycle manufacturer. Its main business divisions are motorcycles, automobiles and power products, but it also operates in aviation, marine and robotics industries and it offers financial services too. Moreover, Honda Racing is dedicated to motor sports. In the financial year ending on the 31st of March 2017, it accounted sales for 116,468 million € and operating income for 6,994 million €. Its employees amounted at 211,915. Honda it's a Japanese company with a global footprint: it has production facilities and R&D centres all around the world, selling its products in all the continents. Founded in 1948 in Japan, it opened its first US storefront in Los Angeles in 1959 and quickly grew to astounding heights, excelling in respecting and exceeding government requirements about emissions. As a matter of fact, Honda believes in the power of dreams, continuing to challenge creating intelligent products that enhance mobility and ensure advanced safety, sharing joys and excitement with customers.

Given the huge dimensions of the company, Honda's supply chain is complex, both from a structural and dynamic point of view.

Table 5.21: *Honda Motor's supply chain complexity drivers.*

Product structural complexity	➢ Broad portfolio The three main businesses are: motorcycles (Honda Motorcycles, ATVs, Scooters and SxS), automobiles (Honda Autos and Acura Autos) and power products (Honda Power Equipment and Honda Engines). Moreover, Honda operates in other industries: aviation, marine, robotics, motor sports and financial services. ➢ High product variety Extensive environmental and other governmental regulations impose different standards in different countries, regarding emissions, fuel economy, noise, vehicle safety and others. Moreover, some products are designed for specific local customers.
Internal structural complexity	➢ Many facilities around the world Production facilities are in Japan (10), in USA (7), in Canada (1), Mexico and Latin America (6), Europe (5), Africa and Middle East (4) and Asia and Oceania (35). R&D centres, parts centres and marketing, sales, service and finance operations and other offices locates all over the world too. ➢ Differences between facilities in different territories Often Honda prefers to build products close to customers, in order to support local communities.
External structural complexity	➢ High number of suppliers, but also single-sourcing Honda has numerous external suppliers for raw material. It counts around 620 OEM suppliers and additional 12,000 service suppliers. However, certain suppliers for some raw materials/parts are unique for the company, determining single-sourcing. ➢ Open innovation External partners are involved in projects, for instance GM, Yamaha Motor and Hitachi Automotive Systems. ➢ High number of customers Honda has about 28 million customers around the world.

(continue)

Product dynamic complexity	➢ Product introduction R&D plays a fundamental role for the company, which aims to create distinctive products internationally competitive. Since 1991, 29 models have been designed in USA, with a particular focus on the importance of environmental technologies (eco-friendly vehicles) and advanced safety technologies. In addition, considering robotics and other industries, Honda developed ASIMO, an autonomous robot, and Honda Smart Home.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities Honda is reforming its six-region global operation structure, through inter-regional cooperation and coordination to evolve models more efficiently and to further expand potential of regional models. For instance, to achieve more efficient business operations, region with similar customer needs will work together to realize common regional models. Furthermore, the company is continuously expanding the production capacity, introducing new facilities. ➢ Improvements to equipment, procedures and systems The company is transforming how it operates at every level, from design and manufacturing to transportation and sales, in order to reduce environmental impact. In addition, it is working to establish a more flexible production system and mutually complementary production among six regions, to balance supply and demand in global production and sales. Finally, aiming at increasing quality of corporate activities, Honda invests in the SED (Sales, Engineering and R&D) development system, a project that will significantly advance its development system and capability, introducing a new development process. ➢ Acquisitions The company made many acquisitions of subsidiaries.
External dynamic complexity	➢ Demand side dynamics In Europe, sovereign debt crisis, rising oil prices and other factors led to stagnation, slowing economy to a crawl. In US, high unemployment rate, sluggish sales of homes and fiscal austerity brought economy to slip into recession. Also in Asian countries, the pace of growth slackened.

Starting from July 2011, soon after the Japan's earthquake and tsunami, Thailand was affected by a severe flooding, which forced more than 1,000 factories to close, leading to global shortages, especially in automotive and electronics industries. The event had a double effect on Honda's operations: it directly affected a manufacturing facility, but also disrupted components supply, since Thailand is the regional production base for stamped parts, body panels and engines. On the one hand, the company was forced to suspend production at the assembly plant in Ayutthaya, north of Bangkok, directly damaged in October. The plant was responsible of 5% of Honda's global output, producing up to 240,000 vehicles a year. On the other hand, the company suffered of supply chain disruption due to a lack of parts from Thailand. Honda Motor stopped production in Malaysia and other Honda plants in Asia adjusted production volume or suspended production due to the limited parts supply. Supply constraints had negative impact on North America and Europe vehicle availability too: adjustments such as overtime cancellation and non-production days scheduling were adopted in Canada and USA. Due to the two combined reasons, Honda's unit production of automobiles declined 4.6% from the previous fiscal year and net profit decreased more than half (60 billion JPY instead of 136 JPY). The production was gradually resumed at all factories since January 2012.

The decisive element that allowed Honda to promptly react to the event was the collaboration, not only among its subsidiaries and affiliates around the world, but also with suppliers and public sector. The supply chain structure, both internal and external, played an important role in it. As previously described, Honda's internal supply chain is characterized by many production facilities located around the world. The close cooperation among these subsidiaries and affiliates allowed to keep production lines running and to support a smooth recovery. For instance, Thai-built models made for Australia in the directly affected plant were temporary substituted with Japanese-made models, leveraging collaboration among facilities and the subsequent flexibility. However, the greatest support was received by suppliers, who work together with the company to change production bases and switch to alternative parts in order to face the supply shortage. Even though obtaining general-purpose electronic parts was difficult, Honda shared information with suppliers and worked with them to minimize the effects of the disaster by securing market inventory on a global scale and quickly developing alternative parts. To better assist providers in their operations, the company dispatched support teams to suppliers' facilities. Moreover, for what concern the affected plant in Ayutthaya, an army of Japanese engineers and production equipment supplier staffers, with the help of Honda workers, had the factory up and running in just three months. Therefore, collaboration with suppliers was determinant and Honda presented special letters of appreciation to 25 suppliers that made a particularly significant contribution to the recovery. It emerges that only some of the thousands of suppliers closely collaborated with Honda, demonstrating that a low number of providers allows more stability and closer relationships, thus a negative link between external supply chain complexity and resilience. Nevertheless, single-sourcing determines a lower flexibility in the supply: having only certain providers for some raw materials and parts, Honda could not shift request to alternative sources or diversified suppliers and was forced to suspend production due to the limited part supply.

Considering the demand side, both Honda and dealer representatives visited every Thai customer, in order to apologize for the delay and promise to deliver the cars as soon as possible. This had a positive effect on Honda-customer relations and most customers retained their order. It is quite logical to suppose a negative link between the number of customers and the velocity of action: more are the customers to visit, higher the required time.

The product dynamic complexity characterizing the supply chain positively affected the flexibility in reacting to the event. The high investments in innovation initiatives allowed to the R&D function to promptly act. Honda, together with the help of Australian government, homologated Japanese-made Honda Jazz and Civic cars in record time, allowing to substitute vehicles for Australia made in Thai plant with Japanese ones, avoiding any lack of vehicles in Australian showrooms. Furthermore, the company progressively procure alternative parts to face the supply shortage.

Table 5.22: *Influence of complexity drivers on resilience constituents in Honda Motor's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Many facilities around the world	+			+
High number of suppliers	+			-
High number of customers			-	
Product introduction	+			

5.12 Sapporo Group

The Sapporo Group is a Japanese group operating under a holding company framework in five different segments: Japanese Alcoholic Beverages, International Alcoholic Beverages, Food & Soft Drinks, Restaurants and Real Estate. It employs 7,858 employees and its yearly sales in 2016 amounted to about 4,508 million €, with an operating income of 169 million €. Brewing beer since 1876, it currently sells beer in about 45 countries and soft drinks in around 60 national markets. Mainly based in Japan, but with facilities in other countries too, Sapporo Group is pursuing strong growth all over the world thanks to its wide range of distinctive products and services, characterized by carefully selected ingredients.

The main characteristics determining Sapporo's supply chain complexity are (Table 5.23):

Table 5.23: *Sapporo Group's supply chain complexity drivers.*

Product structural complexity	➢ Broad portfolio Sapporo operates in 5 main segments: Japanese Alcoholic Beverages, including beer, wine and western spirits, (52% of 2016 net sales), International Alcoholic Beverages and Soft Drinks (12%), Food and Soft Drinks (26%), Restaurants (5%) and Real Estate, including leasing, management, operations and development of commercial complexes, office buildings and others (4%). Moreover, it is also present in other small businesses (1%). ➢ High product variability In the past, the company was engaged in activities that enable customers to customize their beer, such as the personalised labels of Wakuwaku Brewery. Moreover, it established a unique market position by launching various products tailored to customer preferences (e.g. Nippon Oolong)

(continue)

Internal structural complexity	➢ Facilities in different countries, but mainly in Japan Balance of property, plant and equipment located in Japan amounted to more than 90% of the total balance of property, plant and equipment. Considering the Alcoholic Beverages segments, the group has 8 breweries: 5 in Japan, 1 in Canada, 1 in USA and 1 in Vietnam. ➢ Outsourced activities Sapporo Group outsources the manufacturing of some products to external parties. It also handles products purchased from outside the group.
External structural complexity	➢ Close collaboration with suppliers Growers supplying Sapporo Breweries are involved in the Collaborative Contract Farming System (CCFS), a raw material procurement system based on specifying growing areas and methods and establishing close communication between growers and Sapporo (pre-seeding, pre-harvest and post-harvest meetings). This allows to ensure safe, reliable and high quality raw materials. In 2013 about 3.000 CCFS growers worked for Sapporo Breweries. ➢ High number of small customers The group serves a wide range of end consumers, with demand for products that match a wide range of occasions. Even though there is one customer whose share of sales accounts for about 15% of net sales (Kokubu & Co. Ltd., a food marketing company), all the others have a share lower than 10%.
Product dynamic complexity	➢ Product introduction The group leverages its unique knowledge and technology to promote research, ranging from traditional foods to new proposals, such as the use of soybeans as a source of vegetable protein.
Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities Sapporo Group is promoting global business expansion in North America and Southeast Asia. ➢ Improvements to equipment, procedures and systems In 2016 the group introduced a business structure reforms and a promotion of segments management, implementing a structure that fits actual state of growth and optimisation. R&D, HR and finance functions were strengthened. Moreover, new processing methods were developed, such as freeze-drying, granulation and pulverisation. ➢ M&A In 2016 Sapporo Group acquired three subsidiaries, lost one that ceased to exist after a merger and lost another one to liquidation. Thus, the number of consolidated subsidiaries at the end of the year was 55.
External dynamic complexity	➢ Demand side dynamics Asian beer market continues the steady expansion seen in recent years. Demand is highly affected by seasonality, with peaks in summer.

In March 2011, Sapporo Group suffered a big disruption due to the Japan earthquake, with heavy consequences over an extended period. Two out of five core breweries in Japan were damaged, accounting for a large share of sales. The disaster destroyed or damaged buildings, equipment, logistics facilities, product inventories and other assets in Sendai and Chiba, forcing the stop of production and product shipping activities. Other plants of Sapporo Breweries Ltd. were affected too, as well as some restaurants and other group's facilities. In addition, some of Sapporo Lion Ltd. restaurants in the interested areas had to shorten opening hours due to the bad state of infrastructures and other conditions. The most negative consequences of the event were suffered by the Japanese Alcoholic Beverage segment, which reported a loss of 4% in net sales, and, since it accounted for a large share of sales, product supply and marketing activities were heavily impacted. In total, the net income decreased of 70.6%, from 7.6 to 3.2 billion JPY. However, the group could quickly react and Sendai and Chiba plants completely reinstated the entire brewing process in a couple of months. Although Sapporo worked hard to ensure the stable supply of three core products (Sapporo Draft Beer Black Label, Yebisu Beer and Mugi to Hop), the impact of the event was heavy and it was forced to suspend others supplies, such as Yebisu the Black and Sapporo Lager Beer. It had to focus only to a few brands and delayed new product launches.

In such a situation, the internal structure of the Sapporo Breweries' supply chain negatively contributed to the consequences of the incident. As a matter of fact, five out of eight plants were concentrated in Japan, avoiding geographic diversification and making the company closely dependent on that area. This reduced the flexibility of the company, which could not leverage alternative breweries in different regions not affected by the earthquake, and thus its results were heavily affected.

A positive role, instead, was played by the wide portfolio breadth characterizing the group. Due to the earthquake, customers demand in Japan shifted from Alcoholic Beverages to Soft Drinks, making sales of mineral water and unsweetened beverages rise. Therefore, Sapporo could leverage a different business segment, whose production facilities were in other countries, such as Germany. This allowed the company to flexibly cover losses in Alcoholic Beverages business.

Other supply chain complexity drivers did not play a significant role in the event.

Table 5.24: *Influence of complexity drivers on resilience constituents in Sapporo Group's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Wide portfolio breadth	+			
Facilities in different countries	+			

5.13 Goodyear Tire and Rubber Company

The Goodyear Tire and Rubber Company is one of the world's leading tire companies, developing, manufacturing, marketing and distributing tires for most applications. In addition, it also manufactures and markets rubber-related chemicals for various applications. Founded in 1898, with only 13 workers producing bicycle and carriage tires, it nowadays employs nearly 66,000 employees and has operations in most regions of the world, with 48 facilities in 21 different countries. In 2016, its sales were 13,694 million € and its operating income was 1,793 million €. Goodyear's mission is to deliver quality products driven by integrity, innovation and teamwork, thus it has always strived to serve customers in the best way.

Goodyear's supply chain is characterized by the following elements (Table 5.25):

Table 5.25: *Goodyear's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth Goodyear mainly operates in the tire manufacturing industry, serving 5 different segments: aviation tires, commercial truck tires, off-the-road tires, racing tires, recreational vehicle tires. Moreover, it also produces rubber-related chemicals for various applications, such as synthetic rubber, latex, rubber chemicals etc. Finally, it offers automotive and commercial repair services and other products and services. It has six important brands: Goodyear, Fulda, Dunlop, Sava, Kelly and Debica. ➢ High quality The company's mission is focus on the high quality of products.
Internal structural complexity	➢ Many facilities across the world The company has operations in most regions of the world, having 48 facilities in 21 different countries. Moreover, it has approximately 180 warehouse distribution facilities. Most assets are in Americas (49%) and Europe, Middle East and Africa (32%), while only 19% are in Asia Pacific area. Goodyear operates approximately 1,100 tire and auto service centre outlets, where it offers products for retail sale and provides automotive repair and other services.
External structural complexity	➢ Few rubber suppliers, many other suppliers Manufacturing and processing of both natural and synthetic rubber are done by a few large players, who produce great volumes around the world. On the contrary, most of other raw materials and components are purchased in significant quantities from several suppliers, except in those instances where only one or a few qualified sources are available. Many suppliers are large multinational companies that invest in production capacity, thus business continuity is ensured on a global level. Transparency is a key characteristic of Goodyear's supply chain: it continuously evaluates the raw materials, including material characteristics, country of origin, energy composition and social and regulatory activities. Periodic supplier audits are performed and supply sustainability is formalized through the Supplier Code of Conduct. ➢ High number of customers Goodyear serves two kinds of customers: OEM (20%) and replacement (80%). Its main channels are independent multi-brand tire dealers, numerous national and regional retailers and its own stores. Most of net sales are concentrated in Americas (54%), the other in Europe, Middle East and Africa (32%) and Asia Pacific (14%).
Product dynamic complexity	➢ Product introduction Goodyear is committed to continuous improvement and innovation, developing great products and services. In 2016 it received 765 worldwide patens and 16 new consumer and commercial truck tire products were launched across the world. The tire portfolio is continuously refreshed and revitalized.

(continue)

Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities To support growth, last years have been characterized by construction, expansion and modernisation of manufacturing capacity in USA, Brazil, China, Germany and Mexico. The advantaged supply chain is focused on reducing total delivered costs, optimizing working capital levels and delivering best in industry customer service. ➢ Improvements to equipment, procedures and systems Recently the unification of North America and Latin America into a unique strategic business unit determines a new organisational structure. Furthermore, rationalisation actions were initiated in 2011, in order to reduce manufacturing, selling, administrative and general expenses through headcount reductions. ➢ M&A The company restructures itself through mergers and acquisitions. For instance, in 2016, it grew due to the acquisition of a controlling interest in Nippon Goodyear Ltd. in Japan. But it also dissolved the global alliance with Sumitomo Rubber Industries.
External dynamic complexity	➢ Supply side dynamics Naturally and synthetic rubber prices and other commodity prices historically experienced significant volatility. Therefore, Goodyear is working to identify additional substitution opportunities, to reduce the amount of material required and to pursue alternative raw materials. ➢ Demand side dynamics The global demand for premium is increasing: market doubled between 2010 and 2015 and is expected to double again by 2020.

The catastrophic flood in Thailand in autumn 2011 disabled many manufacturing operations, including Goodyear's main aviation tire manufacturing facility in Bangkok, which stopped its production in October. The company worked around the clock to bring the manufacturing facility back to full production as soon as possible. However, re-start was subject to many factors, such as equipment status, availability of materials, ability to ship product and materials in and out of Thailand, and the plant was completely restored only in the third quarter of 2012. Despite other facilities outside of affected region ramped up aviation tire production and Goodyear searched for alternative solutions, the shutdown in Bangkok led to a decrease in available supply of tires for the commercial airline industry in February and March 2012, determining a business loss of 16 million $, including business interruption and clean-up costs.

Some of the complexity drivers characterizing its supply chain allowed Goodyear to resiliently react to the incident. As aforementioned, the first countermeasure adopted was to ramp up production in facilities outside of Thailand: the company started a new tire manufacturing in Virginia and re-treaded production in Georgia, Arizona and Netherlands. Therefore, the presence of many facilities around the world enhanced the flexibility of the company, but also the collaboration among different plants. Furthermore, Goodyear could be more flexible and rapid in doing it, since it is used to construct, expand and modernize manufacturing capacity in different regions of the world.

The high quality of Goodyear's products contributed to flexibility too: leveraging on material resistance, the company reminded aircraft operators to follow recommended tire care and maintenance procedures to safely ensure maximum tire performance and maximize tire life. This was also possible thanks to the regular communication that Goodyear maintained with its customers. Since October, a regular contact with commercial airline customers was established, to keep them apprised of the situation as more information became known and regarding potential global shortage of bias aviation tires. It played a fundamental role in the event and the velocity of this action was determined by the number of customers the company had to communicate to.

Then the company also leveraged the assistance and support from its suppliers to enable the fastest possible return of full supply of global aviation tires in addition to restoring full production at Goodyear’s Bangkok facility. It is possible to assume that a higher number of available suppliers implies a higher help from this side, thus increasing the collaboration of different companies with Goodyear.

Finally, the company pursued other viable sources of tire supply for its customers, leveraging assistance from other aircraft tire manufacturers, being confident in the high-quality tires it obtained from qualified sources. The visibility of Goodyear on competitors to which ask for help derived from its ability in building alliances in the industry, as indicated by the mergers and acquisitions characterizing its history, which also increased collaboration.

Table 5.26: *Influence of complexity drivers on resilience constituents in Goodyear's case.*

Complexity drivers	**Flexibility**	**Visibility**	**Velocity**	**Collaboration**
High product quality	+			
Many facilities across the world	+			+
High number of suppliers				+
High number of customers			-	
Reconfiguration of SC	+		+	
M&A		+		+

5.14 Procter and Gamble Co.

Procter and Gamble Co., known as P&G, is a global leader in fast-moving consumer goods, including fabric care, home care, grooming, oral care, baby care, feminine care, family care, personal heat care, hair care, and skin and personal care products. It operates in 70 countries and sells products in more than 180 countries around the world, employing approximately 95,000 people. In the fiscal year ended in June 2017, its sales amounted to 58,813 million € and its operating income to 12,648 million €. Founded in 1837, during its 180 years of history P&G grew and changed a lot, but its focus on making peoples’ lives easier endured. The company’s mission is to provide branded products and services of superior quality and value, improving lives of world’s consumers.

Even though streamlined in recent years, Procter and Gamble's supply chain is quite complex, both from a structural and dynamic point of view, as shown it Table 5.27.

Table 5.27: *P&G's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth P&G's businesses are grouped in 5 segments: Beauty (18% of 2017 net sales), baby, Feminine and Family Care (28%), Fabric and Home Care (32%), Health Care (12%) and Grooming (10%). In total, the company has 66 brands. ➢ High product specificities P&G focuses on high standard of excellence for all the brands, with greater superiority in products, packaging and marketing. Moreover, products must be ensured to be safe for their intended use, complying with a wide variety of laws and regulations.
Internal structural complexity	➢ Many facilities across the world The company owns and operates 24 manufacturing sites located in 18 different states in USA, as well as 89 manufacturing sites in 38 other countries. ➢ Outsourcing Given the wide scope and the high scale of the business, P&G relies on relationships with third parties, such as contractors, joint venture partners and external business partners, for certain functions. ➢ Few differences between different facilities in different territories Many of the domestic and international sites manufacture products for multiple businesses (Beauty products are manufactured at 24 locations, Grooming products at 21, Health Care products at 17, Fabric & Home Care products at 43, and Baby, Feminine & Family Care at 41). In rare cases, the company has to rely on sole manufacturing plant arrangements.
External structural complexity	➢ High number of suppliers Even though P&G produces certain raw materials, primarily chemicals for further use in the manufacturing process, almost all raw and packaging materials are purchased from nearly 80,000 suppliers. Some of them are sole-source suppliers. The company highly relies on fuel, natural gas and derivative products, fundamental commodities consumed in manufacturing process and in the transportation of input materials and of finished products. ➢ High variety of customers P&G's customers are mass merchandisers, grocery stores, membership club stores, drug stores, department stores, distributors, wholesalers, baby stores, specialty beauty stores, e-commerce, high-frequency stores and pharmacies. Wal-Mart Stores Inc. and its affiliates represent approximately 16% of total sales, while no other customer represents more than 10%. The top ten customers accounted for approximately 35%. The company establishes close mutually productive relationships with its customers, in order to develop superior understanding of their needs.
Product dynamic complexity	➢ Product introduction Innovation is a pillar of Procter and Gamble's strategy, continuously challenging convention and reinvent the way to do business. In 2016 the company introduced 16 new products, while 12 in 2015.

(continue)

Internal dynamic complexity	➢ Reconfiguration of supply chain activities and facilities In the past ten years, P&G drastically reduced its manufacturing platforms, passing from 500 to few more than 100 facilities. In addition, the company is seeking opportunities ahead in raw and packaging materials and savings in manufacturing expense, transportation and warehousing. Therefore, it synchronized the supply network and replenishment systems from suppliers to customers. ➢ Improvements to equipment, procedures and systems The company is moving to an end-to-end business ownership and accountability approach in large markets, meaning that category business leaders have full decision-making authority from the front end of innovation all the way through to the customer. Moreover, to improve operational effectiveness and organisational culture, clarity of roles and responsibilities is enhanced and incentive compensation programs are introduced. ➢ M&A As a company that manages a portfolio of consumer brands, ongoing business model includes a certain level of acquisition, joint venture and divestiture activities. During 2016/2017 P&G completed the brand portfolio transformation: it streamlined and strengthened it by divesting, discontinuing and consolidating 105 brands. It also completed divested Batteries and Pet Care businesses.
External dynamic complexity	➢ Supply side dynamics Certain commodities, such as oil-derived materials like resins, are characterized by volatility, thus their prices highly fluctuate. ➢ Demand side dynamics Grooming and personal health care segments are quite seasonal.

In August 2005 Hurricane Katrina devastated the New Orleans area, hardly hitting every supply chain with a presence there. Folgers, a Procter and Gamble's brand producing coffee, was forced to stop manufacture and distribution, negatively affecting the operating earnings of approximately 2%, due to write-offs of damaged inventory and physical assets and clean-up and repair costs. Folgers represented the 40% of all coffee sold in USA for home consumption and more than half its production was based in New Orleans, in four main facilities: a huge plant, a smaller one adjacent to previous, a large storage operation centre and a distribution centre, where packaged coffee is held for shipment to retailers. Both the manufacturing plants are in Orleans Parish, one of the areas hit hardest by the storm and the following flooding. The biggest plant suffered damages for more than 10 million $ and it was inaccessible, since all the routes where disrupted and the only access to the facility was by helicopter. Even though the company had preventive shutdown procedure, it was not able to complete them before the hurricane hit, thus the equipment became clogged with coffee tar.

Despite of the severity of the incident, a coordinated and well-rehearsed strategy allowed Procter and Gamble to quickly get back in operations in record time, also thanks to some supply chain complexity drivers. First, the company was prepared to face the event thanks to its detailed business continuity plant, designed for each facility and rehearsed annually. In particular, a series of emergency countermeasures were adopted before the hurricane hitting the area: inventory was transferred to distribution centres outside New Orleans, inventory backup tapes were sent to headquarters in Cincinnati, Ohio, and a procedure for the facilities shutdown was started. The first two actions were possible thanks to the high number of facilities owned by the company. Therefore, the structural complexity of the internal supply chain positively affected the flexibility and the collaboration among different sites. Cincinnati became the command centre for dealing with suppliers and engineering contractors and a command post was established at a plant in Louisiana (225 miles north of New Orleans). Executives began working on logistical issues, reshuffling schedules for local managers who had no working computers. Production was restored in other sites around the country and workers from P&G's operations outside coffee were employed, since many of those in that division personally suffered the disruption and had to pull their lives together. This was possible due to the wide portfolio breadth of the company, but also because many of the domestic manufacturing facilities were similar and planned for multiple businesses. Thus, it emerges that apart from the high number of sites increasing flexibility and collaboration, also the portfolio breadth positively contributes, while differences between facilities in different territories have a negative impact.

Then, the support for recovery provided by suppliers was tireless and invaluable. They, included former suppliers with whom Folgers maintained positive relationships, proactively offered people, supplies and other resources to create alternative supply channels and accelerate recovery effort. It is possible to assume that higher the number of suppliers, higher the help and collaboration received by these actors.

Finally, a dual role was played by the high number and variety of customers, to which Folgers rationed existing supplies, to minimize disruptions. On the one hand, for the same previous logic, collaboration is more if more customers are available for help: distributing coffee to many retailers and grocers the company could exploit them to manage the volumes. On the other hand, the ration on a high number of actors was complex and slow, thus negatively affecting velocity.

Table 5.28: *Influence of complexity drivers on resilience constituents in P&G's case.*

Complexity drivers	**Flexibility**	**Visibility**	**Velocity**	**Collaboration**
High portfolio breadth	+			+
Many facilities across the world	+			+
Differences between facilities	-			-
High number of suppliers				+
High variety of customers			-	+

5.15 Johnson & Johnson

Johnson & Johnson is a multinational company broadly based in human health care, manufacturing medical devices, pharmaceuticals and consumer personal care goods.

Headquartered in New Jersey, it operates through more than 230 subsidiaries located in 60 countries around the world. Its sales in 2016 were 64,947 million €, while operating income was 19,803 million €. The company, which nowadays employs nearly 126,400 workers, was founded in 1886 by the three Johnson brothers and for over 130 years it has been creating value by developing accessible, high quality and innovative products and services. Following the mission of helping people everywhere live longer, healthier and happier lives, the company keeps the patient and consumer at the centre of everything it does.

Johnson & Johnson's supply chain can be described through complexity drivers in Table 5.29.

Table 5.29: *Johnson & Johnson's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth The company operates in three segments: Pharmaceuticals, divided in 5 therapeutic areas (immunology, infectious diseases and vaccines, neuroscience, oncology, and cardiovascular and metabolic diseases), Consumer, including products used in the baby care, oral care, beauty, over-the-counter pharmaceutical, women's health and wound care markets, and Medical Devices, with a broad range of products used in the orthopaedic, surgery, cardiovascular, diabetes care and vision care fields. ➢ High product specificities Drug, medical device and cosmetic industries are subject to regulation by various federal and state agencies.
Internal structural complexity	➢ Many facilities all around the world Johnson & Johnson operates in 60 countries around the world, with 119 manufacturing facilities. It has 35 plants in USA, 37 in Europe, 33 in Africa, Asia and Pacific, and 14 in Western Hemisphere excluding USA. Moreover, it has many offices and warehouses. R&D facilities are in the US, Belgium, Brazil, Canada, China, France, Germany, India, Israel, Japan, the Netherlands, Singapore, Switzerland and the UK.
External structural complexity	➢ High number of suppliers Raw materials are generally readily available from multiple sources and Johnson & Johnson has thousands of suppliers around the world (over 78,000 in 2014). There are few exceptions, but the company ensures that their temporary unavailability would not have a material adverse effect on financial results. Building collaborative relationships with suppliers is important because it helps to identify innovative new approaches to grow mutual businesses. Moreover, since having a diverse supplier base reflecting patients and customers ensures better innovation, the company works with small and diverse suppliers, such as certified minority-owned businesses, certified woman-owned businesses and certified small disadvantaged businesses.

(continue)

External structural complexity	➢ High variety of customers Johnson & Johnson sells to many different customers globally. On the one hand, Consumer segment products are sold to retail outlets and distributors throughout the world, on the other hand Pharmaceuticals are distributed directly to retailers, wholesalers, hospitals and health care professionals. Finally, Medical Devices are sold to wholesalers, hospitals and retailers, and used principally in the professional fields by physicians, nurses, hospitals, eye care professionals and clinics.
Product dynamic complexity	➢ Product introduction One of the growth drivers characterizing Johnson & Johnson's strategy framework is innovation, demonstrated by the continuous launching of key science-based new products. Approximately 22% of 2016 sales was constituted by new products introduced within the past 5 years. Considering for instance Medical Devices segment, at least 12 launches are planned for 2017, more than doubling the 2016 number.
Internal dynamic complexity	➢ Restructuring The company is restructuring the Medical Devices segment, aiming at strengthening the go-to-market model, accelerate the pace of innovation, further prioritize key platforms and geographies and streamline operations, while maintaining high quality standards. ➢ M&A In 2016, 14 acquisitions or significant licensing deals and 8 divestitures were completed. As a matter of fact, acquisitions, if done at the right time and price, are considered a strong mean to drive growth and create value for the shareholders.
External dynamic complexity	➢ Demand side dynamics Demand in health care industry in developing market is growing 3 or 4 times faster than in developed ones.

In 2010, quality and safety violations led to the shutdown of a manufacturing plant in Fort Washington, Pennsylvania, belonging to McNeil Consumer Healthcare, a Johnson and Johnson's subsidiary producing Tylenol and other over-the-counter drugs. As matter of fact, after an inspection, the US Food and Drug Administration accused the company of 20 violations: the plant had a large gap in the ceiling and dust in areas that should have been clean, such as incubators and a filtered cabinet; quality control procedures were not followed and did not ensure product uniformity; since employees were not trained in current good manufacturing practices, they failed to reject any non-compliant lot; although they had never reached the Fort Washington facility, some vendor's drums used to transport raw materials were contaminated with a bacteria. Since the lack of proper controls in the manufacturing process led to some batches of infant's Tylenol having too much of some ingredients, thus being "super-potent", McNeil was forced to recall the drugs and to suspend production at the plant, while making significant investment in new equipment and outfitting it. In addition, the company failed to follow up on 46 consumer complaints received from June 2009 to April 2010 due to foreign materials, unusual odours or dark specks, causes that had determined a long series of recalls in those years. Given the scope of the problem, the shutdown lasted more than two years and costed the company 900 million $ in lost sales. Moreover, the reputation damages were heavy.

Only two supply chain complexity drivers played an important role in the event: the internal structure of the supply chain and the external one on the supply side. Regarding the former, on the one hand, Fort Washington facility was the only one manufacturing all of McNeil paediatric over-the-counter drugs, while the other two plants made adult medicines. Therefore, even though facilities in Las Piedras, Puerto Rico, and Lancaster, Pennsylvania, continued to operate, the shutdown represented a heavy disruption in the industry. However, Johnson & Johnson had other brands' facilities that could be involved in the effort to re-site the affected products and return them to store shelves. In 2011 McNeil validated alternative sites and a modest amount of drugs could return to the market in the fourth quarter. Both the considerations demonstrate the positive link between the redundant and high number of facilities and flexibility and collaboration.

Considering instead the supply side complexity, it positively affected collaboration. Hundreds of supply chain associates were involved in the effort to find an alternative supply and to ramp up their production in the following period, in order to return drugs on the market. Therefore, many actors collaborated, increasing resilient response of the company to the event.

Table 5.30: *Influence of complexity drivers on resilience constituents in Johnson & Johnson's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
High number of facilities	+			+
High number of suppliers				+

5.16 Volkswagen Group

Headquartered in Wolfsburg, Volkswagen AG is a German group leader in the automotive sector, manufacturing and distributing passenger and commercial vehicles, motorcycles, engines and turbomachinery, and offering related financing services. It includes twelve famous brands, such as Audi, Lamborghini, Porsche, Seat and Volkswagen, each one with its own individual identity, but all having mobility for everyone all over the world as common goal. At the end of the fiscal year 2016, Volkswagen's sales were 217,267 million € and operating income was 7,103 million €. Having nearly 626,715 employees, the has 120 production locations in different countries: the majority in Europe (71) and Asia-Pacific (31), the others in America (14) and Africa (4). Founded in 1937, Volkswagen rapidly scaled up in 1950s and 1960s, subsequently acquiring other companies and becoming an international group, promising sustainable, safe and individual mobility to everyone.

Table 5.31 collects the static and dynamic complexity drivers characterizing Volkswagen's supply chain.

Table 5.31: *Volkswagen's supply chain complexity drivers.*

Product structural complexity	➢ High portfolio breadth Volkswagen AG has two divisions: Automotive and Financial Services. The former includes 12 brands (Volkswagen Passenger Cars, Audi, ŠKODA, SEAT, Bentley, Bugatti, Lamborghini, Porsche, Volkswagen Commercial Vehicles, Scania, MAN, Ducati), manufacturing more than 335 models. It serves three different segments: Passenger Cars, Commercial Vehicles, Power Engineering Business Areas. Its products are passenger cars, light commercial vehicles, trucks, buses and motorcycles, genuine parts, large-bore diesel engines, turbomachinery, special gear units, propulsion components and testing systems. The latter, instead, offers dealer and customer financing, leasing, direct bank, insurance, fleet management and mobility offerings. ➢ High product variety, but modularity Volkswagen offers tailor-made mobility solutions, meeting diverse customers' needs. For instance, the new Crafter has been completely redesigned based on specific customer requirements, offering customer-friendly functionality and practical solutions. Phideo, instead, is a model specially designed for the needs of Chinese customers. Finally, with Scania customers are able to choose from 24 different cab models offering bespoke configuration. To be flexible, the group leverages modular toolkits and architectures. ➢ Strict product specificities The group has to satisfy stricter and stricter emission standards.
Internal structural complexity	➢ Many facilities all around the world Volkswagen's global cross-brand production network has 120 production locations: 71 in Europe, 31 in Asia-Pacific, 14 in America and 4 in Africa. The group has three R&D centres in Germany, China and the USA. ➢ No differences between facilities in different territories Out of 120 locations, 68 are dedicated to passenger cars, commercial vehicles and motorcycles, while 52 to powertrains and components. The production process is standard across facilities, since the goal is to optimize and expand production system throughout the world at all brand and regional locations. Therefore, several brands use the same production locations and exploit synergies based on platform strategy. This network designed, called multi-brand locations, allows to flexibly respond to market requirements and dynamically adapt to demand changes.
External structural complexity	➢ High number of suppliers, mainly local Even though the group relies on a huge base of suppliers, only 55 of them are strategic, meaning they selected suppliers to which Volkswagen is dialoguing for 61 competencies and agreed joint targets. In 2016, 25,000 supplier locations completed the online training program, while more than 800 completed the face-to-face training sessions. In order to ensure worldwide availability of uniform components, suppliers are assessed before being commissioned to perform projects. The group prefers local suppliers close to production plants. However, suppliers who meet requirements, also have an opportunity to move beyond their local market and deliver their products to other locations around the world.

(continue)

External structural complexity	➢ High customer requirements Although different brands satisfy different needs, all Volkswagen's customers expect a high-quality range of mobility products and first-class service. Therefore, customer satisfaction is the top priority of the group, often concretized in long-term partnerships. In particular, customers can be divided in two main categories: retail and fleet customers. The latter are more stable and satisfy their individual mobility needs from a single source. They are mainly in Germany, but also in the rest of Europe. Variety of requirements depend on the different markets. For instance, some vehicles are developed exclusively for the Chinese market (e.g. Volkswagen Lamando, Lavida, New Bora, New Jetta and New Santana)
Product dynamic complexity	➢ Product introduction Each year new models are introduced, e.g. 60 new vehicles are planned for 2017, and the group is investing a lot in e-mobility and connectivity. The aim is to develop or acquire new services more and more tailored to customer requirements, such as robotaxis, car-sharing or on-demand transport for the logistics industry. A key building block of the Volkswagen's strategy is to transform core business by sharpening positioning of brands and optimizing vehicle and drivetrain portfolio to focus on the most attractive and fastest-growing market segments. As a matter of fact, the group is completely repositioning the Volkswagen Passenger Cars brand. Moreover, it is reviewing and streamlining modular toolkits to reduce complexity in development and production.
Internal dynamic complexity	➢ Reconfiguration of SC activities and facilities In 2016 production began at two new plants in Poland and Mexico. Furthermore, capacity at the Chengdu site, in China, was increased by 100,000 vehicles. Finally, the group will develop battery technology as a new core competency, thus reducing the risk of becoming dependent on suppliers. ➢ Improvement to equipment, procedures and systems Volkswagen's strategy includes the implementation of a product line organisation in the high-volume passenger car brands, as well as the development of new core competencies in forward-looking areas such as autonomous driving and artificial intelligence. To improve the operational excellence, the group is digitally transforming itself, introducing Industry 4.0 in production and logistics and digitalizing sales. Moreover, the Organisation 4.0 initiative aims at putting in place a more attractive and up-to-date work organisation. Therefore, structures and processes are changed in everyday work situations. Volkswagen Truck and Bus, bundling Man and Scania, has a pioneering role in digitalisation: an open cloud-based platform is used across the entire transport and logistics system, thus everyone in the supply chain is connected via a single information and application system with forecasting feature.

(continue)

Internal dynamic complexity	➢ Restructuring A plan for restructuring was approved in September 2015, introducing a new management model to be implemented since 2016. The main changes are: the introduction of a management structure based even more consistently on modular toolkit system, the set-up of organisational units for digitalisation, new business fields and cooperation, the streamlining of structures and processes at group level, strengthening individual brands and regions, and, finally, the transferring of existing responsibilities for R&D, production and sales functions to a new organisational structure. ➢ M&A Acquisitions and venture capital investment characterize the company's strategy. Furthermore, it leverages joint ventures, e.g. the wide-ranging alliance with US commercial vehicle manufacturer Navistar, including a supply cooperation pursuing joint global sourcing opportunities.
External dynamic complexity	➢ Demand side dynamics Automotive world is transforming due to e-mobility, autonomous driving and connected vehicle concepts. These technological trends are influencing customer needs and business models, together with stricter emission standards, increased market volatility and shorter innovation cycles. In addition, worldwide the number of passenger car registrations increased to 81.1 million in 2016, while demand for light commercial vehicles was up slightly overall on the previous year. ➢ New suppliers Volkswagen has been forging new partnerships in recent months. ➢ New customers Volkswagen is expanding global presence, focusing on North America and China.

In September 2015, the US Environmental Protection Agency (EPA) issued a notice of violation of the Clean Air Act to Volkswagen AG, accused to have used undisclosed engine management software installed in certain four-cylinder diesel engines in vehicles produced between 2009 and 2015 in order to circumvent nitrogen oxide emissions testing to comply with certification requirements. The company intentionally programmed turbocharged direct injection diesel engines to activate certain emissions controls only during emissions testing. Following these announcements, authorities in various other jurisdictions worldwide started their own investigations and independent tests proved that under normal driving conditions diesel vehicles exceeded legal European emission limits for nitrogen oxide by more than 10 times. On September 22, the group publicly admitted to irregularities affecting more than 11 million diesel vehicles in the world. The starting point of emission scandal was the strategic launch of a large-scale promotion of diesel vehicles in the USA, decided in 2005, which determined the development of a new diesel powertrain unit featuring high performance and cost-efficient production. Since the strict standards for emissions of pollutants in the USA were conflicting because measures to reduce nitrogen oxide categorically had a knock-on effect on other parameters (e.g. CO2), a group of persons decided to modify the engine management software that generated emissions values in bench testing substantially different from those under real driving conditions. The current Board of Management of Volkswagen AG had no knowledge of the use of unlawful engine management software.

As a result of the diesel issue, 16.2 billion € of provisions were totally recognized and charged to operating result, primarily for pending technical modifications, for recalls and repurchases and for customer-related and legal risks measures. The significant impact on the company was reflected by the 2015 financial key performance indicators: despite the increase of sales revenue, the operating result was negative, - 4,069 million €. However, in 2016 it was again positive, even though halved with respect to 2014 (7.1 instead of 12.6 billion €).

Considering the complexity drivers characterizing Volkswagen's supply chain, some of them played a role in facing the emission scandal. Volkswagen AG worked intensively to implement technical solutions and modify affected vehicles recalling them. The strict emissions rules and high specifications typical of the automotive industry negatively affected the velocity and the flexibility of the company in finding technical solutions, due to the needed approval by different agencies (e.g. US EPA, Environmental Protection Agency, and CARB, California Air Resources Board), ensuring that all legal requirements are met. In addition, since different countries have different standards (i.e. customer requirements) the group adopted different approaches to fixing vehicles. As a matter of fact, stricter nitrogen oxide limits in the USA made greater the technical challenge to refill the vehicles and thus agreements were reached only in December 2016, almost one year after Europe. On the one hand, the installation of a new emission filtration system using urea as an additive was expected in many vehicles in the USA, due to the tougher pollution standards. On the other hand, it was not involved in repairs in Europe, where the solution was a flow transformer fitted in front of the air mass sensor to improve sensor's measuring accuracy. Therefore, while in Europe all vehicles were recalled for the modifications, in the USA customers were provided with option of a buyback or, for leased vehicles, early lease termination, or a free emissions modification of the vehicles only if possible.

Recalls for free modifications were implemented with the same approach all over the world: owners of affected vehicles, after being notified, took an appointment for modification in an authorized partner workshop of their choice and were offered an appropriate replacement vehicle free of charge. The presence of Volkswagen all over the world, not only gave it a higher visibility on the involved customers, but also increased velocity of implementation. Thus, the high number of facilities in different region positively affected these two resilience constituents, offering production of technical solutions close to customers. For the same reason, if facilities had been different, it would have negatively affected velocity.

Technical solutions were flexibly and quickly identified thanks to the investments of the company in R&D and new products introduction. The company intensively focused on the issue, in order to introduce software and in some cases hardware modifications, which would not bring about any unfavourable changes in fuel consumption, engine power, torque and noise emissions.

As for the variety and number of customers, in the 2015 Annual Report is reported that fleet customers business did not record significant volume decreases, given clarification and technical solutions. This category of customers is the more stable and it is supposed to be not numerous and characterized by strong partnerships, also because they consider Volkswagen as single source. Therefore, a lower number of customers allows a deeper relationship with them, increasing collaboration. In the considered event, it allowed to maintain their sales volume.

Finally, after the diesel scandal, Volkswagen decided to comprehensively change testing practices on the technical side, as well as to implement a new group structure. It introduced more clearly structured and systematic processes on the technical side and decided that emissions tests should be externally evaluated by independent third parties. Moreover, it introduced a new set of regulations for the procedure in control unit software development, emission classification and escalation management. Considering the restructuring of the group, the company decided for a more decentralized management, with greater independence for brands and regions, in order to have better responsibility sharing and more efficient decisions. On January 2016, it set up a new Board of Management position for Integrity and Legal Affairs, responsible for planning and implementing programs aimed at intensifying collective awareness of integrity. Being used to continuous processes improvement and being already approving an organisational restructuring of the group, Volkswagen could better manage these interventions, being more flexible and rapid.

Table 5.332: *Influence of complexity drivers on resilience constituents in Volkswagen's case.*

Complexity drivers	Flexibility	Visibility	Velocity	Collaboration
Strict product specificities	-		-	
Many facilities around the world		+	+	
Differences between facilities			-	
Different customer requirements	-		-	
High number of customers				-
Product introduction	+		+	
Procedures and systems improvements	+		+	
Restructuring	+		+	

5.17 Results

After the presentation of the critical incidents, this section collects the results, through tables summarizing the emerging evidence. The first two matrixes (Table 5.33 and Table 5.34) are a synthesis of the impact of the supply chain complexity drivers on the resilience constituents in each incident case, considering static and dynamic complexity respectively. Each cell reports if the role of the driver is positive or negative and which resilience constituent was influenced. In some cases, there is not proper information to clearly assess the role (i.e. those reporting "no evidence"). Cells are blank where the complexity driver cannot be identified for the considered case, due to the scarce information.

Table 5.33 *Influence of supply chain structural complexity drivers on resilience constituents.*

		Portfolio breadth	**Product var. and spec.**	**N. and layers SC facilities**	**Differ. between facilities**	**N./var. of suppliers**	**Variety customer requires**
1	**Takata Corporation**	no	+, collab.	+, flex. +, visib. +, collab.	-, flex -, collab.	no evidence	-, visib. -, collab.
2	**Dell Inc.**	no	+, flex	no evidence		-, visib. -, collab.	+, flex
3	**Evonik Industries**	no	+, flex	no evidence	-, flex -, collab.	no evidence	+, flex +, collab.
4	**Boeing**	+, flex	no evidence	no evidence	no evidence	+, flex -, visib. -, collab.	no evidence to assess the role
5	**Sanofi Genzyme**	no	no evidence	no evidence	-, flex -, collab.	no evidence	+, flex +, collab.
6	**Mitsubishi Motors Corporation**	no		+, flex +, veloc. +, collab.		+, flex	
7	**Nestle S.A.**	no evidence		no evidence	no evidence	-, visib. -, veloc. -, collab.	-, veloc.
8	**SK Hynix Inc.**	no	-, flex	+, flex +, collab.	no	no	no evidence to assess the role
9	**PSA Peugeot Citroën**	no	no evidence	no evidence	no evidence	+, flex -, visib. -, veloc.	no evidence to assess the role
10	**Mattel Inc.**	no	no evidence	+, flex +, visib.	no evidence	no evidence	-, visib. -, collab.
11	**Honda Motor Co. Ltd.**	no evidence	no evidence	+, flex +, collab.	no evidence	+, flex -, collab.	-, veloc.
12	**Sapporo Group**	+, flex	no evidence	+, flex		no evidence	no evidence to assess the role
13	**Goodyear Tire and Rubber Company**	no	+, flex	+, flex +, collab.		+, collab.	-, veloc.

(continue)

		Portfolio breadth	Product var. and spec.	N. and layers SC facilities	Differ. between facilities	N./var. of suppliers	Variety customer requires
14	**Procter and Gamble Co.**	+, flex +, collab.	no evidence	+, flex +, collab.	-, flex -, collab.	+, collab.	-, veloc. +, collab.
15	**Johnson & Johnson**	no evidence	no evidence	+, flex +, collab.		+, collab.	no evidence to assess the role
16	**Volkswagen Group**	no	-, flex -, veloc.	+, visib. +, veloc.	-, veloc.	no	-, flex -, veloc. -, collab.

Table 5.34: *Influence of supply chain dynamic complexity drivers on resilience constituents.*

		Product LC events	Reconfig. of SC	Impro-vements	M&A	Demand /supply dynamics	New customers /suppliers
1	**Takata Corporation**	+, veloc.	+, flex. +, veloc.	no evidence	+, visib. +, collab.	no evidence	no evidence
2	**Dell Inc.**	no evidence	+, flex. +, visib. +, veloc.	+, flex. +, visib. +, veloc.	no	+, flex. +, collab.	
3	**Evonik Industries**	+, flex.	no evidence	no evidence	no evidence	no evidence	no evidence
4	**Boeing**	no evidence	no evidence	no evidence	no evidence		+, flex. +, visib.
5	**Sanofi Genzyme**	+, flex.	no evidence	no evidence	no evidence		
6	**Mitsubishi Motors Corporation**	no evidence	no evidence	no evidence	no evidence		
7	**Nestle S.A.**	+, flex. +, veloc.		no evidence	no evidence	+, veloc. +, collab.	
8	**SK Hynix Inc.**	no evidence	no evidence	+, flex. +, veloc.	no evidence	no evidence	no
9	**PSA Peugeot Citroën**	no evidence	no evidence	no evidence	no evidence	no evidence	no evidence
10	**Mattel Inc.**	no evidence	+, flex. +, veloc.	+, flex. +, veloc.	no	+, veloc.	no evidence
11	**Honda Motor Co. Ltd.**	+, flex.	no evidence	no evidence	no evidence	no evidence	
12	**Sapporo Group**	no	no evidence	no evidence	no evidence	no evidence	
13	**Goodyear Tire and Rubber Company**	no	+, flex. +, veloc.	no evidence	+, visib. +, collab.	no evidence	

(continue)

		Product LC events	Reconfig. of SC	Impro-vements	M&A	Demand /supply dynamics	New customers /suppliers
14	**Procter and Gamble Co.**	no	no evidence	no evidence	no evidence	no evidence	
15	**Johnson & Johnson**	no			no evidence	no evidence	
16	**Volkswagen Group**	+, flex. +, veloc.	no evidence	+, flex. +, veloc.	+, flex. +, veloc.	no evidence	no evidence

Then, table 5.35 maps the considered incident cases, identified with a number, crossing the supply chain complexity drivers and the resilience constituents. The presence of a company's number in a cell means that in that case the specific complexity driver affects the resilience constituents, either positively (i.e. dark values, "X") or negatively (i.e. light values in brackets, "[X]"). The matrix is well populated: each driver affects at least two constituents, demonstrating the relationship between supply chain complexity and resilience. From a first glance, it emerges that flexibility and collaboration are the most impacted, while structural drivers are the most relevant.

Deepening the analysis, it is possible to notice that the positive relationships are much more than the negative ones, as each complexity driver positively affects at least two resilience constituents. On the contrary, the table is poorly populated by negative links, particularly dynamic complexity drivers do not decrease resilience. The only three drivers significantly decreasing resilience are *differences between facilities in different territories*, *number/variety of partners and suppliers* and *variety and breadth of customer requirements*.

Table 5.35: *Map of incident cases presenting links between supply chain complexity drivers and resilience constituents*

	Flexibility	Visibility	Velocity	Collaboration
Portfolio breadth	4, 12, 14			14
Product var. and spec.	2, 3, 13, [8], [16]		[16]	1
N. and layers SC facilities	1, 6, 8, 10, 11, 12, 13, 14, 15	1, 10, 16	6, 16	1, 6, 8, 11, 13, 14, 15
Differ. between facilities	[1], [3], [5], [14]		[16]	[1], [3], [5], [14]
N./var. of suppliers	4, 6, 9, 11	[2], [4], [7], [9]	[7], [9]	13, 14, 15, [2], [4], [7], [11]
Variety customer requires	2, 3, 5, [16]	[1], [10]	[7], [11], [13], [14], [16]	3, 5, 14 [1], [10], [16]

(continue)

	Flexibility	Visibility	Velocity	Collaboration
Product LC events	3, 5, 7, 11, 16		1, 7, 16	
Reconfig. of SC	1, 2, 10, 13	2	1, 2, 10, 13	
Improvements	2, 8, 10, 16	2	2, 8, 10, 16	
M&A	16	1, 13	16	1, 13
Demand/supply dynamics	2		7, 10	2, 7
New customers/suppliers	4	4		

After having summarized the evidence, findings are more deeply analysed. In the analysis, each company's supply chain is described through the static and dynamic supply chain complexity drivers. Even though not all of them can be investigated for each case, since available information are not enough, most drivers can be identified in most of the considered companies, with frequencies between 80% and 100%, as reported in Table 5.36. The percentage of cases in which each complexity driver was identified is the ratio between the number of cases in which the complexity driver was identified and the total number of analysed cases (i.e. 16). Only *new customers or suppliers* has a frequency of 44%, being available for the description in 7 cases out of 16, while the second lowest one, *differences between facilities in different territories*, is 69%. As previously commented in Chapter 4, *variety of/interaction between teams and functions* and *internal operational dynamics* were excluded from the analysis because secondary data do not allow to well document them.

Although complexity is comprehensively described through the 12 drivers, only some cases have proper information to assess their role in the event: their percentage is computed dividing the number of cases in which there is proper evidence by the total number of analysed cases (i.e. 16). Since the companies and the related incidents are investigated through secondary data, the role of some supply chain characteristics cannot be easily analysed, especially from a dynamic point of view. As a matter of fact, while it is possible to collect information about most static drivers in the majority of the cases, supply chain dynamicity is not much well documented and thus percentages are lower.

Finally, the last column reports the relative percentage of cases in which the complexity driver played a role, computed as the ratio between the number of cases in which the complexity driver played a role and the number of cases with proper information to assess the role.

Table 5.36: *Percentages of cases in which complexity drivers were identified, in which there is proper information to assess their role and in which they played a role.*

Complexity drivers	**% cases in which the complexity driver was identified**	**% cases with proper info to assess its role**	**% cases in which it played a role**
Portfolio breadth	100%	81%	23%
Product var. and spec.	88%	38%	100%
N. and layers SC	100%	63%	100%
Differences between facilities	69%	38%	83%
N./var. of suppliers	100%	69%	82%
Variety customer requires	94%	63%	100%
Product LC events	100%	63%	60%
Reconfig. of SC	88%	25%	100%
Improvements	94%	25%	100%
M&A	100%	31%	60%
Demand/supply dynamics	81%	19%	100%
New customers/suppliers	44%	13%	50%

Investigating the incidents affecting the different companies, most of the drivers played a significant role and there is evidence that supply chain complexity affects resilience. From a first glance, it is possible to notice that the static drivers have a higher influence with respect to the dynamic ones. The formers present all percentages higher than 80%, apart from *portfolio breadth*, which has the lowest value. *Product variety and specificities*, *number and layers of supply chain facilities* and *variety and breadth of customer requirements* significantly affected the resilience of the companies in all the incident cases, showing a frequency of 100%. Considering dynamic drivers, instead, even though some dynamic complexity drivers always played a role, they could be investigated only in some cases because not always secondary data allows to collect proper information, as mentioned before.

The link between supply chain complexity and resilience can be either positive or negative, as summarized in Table 5.37, in which frequencies of results are computed as percentage of cases in which the role was positive/negative/both out of the total number of cases presenting the considered complexity driver.

Table 5.37: *Percentages of cases with positive/negative/both links between supply chain complexity drivers and resilience constituents.*

Complexity drivers	**% cases revealing a positive role**	**% cases revealing a negative role**	**% cases revealing both roles**
Portfolio breadth	100%	-	-
Product var. and spec.	67%	33%	
N. and layers SC	100%	-	-
Differences between facilities	-	100%	-
N./var. of suppliers	44%	22%	34%
Variety customer requires	30%	60%	10%
Product LC events	100%	-	-
Reconfig. of SC	100%	-	-
Improvements	100%	-	-
M&A	100%	-	-
Demand/supply dynamics	100%	-	-
New customers/suppliers	100%	-	-

On the one hand, all the dynamic supply chain complexity drivers positively affect resilience, on the other hand, static ones can have different impacts. Apart from *differences between different facilities in different territories* and *variety and breadth of customer requirements*, the positive role is the dominant one, but there are also some cases in which the drivers played both roles (ambivalent drivers).

In order to better understand the kind of relationship between each supply chain complexity driver and resilience, it is necessary to deepen the analysis considering resilience constituents, i.e. flexibility, visibility, velocity and collaboration. The occurrence of the impact has been quantified as the ratio between the number of cases in which the complexity driver positively/negatively affected the resilience constituent and the number of cases with proper information to assess the role. Table 5.38 collects the results.

Table 5.38: *Occurrences of impacts of supply chain complexity drivers on resilience constituents.*

Complexity drivers	**Flexibility**		**Visibility**		**Velocity**		**Collaboration**	
	+	**-**	**+**	**-**	**+**	**-**	**+**	**-**
Portfolio breadth	23%	-	-	-	-	-	8%	-
Product var. and spec.	50%	33%	-	-	-	17%	17%	-
N. and layers SC	90%	-	30%	-	20%	-	70%	-
Differences between facilities	-	67%	-	-	-	17%	-	67%

(continue)

Complexity drivers	Flexibility		Visibility		Velocity		Collaboration	
	+	-	+	-	+	-	+	-
N./var. of suppliers	36%	-	-	36%	-	18%	27%	36%
Variety customer requires	30%	10%	-	20%	-	50%	30%	30%
Product LC events	50%	-	-	-	30%	-	-	-
Reconfig. of SC	100%	-	25%	-	100%	-	-	-
Improvements	100%	-	25%	-	100%	-	-	-
M&A	20%	-	40%	-	20%	-	40%	-
Demand/supply dynamics	33%	-	-	-	67%	-	67%	-
New customers/ suppliers	50%	-	50%	-	-	-	-	-

Flexibility is the most affected constituent: *differences between facilities in different territories* has a negative impact on it, while all the other complexity drivers mainly positively affect it. In most of cases, the higher the supply chain complexity, the higher the flexibility due to the redundancies and different alternatives exploitable by the company. A wide portfolio and a high product variety allow to offer substitutes or different configurations to customers, as proved by Boeing, Sapporo, Evonik and Dell's experience. However, a higher modularity and similarity could help, such as in Hynix case, and strict specificities determine less freedom in approving new technical solutions, as it was for Volkswagen. Therefore, *product variety and specificities* has both a positive and negative role. Structural complexity, both internal and external, increase flexibility too: a complex supply chain offers geographic diversification, many facilities available to ramp up production, different suppliers to which shift the sourcing and new customer requirements to leverage, as it emerged from most of the analysed incidents. The driver with the highest rate of evidence is *number and layers of supply chain facilities* (90%). Nevertheless, support from other facilities is possible only if they are similar, this is why *differences between facilities in different territories* shown a negative role (e.g. Takata, Evonik, Genzyme and Procter and Gamble cases).

For what concerns dynamic complexity drivers, they all play a positive role, increasing flexibility. Product dynamicity fosters research of substitutes and technical solutions, while internal and external dynamic complexity increases the ability to shift to new structures and procedures or change customers or suppliers with a lower effort. The influences with better evidence are those of *reconfiguration of supply chain activities and facilities* and *improvements to equipment, procedures and systems* (100%).

Differently, the other constituents are not influenced by all the complexity drivers. However, collaboration is strongly impacted too, mainly by structural drivers. As a matter of fact, dynamic ones did not play a role, apart from *restructuring and M&A* and *demand/supply side/internal operational dynamics*, which have occurrences of 40% and

67% respectively. The former was exploited by Takata and Goodyear in order to offer alternative suppliers to their customers, the latter allowed suppliers development in Nestlé and Dell cases. As for static drivers, the internal structure of the supply chain ensures higher collaboration among different facilities if they are many, but not much different between different territories. On the contrary, even though a higher number of customers and suppliers allows a wider set of collaborative actors, collaboration with them is better if their number is low, due to the stronger partnerships. Thus, *number/variety of partners and suppliers* and *variety and breadth of customer requirements* have both positive and negative influence.

Considering velocity, the highest positive role determining it is played by dynamic complexity drivers: all of them, except *new customers or suppliers*, increase it, since they allow the company to be already used to change its operations and adopt new solutions. As a matter of fact, being used to dynamicity, the affected companies can rapidly develop technical solutions, identify substitutes, rebuild facilities, ramp up production, change the manufacturing process and introduce new procedures. On the other hand, static complexity decreases velocity of reaction: for instance, from Nestlé and Peugeot cases it emerges that a high number of suppliers hinders their management. Moreover, higher number and variety of customers make more difficult communication and image rebuilding, as proved by Nestlé, Honda and Goodyear examples.

Finally, visibility is affected by the supply chain structure and its evolution in time: the more complex is the set of actors the company relates to, the less is the visibility on them, but the greater is the dynamicity characterizing the supply chain, the higher is the visibility on new and innovative alternatives in case of disruption. Therefore, static complexity drivers play a negative role, while dynamic ones increase visibility. As for the former, the higher is the number of external actors to manage, the lower is visibility on them (e.g. Peugeot and Mattel incidents). Considering the layers of supply chain, a vertical integrated company directly faces final customers and raw materials suppliers, better communicating with them and having a higher visibility, which allows to manage actions such as recalls, as confirmed by Mattel and Volkswagen cases.

In conclusion, the analysis proves the link between supply chain complexity, both structural and dynamic, and resilience, answering to the first two research questions. Furthermore, it investigates the direct or inverse proportionality among complexity drivers and resilience constituents, determining the kind of influence that the first have on the second. Although for most of the drivers the link is positive, thus the higher the complexity the higher the resilience, there are also inverse proportional relationships attesting that not always complexity is a strength.

Chapter 6
From complexity management to operational resilience: a case study approach

In this chapter, the influence of complexity management practices on resilience constituents is investigated to answer the third research question. The starting point is the study about supply chain complexity by Fernandez Campos (2018), whose body of knowledge represents the framework for this further analysis. Recalling his findings, the first section highlights which supply chain complexity drivers are managed by which practices. Then, a section is dedicated to the links between complexity management practices and supply chain resilience constituents, detailing their positive or negative role. The adopted methodology is inductive case study, as explained in Chapter 4, and the selected sampling is the same of Fernandez Campos' study (2018) (i.e. four case studies: Percomp, Auto, Drinks and Defence). Particularly, for each case study, after a short description of the approaches and tools employed to manage supply chain complexity, adopting the definitions from Fernandez Campos (2018)[1], their influence on flexibility, visibility, velocity and collaboration is identified. Finally, the last section presents a synthetic table collecting the results for the four clusters and some comments about it.

6.1 Prior findings on complexity management practices and related supply chain complexity drivers

To manage structural and dynamic supply chain complexity, companies develop specific management approaches and tools, which enable to reduce or accommodate it, physically reducing it or mitigating its negative effects on performance. In his study about supply chain complexity, Fernandez Campos (2018) investigated the different scopes and limitations of four clusters of practices, namely: variety reducing, confinement and decoupling, coordination and collaboration, and decision support and knowledge generation. Then, he identified which structural and dynamic complexity drivers are tentatively managed through each single practice (Appendix B). Therefore, the link between the two dimensions has been already proved through empirical evidence. Since it represents a starting point for this study, Fernandez Campos' findings (2018) are reported in Table 6.1 and Table 6.2, which respectively refer to static and dynamic complexity. The matrixes map the four analysed case studies, identified with a number:

[1] The detailed within-case analysis of the four case studies performed by Fernandez Campos (2018) can be found in Appendix B. It directly reports an excerpt of his study on supply chain complexity.

1 = Percomp, 2 = Auto, 3 = Drinks and 4 = Defence. The presence of a number in a cell means that in the enumerated case study there is evidence of the linkage, as the practice is leveraged to cope with the considered complexity driver. The tables are well populated and most of the practices allows to manage more than one complexity driver, either structural or dynamic. Moreover, some relationships are evident in more than one case study.

Adopting these findings, the next sections further investigate complexity management practices, analysing their influence on resilience constituents.

Table 6.1: *Map of case studies presenting links between complexity management practices and structural supply chain complexity (Fernandez Campos, 2018).*

		Portfolio breadth	**Product var. and spec.**	**Interact. between functions**	**N. and layers SC facilities**	**Differ. between facilities**	**N./var. of suppliers**	**Var. customer requires**
Variety reducing practices	Accessory-based customisation		1					
	Product platforms and standards		2					
	Product portfolio rationalisation	4	3, 4					
	Product-centric organisational design	1, 4	1	1, 4		1		4
	Platform teams			1		1		
	Rationalisation of SC facilities			1	1			
	Process standardisation					2		
	Unification of customer requirements		4					1, 2, 4
	Centralisation of purchasing					2	3	
Confinement and decoupling practices	Outsourcing	4	4	1			1	1
	Customised distribution channels							3
	Modular design and software customisation		4					4
	Category management		4				3, 4	
	Localisation of activities		3					3
	Additive manufacturing postponement		1					
	Organisational buffers	2						2
	Split of sourcing activities	4	4					
	Flexible workforce							
	Stocks							
	Intermediate interface teams							

(continue)

		Portfolio breadth	Product var. and spec.	Interact. between functions	N. and layers SC facilities	Differ. between facilities	N./var. of suppliers	Var. customer requires
Coordination and collaboration practices	Decentralisation of procurement						4	
	Global SC forums			1		1		
	Integrated product teams	4		4				4
	Strategic relations with partners and suppliers		4	1			3, 4	
	Integrated ERP systems	3, 4	3, 4	2, 3	3			
	Benchmarking					2		
	Collaboration with prod. design/front-end teams							
	Project management	4	3	3, 4				4
	Cross-functional KPIs							
	Multi-level supply-demand reconciliations							
	Unique customer interfaces							2
	Supplier development		4				2, 4	
Decision support and knowledge generation practices	Forward-looking forecasting		1					
	Cellular manufacturing and product tech. Groups	4	4					
	Product segmentation and specialised teams	3						
	Automation		1, 2					
	Traceability and anti-mixing systems	3, 4	2, 3, 4					
	Multi-Echelon ERPs and optimisation IT tools	3	1, 3	1, 3	3			
	Product lifecycle management processes and tools	4	4					
	Vendor rating tools						2	
	Specific training							
	Product design carry-over							
	Simulation							

Table 6.2: *Map of case studies presenting links between complexity management practices and dynamic supply chain complexity (Fernandez Campos (2018).*

		Product LC events	Reconfig. of SC	Improve-ments	M&A	Internal dynamics	Demand /supply dynamics	New customers /suppliers
Variety reducing practices	Accessory-based customisation							
	Product platforms and standards							
	Product portfolio rationalisation	4					1	
	Product-centric organisational design	1, 4					1, 4	
	Platform teams							
	Rationalisation of SC facilities							
	Process standardisation							
	Unification of customer requirements							
	Centralisation of purchasing							
Confinement and decoupling practices	Outsourcing							
	Customised distribution channels							
	Modular design and software customisation							
	Category management							
	Localisation of activities						2, 3	
	Additive manufacturing postponement							
	Organisational buffers				2			
	Split of sourcing activities	4					4	
	Flexible workforce					4	4	
	Stocks					2	2, 3	
	Intermediate interface teams						3	

(continue)

		Product LC events	Reconfig. of SC	Improve-ments	M&A	Internal dynamics	Demand /supply dynamics	New customers /suppliers
Coordination and collaboration practices	Decentralisation of procurement							
	Global SC forums	1						
	Integrated product teams	4					4	
	Strategic relations with partners and suppliers	4					4	1
	Integrated ERP systems					2, 4	2	
	Benchmarking						2	
	Collaboration with prod. design/front-end teams	1						
	Project management	2, 3	1, 3	1, 2	3			
	Cross-functional KPIs						1	
	Multi-level supply-demand reconciliations					4	4	
	Unique customer interfaces						2	
	Supplier development	4				4	2, 4	
Decision support and knowledge generation practices	Forward-looking forecasting	1					1	
	Cellular manufacturing and product tech. Groups							
	Product segmentation and specialised teams							
	Automation					2	2	
	Traceability and anti-mixing systems						2, 4	
	Multi-Echelon ERPs and optimisation IT tools							
	Product lifecycle management processes and tools	2, 4					4	
	Vendor rating tools							
	Specific training	2	3	2, 4	3, 4			
	Product design carry-over	2, 4			4	4	4	
	Simulation	2					1	

6.2 Influence of complexity management practices on resilience constituents

In this section, the link between supply chain complexity management practices and resilience constituents is investigated, through the selected inductive case studies (i.e. Percomp, Auto, Drink and Defence). A sub-section is dedicated to each one of them, in which there are, first, an introduction of the company and a description of complexity management approaches and tools, adopting definitions provided by Fernandez Campos' study (2018), and, secondly, an analysis of their positive or negative influence on flexibility, visibility, velocity and collaboration.

6.2.1 Percomp case study

Percomp is a large information technology multinational company providing products, technologies and solutions to individual consumers as well as small, medium and large companies worldwide, especially in the health, education and public administration sectors. Employing about 50,000 employees, it has strong leadership global positions in its two core product segments and its yearly net revenue amounts to about 50,000 million $. The firm is organised into three regions: Americas, EMEA (Europe, Africa, Middle East and Eastern Europe) and APJ (Asia Pacific and Japan). The focus of the case study is the EMEA's customer support supply chain, which generates about a third of Percomp's revenue. Managers and consulted secondary data suggest that management practices here reviewed are unlikely to differ considerably to those in Americas and APJ.

The complexity management practices adopted by Percomp to reduce or mitigate the effect of supply chain complexity drivers are defined in Table 6.3, divided in the four clusters.

Table 6.3: *Percomp's complexity management practices (Fernandez Campos, 2018).*

Variety reducing practices	➢ Accessory-based customisation Customisation of components is postponed, reducing the number of SKUs associated with product variants. All parts except for those common to low and high-end product variants are add-on components, used to bring products from low to high-end specifications. ➢ Product portfolio rationalisation Percomp adopts new practices to manage supplier obsolescence, such as component repair strategies, leveraged because they are less expensive than new parts purchasing. Moreover, customers are proposed to upgrade to a newer generation of products rather than attempting to continue supporting the impacted product through the remaining of its lifecycle. This limits the growth of product portfolio.

(continue)

Variety reducing practices	➢ Product-centric organisational design Organisational design is characterised by "end-to-end planners", who are responsible for a part or sets of spare parts in the portfolio across the entire supply chain network and processes. Focusing on a reduced set of parts, managers can better understand products, unify procedures and tools, have more visibility and better synchronisation of different layers, enhance accountability and empowerment. ➢ Platform teams At the core of each supply chain area (e.g. planning or logistics) there are teams that define the common architecture of processes, tools and solutions for the given area, establishing commonalities in the organisation, standardising the processes and unifying solutions and infrastructures. ➢ Rationalisation of supply chain facilities In recent years, Percomp underwent a large and fast rationalisation of supply chain, reducing facilities from 200 to 56, especially field stock locations, which are the third and most granular layer. Moreover, it introduced new delivery models to meet customer requirements (e.g. customer-dedicated stock at their premises instead of field stock locations depots). ➢ Unification of customer requirements Customer requirements are rationalised according to two approaches: on the one hand, striving to find commonalities within requirements, thus supply chain can leverage common processes and infrastructures, driving scale and efficiency; on the other hand, bounding requirements by setting limits for customer specific solutions and clearing priorities within requirements, differentiating must-have and nice-to-have.
Confinement and decoupling practices	➢ Outsourcing Outsourcing all the procurement-related activities (i.e. supply parts planning and storage) for segment A, Percomp can better focus on the segment B. Moreover, it outsources all the supply chain activities for consumer segment, focusing on the commercial one. Finally, it assigns to external providers ownership and management of physical facilities, as well as non-core activities, better internally performing key activities. ➢ Additive manufacturing postponement Percomp postpones customisation of components by adapting generic spare parts to specific products, in order to reduce the number of SKUs associated with product variants.
Coordination and collaboration practices	➢ Global supply chain forums Percomp's managers are pushing and establishing world-wide supply chain forums on most critical topics to foster establishment of links across levels and regions, promoting joint approaches to supply chain. The aim is not only to find better solutions, enhancing connectivity, sharing best practices and joining resources, but also to homogenise and reduce disparities between different regions. For instance, rallying both global supply chain teams and regional teams together, forums increase interaction among them and allow to discuss common topics or to have common processes or common decision-making process. Furthermore, global forums are important to improve management of dynamic complexity drivers, such as product lifecycle events, leveraging global governance models.

(continue)

Coordination and collaboration practices	➢ Strategic relations with partners and suppliers The company focuses on a rationalised limited number of partners and establishes strategic win-win relationships with them, sharing gain and pain, knowledge, know-how, collaborative processes, common profits on returns etc. However, it encounters two main difficulties: on the one hand, ability to carefully nurture and manage these partnerships; on the other hand, the implementation of robust data strategy, including comprehensive and structured info data flows. ➢ Collaboration with product design/front-end teams Percomp establishes effective links with other functions outside the supply chain, for instance introducing joint reparability strategies that link supply chain and product design functions. Moreover, it devises new methods to increase potential use of component repair, collaborating with front-end functions (i.e. customer engineers or other internal customers) to understand and overcome the barriers that prevent the latter from doing more spare parts support instead of whole-unit support. ➢ Project management Project management office is the part of the supply chain function responsible for managing supply chain transformations, such as rationalisation of supply chain facilities, implementation of standard and premium delivery models, reconfiguration of flows in the network etc. It structures and monitors progress of activities and coordinates them, reducing intrinsic uncertainty and facilitating transitions. Furthermore, it keeps track of all the changes in the Program of Record. Having an end-to-end view of the supply chain, understanding and foreseeing implications, it allows multiple-stage transitions and management of changes. ➢ Cross-functional KPIs Reporting metrics and KPIs enable managers to better understand customer behaviours and foster collaboration with front-end teams. They allow to overcome supply chain silo logic, involving other functions.
Decision support and knowledge generation practices	➢ Forward-looking forecasting The new forecasting logic, mainly based on future rather than past and historical data, facilitates managers coping with the wide spare parts portfolio and with product lifecycle events. ➢ Automation Automation reduces reliance of supply chain on managers' experience and decrease the number of decisions they have to face. ➢ Multi-echelon ERPs and optimisation IT tools The in-house tailored ERP enhances multi-echelon and mix optimisation capabilities, allowing optimisation of inventories across the whole network, as well as planning to account for demand and lead-time variations. Furthermore, it improves accurate segmentation and underpins the use of automation. ➢ Simulation Simulation is adopted to aid managers make decisions, since they can foresee implications of potential changes. As a matter of fact, although a vast amount of data is available through supply chain's main IT infrastructures, it is difficult to leverage them without simulation.

The listed complexity management practices can have a positive influence, a negative one or both on firm's flexibility, visibility, velocity and collaboration, as shown by the empirical evidence emerging from the managers' interviews.

First, accessory-based customisation enhances flexibility in managing inventories and reduces lead times, allowing the company to better and more quickly react to demand.

Supplier obsolescence management practices, classified as product portfolio rationalisation, positively affect flexibility and velocity. The former is increased because amplifying repair of spare parts and whole units helps to mitigate inventory liabilities. Moreover, introducing repair strategies together with product design functions enables to repair products more easily, thus more quickly too.

Product-centric organisational design plays a dual role influencing flexibility, visibility and velocity, while it has a positive impact on collaboration. Even though it ensures better operational efficiency, it increases the scope, types of things and decisions that a single planner is making, slowing and stiffening processes. On the one hand, the helicopter view increases managers' end-to-end knowledge of the process, from the beginning to the end, with whole responsibilities over service level, inventory and costs, allowing better efficiency and synchronisation. On the other hand, complexity characterising each different country is difficult to integrate, and managers strive to look at things at a global level, identifying local specificities at the same time. As for collaboration, product-centric organisational design allows a better synchronisation of different layers and planning activities and a cross-regional exchange of parties, which are fair shared and dispatched among different countries.

Considering rationalisation of supply chain facilities, even though they are easier to be managed, they mainly negatively impact on flexibility and velocity, since rationalisation could kill supply chain capabilities, get missing scale to have an economically efficient supply chain, and slower speed of delivery for non-critical parts.

Unification of customer requirements enhances collaboration, because supply chain can leverage common processes and infrastructures, driving scale and efficiency.

Moving to confinement and decoupling practices, outsourcing plays a negative role in terms of both flexibility and visibility. As a matter of fact, Percomp may face issues on its own performance caused by service provider's ability to supply parts, due to the high dependence on it. Furthermore, it causes the loss of holistic view: when a company own its own network and manage it, it knows it, otherwise it needs to define and design very well the processes. Working with functions inside and outside does not help to develop a holistic view.

As for additive manufacturing postponement, it positively affects both flexibility and velocity, ensuring more flexibility to manage inventories and lower lead times, enabling the company to react to one or another demand.

Considering global supply chain forums, it increases collaboration, due to connectivity across levels and cross-regional exchange of topics, processes and decision-making processes, as well as best practices sharing. The latter positively impacts on visibility too, since info about how to do things are exchanged. Moreover, global governance models allow to early detect upcoming decisions. Nevertheless, global governance models negatively affect flexibility: the world-wide system is less flexible because to do something specific for one region agreement of other regions is required.

Strategic relations with partners and suppliers play a role influencing all the four dimensions. A lower number of partners means less diversity and thus less flexibility. In addition, partnerships determine the need to engage with suppliers to negotiate for repair rather than production, reducing flexibility. Nevertheless, strategic relationships have a positive impact on visibility, velocity and collaboration. First, visibility increases due to the possibility of applying forward-looking forecasting. Then, stronger are the partnerships, more rapid is the implementation of solutions. Finally, Percomp share gain and pain, knowledge, know-how, collaborative processes, common profit on return, etc. with partners.

Collaboration with product design/front-end teams is a practice identifiable with collaboration, including joint reparability strategies that link supply chain and product design functions.

Another relevant approach to manage complexity is project management. Constructing an end-to-end view of the supply chain, understanding and foreseeing all the implications, and keeping track of events through the Program of Records, it contributes to increase visibility.

The last practice belonging to coordination and collaboration cluster adopted by Percomp is the use of cross-functional KPIs. The new cross-functional data reporting and KPIs system help in understanding patterns of orders and customer behaviours. For instance, they allow to control points on how front-end teams or channel partners are going to use standard rather than premium deliveries. Therefore, they give a clear visibility on what is happening.

Since it enables projections based on future prediction rather that past data and history, forward-looking forecasting increases visibility, giving the firm sufficient time to understand and to prepare for a different output if necessary.

Automation influences on both velocity and visibility, due to the independence from human experience. On the one hand, this independence allows higher efficiency, thus increasing velocity. On the other hand, it hinders a comprehensive understanding decreasing visibility, as some aspects are frequently invisible and difficult to understand.

Moving to multi-echelon ERPs and optimisation IT tools, since they enable a planning driven by demand and its variation, lead times and their variations, and service levels, they increase flexibility. Furthermore, together with automation, they positively impact on velocity, increasing efficiency in planning process. However, they also negatively affect visibility, because they constitute a less operational and more analytical approach, which looks less at what is happening, but instead relies on logic and algorithms. In addition, they require more prediction, more structured data and more broad knowledge to be understood.

Finally, simulation tools play a positive role only in terms of visibility. Simulation allows to foresee implications of potential changes in network and offers to leverage the vast amount of data available through supply chain's main IT infrastructure.

Table 6.4 reports the role that each complexity driver plays with respect to resilience constituents, as previously described, indicating both the positive and the negative ones.

Table 6.4: *Influence of complexity management practices on resilience constituents in Percomp case.*

	Flexibility	Visibility	Velocity	Collaboration
Variety reducing practices				
Accessory-based customisation	+		+	
Product portfolio rationalisation	+		+	
Product-centric organisational design	+/-	+/-	+/-	+
Platform teams				
Rationalisation of SC facilities	+/-		+/-	
Unification of customer requirements				+
Confinement and decoupling practices				
Outsourcing	-	-		
Additive manufacturing postponement	+		+	
Coordination and collaboration practices				
Global SC forums	-	+		+
Strategic relations with partners and suppliers	-	+	+	+
Collaboration with prod. design/front-end teams				+
Project management		+		
Cross-functional KPIs		+		
Decision support and knowledge generation practices				
Forward-looking forecasting		+		
Automation		-	+	
Multi-Echelon ERPs and optimisation IT tools	+	-	+	+
Simulation		+		

6.2.2 Auto case study

Auto is a leading manufacturer of wheels in the automotive industry, producing steel wheels for passenger cars and light commercial vehicles and spoke wheels for motorcycles. It is part of a larger group whose main businesses regard the distribution of steel and manufacturing (other) components for the automobile industry. The company currently employs about 1,500 employees and its yearly turnover is approximately 200 million €. It is active in two markets: direct sales to automotive OEMs and the after-sales market, for which the company employs a dedicated sales network. Despite its dense European footprint, the firm has facilities in Asia, Central America and Africa too. The case study focuses on the firm's entire internal supply chain activities.

Table 6.5 collects the complexity management practices aiding Auto to cope with supply chain complexity drivers.

Table 6.5: *Auto's complexity management practices (Fernandez Campos, 2018).*

Variety reducing practices	➢ Product platforms and standards In order to reduce variety and specificities, Auto defines product platforms and standards, being guided by customers to be successful. However, platforms and standards shared by more than a single automaker are still missing. ➢ Process standardisation Production processes are unified and standardised with general rules deriving from best practices or consolidated techniques (e.g. adoption of lean practices). Nevertheless, differences in equipment, resources and layout between plants, as well as exceptions and variations, hinder the ability to unify processes. ➢ Unification of customer requirements In order to maximise economies of scale and utilisation of production capacities, the company leverages cross-market unification of requirements from after-sales market and OEMs. IT is possible thanks to common suppliers and well-known technologically mature product designs. Moreover, the after-sales market's requirements are less restrictive, for instance tolerances are larger, thus facilitating the unification. ➢ Centralisation of purchasing Central purchasing teams manage supplies for key direct and indirect materials, securing better deals, establishing longer relationships and unifying materials across plants. A similar approach is adopted for steel: manufacturing facilities demands are aggregated and managed by a separate central team, allowing a stronger power of negotiation. On the contrary, other materials are managed through a different approach (i.e. localisation of purchasing activities).
Confinement and decoupling practices	➢ Localisation of activities Purchasing of materials different from key direct and indirect materials or steel is localised, resulting in lower lead times and a higher flexibility, but also a lower negotiation power due to the larger supply base. Therefore, this approach is adopted for cheaper materials, such as packaging.

(continue)

Confinement and decoupling practices	➢ Organisational buffers Auto's supply chain relies on additional independent organisations, which represent organisational redundancies. A central after sales organisation, which is responsible for demand forecasting management and allocation and interactions with customers, is completely independent from the supply chain. Moreover, facilities dedicated to motorcycle wheels production are autonomous. Finally, plants in America and Asia re independent joint ventures. Even though this approach aids the structural complexity reduction, it asks for additional human resources and prevents the supply chain optimisation. ➢ Stocks The use of stocks is a key practice to cope with the short lead times demanded by customers and the uncertainties characterising the market (i.e. demand variability, raw material delays and machines breakdowns). Nevertheless, it implies quality issues and extra costs.
Coordination and collaboration practices	➢ Integrated ERP systems Only some facilities adopt an integrated ERP system (SAP), facilitating communication and coordination between different functions and enhancing data to support decision-making. It also enables a better integration with suppliers' ERP systems. ➢ Benchmarking Solutions put in place by a single plant are transferred to other plants, turning them into standards. These are copied-and-pasted relying on know-how and experience of other plants, adopting tools such as scorecard systems, monthly performance reports, shared spreadsheet software and shared folders. Managers from quality, engineering and industrial investments functions are involved in the implementation. Differences between plants and high implementation costs represent possible limitations. ➢ Project management The project management team is part of the engineering function and it manages continuous improvement activities characterising the company. It follows a five-stage gated process that structures all activities for new product introduction. Moreover, it measures and monitors the product design changes and the projects' performances. ➢ Unique customer interfaces In Auto, there are Key Account Managers, who act as unique interface for specific OEM customers. Not only they are responsible for customers' demand and generate monthly forecasts, but they also manage disruptions and communications and give direct on-site support. ➢ Supplier development Auto adopts a series of initiatives enabling development of suppliers, focused mainly on three areas: first, supplier managerial processes and certification (e.g. ISO technical specifications), then, supplier production equipment and, finally, communication processes between firms.
Decision support and knowledge generation practices	➢ Automation Automation of certain tasks, such as purchase requests for direct materials, is allowed by the use of integrated ERP systems.

(continue)

Decision support and knowledge generation practices	➢ Traceability and anti-mixing systems Anti-mixing systems and practices are a series of practices implemented in all the manufacturing facilities to reduce product mixing and manage variety of SKUs, especially different packaging types. They include bespoke kitting trolleys to supply specific packaging types to the packaging line, 5S lean management tool to improve organisation of workspace through visual cues and fixed roads for material handling, and electronic links between the packaging line and the warehouse. ➢ Product lifecycle management processes and tools Auto has a bespoke communication software tool to facilitate and accelerate exchange of information between the headquarter and plants and within functions, facilitating communication and interaction. Furthermore, it allows the development of a digital archive. In future, the company is going to expand it into a full product lifecycle management tool. ➢ Vendor rating tools Local purchasing managers collect data on suppliers' certification level, inbound material quality and on-time delivery rates, and share it with central management. Therefore, suppliers' performance to prioritise are monitored, possible corrective actions are set and suppliers' change are managed, in order to improve quality and costs of supplies. ➢ Specific training Specific employees training accelerates implementation of changes and alleviates effect of associated transitions, improves learning curves and helps workforce understand the reasons behind the change. ➢ Product design carry-over Carry-over is the setting point for all new product development activities. Despite their differences, the maturity of the products facilitates that models already in production, or at least some of their components, can be slightly modified and adapted to satisfy the new requirements. ➢ Simulation Auto puts in place a series of simulation tools to better predict behaviour and properties of potential wheel designs. It allows the company to reduce the number of design changes and the interactions with production facilities and customers.

The complexity management practices listed in Table 6.5 can positively and/or negatively affect firm's flexibility, visibility, velocity and collaboration, as the empirical evidence emerging from the managers' interviews suggests.

Starting from the variety reducing practices, product platforms and standards have a positive influence on velocity, as they enable the steel to arrive on time in the production process. The impact of this practice on flexibility instead could be negative or null. Suppliers homologated for the more strategic grades of production are considered few by the purchasing manager, according to whom flexibility could be negatively affected by it. Nevertheless, although having a standardized set of steels and relying only on homologated supplier steel shops close the way for steel, it is not a limitation because Auto's steel suppliers are six and steel market is a very specific and huge one. As a matter of fact, steel shops are big plants and Auto's yearly consumption corresponds to about two days of work, thus it is a very small costumer.

Process standardisation plays a dual role on velocity. On the one hand, it increases it due to the creation of fix roads, places, quantities and colours, and the adoption of visual management and standards reducing material handling and non-value activities, such as the e-canvas solution. Standard procedures allow to make transition phases as fast as possible, for instance, “theoretical transfer duties” help personnel changes. On the other end, velocity is reduced because, despite the internal pressure to proceed quickly, it imposes procedures to respect. Additional papers and “pointless stuff” take a significant amount of time. As a matter of fact, big corporations have standards and just cascade them to suppliers. For example, before audit for customers, they have to put everything nicely into one place, print stuff and make other preparations.

Unification of customer requirements positively affects collaboration, as it maximises economies of scale and utilisation of production capacities.

An important role is played by centralisation of purchasing, which impacts on all the four constituents. First, it reduces velocity, since transforming engineers’ questions into understandable questions for suppliers consumes quite a lot of time, as well as transfer the suppliers’ feedback to the teams. On the contrary, it positively impacts on flexibility, due to the possibility to shift production from one plant to another without need to homologate new suppliers with new validation tests. Collaboration increases too, thanks to knowledge sharing between facilities, group management of raw materials and a higher power of negotiation. Finally, centralisation positively affects visibility on centralized needs from all the plants. Therefore, it allows to know which other plants are planning a similar project and buy similar equipment.

The opposite practice is localisation of purchasing activities, adopted by Auto for cheaper materials. Since distance is shorter and they can adjust quicker due to their low dimensions, local suppliers are more flexible and have lower lead times than divisional ones.

Leveraging stocks, Auto can improve both flexibility and velocity, coping with operational dynamic complexity. In case of high demand variability, products buffers enable to respond to the real demand if different from the forecast or when unpredictable events happen. Then, stocks are at the basis of the make-to-stock approach that allows to quickly satisfy OEMs’ demand, which is characterized by required lead times lower than raw materials and production ones.

Moving to coordination and collaboration practices, integrated ERP systems facilitate stock management and create planning production orders depending on specific indicators, improving the operational velocity. Furthermore, when particular data is introduced, the system (SAP) calculates the required materials, sends an automatic purchase request and makes automatically the orders. Therefore, it facilitates coordination between different functions. Finally, it helps to see production costs and production declaration online, allowing everybody to see the current level of produced goods. From

SAP, it is possible to extract what parts are finished and what their value is, how many pieces there are and what the historical usage per part is, thus improving real-time visibility and facilitating communication.

As for benchmarking, it enhances collaboration because it is based on parameters comparison, best practices sharing and copy-pasting activities. A single plant plans its activities in advance and then share them with other facilities.

Project management allows a more rapid launching of new products, leveraging the use of corrective actions on the original idea. Moreover, it coordinates purchasing and engineers when purchasing for a new project are required, thus increasing collaboration among functions.

Considering unique customer interfaces, Key Account Managers are close to customers and offer them a direct support with a daily presence. Moreover, they are responsible of coordinating all activities regarding customers, both technical and quality issues. Therefore, this practice increases velocity. In addition, since KAMs belong to the communicative company-customer loop, they enable a better visibility.

Supplier development negatively affects velocity: ISO/TS certifications, together with added particular customer requirements, involve a heavy bureaucracy and pointless papers and additional stuff. On the contrary, this practice develops communication, allowing to avoid certain problems and ensuring a better visibility.

Automation negatively affects both flexibility and visibility. The latter because it overcome the need to supervise contract point by point, while the former because it considers a rigid list of materials, without bundling atypical cases. As a matter of fact, when non-typical materials are purchased, they are not provided in via the automatic way and they are managed directly by each production unit or by maintenance. On the contrary, velocity is positively impacted, due to the less manual work to do, that allows to save time by integrating in the system new automatic procedures. Moreover, through SAP system, automatic purchase requests and orders are quickly managed. Finally, automation also includes modern transport solutions that work without human resources. However, the influence of this last point is not so strongly highlighted by managers.

For what concerns product lifecycle management processes and tools, the communicative software to define offer for a new product is really quick and accelerates exchange of information between headquarters and plants and within various functions. Furthermore, enabling communication and information sharing through the digital archive, it increases visibility.

Vendor rating tools aggregate information from different plants and centralise data, in order to compare how particular suppliers are evaluated in particular plants. Therefore, collaboration among facilities is higher. In addition, visibility raises too, as data collected by local purchasing managers are shared with central management and thus if a supplier is notorious for quality issues this is immediately seen.

Considering specific training of employees, it accelerates the implementation of changes and alleviates the effect of associated transitions, improving learning curves. Hence, it is positively linked to velocity.

Product design-carry over increases velocity too: Auto leverages it to reduce uncertainty of new products, thus being faster in their introduction.

Finally, simulation practices allow to better predict behaviours and properties of potential new wheel design, improving the firm's visibility on possible consequences.

These relationships are summed up in Table 6.6.

Table 6.6: *Influence of complexity management practices on resilience constituents in Auto case.*

	Flexibility	Visibility	Velocity	Collaboration
Variety reducing practices				
Product platforms and standards	-		+	
Process standardisation			+/-	
Unification of customer requirements				+
Centralisation of purchasing	+	+	-	+
Confinement and decoupling practices				
Localisation of purchasing activities	+		+	
Organisational buffers				
Stocks	+		+	
Coordination and collaboration practices				
Integrated ERP systems		+	+	+
Benchmarking				+
Project management			+	+
Unique customer interfaces		+	+	+
Supplier development		+	-	
Decision support and knowledge generation practices				
Automation	-	-	+	
Traceability and anti-mixing systems				
Product lifecycle mgmt processes and tools		+	+	
Vendor rating tools		+		+
Specific training			+	
Product design carry-over			+	
Simulation		+		

6.2.3 Drinks case study

Drinks is an Italian-based manufacturer in the beverages and liquors industry. It is characterised by a wide portfolio of products, especially wines and soft-drinks, having a strong market presence in Europe and Americas. It employs about 4,000 employees worldwide and has a yearly revenue of approximately 1,500 million €. The global supply chain, shaped by the M&A strategy of expansions of the firm, is organised according to four regions: Europe, North America, South America and Asia Pacific. The case study focuses on the former, which accounts for 50% of total firm revenues. Nevertheless, data collected on the global firm operations suggest that the critical complexity factors reported in the case are similar across regions.

In order to reduce or mitigate the effect of supply chain complexity drivers, Drinks adopts the complexity management practices defined in Table 6.7.

Table 6.7: *Drink's complexity management practices (Fernandez Campos, 2018).*

Variety reducing practices	➢ Product portfolio rationalisation The number of references is reduced, unifying materials between otherwise similar SKUs or adopting English labels instead of the country's local language ones. The Project Management Office is responsible of product rationalisation, standardising a part of every project that involves the supply chain. ➢ Centralisation of purchasing Drinks' procurement design consists of a Global Purchasing Office and a layer of global category managers that look after the main groups of direct materials, don't relying anymore on Global Purchasing Director and divisional purchasing managers. It enables to negotiate better deals to the consolidate global procurement volumes, as well as the rationalisation of materials and suppliers a global level.
Confinement and decoupling practices	➢ Customised distribution channels To accommodate diversity of requirements from different types of customers, the company uses bespoke supply chain distribution channels, satisfying distinct customer segments. ➢ Category management There are global category managers charged of looking after the main groups of direct materials, i.e. glass, raw materials and primary and secondary components. ➢ Localisation of activities Promotional and customisation activities are pushed downstream in the supply chain, for instance customised promotional packaging is close to customers, as they are dedicated to the specific sales point. The process is decoupled: upstream production activities are standardized, while customisation plays a role downstream in the supply chain. Moreover, warehouses emplacement is carefully design, to be close to borders between countries. ➢ Stocks Drinks considers inventories as a method to decouple production from sales. As a matter of fact, it manufactures each SKU once a month (once a week in the smaller plants) to optimise batch size. Therefore, it relies on stocks to cover unexpected demand. ➢ Intermediate interface teams A single centralised planning team is the unique interface between marketing and production facilities. It is responsible for designing production plans that meet sales forecasts.

(continue)

Coordination and collaboration practices	➢ Strategic relations with partners and suppliers The creation of long-term relationships with critical suppliers is fundamental. Suppliers are assessed not only on cost, quality and service, but also in terms of capacity to innovate and strategic orientation. Strategic relations are also enabled by the centralisation of procurement. ➢ Integrated ERP systems Drinks adopts a unique integrated ERP in all the supply chain facilities, to foster information sharing and enhance coordination between the different facilities, teams and functions involved in the supply chain activities. ➢ Project management The Project Management Office is a part of the Innovation function. In Drinks, there are two different types of projects: on the one hand, innovation projects, which include new products development and introduction, new brands launching, product lines extensions, packaging updating and formula modifications; on the other hand, fast-track innovation projects, focused on minor activities that involve extant products (e.g. existent products to new markets, new SKUs to the market, limited editions or value-added packs). While the formers follow a structured three-stages toll-gate process, the latter ones have a shorter duration. Therefore, while the formers are about 30 per year, the latter ones are 400, considering Europe. Project managers adopt a series of practices helping to structure and implement strategic activities that modify the internal supply chain. Finally, PMO is responsible for formal definition and consolidation of key processes in 2015, fostering formalisation.
Decision support and knowledge generation practices	➢ Product segmentation and specialised teams Since some product lines have distinct managerial necessities, products are segmented and managed according to their production technologies. Furthermore, few specific teams are created to tackle the most demanding technical challenges (e.g. the long-term capacity planning team). ➢ Traceability and anti-mixing systems A comprehensive traceability system allows the recall of any production batch before it reaches the final customer, through visual inspections and sample checks. A custom system avoids mixing in handling a large variety of labels: a large structured container is further divided in sub-containers in which labels are stored and there is a device synchronised with the production, thus a required set of labels is automatically released. ➢ Multi-echelon ERPs and optimisation IT tools Drinks adopts many systems and tools: from a major ERP integrated across facilities to planning modules, as well as smaller dedicated systems to perform analysis at the basis of portfolio rationalisation and others. Therefore, variety and relevance of IT systems are high and there are plant-dedicated local master data, reporting to a global master data. It ensures the correct use of systems, the alignment between them and the accuracy of data all times. ➢ Specific training In case of production relocation, adaptation of production lines or addition of new equipment, the production personnel are provided with specific training to accelerate learning curves. It is required by the temporary increase of stocks or by on-site tests.

The described complexity management practices affect in different ways the four resilience constituents, i.e. flexibility, velocity, collaboration and visibility.

First, the product portfolio rationalisation enables a better planning control, as less references mean less probability of mistakes in planning activities. Therefore, it increases visibility. In addition, reducing number of items positively affects flexibility and velocity, as stated by the interviewed local master data, due to, for instance, the higher transport efficiency or the less time required to introduce a SKU change.

Centralisation of purchasing positively impacts on flexibility too: it determines material standardisation, batches optimisation and supplier typologies optimisation, increasing the firm's flexibility in procurement management.

Considering localisation of activities, warehouses placed close to markets and on borders between countries represent a strategic point of decoupling and simplification. As a matter of fact, they enable Drinks to flexibly and quickly react to the market events, while optimising costs.

Stocks represent a buffer that can be exploited to quickly cover unexpected demand.

The centralised planning hub, intermediating between marketing and production facilities, increases collaboration among functions. Therefore, intermediate interface teams play a positive role.

Going through the third cluster of practices, the integrated ERP system (i.e. SAP) affects visibility and collaboration, as it shares info and real-time data and enhances coordination and communication among supply chain teams. However, it could be better developed, since it often fails in case of unexpected events, due to the tailored interfaces, the limited access and the not real-time updated data.

A key practice in drinks is project management, which impacts on three out of four resilience constituents. First, it increases the speed at which supply chain can introduce and cope with changes, reducing length of innovation processes. Second, the Project Management Office fosters visibility, because it consolidates data and information across different project managers around the world. Finally, since project managers have a coordination and homogenisation role, collaboration raises. As a matter of fact, they coordinate different functions having different objectives. For instance, the innovation project manager is the interface between marketing and supply chain, creating a dialogue across them.

As for traceability and anti-mixing systems, the fosters allow to recover all the data of a certain batch in case of recall, increasing visibility.

Finally, multi-echelon ERPs and optimisation IT tools play a dual role: on the one hand, they increase both collaboration and visibility, since, similarly to the integrated ERP, IT tools enhance coordination and communication and share information and data. On the other hand, IT systems could accentuate separation between functions and their tendency to think in silos, limiting accesses and having bespoke tailored interfaces, thus negatively impacting on the two same resilience constituents.

Table 6.8: *Influence of complexity management practices on resilience constituents in Drink case.*

	Flexibility	Visibility	Velocity	Collaboration
Variety reducing practices				
Product portfolio rationalisation	+	+	+	
Centralisation of purchasing	+			
Confinement and decoupling practices				
Customised distribution channels				
Category management				
Localisation of activities	+		+	
Stocks			+	
Intermediate interface teams				+
Coordination and collaboration practices				
Strategic relations with partners and suppliers				
Integrated ERP systems		+		+
Project Management		+	+	+
Decision support and knowledge generation practices				
Product segmentation and specialised teams				
Traceability and anti-mixing systems		+		
Multi-echelon ERPs and optimisation IT tools		+/-		+/-
Specific training				

6.2.4 Defence case study

Defence is an Italian and UK-based high-tech company and a key player in the Defence, Aerospace and Security industries. It offers an extremely diversified range of products and solutions to both military and civil markets, including aircrafts, sensors, systems, infrastructure and weaponry. They are sold in more than 100 countries, as the company has a global manufacturing footprint. Indeed, it leverages close to 200 facilities, with a strong presence in Poland and the US as well as in Italy and the UK, and runs operations in more than 50 countries. It employs more than 45,000 employees worldwide and has a yearly revenue of approximately 12,000 million €. The case study analyses the internal supply chain the Airborne and Space systems division in the UK, which designs, develops and produces a wide range of solutions for aircraft platforms (e.g. radars and sensors, simulation systems and aerial target systems), generating about 20% of the company's revenues. Since the analysis of the collected data reveals significant differences with the divisions in other key territories, the management practices presented in the case study are not in principle generalisable to the rest of the divisions.

Complexity management practices characterizing the Defence case study are listed in Table 6.9.

Table 6.9: *Defence's complexity management practices (Fernandez Campos, 2018).*

Variety reducing practices	➢ Product portfolio rationalisation Defence rationalises its portfolio removing products that cause losses, making space for new products and focusing on those that are driving sales. This practice frees up resources, enhances management focus, improves efficiency and reduces internal variability. ➢ Product-centric organisational design Integrated product teams are product-focused, running through the entire lifecycle of products, thus maximising team members' learning. ➢ Unification of customer requirements The company strives to find and establish commonalities within the variety of customer requirements, having close relationships with key customers and aligning organisation with this purpose (e.g. one bespoke single team for common processors of radar lines instead of individual product teams).
Confinement and decoupling practices	➢ Outsourcing To be able to cover the full technological spectrum of products, Defence relies on outsourcing, only keeping core competences in house. Apart some exceptions, for the majority of products it focuses on the final acceptance and integration of components and on product testing in-house, outsourcing the previous production activities. ➢ Modular design and software customisation Modular product designs and software customisations enable the company to adapt products' functionality to the needs of individual customers. ➢ Category management Similar components and parts (i.e. having common suppliers and technologies) are grouped under a unique category, reducing the effect of diversity on bargaining power. Each category is managed by a category team, which is part of the procurement function but has its own strategy. ➢ Split of sourcing activities Operational responsibility to manage suppliers is split between manufacturing and procurement teams: the supply chain and manufacturing group is responsible for managing the stable phases of procurement for regular components, while procurement handles the operational sourcing of especially complex product parts and of all parts during non-stable product phases. ➢ Flexible workforce A group of employees is trained with the necessary skills to be able to work across a range of manufacturing cells, learning to respond and adapt to external (i.e. suppliers and customers) or internal (i.e. testing and manufacturing) uncertainties. Personnel is moved across product lines once approximately every three months so as to maintain their varied skill-sets up.
Coordination and collaboration practices	➢ Decentralisation of procurement In order to have close relationships with suppliers, which are fundamental in such a complex business, procurement is decentralised. ➢ Integrated product teams Integrated product teams are teams that comprise of procurement, engineering and manufacturing and supply chain personnel who work physically together on a daily basis. They are collocated with products and dedicated to their specific manufacturing cell. Moreover, each project has an integrated product team, whose members are responsible for interfacing with their respective functions and bringing in the necessary resources.

(continue)

Coordination and collaboration practices	➢ Strategic relations with partners and suppliers Close relationships with suppliers allow managers to understand and expand suppliers' capabilities and enable Defence to ensure that product design have an adequate manufacturability for suppliers. Therefore, they are fundamental to bring the right innovations, Involving providers in development of new products from the very beginning of the design process. ➢ Integrated ERP systems The whole IT system is very integrated and directly linked with SAP. In particular, ERP system is integrated with traceability and anti-mixing systems. ➢ Project management Operations are managed through a project-based model, according to which each project delivers a product to a customer. ➢ Multi-level supply-demand reconciliations Different kind of meetings at different fixed time intervals and organisational levels are held ensure the continuous alignment between supply and demand. On the one hand, there are daily and weekly "drumbeat" meetings focusing on the daily progress of production and incorporating updated feedback from procurement regarding potential supply issues. On the other hand, monthly "hard supplier reviews" meetings of procurement, manufacturing and project management managers are held to prevent and discuss any potential mismatches between supply and demand. In addition, the two sides are strategically aligned via the integrated business plan, which establishes the goals for procurement and commercial functions for the following 5 years. ➢ Supplier development Thanks to close relations with them, managers understand and expand suppliers' capabilities. Developing providers, the variability of testing and manufacturing processes decreases, allowing more stable operational dynamics on the job floors.
Decision support and knowledge generation practices	➢ Cellular manufacturing and product technology groups Manufacturing is organised into large cells and a different manufacturing technique can be adopted within each cell depending on product. Technology groups around products are set up in the best way to manufacture each product segment. ➢ Traceability and anti-mixing systems All warehousing and goods receiving and dispatching activities are performed with the support of bespoke logistics facility and practices. For instance, materials coming in are logged into a system fully integrated with the ERP solely through barcode readers. Then, activities rely on real time visual feedbacks, not only inside the ERP, but also outside (e.g. a traffic-light colour code). Product-specific trolleys are adopted to pick up the materials, comprised of various drawers for the product specific parts to be arranged in sequence, and containers are dedicated to bolts, screws and other smaller components, which are integrated with suppliers and are automatically topped up in kits when necessary.

(continue)

Decision support and knowledge generation practices	➢ Product lifecycle management processes and tools Defence has a lifecycle management process, i.e. a formalised gated process that sets the foundations for managing all products and through which all projects are run. It aims at ensuring that all customer requirements are met and setting supply chain activities (concept, proposal and contract, design and qualify, scheduling, planning, sourcing, production). It supports managers in managing dynamic stages of their lifecycle, such as new products introduction or supplier obsolescence. ➢ Specific training When implementing a change, the company leverages bespoke training programs and strives to effectively communicate why and what the expected benefits are. ➢ Product design carry-over Some previous product design elements are reutilised when upgrading or designing new products, thus it is more evolution rather than revolution. This approach leverages on the specialised expertise that the integrated product teams have acquired on the preceding products, and it allows to introduce little modifications to the extant supply base.

These supply chain complexity management practices can increase or decrease resilience constituents. First, product-centric organisational design enables cross-functional collaboration and coordination, as well as it increases visibility on issues due to the specialised product-focus knowledge.

Considering modular design and software customisation, it positively affects visibility, due to the commonality of design allowing to understand many different products. Also, the practice allows to flexibly and quickly tailor a solution from an existing one, allowing to deal with a large scale of requirements and small-scale requirements. Finally, common elements can be procured in higher quantities, thus in a more flexible manner.

As for the category management, since discussions of category are centralised, information is shared across geographies, affecting both collaboration and visibility. Moreover, negotiating deals for categories enable a higher bargaining power and a joint strategy, increasing collaboration.

The flexible workforce is able to deal with perturbations and adapt to external events. Personnel is characterised by a variety of skill-sets, leverageable across a range of different manufacturing cells.

The procurement decentralisation enables a close coordination, due to close relationship with the field, which allow right and early conversations with suppliers about how to design products and manufacture. It increases not only collaboration, but also visibility, due to the close monitoring.

Integrated product teams comprise personnel from different functions, involving procurement, engineering, manufacturing and supply chain, which work together leveraging cross-functional collaboration and coordination. Moreover, it gives a higher visibility to all the members, as well as it avoids to spend time going down the chain due to the integration.

Strategic relations with partners enable not only close coordination and collaboration, getting suppliers to work with the company, but also close monitoring, due to the knowledge sharing (e.g. about what suppliers' capability is in order to not specify something they cannot make).

As for Integrated ERP, since it actually hinders capacity to adapt to new things efficiently, it negatively affects flexibility. It also plays a role in terms of visibility, which is both positive and negative. On the one hand, it allows complete visibility of materials and real-time visual feedbacks on how in-bound and dispatching orders are meeting service level agreements. On the other hand, it fosters the tendency to think inside the box, preventing employees from developing a broader understanding and hindering development of a holistic scenarios.

Multi-level supply-demand reconciliations bases on interactive processes and meeting during which procurement interacts with supply chain and manufacturing functions, thus increasing collaboration.

Supplier development positively affects velocity, because monitoring suppliers the firm makes sure that they are doing right, avoiding reworks and thus reducing lead times. It affects visibility too, due to full the requirements feeding out.

Passing to the last cluster of practices, cellular manufacturing and product technology groups reduce flexibility, as workforce is dedicated to cell and knowledge is consequently restricted to certain products. However, developing dedicated specialist skills to a very competent level and leveraging dedicated technology increases efficiency and speed.

Traceability and anti-mixing systems include a bespoke one self contained facility that gives much flexibility across workforce. Secondly, they allow complete visibility of materials and real-time visual feedbacks on how in-bound and dispatching orders are meeting service level agreements. Third, they enhance speed reducing time to get orders out from days to hours, also thanks to bespoke containers that minimize the amount of time spent in picking.

Apart from reducing speed, advantages of product lifecycle management processes are in terms of visibility. As a matter of fact, issues related to the new products introduction and around their manufacturability are well visible due to the comprehensive approach. Then, through them the firm leverages past lessons learned in supplier obsolescence management.

As for specific training, it accelerates the transition in case of change.

Finally, the product design carry-over enables to maximise learning, leveraging on specialised expertise that the integrated product teams have acquired on the preceding products, thus increasing visibility.

Table 6.10: *Influence of complexity management practices on resilience constituents in Defence case.*

	Flexibility	Visibility	Velocity	Collaboration
Variety reducing practices				
Product portfolio rationalisation				
Product-centric organisational design		+		+
Unification of customer requirements				
Confinement and decoupling practices				
Outsourcing				
Modular design and software customisation	+	+	+	
Category management		+		+
Split of sourcing activities				
Flexible workforce	+			
Coordination and collaboration practices				
Decentralisation of procurement		+		+
Integrated product teams		+	+	+
Strategic relations with partners and suppliers		+		+
Integrated ERP systems	-	+/-		
Project management				
Multi-level supply-demand reconciliations				+
Supplier development		+	+	
Decision support and knowledge generation practices				
Cellular manufacturing and product technology groups	-		+	
Traceability and anti-mixing systems	+	+	+	
Product lifecycle management processes and tools		+	+	
Specific training			+	
Product design carry-over		+		

6.3 Results

This section is an analysis of the impact of supply chain complexity management practices on resilience constituents as emerged from the previous case studies. First, Table 6.11 maps the four case studies, identified with a number: 1 = Percomp, 2 = Auto, 3 = Drinks and 4 = Defence, reporting when there is evidence of a link between the practice and the resilience constituent. The matrix is well populated, proving the existence of a relationship between the two dimensions. Only 6 out of 45 practices seem not to have any impact on resilience: *platform teams*, *customised distribution channels*, *organisational buffers*, *split of sourcing activities*, *product segmentation and specialised teams*, and *incremental organisational changes*. They represent a small percentage of the overall practices (i.e. 13%) and half of them are belonging to the confinement and decoupling cluster. All the others affect at least one resilience constituent, and many links' evidence emerges from more than one case. The strongest relationship is between integrated ERP systems and visibility, proved in three case studies. Reading the columns, all the constituents are impacted by more than 20 practices, around half of the total list. The most affected one is collaboration (60% of practices), while the less one is velocity (47% of practices). As consequence, it is evident the linkage between supply chain complexity management practices and resilience constituents. This relationship is then further investigated considering practices clusters (i.e. variety reducing, confinement and decoupling, coordination and collaboration, and decision support and knowledge generation) against resilience constituents, as reported in the next four tables (Table 6.12, Table 6.13, Table 6.14 and Table 6.15).

Table 6.11: *Map of case studies presenting links between complexity management practices and resilience constituents.*

	Flexibility	**Visibility**	**Velocity**	**Collaboration**
Variety reducing practices				
Accessory-based customisation	1		1	
Product platforms and standards	2		2	
Product portfolio rationalisation	1, 3	3	1, 3	
Product-centric organisational design	1	1, 4	1	1, 4
Platform teams (Organisational and processes' platforms)				
Rationalisation of SC facilities	1		1	
Process standardisation			2	
Unification of customer requirements				1, 2
Centralisation of purchasing	2, 3	2	2	2
Confinement and decoupling practices				
Outsourcing	1	1		
Customised distribution channels				
Modular design and software customisation	4	4	4	
Category management		4		4
Localisation of activities	2, 3		2, 3	
Additive manufacturing postponement	1		1	
Organisational buffers				
Split of sourcing activities				
Flexible workforce	4			
Stocks	2		2, 3	
Intermediate interface teams				3
Coordination and collaboration practices				
Decentralisation of procurement		4		4
Global SC forums (and governance models)	1	1		1
Integrated product teams		4	4	4

	Flexibility	Visibility	Velocity	Collaboration
Strategic relations with partners and suppliers	1	1, 4	1	1, 4
Integrated ERP systems	4	2, 3, 4	2	2, 3
Benchmarking				2
Coll. with prod. design/front-end teams				1
Project management		1, 3	2, 3	2, 3
				(continue)
Cross-functional KPIs		1		
Multi-level supply-demand reconciliations				4
Unique customer interfaces		2	2	2
Supplier development		2, 4	2, 4	
Decision support and knowledge generation practices				
Forward-looking forecasting		1		
Cellular manufacturing and product tech. groups	4		4	
Product segmentation and specialised teams				
Automation	2	1, 2	1, 2	
Traceability and anti-mixing systems	4	3, 4	4	
Multi-Echelon ERPs and optimisation IT tools	1	1, 3	1	1, 3
Product lifecycle management processes and tools		2, 4	2, 4	
Vendor rating tools		2		2
Specific training			2, 4	
Product design carry-over		4	2	
Simulation		1, 2		

For each resilience constituent, a table summarizes the results indicating for each cluster the number of practices that have a positive influence on it and those with a negative role. Furthermore, the percentage value is reported, computed as the ratio between the number of positively/negatively affecting practices and their sum.

The first investigated resilience constituent is flexibility, which is mainly positively impacted by variety reducing, and confinement and decoupling practices. Coordination and collaboration practices play uniquely a negative role, while the last cluster has a both positive and negative contribute.

Table 6.12: *Impact of complexity management practices clusters on flexibility.*

	N. positive	**N. negative**	**% positive**	**% negative**
Variety reducing practices	7	3	70%	30%
Confinement and decoupling practices	7	1	87,5%	12,5%
Coordination and collaboration practices	0	3	0%	100%
Decision support and knowledge generation practices	2	2	50%	50%

Secondly, visibility is impacted both positively and negatively by all the clusters. On the one hand variety reducing and coordination and collaboration practices have mainly a positive role, on the other hand the other two clusters have a high percentage of negative linkages.

Table 6.13: *Impact of complexity management practices clusters on visibility.*

	N. positive	**N. negative**	**% positive**	**% negative**
Variety reducing practices	4	2	80%	20%
Confinement and decoupling practices	2	1	66,7%	33,3%
Coordination and collaboration practices	15	1	93,7%	6,3%
Decision support and knowledge generation practices	8	4	66,7%	33,3%

Then, the velocity is increased by practices belonging to cluster confinement and decoupling and decision support and knowledge generation. The other two clusters mainly have a positive influence too.

Table 6.14: *Impact of complexity management practices clusters on velocity.*

	N. positive	**N. negative**	**% positive**	**% negative**
Variety reducing practices	7	4	63,6%	36,4%
Confinement and decoupling practices	6	0	100%	0%
Coordination and collaboration practices	7	1	87,5%	12,5%
Decision support and knowledge generation practices	10	0	100%	0%

Finally, collaboration is only increased by complexity management practices of all the clusters, except decision support and knowledge generation, which, however, has a strong positive percentage.

Table 6.15: Impact of complexity management practices clusters on collaboration.

	N. positive	N. negative	% positive	% negative
Variety reducing practices	5	0	100%	0%
Confinement and decoupling practices	2	0	100%	0%
Coordination and collaboration practices	12	0	100%	0%
Decision support and knowledge generation practices	5	1	83,3%	16,7%

These results emerge from the empirical evidence of the link between supply chain complexity management practices and resilience constituents. However, analysed case studies do not provide evidence of exploitation of these approaches and tools under disruption. Therefore, to strengthen the consistency of the results and build some theory about them, they can be triangulated, leveraging the findings of both Chapter 5, i.e. the relationship between supply chain complexity and resilience, and Section 6.1, i.e. the linkage between supply chain complexity and complexity management practices. In this vein, the next chapter provides a detailed discussion of findings, further providing elements to answer the third research question.

Chapter 7
Discussion

The chapter presents a unified discussion about the findings reported in Chapter 5 and Chapter 6, i.e. resulting from the Critical Incident Technique and the inductive case studies analysis. A first paragraph illustrates how the whole results are collected and organised into a comprehensive matrix. The matrix highlights the relationships between complexity management practices and resilience constituents that are disclosed by the present study, through the analysis of the role of static and dynamic complexity drivers. However, coherently with the study's qualitative approach, only the most relevant practices, i.e. those with the widest set of mechanism of influence on resilience are selected for a deeper analysis and discussion. Therefore, the rest of the chapter focuses on the five selected practices. For each one, the first sub-section summarises its linkages with resilience constituents, going through the mediation of complexity drivers. Then, a second sub-section, discusses the role of the specific complexity management practice on resilience linking the proposed results with the prior state-of-the-art. A final section discusses the level of originality and the relevance of the results achieved.

7.1 Summary matrix of findings and selection of the most relevant complexity management practices

The last step of the study consists in a comprehensive analysis of the results emerging from the previous two phases. Drawing from the evidence of linkages between supply chain complexity drivers and resilience and between the complexity management practices and resilience, proved in Chapter 5 and 6 respectively, a summary matrix matching the three dimensions is set forth. As designed into the study methodology, described in Chapter 4, results from the two analyses are triangulated, increasing the consistency of the links reported in the final table and consequently the robustness of results. Actually, the matrix unifies both the direct link between complexity management practices and resilience constituents, defined through the four inductive case studies, and the indirect link between them, considering the interplay between complexity drivers, as emerged from the Critical Incident Technique.

The summary matrix of findings, reported in Annex C, matches the complexity management practices, on the rows, and the resilience constituents, on the columns. Positive (i.e. increasing) and negative (i.e. decreasing) effects on resilience are reported separately. In each cell, the complexity drivers mediating the relationship and linking the two dimensions are reported. Nevertheless, this representation is inconveniently fragmented and could impair the quality of a truly in-depth analysis of the phenomena.

Therefore, analysis and discussion of results focus on dominant practices only. This approach is coherent with the qualitative approach adopted in the whole study.

Consequently, the most relevant complexity management practices are selected, considering those that present at least three links, either positive or negative, with different resilience constituents. Furthermore, since they are consistently proved by the triangulation, a higher number of relationships corresponds to a richer and more reliable evidence emerging from the two different phases of the study. In this manner, five dominant practices are identified as reported in Table 7.1.

Table 7.1: *Selected complexity management practices.*

Complexity management practices	N. of links with resilience constituents
Product-centric organisational design	6
Centralisation of purchasing	3
Strategic relations with partners and suppliers	5
Project management	3
Multi-echelon ERPs and optimisation IT tools	5

7.2 Product-centric organisational design

7.2.1 Linking product-centric organisational design and resilience

Considering the number of links with resilience constituents as a proxy, the complexity management practice which most impacts on supply chain resilience is *product-centric organisational design*, presenting six linkages, as shown in Table 7.2. In its cells, the role of complexity drivers interplaying the relationships between management practices and resilience constituents are reported, distinguishing between positive and negative influence.

Table 7.2: *The role of complexity drivers in mediating the relationship between product-centric organisational design and resilience constituents.*

	Positive influence	Negative influence
Flexibility	➢ Simpler and more effective mgmt. of *portfolio breadth, product variety and specificities, variety and breadth of customer requirements, product introduction and LC events* and *demand/supply sides operational dynamics*, due to the focus on product, across entire SC network and processes, enabling a flexible range of alternatives in case of disruption. ➢ Better mgmt. of *differences between facilities in different territories*, thanks to unified procedures and tools, increasing similarity that enables flexibility.	➢ Fostering of increasing *product variety and specificities*, difficult to easily manage if they are more, thus hindering flexibility. ➢ Fostering of increasing number of customers, thus *variety and breadth of customer requirements*. This increases the external interrelationships of the company, also through different communication channels, reducing flexibility.
Visibility		➢ Fostering of increasing number of customers, thus *variety and breadth of customer requirements*. This increases the external interrelationships of the company, also through different communication channels, reducing visibility.
Velocity	➢ Better mgmt. of *differences between facilities in different territories*, thanks to unified procedures and tools, rapidly extendible and implementable in different plants. ➢ Faster mgmt. of *product introduction and LC events*. ➢ Simpler mgmt. of *demand/supply sides operational dynamics*, increasing velocity of reactions.	➢ Fostering of increasing *product variety and specificities*, difficult to easily manage if they are more, thus hindering velocity. ➢ Fostering of increasing number of customers, thus *variety and breadth of customer requirements*. This increases the external interrelationships of the company, also through different communication channels, reducing velocity.

(continue)

	Positive influence	Negative influence
Collaboration	➢ Simpler and more effective mgmt. of *portfolio breadth, product variety and specificities, variety and breadth of customer requirements* and *demand/supply sides operational dynamics*, due to the focus on product, across different SC actors, and the higher synchronisation. This enables collaboration between resources of different businesses, or between substitutive products. ➢ Better coordination, and thus collaboration, of *differences between facilities in different territories*, thanks to unified procedures and tools.	

Product-centric organisational design has a dual nature, as it is both a complexity accommodation and a complexity reduction practice (Bozarth et al., 2009; Manuj and Sahin, 2011; Perona and Miragliotta, 2014; Serdarasan, 2013). As for the accommodation approach, focusing on a single product or a set of products across the entire supply chain network and across all the supply chain processes enables a better understanding of it, thus allowing to manage product structural complexity drivers (i.e. portfolio breadth and product variety and specificities), as well as variety and breadth of customer requirements in a simpler and more effective way. Moreover, since managers have more visibility and synchronisation, the company benefits in managing product introduction and lifecycle events, and to be effective in facing operational dynamics related to unexpected customer demand. A clear example of it is given by the "end-to-end planner" organisational design characterizing Percomp, but also by the product-centricity of integrated product teams, which run through the entire lifecycle of products in Defence.

Accommodating the aforementioned complexity drivers, the practice has a synergic contribution on the impact on resilience constituents. First, a wide portfolio breadth increases both flexibility and collaboration, as resources belonging to different businesses can be leveraged in face of a disruption. For instance, Sapporo's sales of mineral water and unsweetened beverages increased following the Japanese earthquake in 2011 and the demand shift allowed to cover losses in alcoholic beverages business. As consequence, increasing the ability to manage a broad portfolio, due to the specialised end-to-end product knowledge, *product-centric organisational design* increases the two resilience constituents. The same reasoning is valid for product variety and specificities too: the possibility to offer substitutes or different configurations of products increases flexibility and collaboration (e.g. Dell Inc. in facing the US west coast lock out due to longshoremen strike, or Evonik Industries after the fire at a German plant), thus the considered practice does the same.

However, offering a high variety of products with different specificities could also reveal a limit in facing disruptions, as proved by Volkswagen Group's experience. Since the company adopted different approaches to cope with the diesel issue in different countries, due to the different emissions standards and rules affecting its products, the high number of specificities hindered flexibility and velocity. Therefore, although *product-centric organisational design* enables a better management of specificities, the risk is to increase them too much, hindering resilience in case of disruption.

For what concerns variety and breadth of customer requirements, it plays a dual role in terms of resilience, both increasing and decreasing it, even though the main influence is negative. Serving a lower number of customers not only fosters partnerships creation, but also facilitates the reaction to incidents involving them. For example, since Nestle S.A. addressed many different typologies of customers, it was more difficult to rebuild image destroyed by the social media attack on KitKat, due to the variety of involved communication channels. Another example is the velocity showed by Mattel in recalling unauthorized toys, thanks to the limited number of customers (i.e. three biggest retailers in USA) that allowed to quickly prevent more affected toys from reaching end-consumers. Therefore, flexibility, visibility and velocity are negatively influenced by the number of customers, represented by the complexity driver called variety and breadth of customer requirements. Since *product-centric organisational design* accommodates this driver, firms adopting this practice are fostered to increase customers base, decreasing the three resilience constituents. Nevertheless, despite the low evidence about it, broader customer requirements could also have a positive impact on flexibility and collaboration (e.g. Sanofi Genzyme having a higher variety on customers had more possibilities to serve some of them, according to prioritisation criteria set with patient communities), determining the same effect of the practice under analysis.

Moving on to dynamic complexity drivers, as *product-centric organisational design* facilitates the management of product introduction and lifecycle events, which in turn increase flexibility and velocity, resilience is positively influenced thanks to this additional mechanism. In case of disruption, established capabilities to launch, acquire and integrate many new products and to study potential new services increase the ability to introduce substitutes, as proved by Sanofi Genzyme experiences with experimental drugs.

Considering the complexity reduction approach, instead, *product-centric organisational design* fosters the unification of procedures and tools across territories, reducing variety of teams and functions, as well as differences between facilities in different territories. As a matter of fact, Percomp's "end-to-end planner" organisational design overcomes silos-thinking of the previous geography-oriented design. Therefore, since the practice reduces the complexity, its impact on resilience is inversely proportional to that of complexity drivers. Differences between facilities in different territories hinders flexibility, velocity and collaboration. Having a single plant in the world producing a specific product prevents from leveraging on the support of others, while, instead, similarity between plants allows to flexibly ramp up production. For instance, Takata could manage the additional production volume required by the replacement of recalled vehicles' airbags thanks to production not dependent on a specific facility. Since the extent of the disruption was too much for the company (after several chains of recalls it filed for bankrupt in July 2017), if it was not for such a resilient reaction it would may have defaulted 5 years earlier. It is evident that reducing this complexity driver, flexibility, velocity and collaboration increase, thus *product-centric organisational design*, as complexity reduction practice, positively affects resilience.

7.2.2 Results and prior state-of-the-art

In conclusion, the *product-centric organisational design* plays a dual role, as it positively influences flexibility, velocity and collaboration, but at the same time it could impair flexibility, visibility and velocity.

On the one hand, the ability to manage a broad portfolio and a high product variety allows higher flexibility and collaboration. This is a completely new contribution to literature. Indeed, although Serdarasan (2013) identifies the number and variety of products as a static internal complexity driver, there is a lack of literature discussing its impact on resilience constituents. Most authors focus their studies on the number of nodes and flows characterising the supply chain (Adenso-Diaz et al., 2012; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca et al., 2008; Hearnshaw et al., 2013; Thome et al., 2016; Skilton and Robinson, 2009), without considering product design complexity.

Moreover, product-centric tools and approaches enable companies to keep high dynamicity on the demand side and continuously introduce new products and manage lifecycle events, and these are complexity drivers that are revealed as fundamental for a flexible and rapid reaction to incidents. Despite the amount of research that assesses the effect of dynamic complexity on resilience constituents (Durach et al., 2015; Gunasekaran et al., 2015; Hearnshaw et al., 2013; Hosseini et al., 2016; Thome et al., 2016), product dynamic complexity has not yet been investigated. In addition, the existing studies theoretically discuss how flexibility, velocity, visibility and collaboration are expected to influence supply chain dynamic complexity, and not, vice versa.

Finally, the considered practice also accomplishes the reduction of differences across countries, fostering functional redundancy exploitable in case of local supply chain disruptions. This finding expands knowledge from the existing literature, as it demonstrates the influence on additional constituents. In fact, Brandon-Jones et al. (2014)

demonstrated, through regression analysis, that geographic dispersion or concentration of suppliers, as well as their level of differentiation or similarity, do not affect visibility, but they do not refer to other resilience constituents. On the contrary, this study suggests that more similarity across different territories determines higher flexibility, velocity and collaboration.

On the other hand, managers need to consider the variety and breadth of customer requirements separately. Although product-centricity seems to manage and accommodate them effectively (Fernandez Campos, 2018) - as it facilitates customisation of products to meet the requirements of each customer (e.g. Defence case) - in case of disruption this complexity driver plays a negative role, due to the difficulties in relating and communicating with a high number and variety of customers involved. Therefore, flexibility, velocity and visibility decrease. This resonates with Skilton and Robinson's work (2009), which states that numerousness of nodes and the level and types of interrelationships negatively affect visibility. In addition, this constituent is negatively affected by this product-centricity, because focusing only on products, country complexity and local specificities are difficult to be integrated in the global vision (Fernandez Campos, 2018).

However, broader customer requirements could also have a positive impact on flexibility and collaboration, confirming what is only theoretically discussed by Falasca et al. (2008) and Arkhipov et al. (2001), i.e. that the number of supply chain entities and flows between them are directly proportional to flexibility. Furthermore, the result is also consistent with the evidence provided by case studies and scenario analysis by Cardoso et al. (2014; 2015).

7.3 Centralisation of purchasing

7.3.1 Linking centralisation of purchasing and resilience

Another variety reducing practice that affects resilience is *centralisation of purchasing*, which presents positive links with flexibility, visibility and collaboration. Table 7.3 collects the role that complexity drivers play in increasing the ability of companies to recover from disruption and return to normal operating performance.

Table 7.3: *The role of complexity drivers in mediating the relationship between centralisation of purchasing and resilience constituents.*

	Positive influence	Negative influence
Flexibility	➢ Reduction of *differences between facilities in different territories*, thanks to the rationalisation of required materials, increasing similarity that enables flexibility.	
Visibility	➢ Reduction of *number and variety of partners*, due to the rationalisation of supply base. A narrower base enables a better control and visibility, also thanks to stronger relationships.	
Velocity		
Collaboration	➢ Reduction of *differences between facilities in different territories*, thanks to the rationalisation of required materials. This standardisation enables a better coordination and collaboration among plants. ➢ Reduction of *number and variety of partners*, due to the rationalisation of supply base. A narrower base enables deeper relationships with suppliers, increasing collaboration.	

Although belonging to the variety reducing cluster, *centralisation of purchasing* is also a complexity accommodation practice, aiming at coping with internal and external structural complexity drivers. Managing supplies for key materials through a central purchasing team enables to unify materials across plants, hence reducing differences between facilities in different territories. Furthermore, by aggregating demand, the company can rationalise required materials and suppliers at a global level, to negotiate better deals and establish longer relationships with suppliers, better managing number and variety of partners. For instance, the Global Purchasing Office and the global category managers in Drinks secure more convenient and durable deals, due to the consolidated global volumes. A similar experience is evident in Auto, where a central purchasing team manages key direct and indirect materials purchasing.

Accommodating the two structural complexity drivers, i.e. differences between facilities in different territories and number/variety of partners and suppliers, *centralisation of purchasing* mitigate their negative effect on supply chain resilience constituents, thus determining a positive influence of the practice on them. First, by decreasing differences between facilities, the practice increases flexibility and collaboration. Indeed, these two resilience constituents are negatively impacted by the considered complexity driver, as having a certain product manufactured in a one facility only hinders support from others, reducing recovery options. It clearly emerges from Evonik Industries case: after the fire, due to the high differences between plants, the firm was forced to stop production, paralysing the whole supply chain. Moreover, the entrepreneurial independence characterising different facilities determined difficulties in collaboration even within the group. The same issue was faced by Sanofi Genzyme, which at the time of disruption had only one plant producing the affected drug, due to the pharmaceutical uniformity requirements. Opposite evidence is provided by Procter and Gamble, which, thanks to the many international sites manufacturing products for multiple businesses, could guarantee production from other sites. Even though examples are related to production capacity, the same logic can be extended to the supply process. Therefore, considering *centralisation of purchasing*, rationalising volumes and typologies of purchased materials enables to leverage collaboration with other plants in case of materials shortage, hence increasing both flexibility and collaboration.

For what concerns number/variety of partners and suppliers, purchasing centralisation plays a dual role in terms of resilience. On the one hand, it decreases visibility, velocity and collaboration, as proved for instance by Dell when it faced the 10-days labour lockout shutting down ports: a lower number of partners guarantees a stronger relationship with them, characterized by constant communication and working collaboration. Differently, a huge quantity of suppliers to manage is more difficult and requires a higher effort (e.g. difficult and time-consuming certification of suppliers at Nestlé). Consequently, since *centralisation of purchasing* reduces the number and variety of providers, it positively influences the three resilience constituents. However, triangulation with the four inductive case studies confirms only the positive links with visibility and collaboration.

On the other hand, number/variety of partners and suppliers increases flexibility, as a wider base of available suppliers reduce the dependency on a sole provider, ensuring lower time to shift to substitutive suppliers to resume production. The negative impact determined by single sourcing is evident in more than one analysed critical incident, including Boeing, Mitsubishi Motors Corporation, PSA Peugeot Citroën and Honda Motor, whose negative consequences under the disruptive events were strongly influenced by their dependence on single suppliers. Nevertheless, centralisation of purchasing means standardisation of the sourcing purchasing strategy, but not necessarily single sourcing. Indeed, the negative relationship between *centralisation of purchasing* and flexibility is not assessed in any case study, thus there is not consistency of results and the link is not reported as a finding in Table 7.3.

7.3.2 Results and prior state-of-the-art

As previously described, differently from product-centric organisational design, *centralisation of purchasing* only positively influences resilience constituents, increasing flexibility, visibility and collaboration. Indeed, it decreases two structural complexity drivers which in turn play a negative role in terms of resilience, hence the final effect is positive.

First, by centralising supplies, companies can rationalise the materials base, thus reducing differences between facilities in different territories. The role of this complexity driver under disruption is somewhat less discussed in the literature, and, differently from this study, no author has discussed its influence on flexibility and collaboration. As a matter of fact, although Skilton and Robinson (2009) theoretically analyse nodes' degree of coupling (i.e. how many variables two separate subsystems have in common), they focus only on the impact on traceability and transparency, thus visibility. The only link between variety of elements of a network and flexibility is presented by Arkhipov (2011), but it is a positive one, since according to him higher variety of nodes means higher alternatives to exploit. Therefore, this study, which sustain, supported by empirically evidence, a negative relationship between differences between facilities in different territories and flexibility and collaboration represents an original contribution to the literature.

Secondly, *centralisation of purchasing* determines lower number and variety of suppliers to manage, allowing a higher visibility on them and a deeper collaboration with them. There is a lack of discussion about it in the prior state-of-the-art too. The only consistent contribute is by Skilton and Robinson (2009), stating that the more the level and types of interrelationships, the more the complexity of supply chain, hence the less the transparency and the traceability in it. Instead, other authors discuss about the connection between this complexity driver and flexibility. Both Falasca et al. (2008) and Cardoso et al. (2014; 2015) assess the increase of the resilience constituent due to the high number of redundant suppliers. Indeed, multiple sourcing determines a wide range of alternatives in case of supply disruptions. While the formers only theoretically discussed it, the latter ones empirically proved the evidence through case study analysis methodology. However, purchasing centralisation does not necessarily mean single sourcing, and the negative consequences of central-single sourcing in terms of flexibility are not evident in any of the considered case studies.

7.4 Strategic relations with partners and suppliers

7.4.1 Linking strategic relations with partners and suppliers and resilience

Among the complexity management practices with the highest impact on supply chain resilience there is *strategic relations with partners and suppliers*, which presents five links with resilience constituents, as reported in Table 7.4. Here, the role of complexity drivers mediating the relationships resulting from Critical Incident Technique and case studies investigation are shown, considering not only *strategic relations with partners and suppliers*, but also *supplier development*. In fact, despite their distinction in Fernandez Campos' study (2018), the latter can be considered a form of strategic relationship, and thus included in a broader definition of the former. Therefore, in this analysis, the two practices were merged and discussed together.

Table 7.4: *The role of complexity drivers in mediating the relationship between strategic relations with partners and suppliers and resilience constituents.*

	Positive influence	**Negative influence**
Flexibility		➢ Reduction of *number and variety of partners and suppliers* and *new customers or suppliers*, due to supply base rationalisation. This decreases the number of available alternatives in case of disruption, thus reducing flexibility. ➢ Fostering of increasing *product variety and specificities*, thanks to knowledge sharing and collaborative processes to better manage them. Variety reveals difficult to easily manage, thus hindering flexibility.
Visibility	➢ Reduction of *number and variety of partners and suppliers*, due to supply base rationalisation. A narrower base enables a better control and visibility, also thanks to stronger relationships.	
Velocity	➢ Reduction of *number and variety of partners and suppliers*, due to supply base rationalisation. A narrower base can speed up required procedures. ➢ Better and timely mgmt. of *product introduction and LC events* and *demand/supply sides operational dynamics*, thanks to early knowledge sharing and collaborative processes.	➢ Fostering of increasing *product variety and specificities*, thanks to knowledge sharing and collaborative processes to better manage them. Variety reveals difficult to easily manage, thus hindering velocity.

(continue)

	Positive influence	Negative influence
Collaboration	➢ Reduction of *number and variety of partners and suppliers*. A narrower base enables a better communication, also thanks to stronger relationships. ➢ Better mgmt. of *product variety and specificities* and *demand/supply sides operational dynamics*, thanks to knowledge sharing and collaborative processes. This enables collaboration between resources of different businesses, or between substitutive products.	

Like *product-centric organisational design*, also the *strategic relations with partners and suppliers* has a twofold nature, being both a complexity accommodation and a complexity reduction practice (Bozarth et al., 2009; Manuj and Sahin, 2011; Perona and Miragliotta, 2014; Serdarasan, 2013). When it comes to the second, limiting the number of critical partners selected for win-win relationships it enables to reduce the number and variety of suppliers managed by a company, as well as to decrease the number of new suppliers when new products are introduced. Indeed, in order to set strategic partnerships - i.e. having collaborative processes, sharing profits on returns, exchanging information and knowledge - a company needs to rationalise the supply base and carefully nurture and manage the few selected providers, as proved by Percomp case.

Consequently, the reduction of these two supply chain complexity drivers hinder their impact on resilience constituents. First, higher the number and variability of suppliers, higher the flexibility leverageable under disruption. For instance, after the Thailand flood, Mitsubishi Motors could exploit the high number of auto parts makers, temporarily shifting to providers outside the affected area. On the contrary, having only certain suppliers for some raw materials and parts, Honda could not shift requests to alternative sources, being forces to interrupt the production. The capability to rely on new suppliers aids a company to flexibly react to a supply shortage too, as demonstrated by Boeing in answering to the Japan earthquake damages to providers. Thus, *strategic relations with partners and suppliers* reduces flexibility.

On the other hand, strategic relationships mitigate the negative effect that a high number and variety of partners have on visibility, velocity and collaboration. First, closely collaborating with suppliers, companies can have higher visibility on disruption impact. For instance, through collaboration with first-tier providers, Boeing could easily determine second-tier ones affected by the Japan earthquake. Then, a lower number of involved actors can speed up procedures of certification (e.g. Nestlé’s certification of suppliers was difficult and time consuming due to the large number of interested companies). Finally, another example is given by Dell, where a low number of parts makers allowed a constant round-the-clock communication and a tight integration with them, enabling to work together. However, Dell compensated the reduced flexibility on the supply side with a very highly flexible product portfolio and marketing strategy.

For what concern the complexity accommodation nature of the practice, *strategic relations with partners and suppliers* aids in managing product introduction and lifecycle events, as well as product variety and specificities, since suppliers are involved in new products development from the very beginning of the design process. As proved in Defence, close partnerships are fundamental to bring the right innovations and to have conversation about how to design and manufacture products early enough. Moreover, supplier development ensures that the product design have an adequate manufacturability for components makers. Therefore, the practice synergistically increases velocity and collaboration. First, product introduction and lifecycle events positively impact on the former, as orientation to innovation facilitate introduction of substitutes or renovation of existing products, as proved by Nestlé in rapidly renovating products and eliminating palm oil. Secondly, high product variety and specificities play a positive role in terms of collaboration, as severe specificities force customers to not change supplier, but to work together with him in order to solve issues, as emerged in the Takata case. Thus, since strategic partnerships enable to better define a higher level of specificities, they push supply chain collaboration.

On the other hand, product variety and specificities decrease flexibility and velocity. Indeed, having similar equipment specificities for different products enables companies to shift production among different facilities, as done by SK Hynix for DRAMs production. Furthermore, strict rules, such as emissions rules typical of the automotive industry, force products to be approved by different agencies, negatively impacting flexibility and velocity (e.g. Volkswagen case). Hence, even though strategic relationships allow to more effectively manage these issue, they determine a collateral effect, reducing the two resilience constituents.

Finally, the last complexity driver managed by *strategic relations with partners and suppliers* is supply side operational dynamics. As a matter of fact, Auto adopts suppliers development initiatives in order to cope with the variability in the supply base and with supplier-triggered operational dynamics. Consequently, since supply side dynamics increase velocity and collaboration, by accommodating them the practice has a positive effect on them too. For instance, the experience gained with past recalls allowed Mattel to quickly manage all the aspects of the crisis due to non-approved toys. Another example comes from Nestlé: being used to encourage continuous improvement of suppliers, the company leveraged collaboration with them to face the social media attack.

7.4.2 Results and prior state-of-the-art

Drawing from the literature review, described in Chapter 2, Gunasekaran et al. (2015) introduce partnerships as a key for successful supply chain operations. However, they do not directly link the practice to supply chain resilience, and the topic in general is somewhat less discussed in literature, hence this study represents an additional and original piece of knowledge.

Summarizing what previously described, *strategic relations with partners and suppliers* plays a twofold role, because, on the one hand, it positively influences visibility and collaboration, on the other hand, it could impair flexibility and shows an ambivalent influence on velocity. The positive influence on resilience is given by the better management of product introduction and lifecycle events and supply sides operational dynamics, while the negative one by the reduction of new suppliers. The reduction of number and variety of partners and suppliers and of product variety and specificities, instead, have a dual role, as they increase some constituents and decrease others, as shown in Table 7.4.

First, while the positive link between the number of redundant suppliers in a network and flexibility has been investigated, both theoretically (Falasca et al., 2008) and empirically (Cardoso et al., 2014; Cardoso et al., 2015), there is a lack in the state-of-the-art about the negative influence of this complexity driver on visibility, velocity and collaboration. Only Gunasekaran et al. (2015) state that strategic relationships, based on supply base rationalisation, foster collaboration between companies.

Considering product variety and specificities, product introduction and lifecycle events and supply side operational dynamics, extant studies about supply chain complexity focus mainly on supply chain nodes and flows (Adenso-Diaz et al., 2012; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca et al., 2008; Hearnshaw et al., 2013; Thome et al., 2016; Skilton and Robinson, 2009). Moreover, literature lacks discussions about dynamic complexity, which is identified with uncertainty and randomness (Adenso-Diaz et al., 2012; Durach et al., 2015; Gunasekaran et al., 2015; Thome et al., 2016), and not with drivers introduced by Fernandez Campos (2018). However, the findings resonate in the study by Gunasekaran et al. (2015), in which the authors argue that collaboration entailing from strategic partnerships is fundamental during product and supply chain design, since it reduces complexity and uncertainty in the supply chain.

7.5 Project management

7.5.1 Linking project management and resilience

One of the most common complexity management practices is *project management*, which is adopted by all the four case companies. Accommodating many static and dynamic complexity drivers, it positively affects visibility, velocity and collaboration, as indicated in Table 7.5.

Table 7.5: *The role of complexity drivers in mediating the relationship between project management and resilience constituents.*

	Positive influence	Negative influence
Flexibility		
Visibility	➢ Simpler and more effective mgmt. of *reconfiguration of SC activities and facilities, improvements to equipment, procedures and systems*, and *restructuring and M&A*, due to the focus on project, across entire SC network and processes. This increases visibility on possible options to face disruption.	
Velocity	➢ Simpler and more effective mgmt. of *product introduction and LC events*, *reconfiguration of SC activities and facilities, improvements to equipment, procedures and systems*, and *restructuring and M&A*, due to the focus on project, across entire SC network and processes.	
Collaboration	➢ Simpler and more effective mgmt. of *portfolio breadth, product variety and specificities, variety and breadth of customer requirements*, and *restructuring and M&A*, due to the focus on project, across entire SC network and processes, thus increasing collaboration, both internally (among businesses) and externally (with customers).	

Project management is a complexity accommodation practice, as it does not physically reduce any complexity driver, but it entails some approaches and tools that mitigate the negative effects of many. Indeed, focusing on a project or a set of projects, activities across the supply chain network and processes are coordinated and integrated, helping in structuring and implementing strategic initiatives. On the one hand, it is mainly associated to dynamic complexity drivers, including changing events such as supply chain reconfiguration, equipment improvements, company restructuring, and mergers and acquisitions. On the other hand, *project management* is often exploited for the introduction of new products or services, enabling to manage not only the corresponding dynamic product driver, but also some structural complexity drivers, such as portfolio breadth, product variety and specificities, and variety and breadth of customer requirements. For instance, in Drinks, where the Project Management Office is part of the Innovation function, it aids introduction of new products, launching of new brands, product line extensions, packaging updating, entering in new markets and formula modifications. Since the simpler management of these complexity drivers enables companies to increase their structural and dynamic complexity, exploitable as source of competitive advance, this practice is positively related with them. Therefore, it plays a synergistic role considering their effects on resilience constituents.

First, product structural complexity drivers, such as portfolio breadth and product variety and specificities, increase collaboration, both internally among company's businesses and externally in the relationship with customers. As for the former, after Hurricane Katrina, Procter and Gamble shifted workers from operations outside coffee to the affected business; as for the latter, Takata's customer carmakers were forced to not change supplier, as the severe product specificities would have determined time-consuming and costly verification of safety of new airbag designs. Consequently, increasing effectiveness in managing them, *project management* positively influences collaboration too. Similarly, variety and breadth of customer requirements, including the kind of relationship with them, have a positive influence on coordination. Analysing the critical incident occurred to Evonik Industries, i.e. the fire at the German plant, it emerged that the firm collaborated with customers to find right substitutes, thanks to the deep involvement in partnerships determined by the tailored breadth of requirements. It is arguable that different companies collaborating in finding countermeasures under disruption may better coordinate among themselves through *project management* techniques and organisational means.

As previously mentioned, *project management* is a good practice to cope with dynamicity. Considering product introduction and lifecycle events, a structured process (e.g. gated one) characterized by progress monitoring determines a more rapid launching of new products, through corrective actions on the original idea, as proved by the Auto case. Moreover, the practice plays a synergistic role with the positive impact of the complexity driver on velocity. For instance, after the diesel gate scandal, Volkswagen could quickly identify technical solutions thanks to its investments in R&D and new products introduction.

Reconfiguration of supply chain activities and facilities positively influences velocity too, as it enables to timely react to incidents, for example easily changing transportation mode. It was the case of Dell, which, to face the labour lockout involving union dockworkers, chartered 18 planes to cover the lack of cargo ships. Furthermore, from the same critical incident is evident also the impact of supply chain reconfiguration on visibility. As a matter of fact, the company realized the planes option before other companies, gaining competitive advantage. The same is assessed for what concerns improvements to equipment, procedures and systems. Since they entail a continuous visibility on the supply chain, a company can rapidly detect a disruption and flexibly identify an alternative transportation channel (e.g. Dell critical incident). It is well evident from Mattel case as well: being used to invest in initiatives to improve supply chain, the company could better manage the supply reconfiguration determined by the incident, i.e. stopping of accepting goods from the not compliant subcontractor and slowing down the shipments out of Asia. In addition, continuous improvements to procedures allowed to rapidly introduce procedures for the recall management, through the dedicated website.

Finally, restructuring and M&A play a positive role in terms of resilience too. First, they increase collaboration, as they enable to build alliances with competitors that could reveal fundamental in aiding under disruption, as evident in the reaction of Goodyear to the Thailand flood. Secondly, velocity is positively affected, as proved by the experience of Volkswagen, which could manage more rapidly the decentralisation of the organisational structure in response to the diesel gate scandal, thanks to the already happening organisational restructuring. Then, also visibility on possible alternatives is higher thanks to a higher market scouting determined by a strong M&A strategy. Accommodating the consequent complexity and effectively managing them, project management facilitates and fosters restructuring, thus increasing collaboration, velocity and visibility.

7.5.2 Results and prior state-of-the-art

In conclusion, facilitating the management of the aforementioned structural and dynamic complexity drivers, *project management* foster their presence among the main supply chain characteristics, increasing complexity, but in turn also resilience.

As for the static drivers, i.e. portfolio breadth, product varieties and specificities, and variety and breadth of customer requirements, it is empirically proved that they increase collaboration. As already said, this topic has not yet been discussed in literature. Indeed, despite the inclusion of the number and variety of products among the static internal complexity drivers (Serdarasan, 2013), most authors do not identify its link with resilience, and existing theoretical background focuses only on supply chain nodes and flows (Adenso-Diaz et al., 2012; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca et al., 2008; Hearnshaw et al., 2013; Thome et al., 2016; Skilton and Robinson, 2009). Considering variety and breadth of customer requirements, although researches by Falasca et al. (2008) and Arkhipov et al.

(2001) state that it positively contributes to flexibility, the relationship with collaboration has never been investigated before.

Going through supply chain dynamic complexity drivers, there is a lack of discussion in the extant literature. From the state-of-the-art review, reported in Chapter 2, it results that dynamicity has not been investigated a lot with respect to resilience. Moreover, it has been considered only as source of uncertainty (Adenso-Diaz et al., 2012; Durach et al., 2015; Gunasekaran et al., 2015; Thome et al., 2016). The only authors discussing the effects of continuous nodes entering and exiting are Hearnshaw et al. (2013), but they theoretically assessed their positive effect on adaptability and reliability, thus without considering the full spectrum of resilience constituents. Therefore, the analysis of product introduction and lifecycle events, reconfiguration of supply chain activities and facilities, improvements of equipment, procedures and systems, and restructuring and mergers and acquisitions, as well as their impact on visibility, velocity and collaboration, are of high value in covering the extant gap.

7.6 Multi-echelon ERPs and optimisation IT tools

7.6.1 Linking multi-echelon ERPs and optimisation IT tools and resilience

The last considered practice is *multi-echelon ERPs and optimisation IT tools*, in which is included *integrated ERP systems* too. Indeed, even though Fernandez Campos (2018) separates them, the latter can be considered as a specific solution of the former. Unifying the findings related to the two practices, five links between them and resilience constituents emerge, as reported in Table 7.6, where the role of interplaying complexity drivers is indicated.

Table 7.6: *The role of complexity drivers in mediating the relationship between multi-echelon ERPs and optimisation IT tools and resilience constituents.*

	Positive influence	Negative influence
Flexibility	➢ Better and more effective mgmt. of *portfolio breadth, product variety and specificities* and *number and layers of SC facilities*, thanks to IT tools, enabling a flexible range of alternatives and redundancies in case of disruption.	➢ Fostering of increasing *product variety and specificities*, thanks to IT tools that enable a better and more effective mgmt. Variety reveals difficult to easily manage, thus hindering flexibility.

(continue)

	Positive influence	Negative influence
Visibility	➢ Better and more effective mgmt. of *number and layers of SC facilities*, thanks to IT tools. This enables to better control the SC, having higher visibility on it.	
Velocity	➢ Better and more effective mgmt. of *number and layers of SC facilities* and *demand/supply sides operational dynamics*, thanks to IT tools, rapidly facing disruptions.	
Collaboration	➢ Better and more effective mgmt. of *portfolio breadth, product variety and specificities, number and layers of SC facilities* and *demand/supply sides operational dynamics*, thanks to IT tools. This enables collaboration between resources of different businesses and different facilities or between substitutive products.	

Multi-echelon ERPs and optimisation IT tools is a complexity accommodation practice which strongly increases resilience constituents, but induces negative effects too. Integrating and coordinating different functions and facilitating communication and information sharing, systems and tools belonging to this practice allow to cope not only with structural complexity drivers, including portfolio breadth, product variety and specificities, number and layers of supply chain facilities, and variety of/interaction between teams and functions, but also with internal and demand/supply sides operational dynamics. For instance, Drinks adopts a unique integrated ERP across all supply chain facilities to foster information sharing and to enhance coordination between different functions and teams involved in supply chain activities. Also Defence exploits an integrated ERP with traceability and anti-mixing systems, having real time visibility on how in-bound and dispatching orders are meeting service level agreements.

Accommodating product static complexity drivers, i.e. portfolio breadth and product variety and specificities, *multi-echelon ERPs and optimisation IT tools* synergistically increase their positive effect on resilience constituents. First, as previously said, a wide portfolio breadth enhances flexibility and collaboration. As a matter of fact, resources belonging to different businesses can be exploited under disruption, as proved by Sapporo's experience, i.e. shifting the demand from alcoholic beverages to mineral water and unsweetened beverages, or by Procter and Gamble's choice to leverage workers from operations outside coffee business. Aiding in managing portfolio breadth, IT systems and tools, would facilitate these kinds of countermeasures. Similarly, aiding product variety and specificities, integrated ERPs systems facilitate the possibility to offer substitutes or different configurations of products, positively impacting flexibility and business internal collaboration. For instance, Evonik Industries after the fire at the German plant offered various substitutes with comparable technical properties and similar processability.

However, advanced IT tools also allow to manage higher product specificities, which negatively impact flexibility. For instance, automotive industry strict emission rules forced Volkswagen to set high specificities, which revealed effort and time consuming under the diesel gate disruption.

Then, for what concern internal structural complexity, by effectively managing the number and variety of layers forming the supply chain, *multi-echelon ERPs and optimisation IT tools* positively influences all the four resilience constituents. As empirically proved by most of the investigated critical incidents, higher the number of available supply chain facilities, higher the flexibility and velocity in facing disruptions, thanks to the production shifting and ramp up (e.g. Takata, Mitsubishi Motors, SK Hynix, Honda, Goodyear, etc.). In addition, controlling many levels of the supply chain enables higher visibility on products, facilitating recalls management, like in Mattel's and Volkswagen's experiences. Finally, collaboration is increased by supply chain structural complexity too, as different facilities at different layers can help each other. For instance, after plant's quality and safety violations in Johnson and Johnson, other manufacturing facilities were involved in the effort the affected brands to store shelves, through re-siting of production.

Finally, demand/supply sides operational dynamics play a positive role in terms of velocity and collaboration, thus in turn, supporting them, *multi-echelon ERPs and optimisation IT tools* enhances the two resilience constituents. For example, being used to certificate suppliers and encourage them to continuously improve, also thanks to IT solutions, Nestlé rapidly implemented certification practices, collaborating with involved actors.

7.6.2 Results and prior state-of-the-art

In short, *multi-echelon ERPs and optimisation IT tools* mainly positively affects supply chain resilience, thanks to the interplay of some complexity drivers.

The most relevant one is number and layers of supply chain facilities, which affects all the four resilience constituents. Its impact on resilience has been deeply investigated in literature, since there is a large body of knowledge discussing the role of number of nodes and flows in a network. First, the empirical evidence of the positive link between it and flexibility, emerging by the most of investigated critical incidents, is consistent with prior research. Indeed, not only it has been theoretically discussed (Falasca et al., 2008; Hearnshaw and Wilson, 2013; Arkhipov and Ivanov, 2011; Sokolov et al., 2016), but some studies provided practitioners and academics with empirical evidence, through simulation (Mari et al., 2015) or case studies and scenarios analysis (Cardoso et al., 2014; Cardoso et al., 2015). In this respect, this study's findings are a further empirical demonstration strengthening extant knowledge. Secondly, despite Thome et al. (2016) investigated the relationship with velocity, a further exploration is needed, specially to provide practitioners and academics with empirical evidence and details. The same considerations can be done for the link between number and layers of supply chain facilities and collaboration, which has been theoretically analysed by Durach et al. (2015) and Thome et al. (2016). Finally, for what concerns visibility, the positive influence evident from this study is consistent with empirical results of regression analysis by Brandon-Jones et al. (20014). However, it is in contrast with Skilton and Robinson's findings (2009), which assess that the higher the number of nodes, the lower the visibility. The findings hence call for further exploration.

Considering product structural complexity drivers, portfolio breadth and product variety and specificities interplay both the positive linkages with flexibility and collaboration. As previously stated, there is a gap in the state-of-the-art as no author has investigated is, considering only internal and external structural complexity drivers (Adenso-Diaz et al., 2012; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Durach et al., 2015; Falasca et al., 2008; Hearnshaw et al., 2013; Thome et al., 2016; Skilton and Robinson, 2009). Therefore, the described findings are relevant for practitioners and academics.

Similarly, the emerging positive connection of demand/supply sides operational dynamics with velocity and collaboration covers another gap in the theoretical background, as dynamicity has not been discussed in the literature. Furthermore, often it is identified only as uncertainty or randomness (Adenso-Diaz et al., 2012; Durach et al., 2015; Gunasekaran et al., 2015; Thome et al., 2016).

In the end, analysing the role played by *multi-echelon ERPs and optimisation IT tools* under disruption, it is important to recall the contribute of Gunasekaran et al. (2015), who assess that continuous monitoring and intelligence (i.e. knowledge accumulation and use of big data), as well as transparency, increase companies' visibility of the supply chain, preparing them to proactively deal with uncertainties. Since exchanging information enables to accommodating supply chain complexity, the supply chain actors need to share information in real time using a ERP system.

7.7 Summary of results, originality and relevance

Results discussed in the previous sections are here summarized, highlighting their original contribute to the extant state-of-the-art.

Table 7.7 matches the five complexity management practices and their positive or negative influence on resilience constituents, reporting in each cell the supply chain complexity drivers mediating the linkage. It emerges that, when combining the five complexity management practices, it is possible to obtain a positive effect on all the resilience constituents.

Table 7.7: *The influence of complexity management practices on resilience constituents, mediated by supply chain complexity drivers.*

	Flexibility		Visibility		Velocity		Collaboration	
	Increase (+)	**Decrease (-)**	**Increase (+)**	**Decrease (-)**	**Increase (+)**	**Decrease (-)**	**Increase (+)**	**Decrease (-)**
Product-centric organisational design	Portfolio breadth Product var. and spec. Variety customer requires Product LC events Demand/supply dynamics Differences between facilities	Product var. and spec. Variety customer requires		Variety customer requires	Product LC events Demand/supply dynamics Differences between facilities	Product var. and spec. Variety customer requires	Portfolio breadth Product var. and spec. Variety customer requires Demand/supply dynamics Differences between facilities	
Centralisation of purchasing	Differences between facilities		N./var. of partners				Differences between facilities N./var. of partners	
Strategic relations with partners and suppliers		N./var. of partners New customers/suppliers Product var. and spec.	N./var. of partners		N./var. of partners Product LC events Demand/supply dynamics	Product var. and spec.	N./var. of partners Product var. and spec. Demand/supply dynamics	
Project management			Reconfig. SC Improvements M&A		Product LC events Reconfig. SC Improvements M&A		Portfolio breadth Product var. and spec. Variety customer requires M&A	
Multi-Echelon ERPs and optimisation IT tools	Portfolio breadth Product var. and spec. N. and layers of SC	Product var. and spec.	N. and layers of SC		N. and layers SC Demand/supply dynamics		Portfolio breadth Product var. and spec. N. and layers SC Demand/supply dynamics	

The most relevant findings of the analysis are related to complexity management practices. As a matter of fact, even though prior studies investigated the relationship between supply chain complexity and resilience, as reported in Chapter 2, no author has assessed the role of complexity management practices as resilience enablers. Starting from the complexity management approaches and tools defined by Fernandez Campos (2018), this explorative study poses the basis for further investigation in this direction.

Then, considering supply chain complexity drivers and their impact on resilience constituents, this research originally expands on the extant theoretical background. The main analysed gap concerns dynamic supply chain complexity, identified with Fernandez Campos' drivers (2018) and not only with generic sources of uncertainty (e.g. Durach et al., 2015; Gunasekaran et al., 2015; Thome et al., 2016). As a matter of fact, the identification and justification of the positive influence on the four resilience constituents of product introduction and lifecycle events, demand/supply sides operational dynamics, reconfiguration of supply chain activities and facilities, improvements to equipment, procedures and systems, and restructuring and mergers and acquisitions is a completely new result.

Furthermore, in the literature there is lack of discussion concerning product complexity drivers. Despite their identification by Serdarasan (2013), there is not a theoretical background concerning portfolio breadth, product variety and specificities, and product introduction and lifecycle events, nor with respect to their effect on supply chain resilience. The findings hence represent not only an important contribute, but also a starting point for further exploration, as a twofold role of these complexity drivers emerge from the analysis of the 16 critical incidents.

Finally, other results expand already existing knowledge, often empirically proving what prior studies have only theoretically discussed. For instance, the positive impact of the number and layers of supply chain facilities on visibility, velocity and collaboration has been only theoretically investigated by Durach et al. (2015) and Thome et al. (2016), thus this study consistently provides evidence to their assessment. Another example is given by the gap in the state-of-the-art about the negative influence of the number and variety of partners and suppliers on resilience constituents, which has been discussed only for what concerns flexibility (Falasca et al., 2008; Cardoso et al., 2014; Cardoso et al., 2015), but not visibility, velocity and collaboration. In general, this study's findings expand the existing knowledge about the role of supply chain complexity drivers with respect to resilience constituents, providing empirical evidence through critical incidents and case studies analysis.

Chapter 8
Conclusions

In Chapter 8, the main theoretical contributions and practical implications of the study are discussed, followed by limitations and suggestions for future research.

8.1 Contributions to theory

This study introduces relevant theoretical contributions to supply chain management science, as it highlights not previously investigated relationships between supply chain complexity and supply chain resilience. The main contributions introduced in the previous chapters are collected in Table 8.1, and then summarised.

Table 8.1: *Key theoretical contributions.*

Contribution	**Research question**
Influence of SC structural complexity drivers on SC resilience constituents	RQ1
Influence of SC dynamic complexity drivers on SC resilience constituents	RQ2
Influence of complexity management practices on SC resilience	RQ3
Interplay of SC complexity drivers on the impact of complexity management practices on SC resilience constituents	RQ3

First, the study provides empirical evidence to further prove the relationship between the level of supply chain complexity and resilience. The impact of structural complexity drivers on the supply chain capability to proactively respond to unexpected events and recover from disruptions has been assessed by many authors, who conceptualized resilience with constituents (Adenso-Diaz et al., 2012; Arkhipov and Ivanov, 2011; Brandon-Jones et al., 2014; Cardoso et al., 2015; Cardoso et al., 2014; Elleuch et al., 2016; Falasca and Zobel, 2008; Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Mari et al., 2015; Sokolov et al., 2016; Skilton and Robinson, 2009; Thome et al., 2016) or core functions (Durach et al., 2015; Hosseini et al., 2016; Mari et al., 2015; Sokolov et al., 2016; Statsenko et al., 2016). Nevertheless, despite the consensus of the positive influence of complexity on resilience, the relation could be further investigated and deeper defined. In this respect, this study provides relevant findings, empirically proving, through the Critical Incident Technique, how supply chain structural complexity drivers affect supply chain resilience constituents, i.e. flexibility, visibility, velocity and collaboration, hence answering to the first research question. On the one hand, new relationships are introduced. For instance, in the literature there is a gap concerning product structural complexity drivers. Even though Serdarasan (2013) identifies the number and variety of products as a static internal complexity driver, there is a lack of discussion of the linkage between portfolio breadth and product variety and specificities on one side, and resilience constituents on the other. Therefore, the emerging twofold role of these drivers represents an important contribute and a starting point for further exploration. On the other hand, extant knowledge is expanded, offering empirical evidence to what some authors previously discussed at theoretical level only. For example, the positive impact of the number and layers of supply chain facilities on visibility, velocity and collaboration has been only theoretically investigated by Durach et al. (2015) and Thome et al. (2016), thus this study consistently provide evidence to their argument.

Secondly, few prior papers cover supply chain dynamic complexity, regarding both resilience constituents and resilience core functions. The extant knowledge background is mainly theoretical (Gunasekaran et al., 2015; Hearnshaw and Wilson, 2013; Thome et al., 2016; Durach et al., 2015; Hosseini et al., 2016) and dynamic complexity is not well conceptualized. As a matter of fact, prior literature investigates only uncertainty or randomness (Durach et al., 2015; Gunasekaran et al., 2015; Thome et al., 2016). Consequently, answering to research question RQ2, this study covers the gap, representing dynamic complexity through the drivers introduced by Fernandez Campos (2018), namely: product introduction and lifecycle events, reconfiguration of supply chain activities and facilities, improvements to equipment, procedures and systems, restructuring and mergers and acquisitions, internal or demand/supply sides operational dynamics, and new customers and suppliers. The empirically proved positive influence of all drivers on the four resilience constituents is a completely new result, thus a relevant contribute to the extant body of knowledge.

Considering complexity management practices, listed and described by Fernandez Campos (2018), this research explores their influence on resilience; first by identifying the direct relationship between the two dimensions in four different case studies, then triangulating results considering the interplay of supply chain complexity drivers. Complexity management approaches and tools can play a dual role in terms of resilience, as, on the one hand, complexity accommodation practices could be leveraged to recover from disruption and return to normal operating performance, on the other hand, complexity reduction ones could reduce resilience due to the physical reduction of its enabler complexity drivers. Since no prior author assessed the role of management practices under supply chain disruption, this study offers a completely new contribute, posing the basis for future investigation.

8.2 Contributions to practice

The study provides not only theoretical contributions, but also practical implications. Managers are informed of the interactions existing between supply chain complexity drivers and resilience constituents. Therefore, companies undergoing significant structural and dynamic supply chain complexity should consider its impact not only on business performances (e.g. costs or quality), but also on resilience constituents, i.e. flexibility, velocity, visibility and collaboration. In this respect, supply chain could be designed aiming at reaching adaptive capabilities to prepare for, respond to and recover from unexpected incidents. As a matter of fact, through Table 5.38, managers could identify for each supply chain complexity driver the positive or negative consequences in terms of resilience. In addition, the rich empirical descriptions of critical incidents can aid in better defining them. The findings hence can support more informed and better supply chain management decisions, especially when it comes to complexity management in globally dispersed supply chains.

Moreover, the emerging results improve the knowledge body regarding supply chain management practices. As discussed by Fernandez Campos (2018), companies can exploit different clusters of approaches and tools to cope with structural and dynamic complexity. This study further investigates them, analysing their impact on supply chain resilience, thus allowing managers to identify which practices could reveal a fundamental weapon under disruption. For instance, complexity accommodation practices could be positively leveraged, while complexity reduction ones could decrease resilience enablers. In Annex C, the relationships between complexity management practices and resilience is collected, aiding managers in the decisions about management practices adoption. Furthermore, the detailed description of the five most relevant ones (i.e. product-centric organisational design, centralisation of purchasing, strategic relations with partners and suppliers, project management, and multi-echelon ERPs and IT tools) provides further insight for proper selection and implementation of key complexity management practices from a supply chain resilience perspective. These could also be combined to maximise the positive effect: practices affecting different resilience constituents could be mixed to cover all flexibility, visibility, velocity and collaboration. In addition, the negative influence of some of them could be balanced by the positive one of others (e.g. the reduction of flexibility due to strategic relations with partners and suppliers could be offset by the positive influence of centralisation of purchasing).

In conclusion, the main practical implication is the managers' awareness that supply chain complexity embraced by the focal company could help under disruption, fostering supply chain resilience, both directly and indirectly through complexity management practices.

8.3 Limitations

Despite the theoretical and practical contributions, the study presents limitations too, mainly due to the adopted methodology. The qualitative inductive and exploratory approach, demanded by the limited extant knowledge about the investigated issues, is appropriate for theory building (Meredith, 1998), without quantitatively supporting findings, thus leaving space for future developments in theory testing. Therefore, although it provides practitioners and academics with valuable insights, it does not allow to fully generalise results, calling for a quantitative analysis.

The first employed methodology is Critical Incident Technique (CIT), which has a built-in bias towards incidents that happened recently, as they are easier to document. The main limitation is determined by the data collecting approach. Indeed, not all the supply chain complexity drivers are covered in the same way, as information is difficult to collect through secondary-data, and variety of/interaction between teams and functions and internal operational dynamics cannot be well documented due to the scarce disclosure of companies about them. Moreover, leveraging secondary-data, the empirical evidence of links between complexity drivers and resilience constituents is more difficult to prove, and the subjectivity of the researcher may affect the analysis and its conclusions.

The second part of the study, instead, is based on inductive case studies analysis. The adopted sample consists of four in-depth cases, focused on manufacturing companies operating in different industries. These have been selected through convenience sampling (Barrat et al., 2011), leveraging a first level analysis performed by Fernandez Campos (2018) in his study on supply chain complexity. Thus, it cannot be claimed that these are exhaustive and comprehensive of all the possible mechanisms ruling the relationships between supply chain complexity, resilience and management practices. Another limitation is given by the subjectivity of the researcher that may influence the study, despite systematic and structured sampling, data collection and data analysis processes. Furthermore, data collection significantly relies on the perceptions of a reduced number of interviewed key informants, hence their subjectivity represents another potential source of bias.

In both the methodologies, the adopted unit of analysis is the manufacturing firm’s internal supply chain, including planning, sourcing, making and delivering activities (Hoole, 2005). This choice limits the study to the management of complexity and its impact on supply chain resilience at the level of the single organisation and not of the chain or network. Consequently, despite considering collaboration with upstream and downstream supply chain actors, multi-tier or cross-functional aspects are not fully captured.

In terms of content, the main limitations are three. First, as previously described, secondary-data collection does not allow to cover in the same way different supply chain complexity drivers, thus variety of/interaction between teams and functions and internal operational dynamics are not considered. Then, the study does not empirically analyse the role of complexity management practices under disruption, but it only indirectly proves it, triangulating the relationship between supply chain complexity drivers and resilience constituents and the linkage between supply chain complexity practices and resilience constituents. Finally, since the high fragmentation of findings could hinder the quality of a truly in-depth analysis of the phenomena, results discussion focuses on five dominant complexity management practices only (i.e. product-centric organisational design, centralisation of purchasing, strategic relations with partners and supplier, project management, and multi-echelon ERPs and optimisation tools), calling for further research with respect to the others.

8.4 Further developments

Starting from the study's findings and limitations it is possible to identify a series of opportunities for future research. The most relevant one regards the use of different methodologies to enhance the robustness and generalisability of findings. As a matter of fact, the employed qualitatively exploratory approach is particularly appropriate for formative stages of theory building (Benbasat et al., 1987), but calls for further developments in theory testing. Therefore, a quantitative method could be adopted to test the results. In addition, it could provide a comprehensive framework of all the possible mechanisms ruling the links between supply chain complexity, resilience and management, here biased by the secondary-data collecting, the convenience sampling and the potential researcher of informants' subjectivity, as previously discussed in section 8.3.

Then, the research can be further developed investigating the validity of findings with respect to a wider unit of analysis. Indeed, even though the adopted unit of analysis, i.e. the manufacturing firm's internal supply chain, limits results at the level of a single organisation, similar considerations could be extended to a multi-tier or cross-functional perspective. For instance, a whole supply chain, considering all the involved companies from raw material suppliers to end consumers, could be analysed.

Furthermore, the exploratory analysis presents some content limitations that future quantitative research could cover. First, the quality of information collected through Critical Incident Technique could be enriched establishing direct connections with the affected companies. Indeed, secondary-data collection could be supported by direct interviews, in order to demonstrate findings consistency and to cover undisclosed complexity drivers, such as variety of/interaction between teams and functions and internal operational dynamics. Secondly, since the study does not empirically investigate the role of complexity management practices under disruption, one or more case studies could be set aiming at theory testing. Particularly, a tailored semi-structured interview protocol could aid in focusing data collection. Finally, the more detailed analysis of the triangulation of findings could be extended from the five most critical complexity management practices selected in this study, to the whole list.

In general, considering the results, there are some linkages between supply chain complexity, resilience and management practices that present both positive and negative correlations, as different analysed situations determined different evidence. In this respect, they should be further investigated, in order to clarify it and distinguish among them, to better define the net result of combined positive and negative effects. In addition, since practices could be mixed to maximize the positive influence on resilience, the possible synergies brought by multiple practices should be considered. Finally, an analysis about how to prioritize practices according to the expected contribution to resilience constituents could be relevant from the practical point of view.

In conclusion, the main aims of future research are two: on the one hand, to test and strengthen the theoretical findings emerging from this study, generalising results through quantitative methodologies; on the other hand, to extend the scope considering still existing gap and widening the unit of analysis.

References

Adenso-Diaz, B., Mena, C., Garcia-Carbajal, S., Liechty, M. (2012). The impact of supply network characteristics on reliability. *Supply Chain Management: An International Journal*, 17(3), 263-276.

Ambulkar, S., Blackhurst, J., Grawe, S. (2015). Firm's resilience to supply chain disruptions: scale development and empirical examination. *Journal of Operations Management*, 33-34, 111-122.

Arkhipov, A., Ivanov, D. (2011). Integrated analysis of supply chain structure design and adaptation potential in an agile environment. *International Journal of Integrated Supply Management*, 6(2), 165-180.

AT Kearney (2004). *The complexity challenge. A survey on complexity management across the supply chain*. A.T. Kearney Publications.

Barratt, M., Choi, T.Y. and Li, M. (2011). Qualitative case studies in operations management: Trends, research outcomes, and future research implications. *Journal of Operations Management*, 29(4), pp.329-342.

Barroso, A.P., Machado, V.H., Cruz Machado, V. (2011). The resilience paradigm in the supply chain management: a case study. *IEEE International Conference on Industrial Engineering and Engineering Management 2011*, 6118052, 928-932.

Barroso, A.P., Machado, V.H., Barros, A.R., Cruz Machado, V. (2010). Toward a resilient supply chain with supply disturbances. *IEEE International Conference on Industrial Engineering and Engineering Management 2010*, 5674462, 245-249.

Benbasat, I., Goldstein, D.K. and Mead, M. (1987). The case research strategy in studies of information systems. *MIS Quarterly*, 11(3), 369-386.

Birkie, S.E., Trucco, P., Kaulio, M. (2014). Disentangling core functions of operational resilience: a critical review of extant literature. *International Journal of Supply Chain and Operations Resilience*, 1(1), 76-103.

Birkie, S.E. (2016). Operational resilience and lean: in search of synergies and tradeoffs. *Journal of Manufacturing Technology Management*, 27(2), 185-207.

Birkie, S.E., Trucco, P., Fernandez Campos, P. (2017). Effectiveness of resilience capabilities in mitigating disruptions: leveraging on supply chain structural complexity. *Supply Chain Management: An International Journal*, retrieved at: [https://doi.org/10.1108/SCM-01-2017-0009].

Bode, C., Wagner, S.M. (2015). Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions. *Journal of Operations Management*, 36, 215-228.

Bozarth, C.C., Warsing, D.P., Flynn, B.B. and Flynn, E.J. (2009). The impact of supply chain complexity on manufacturing plant performance. *Journal of Operations Management*, *27*(1), 78-93.

Brandon-Jones, E., Squire, B., Autry, C.W., Petersen, K.J. (2014). A contingent resource-based perspective of supply chain resilience and robustness. *Journal of Supply Chain Management*, 50 (3), 55-73.

Brandon-Jones, E., Squire, B., Van Rossenberg, Y.G.T. (2014). The impact of supply base complexity on disruptions and performance: the moderating effects of slack and visibility. *International Journal of Production Research*, 53(22), 6903-6918.

Braziotis, C., Bourlakis, M., Rogers, H., Tannock, J. (2013). Supply chains and supply networks: distinctions and overlaps. *Supply Chain Management: An International Journal*, 18(6), 644-652.

Cardoso, S.R., Barbosa-Povoa, A.P.F.D., Relvas, S., Novais, A.Q. (2014). Network design and planning of resilient supply chains. *Computer Aided Chemical Engineering*, 33, 1219-1224.

Cardoso, S.R., Barbosa-Povoa, A.P.F.D., Relvas, S., Novais, A.Q. (2014). Resilience assessment of supply chains under different types of disruption. *Computer Aided Chemical Engineering*, 34, 759-764.

Cardoso, S.R., Barbosa-Povoa, A.P.F.D., Relvas, S., Novais, A.Q. (2015). Resilience metrics in the assessment of complex supply chains performance operating under demand uncertainty. *Omega*, 56, 53-73.

Carvalho, H., Barroso, A.P., Machado, V.H., Azevedo, S., Cruz-Machado, V. (2012). Supply chain redesign for resilience using simulation. *Computers and Industrial Engineering*, 62, 329-341.

Chell, E. (1998). Critical Incident Technique. *Qualitative methods and analysis in organizational research: A practical guide*, 51-72.

Choi, T.Y., Dooley, K.J., Rungtusanatham, M. (2001). Supply networks and complex adaptive systems: control versus emergence. *Journal of Operations Management*, 19, 351-366.

Choi, T.Y., Krause, D.R. (2006). The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation. *Journal of Operations Management*, 24(5), 637-652.

Chopra, S., Sodhi, M.S. (2004). Managing risk to avoid supply-chain breakdown. *MIT Sloan Management Review*, 46(1), 53-61+87.

Craighead, C.W., Blackhurst, J., Rungtusanatham, M.J., Handfield, R.B. (2007). The severity of supply chain disruptions: design characteristics and mitigation capabilities. *Decision Sciences*, 38(1), 131-156.

Dabhilkar, M., Birkie, S.E., Kaulio, M. (2016). Supply-side resilience as practice bundles: a critical incident study. *International Journal of Operations & Production Management*, 36(8), 948-970.

Durach, C.F., Wienland, A., Machuca, J.A.D. (2015). Antecedents and dimensions of supply chain robustness: a systematic literature review. *International Journal of Physical Distribution and Logistics Management*, 45(1/2), 118-137.

Eisenhardt, K.M. (1989). Building theories from case study research. *The Academy of Management Review*, 14(4), 532-550.

Elleuch, H., Dafaoui, E., El Mhamedi, A., Chabchoub, H. (2016). A quality function deployment approach for production resilience improvement in supply chain: case of agrifood industry. *IFAC-Papers OnLine*, 49(31), 125-130.

Falasca, M., Zobel, C., Cook, D. (2008). A decision support framework to assess supply chain resilience. *Proceedings of ISCRAM 2008 - 5th International Conference on Information Systems for Crisis Response and Management*, 596-605.

Fernandez Campos, P. (2018). *Managing the joint influence of structural and dynamic complexity on supply chain performance.* Internal report by School of Management of Politecnico di Milano.

Flanagan, J.C. (1954). The critical incident technique. *Psychological Bulletin*, 54(4), 327-358.

Gilmore, D. (2008). The war on supply chain complexity. *Supply Chain Digest*, retrieved at: [http://www.scdigest.com/assets/FirstThoughts/08-08-21.php].

Gunasekaran, A., Hong, P., Fujimoto, T. (2014). Building supply chain system capabilities in the age of global complexity: emerging theories and practices. *International Journal of Production Economics*, 147, 189-197.

Gunasekaran, A., Subramanian, N., Rahman, S. (2015). Supply chain resilience: role of complexities and strategies. *International Journal of Production Research*, 53(22), 6809-6819.

Hearnshaw, E.J.S., Wilson, M.M.J. (2013). A complex network approach to supply chain network theory. *International Journal of Operations and Production Management*, 33(4), 442-469.

Heckmann, I., Comes, T., Nickel, S. (2015). A critical review on supply chain risk - Definition, measure and modelling. *Omega*, 52, 119-132.

Hoole, R. (2005). Five ways to simplify your supply chain. *Supply Chain Management: An International Journal*, 10(1), 3-6.

Hosseini, S., Al Khaled, A., Sarder, M.D. (2016). A general framework for assessing system resilience using Bayesian networks: a case study of sulfuric acid manufacturer. *Journal of Manufacturing Systems*, 41, 211-227.

Johnson, N., Elliott, D., Drake, P. (2013). Exploring the role of social capital in facilitating supply chain resilience. *Supply Chain Management: An International Journal*, 18(3), 324-336.

Jüttner, U., Maklan, S. (2011). Supply chain resilience in the global financial crisis: an empirical study. *Supply Chain Management: An International Journal*, 16(4), 246-259.

Li, Z., Gulati, R.K. (2015). Supply chain risk mitigation and the application potential of complex systems approaches. *Proceedings of the 18th Asia Pacific Symposium on intelligent and evolutionary systems*, 1, 357-371.

Manuj, I., Sahin, F. (2011). A model of supply chain and supply chain decision-making complexity. *International Journal of Physical Distribution & Logistics Management*, 41(5), 511-549.

Mari, S.I., Lee, Y.H., Memon, M.S., Park, Y.S., Kim, M. (2015). Adaptivity of complex network topologies for designing resilient supply chain networks. *International Journal of Industrial Engineering*, 22(1), 102-116.

Mariotti, J.L. (2008). *The complexity crisis. Why too many products, markets, and customers are crippling your company – and what to do about it*. Avon: Adams Media.

Meredith, J. (1998). Building operations management theory through case and field research. *Journal of Operations Management*, 16, 441-454.

Perona, M. and Miragliotta, G. (2004). Complexity management and supply chain performance assessment. A field study and a conceptual framework. *International journal of production economics*, 90(1), 103-115.

Ponomarov, S.Y., Holcomb, M.C. (2009). Understanding the concept of supply chain resilience. *The International Journal of Logistics Management*, 20(1), 124-143.

Pratt, M. (2009). From the editors: For the lack of a boilerplate: Tips on writing up (and reviewing) qualitative research. *Academy of Management Journal*, 52(5), 856-862.

Rice, J.B., Caniato, F. (2003). Building a secure and resilient supply network. *Supply Chain Management Review*, 7, 22-30.

Scott, S. (2007). Dare to disrupt. *SignIndustry.com*, retrieved at [http://www.signindustry.com/news/newsletterv1809.php3].

Serdarasan, S. (2013). A review of supply chain complexity drivers. *Computers and Industrial Engineering*, 66, 533-540.

Sheel, A. (2016). Supply chain complexity drivers and its management. *Journal of Business and Management*, 18(1), 39-43.

Sheffi, Y., Rice Jr., J.B. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Management Review*, 47(1), 41-48+94.

Skilton, P.F., Robinson, J.L. (2009). Traceability and normal accident theory: how does supply network complexity influence traceability of adverse events? *Journal of Supply Chain Management*, 45(3), 40-53.

Sokolov, B., Ivanov, D., Dolgui, A., Pavlov, A. (2016). Structural quantification of the ripple effect in the supply chain. *International Journal of Production Research*, 54(1), 152-169.

Statsenko, L., Ireland, V., Gorod, A. (2016). Self-organising supply networks: a case study of the SA mining industry. *11th Systems of Systems Engineering Conference, SoSE 2016*, 7542919.

Stewart, G. (1995). Supply chain performance benchmarking study reveals keys to supply chain excellence. *Logistics Information Management*, 8(2), 38-44.

Thome, A.M.T., Scavarda, L.F., Scavarda, A., Thome, F.E.S.D.S. (2016). Similarities and contrasts of complexity, uncertainty, risks and resilience in supply chains and temporary multi-organization projects. *International Journal of Project Management*, 34, 1328-1346.

Tukamuhabwa, B.R., Stevenson, M., Busby, J., Zorzini, M. (2015). Supply chain resilience: definition, review and theoretical foundations for further study. *International Journal of Production Research*, 53(18), 5592-5623.

Voss, C., Tsikriktsis, N., Frohlich, M. (2002). Case research in operations management. *International Journal of Operations & Production Management*, 22(2), 195-219.

Appendix A: Example of interview protocol

1) Brief description of your role and core responsibilities.

2) What are the key aspects that contribute to the complexity of your tasks as part of Percomp's SC? What's the most complex regular activity under your responsibility?

3) In addition to the aforementioned aspects, which of the following factors (i.e. complexity sources) do you find to more directly influence the design and performance of Percomp's planning activities? (About 3 or 4 per table)

Dynamic Complexity
New product introduction and rate of change of the product portfolio
Component obsolescence (suppliers)
Modifications to main processes
Switching between partners
Continuous improvement practices
Innovation projects
Changes to the network design and flows
Rationalisations of the portfolio or supply/customer base

Static Complexity
Variety of customer needs and requirements
Number or diversity of suppliers
Variety and breadth of the product portfolio
Variety of distribution channels
Diversity or number of SC facilities
Complex processes involving other functions
Performance reporting and KPIs
Number of organisational functions or layers involved in SC activities

4) Drawing from the factors you have selected in 3) and those you highlighted in 2). Could you briefly describe how these can positively and negatively influence the performance of the internal SC activities?

	Cost	**Speed**	**Flexibility**	**Quality**
Positive				
Negative				

5) 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?

6) Which of the main SC areas (i.e. planning, purchasing, production and logistics) would you consider to be influenced the most by the complexity factors you have selected? How is the performance of these influenced by the factors?

Appendix B: Within-case analyses
Excerpt from Fernandez Campos (2018)

For each case, the analysis is structured into four sections: (1) a brief introduction in which the firm's background and the boundaries of the case are described, (2) a rich description of the structural and dynamic complexity factors encountered in each of the three investigated complexity categories and of their impact on the performance of the internal SC, (3) a review of the management practices employed by the company to manage the complexity factors […].

4.1 "Drinks" within-case analysis

4.1.1 Introduction and background

Drinks is an Italian-based company that manufactures a wide range of beverages and liquors. The firm portfolio is comprised of products in the wines and soft-drinks business segments, for which Drinks' market presence is stronger in Europe and the Americas. It employs about 4000 employees worldwide and has a yearly revenue of approximately €1500M.

In the second half of the 1990s, Drinks adopted a new strategy with a strong emphasis on M&A. The company has since performed about thirty acquisitions and six disposals over the last two decades, turning into an organisation of global dimensions and establishing itself in leadership positions in several segments. More importantly, this new strategy has completely reshaped and enlarged the firm's product portfolio and internal SC. The global SC is organised according to four regions: Europe, North America, South America and Asia Pacific. The case study focuses on the European region (all interviewees had responsibilities for the European region only with the exception of the SC Director), which accounts for 50% of total firm revenues. Data collected on the global firm operations from secondary sources and the SC Director does suggest that the critical complexity factors reported in the case are similar across regions. However, this remains outside the scope of the case.

4.1.2 Structural and dynamic complexity factors

Product design and portfolio complexity

Product portfolio and design structural complexity in Drinks is mainly driven by the company's portfolio breadth and the large number of product references (i.e. unique product identification codes) and SKUs. The introduction of new products and changes to the firm's portfolio is a relevant source of dynamic complexity that is associated with demand uncertainty and increased operational dynamics.

The product portfolio consists of more than a hundred distinct products organised into approximately fifty brands belonging to the three business segments of soft drinks, spirits and wines. In addition, several factors contribute to increasing the SKU count beyond the breadth of the portfolio. First, in order to meet with the legal requirements of the more than 190 markets (unique combinations of country and distribution channel) the company sells its products in, variants to the content and language of product labels must be introduced. Moreover, the adaptation of products to local tastes and customs and use of limited editions and other promotional techniques notable increases the variety of SKUs. For example, as a result of these factors one of the most popular products of the company amounts to more than a thousand different product references.

The large number of product references is a source of additional costs and lowered speed throughout the entire internal SC: it increases manufacturing change over times and requires the use of additional equipment. It drives inventories in production and distribution facilities. The diversity of recipient sizes and materials also reduces purchasing orders' volume, and therefore the procurement function's ability to close obtain better deals of suppliers in terms of speed and cost. Additional reference numbers require more time for planning and forecasting activities and increase their uncertainty. Also, as the SC director underlines, there are differences between products that require them to be managed in completely different ways. An example of this are products which demand of long natural ageing, which consequently may require forecasts of up to fifty years.

In terms of dynamic complexity, the introduction of new products and of changes to the portfolio is a relevant source of dynamic complexity for Drinks (e.g. six new products were launched in year 2015). Managers underline how new products entail higher uncertainty of demand forecasting and planning activities. The lack of familiarisation with them also prevents the SC functions from detecting potential inaccuracies in the data of the ERP system. These factors contribute to accentuating and complicating the dynamics of operations in the internal SC.

Internal SC design complexity

Two internal SC design factors arise as major sources of structural complexity: the complex network of facilities, characterised by a variety of flows and numerous facilities, and the interactions between functions, which are further complicated by process fragmentation and diversity. In addition, the frequent changes to the network and mergers and acquisitions pose as critical dynamic complexity factors for Drinks' SC managers.

The internal SC network is comprised of 16 production plants and about 20 warehousing facilities (Drinks leverages its own distribution network in 19 countries).

Moreover, single products may be manufactured in several facilities to minimise production costs (e.g. maximise capacity utilisation, minimise taxes), absorb unexpected demand spikes and increase resilience to natural disasters and other SC disruptions. This additional variety of flows are a source of complexity for planning managers, who must take into account additional constraints when allocating production but tend to lose sight of the specificities of the production processes followed in each facility.

With respect to the interactions between functions and teams involved in SC activities, the adopted design demands extensively employs in-line processes (vs. parallel) that are fragmented to involve a variety of functions. A local SC master data manager refers to the challenge that working together with other functions poses as well as its effect on speed:

> "The larger the number of functions that must participate in the validation of a piece of data the more complex the process becomes. If I had someone in the HQs with all the information, the process would take fifteen minutes, but because it has to go through ten people, the process may last ten or even twenty days" [Drinks, MD].

Moreover, the complexity of working with other functions inside and outside the SC (e.g. marketing) is further driven by a lack of process formalization, "*not just in written form but simply clear [processes]*" [Drinks, PMO]. Key processes had not been defined until 2015. In addition, managers point out that the fast job rotation in the firm, especially in front-end functions, prevents these managers from developing a rich understanding of their dependencies with other functions.

Regarding dynamic complexity, the fast rate at which changes to the internal SC facilities and flows are made is a critical factor. As briefly put by the SC director "*the network is continuously changing. I think we introduce five or six modifications per day*" [Drinks, SCD]. Some of these modifications are a result of the SC manager's continuous search to improve performance by relocating production and secondary activities to take advantage of market opportunities; while others are of a more strategic nature (e.g. the creation of a new market-focused company to aid with distribution in the given territory). The latter, of which mergers and acquisitions (M&A) emerge as the most relevant, are the most demanding and relevant for SC managers.

M&A are one of Drink's core competences and a cornerstone of the inorganic growth strategy the company has held over more than a decade. By 2015 the firm had completed more than twenty-five acquisitions, six of which during the preceding year. Acquisitions are leveraged to improve financial performance at firm level via the elimination of redundancies and the aggregating of volumes, but can also be a source of operational knowledge for SC managers regarding the management of operations, production processes or suppliers. In this vein, managers claim that the uncertainty driven by the speed of acquisitions has a high negative impact on cost, flexibility, speed and quality, which are impacted during these challenging transitions.

External SC complexity

External SC network structural complexity is mainly driven by Drinks' diversity of customer requirements and variety of suppliers. Managers underline the uncertainty and variability of demand from customers and front-end processes as relevant dynamic complexity factors.

The company's customer base is comprised of several different types of customers, the variety of which differs slightly from country to country. Moreover, the variety of requirements that each of these types of customer has and places on SC operations is posed as a critical structural complexity factor. For instance, while end-consumers place an emphasis on instant availability (i.e. service level) and on-time delivery on a precise date and time, wholesalers provide a four-day window for delivery but instead require of support from Drinks regarding SC activities (e.g. supply planning). In addition, demand uncertainty and the variability associated to front-end processes and functions (mostly sales and marketing) are a relevant source of continuous changes and dynamic complexity in the SC's operations.

Lastly, the large number of suppliers is mostly related to increased costs for the procurement function, which is hierarchically independent to the SC function, as it increases the number of supplier related activities (e.g. supplier audits, on-site production line assessments) the function must undertake.

4.1.3 Complexity management practices

As with complexity factors, management practices are presented according to the complexity category these are predominantly aimed to manage. Should a practice be adopted as an effective approach to simultaneously cope with complexity factors in different categories this is clearly indicated in the practice description.

Product portfolio complexity management

The product portfolio is the predominant source of complexity in the product portfolio and design complexity category. Various management practices are employed to lessen the effects of product portfolio complexity on the performance of the SC: (1) product segmentation and specialised teams, (2) product rationalisation, (3) anti-mixing and traceability systems, (4) IT systems, and (5) project management practices.

Product segmentation and specialised teams: to aid with the distinct managerial necessities that some product lines have (e.g. long ageing), products are segmented and managed according to their production technologies. In addition, a few specific teams are created to tackle the most demanding of these technical challenges. For instance, a long-term capacity planning team that is independent from the "standard" SC planning group is responsible for forecasting the demand of products that require long ageing times (e.g. certain whiskeys) for the following five, ten, twenty, thirty and fifty years as necessary.

Product rationalisation: Product rationalisation is utilised as a key practice to reduce the number of references and hence its negative effect on SC performance. Rationalisation is a growing practice in the firm that managers present as necessary to offset the variety introduced by front-end functions. As a SC master data manager notes

> "We must make the entire organisation understand the costs of producing the same product in a format of six, a format of twelve, etc. […] If we do not develop this mind-set and ask the customer 'do you want it in twelve's, in twenty-four's in thirty-two's?' The customer says 'of course. I want it in red, green, yellow…'". [Drinks, MD].

The group that is mostly responsible for portfolio rationalisations is the Project Management Office (PMO) (a description of the PMO's various roles to manage SC complexity is provided later in this section), who makes rationalising a standard part of every project that involves the SC. In addition to doing this by terminating older or less-popular products, the PMO looks at reducing the number of references by unifying materials between otherwise similar SKUs or by substituting labels in a country's local language with those in English when possible.

Anti-mixing and traceability systems: In addition to the regular in-bound and out-bound material testing and visual quality controls, the firm employs systems to minimise the potential negative effects of the large number of references on the quality of the final product. For instance, a custom system has been designed to handle the large variety of labels and avoid mixing. This is a large structured container further divided in sub-containers in which the labels are stored. The device is synchronised with production, so that the required set of labels is automatically released in accordance with the production schedule. In the same vein, a comprehensive traceability system is deployed to allow for the recall of any production batch before it reaches the final customer in case that a production anomaly, internal or at a supplier's site, is discovered at a later stage.

IT systems: Lastly, defined by a manager as "*the heart of the business portfolio management*" [Drinks, MD], IT systems are a key resource to manage structural complexity in Drinks' internal SC. The company relies on a number of systems ranging from major ERPs (integrated across all facilities) to planning modules and smaller dedicated systems (e.g. to perform the analyses that are the basis for portfolio rationalisation decisions). In addition to managing portfolio complexity, these systems are leveraged to share information and enhance coordination between SC teams and to facilitate the optimisation of the internal SC (e.g. stocks, capacity utilisation); thus partially offsetting the challenges posed by the complexity of the SC's design.

Because of the variety and relevance of IT systems, the firm has a dedicated master data group that reports to the head of the SC. The master data team works hand-in-hand with the SC function and is responsible for the creation of references for all product-related materials from raw materials to end-products. The function also administers each reference's parameters and the various interfaces through which other functions consult and interact with the data, thus ensuring the correct use of systems, the alignment between them and the accuracy of the data at all times.

Project management practices: With regards to the management of product portfolio dynamic complexity in the internal SC, a central aspect is the collaboration with the Project Management Office, which is part of the Innovation function. This allows the SC to increase the speed at which they can introduce and cope with changes to the product portfolio while fostering the financial traceability and reducing the cost of these activities.

Two types of projects predominantly deal with changes to the portfolio: innovation and fast-track. Innovation projects include the development and introduction of new products, launching of new brands, product line extensions and product formula modifications. There are about thirty of these projects per year in Europe. Fast-track projects instead focus on minor activities that involve extant products such as bringing an existent product to a new market or promotional activities These projects typically last about three months. There are, however, about four-hundred fast-track projects every year in the European division.

In addition to managing product portfolio dynamic complexity, collaborating with the PMO to employ project management practices is central in the management of internal SC dynamic complexity; as these practices help structuring and implementing strategic activities that modify the internal SC's design (e.g. the launch of a market-focused company to manage local SC flows and distribution).

Lastly, the PMO contributes to managing two structural complexity factors: the variety of references (rationalising as previously discussed in this section) and process diversity due to a lack of formalisation. To this regard, the function was responsible for the recent formal definition and consolidation of key processes in 2015 and continuous to foster the formalization of processes inside and outside the SC.

Internal SC design complexity management

Two management practices are employed to mitigate the effects of internal SC design complexity on the performance of the internal SC: (1) specific training and (2) acquisition integration practices. Both practices predominantly aim to aid the SC cope with dynamic complexity factors.

Specific training: Together with the launching of in-market companies, production relocations and mergers and acquisitions are the dynamic complexity factors that continuously alter the internal SC's design. Overall, relocations require to temporary increase stocks as well as on-site testing that can disrupt production schedules and reduction of production line's speed. Most of these issues relate to the adaption of production lines and the addition of new equipment. Drinks provides production personnel with specific training so as to accelerate their learning curves, but employs no other specific management practices to handle relocations.

Acquisition integration practices: From a SC perspective, the management of acquisitions takes place in two phases. The first is a shorter two-month phase that focuses on resolving product legal issues (e.g. labelling) and assimilating the acquisition in terms of forecasting and distribution to enable the shipment of products. The second phase consists of an in-depth analysis of the acquired firm's internal and external SC in order to consolidate it inside Drinks' and maximise efficiency. Hence, this is an activity of strategic nature in which managers seek to establish synergies between firms. It is the first of these two phases that is a critical source of dynamic complexity for SC managers, who must cope with the sudden changes that M&A entails for purchasing, planning and distribution operations in spite of the scarce familiarisation with the recently acquired part of the business. Managers identify three distinct aspects that contribute to accentuating the effects of this dynamic complexity factor on the SC function.

Firstly, there are no specific human resources dedicated to the management of M&A inside or outside the SC function. On the contrary, "*the operative phases are a bit left to the good heart of those who decide to take care of them with regards to their function*" [Drinks, PMO].

Secondly, there are no ad-hoc managerial tools and systems to aid in the management of this first phase after the business has been acquired. Furthermore, it is managers' believe that these traditional tools are of reduced effectiveness to accelerate the integration process. The SC director states:

> "This is a fundamental issue. What I have learnt, having executed thirty acquisitions, is that the error to avoid making is thinking that Power Points, Gantts, workgroups and experiments can solve the integration of an acquisition. These are tools, but they are banal tools. What's necessary are people that have made a lot [of them], that have experience and that have the capacity to make decisions" [Drinks, SCD].

Lastly, managers underline that the absence of a formalised acquisition model or procedure that can guide the various functions involved in the process. Thus, the integration of each acquisition requires the SC to perform a different set of actions and in a different order. This lack of structure leads to a lack of coordination between functions and teams. Managers note that project management practices are likely to be applied in the near future to seek to surpass this lack of coordination and eventually formalise an acquisition integration procedure.

External SC complexity management

A number of practices serve to lessen the outcomes of external SC complexity on SC performance. Customised distribution channels focus on downstream complexities. On the contrary, procurement centralisation and category management focus on upstream complexities. In addition to this, a series of practices are utilised to render production independent from customer-driven requirements and dynamics. Managers refer to this as "decoupling" production from front-end activities and this approach enables the SC to better cope with both customer structural and operational dynamic complexity. These include the localisation of activities, stocks, and the use of the planning group as a unique interface for production facilities.

Customised distribution channels: Regarding the management of structural customer complexity, the use of bespoke SC distribution channels is described as a key lever to accommodate the diversity of requirements from different types of customers. For instance, in one of its core European countries the SC leverages four different distribution channels, each intended to satisfy the requirements from a distinct customer segment.

Procurement centralisation and category management: procurement has been restructured to both reduce and increase performance in the face of the large variety of suppliers. In order to increase the focus on single materials the function has consolidated a Global Purchasing Office and added a layer of global category managers that look after the main groups of direct materials (e.g. glass, raw materials, primary and secondary components). The centralisation first allows the function to consolidate global procurement volumes in order to negotiate better deals with suppliers. More importantly, it enables the rationalisation of materials and suppliers at a global level, thus reducing structural complexity. A key point of this rationalisation of suppliers is that the assessment of suppliers not only on cost, quality and service but also in terms of their capacity to innovate and their strategic orientation, allowing the firm to create long-term relationships with critical suppliers (e.g. alcohol or glass) and reducing supply base dynamic complexity.

Production decoupling practices: Managers seek to decouple production from upstream and, especially, downstream activities. Decoupling is achieved in a number of ways:

- Localisation: Pushing promotional and customisation activities downstream and carefully designing the emplacement of warehouses (e.g. close to borders between countries) to provide logistics with responsiveness to uncertain demand from customers while reducing the effect of these on manufacturing facilities. By assembling customised promotional packaging close to the customer, this technique also reduces the SKU count that burdens production. In the words of the SC director "*the more we succeed in taking complexity local, the more plants can focus on producing, which is their craft*" [Drinks, SCD].

- Planning as unique interface: a single centralised planning team is responsible for designing the production plans that must meet the sales forecasts coming from front-end functions for all products. In doing this, planning acts as a unique interface between marketing and production facilities. Moreover, planning managers describe as part of their role to find a compromise between the operational needs of both functions and to provide production with maximum continuity. Forecasts and production plans are defined in a consensus meeting that takes place once a month and brings together sales, marketing and planning directors and local managers. However, the defined production plans are revised every week to maintain the alignment between the SC and the dynamic market.
- Stocks: While managers stress the firm's intention of reducing its work in progress, the use of inventories is described as a costly but very effective method to decouple production from sales and thus manage customer operational dynamic complexity.

[…]

4.2 "Percomp" within-case analysis

4.2.1 Introduction and background

Percomp is a large information technology multinational company that provides of products, technologies and solutions to individual consumers as well as small, medium and large companies worldwide. The firm enjoys strong ties to organisations in the health, education and public administration sectors.

Percomp employs about 50,000 employees and its yearly net revenue amounts to about $50,000M. In addition, the firm has strong leadership global positions in its two core product segments (referred to as A and B). These segments respectively account for 62% and 38% of the company's revenue.

The firm is organised into three regions: Americas, EMEA (Europe, Africa, Middle East and Eastern Europe) and APJ (Asia Pacific and Japan). The EMEA generates about a third of Percomp's revenue and it is this regions' customer support SC that is the focus of the case study. However, and although not required by the presented analysis, managers and consulted secondary data do suggest that complexity factors and management practices here reviewed are unlikely to differ considerably to those in other regions.

4.2.2 Structural and dynamic complexity

Product design and portfolio complexity

The breadth (i.e. span) and size (i.e. total number of products) of the product portfolio are two relevant structural complexity factors for managers in Percomp's support SC. In addition, three complexity factors concerning dynamic complexity appear to be most critical: the increase of the frequency of lifecycle (LC) events, the introduction of new product lines, and strategic design trends that are impacting product serviceability.

Managers' main concern in the customer support SC is the spare parts portfolio (in contrast to the product portfolio that is managed by the manufacturing SC). This is the portfolio of all product components that are subject to failure and to being repaired and/or replaced by Percomp, and hence includes all products that are being manufactured and those that are no longer sold but are still supported by Percomp, either inside or outside their legal warranty periods. The width (i.e. span) and size of Percomp's spare parts portfolio are relevant sources of structural complexity that bind the performance of the firm's support SC. A first major issue regards the impact on performance of the large number of SKUs. Indeed, the portfolio comprises two product segments, seven main product families, more than one hundred product lines and more than a thousand products. Moreover, product variants are introduced by a number of reasons: due to the fast, ongoing technological development of segment A products, their design may be updated during the sales phase of the lifecycle (LC) either by replacing a component or the components' firmware. Also, managers note the high number of marketing-driven variants as well. Lastly, some product variants respond to local regulations. The high number of product variants requires an increase in the number of product references used (i.e. internal product identification references), increasing inventory size and excesses, spreading out volumes and hindering performance. Furthermore, unlike a typical manufacturing SC, Percomp's support SC works at component level. In other words, forecasting, planning, procurement, warehousing and logistics' activities must all manage the variety of individual components rather than of products; thus, potentially increasing the area of the SC that is subject to portfolio variety and its relevance as structural complexity factor.

In addition to the large number of SKUs, the breadth of the firm's portfolio poses as a structural complexity factor for SC managers. More precisely, the firm's two product segments place very different managerial and operational constraints on the SC, as components of segment A are small, light and fragile, and segment B's components are heavier, bulkier and therefore costlier to transport. Consequently, these contrasting characteristics increase the range of requirements for SC activities.

The frequency of product LC events is a dynamic complexity factor that is a pressing concern for Percomp's support SC and one that is influenced by both portfolio breadth and size. Certainly, the increase in the number of products entails a higher frequency of LC events; but also, the types of events that have to be managed differ significantly between the two product segments. Segment's A products have short and sharp LC curves (products are rarely supported for more than five years) and are associated to intensive new product introduction (NPI) events; whereas segment's B products have much longer LCs (support of up to twenty years in some cases) and consequently often go through Last Time Buy (LTB) events either after product sales are concluded or due to supplier obsolescence.

The introduction of new product lines (NPLs) is a second critical dynamic complexity factor which is described by managers as more uncertain than the introduction of new products. According to the Supply Chain Chief of Staff "*it is like entering a new business*" [Percomp, CS]. Moreover, the introduction of a NPL often requires modifying and adapting many aspects of the SC, and the combination of upstream and downstream requirements may lead to significant changes to the extant SC design.

Lastly, in addition to the frequency of LC events and the introduction of NPLs, strategic design trends that impact the serviceability of the products and increase the complexity of the support SC operations. For instance, the designs implemented in the new generations of products often do not allow for support based on the delivery of spare parts but rather on the exchange of the whole product.

Internal SC design complexity

Managers underline four predominant structural complexity factors that underpin the internal support SC: (1) The vast and highly interconnected topology of the SC (i.e. number of facilities and layers). The network of facilities consists of almost a hundred facilities organised into three tiers, each associated with different customer service levels and processes and management tools. (2) The variety of third party organisations (i.e. partners, service providers, etc.) that participate in the SC. The company boasts more than 250,000 channel partners worldwide. (3) The differences between territories due to country-specific regulation and to the differences between local partners. (4) The complex organisational design and processes (i.e. number of functions involved in the SC, fragmented processes, interactions between the global and regional support SC, etc.).

Concerning dynamic complexity, Percomp has been radically altering the design of its support SC over the past three years through a number of projects, bound by the banner "SC transformation". These innovation projects, as they are labelled in the firm, alter several aspects of the SC structure such as its procedures, the facilities network, the roles and interactions with partners and the configuration of the SC flows and are thus major sources of uncertainty (i.e. dynamic complexity) for managers. Their goal is mainly to reduce SC costs and improve cash flow in response to shifts in the market in recent years.

The implementation of standard and premium flows is the most demanding of these activities. More precisely, in this new design some contracts (e.g. warranty extensions) are served in a no-business-day logic by default, but in other instances (e.g. in-warranty) the customer can choose between both speeds at, of course, different prices. The new model requires the definition of two delivery motions and an end-to-end revision and adaptation of all SC-interfacing processes and systems, as, in fact, different infrastructures will be leveraged for each speed. In addition to the reduction of costs by relying more on cheaper transportation (e.g. road vs airplane), the new design fosters the centralisation of inventories and, thus, the simplification (i.e. rationalisation) of the network of facilities. The role that rationalisations play in reducing structural complexity is discussed in more detail in the coming section.

External SC complexity

Structural complexity from customer is driven by both the requirements of external customers (i.e. end-customers) and internal customers (i.e. intermediary groups that are provided with components by the internal support SC to perform the fixes). Operational dynamic complexity related to demand uncertainty and volatility is a pressing concern for SC managers and one that is accentuated by the implementation of the new premium-standard SC design. The supply base's structure and dynamics are less critical sources of complexity for SC managers. To this regard, supplier obsolescence emerges as the most relevant supplier-related dynamic complexity factor.

A first structural complexity factor regards the variety of requirements within external customers (i.e. end-customers). The support SC's customer base can be divided into consumer and commercial (i.e. companies) segments, which have very different requirements and service level agreements. These requirements vary greatly within product lines, as customers are willing to, for example, wait for the repair of certain technologies and devices more than others. In addition, there are three main interaction channels the customer support SC employs to reach the end-customer depending on the type of failure and customer requirements; and the diversity of requirements of the internal and external groups that run these interaction channels adds to the complexity in the support SC.

Demand uncertainty and front-end dynamics are a relevant source of dynamic complexity that has been aggravated by the implementation of standard and premium flows. More precisely, the adoption of the new SC design introduces the need to take into account customer choices to set adequate inventories in each standard and premium networks' facilities. This stands as a critical challenge for the planning group:

> "How do we, in back-end planning, know what the customer will choose for a particular product for a given case? We can't right. And for back-end SC this will mean that if the customer chooses premium delivery, it will be one location in some country, but if they decide to go for standard delivery, slower delivery TAT, it will be another location. And this is from where the planning complexity comes: how do I assess what will happen in the future for this location and that location?" [Percomp, PL]

Moreover, SC managers claim that the increase of demand volatility per part and location in the network introduced by the new model will give place to the bullwhip-effect, which will amplify required safety stocks as well as logistic costs associated to the need of rebalancing.

The supply base is not presented as a relevant source of dynamic or structural complexity. This appears to be partly due to the fact that all relationships with suppliers for segment A products is outsourced to the partner that is responsible for the replenishment of the central DC. In addition, the firm has close and historical relationships with the much less numerous suppliers for segment B products. Regarding dynamic complexity, however, the management of supplier obsolescence events stands out as a challenging dynamic complexity factor for managers. These are especially frequent for segment B products due to their long life-cycles (of up to twenty years).

4.2.3 Complexity management practices

Product design and portfolio complexity management

Various management practices are employed to lessen the effects of product design and portfolio complexity on SC performance: (1) forward-looking forecasting, (2) automation, (3) additive manufacturing and accessories' customisation, (4) product-centric organisational design, and (5) collaboration with product and front-end functions.

Forward-looking forecasting logic: the support SC has adopted a forecasting logic that facilitates managers, especially planning managers, coping with the large variety of components in the spare parts portfolio as well as with product LC events. Managers refer to the new logic as "forward looking" because of the emphasis on taking into account the future rather than relying on the past and historical data. More precisely, in addition to the currently installed product base, the algorithm now considers future sales forecast to improve the accuracy of support forecasts. First introduced for the more numerous and rapidly rotating segment A components, this technique has improved forecasting accuracy by in some cases up to 20% as is now being implemented for segment B components as well as for certain core partners such as the DC replenishment partner.

Automation: Automation in SC processes plays a critical role in facing the structural complexity (i.e. variety) of the spare parts portfolio. Automation is used hand in hand with other practices that allow for better segmentation of components (e.g. forward-looking forecasting or Multi-echelon ERPs) and allows the SC to deliver consistently by reducing its reliance on managers' experience. Moreover, it can lead to better SC decisions by reducing the number of decisions faced by managers. In the same vein, automation can be leveraged to free managers' resources from handling variety to rather "*focus your workforce on true [SC] art topics*" [Percomp, PL] such as costly and uncertain product LC events.

Additive manufacturing and accessories' customisation: Additive manufacturing and accessories are employed to postpone the customisation of components and products and reduce the number of SKUs associated with product variants. In particular, add-on components are used to bring a unique product from low to high end specifications when necessary, hence making all parts except for the accessories common to low and high-end product variants. In the same manner, additive manufacturing is used to locally adapt generic spare parts to specific products, thus reducing the number of unique components per product.

Product-centric organisational design: the firm implements what managers refer to as an "end-to-end planner" organisational design, in which planners are responsible for a part or sets of spare parts in the portfolio across the entire support SC network and across all SC processes including supply planning and product LC event management. This design brings a series of advantages to manage structural and dynamic complexity over the previous geography-oriented organisational design in which managers' responsibilities were aimed at specific SC echelons, layers and geographies rather than at parts of the portfolio.

First, by focusing managers on a reduced set of parts only, the current product-centric design allows them to develop a better understanding of products and their specificities (i.e. particularities) even in the face of high portfolio variety. Moreover, the fact that managers are aligned with product and not geographic specificities drives the SC to unify procedures and tools across territories (i.e. reducing geographic diversity in the internal SC). For instance, managers note that the end-to-end planner design has led the SC to homogenise IT infrastructure that previously was particular to specific SC layers and echelons:

> "You are not going to look at five locations that are associated to a certain country. You are going to look at fifty locations associated to EMEA. And for each layer or echelon of inventory management you have particularities, planning particularities that you need to observe. You may have different tools as well. […] And that's very essential: to unify as much as possible, in processes; which unifies the tools as well" [Percomp, PL]

Secondly, the product-centric design aids in managing dynamic complexity. In particular, the benefits in managing product LC events are described as some of the most relevant advantages of the product-centric vs. a geographic-oriented design. A critical reason for this is the drastic reduction in the number of layers involved in the management of these events, which before led to lack of alignment and of proper information sharing within different parts of the SC. Thus, managers have more visibility over the underlying issues and root causes behind these dynamic events and better synchronisation of the different layers and SC activities is achieved. Also, the better understanding of product particularities enables managers to respond more effectively to LC events (e.g. pin-pointing a feasible alternative to a Last-Time-Buy event). Lastly, the new design is equally more effective when facing operational dynamics related to unexpected customer demand, thanks to the enhanced accountability and empowerment it brings.

Collaboration with product and front-end functions: Managers underline that establishing effective links with other functions outside the SC is necessary to manage the dynamic complexity related to product designs. An example of this are the initiatives employed to manage the design trends that increasingly force the support SC to exchange full units rather than product components, severely impacting the SC's cost structure. In this respect, joint reparability strategies that link the SC and product design functions have been introduced to ensure that future modifications to all product lines are less costly to repair. New methods to increase the potential use of component repair are also devised.

Internal SC design complexity management

A number of management practices are used to mitigate the effect of internal SC design complexity on the performance of the internal SC: (1) rationalisation of SC facilities, (2) multi-echelon and mix optimisation IT tools and algorithms, (3) global SC forums and governance models, (4) organisational and processes' platforms, (5) rationalisation of partners and strategic partnerships, (6) SC project management office, and (7) multiple-stage transitions and management of change.

Rationalisation of SC facilities: The SC has undergone a large and fast rationalisation to reduce the structural complexity of its network of facilities. The initiative has cut down the about 200 total SC facilities to 56 in less than two years. The rationalisation of the network was partly enabled and triggered by the division of the company into two organisations in 2015, which drastically reduced its product portfolio and customer base. Yet, managers pose this as a continuous activity to keep the complexity of the network to a minimum without compromising current and future delivery initiatives. In order to achieve this, the SC has designed new delivery models that can meet customer requirements without increasing the density of SC layers.

Multi-echelon and mix optimisation IT tools and algorithms: An in-house tailored ERP has been developed to enhance multi-echelon and mix optimisation capabilities. This system is presented as a crucial infrastructure to manage the large variety of components in the spare parts portfolio and the structural complexity of the network of facilities. Multi-echelon and mix optimisation tools allow the optimisation of inventories across the whole network comprehensively, rather than on a node-per-node basis, and allow planning to account for demand and lead-time variations. In other words, these systems facilitate a holistic optimisation of the complex network. In addition, these tools facilitate the accurate segmentation of the portfolio and underpin the use of automation to reduce the negative effects of structural complexity on SC performance.

Global SC forums and governance models: To overcome the information sharing difficulties that stem from the structurally complex organisational design, the firm holds a series of world-wide SC forums that foster the establishment of links across levels and regions and accelerate the development of joint approaches to SC critical issues. Global SC forums perform a dual function regarding the management of internal SC structural complexity. First, they aid the SC find better solutions to some of the inefficiencies that arise in relation to the structural complexity of the organisation and network of facilities. Secondly, these forums have a homogenisation effect, as they tend to reduce the disparities between different regions.

Lastly, managers underline the effectiveness of global forums to improve the management of certain dynamic complexity factors such as product LC events. To this regard, the SC has leveraged on this initiative to build LC global governance models that focus on improving the predictability of these events. For instance, a global governance model has been created to detect upcoming end-of-manufacturing decisions (very much influenced by sales) and pin point potential LTB events as early as possible. Thus, these global initiatives can be leveraged to foster coordination outside the SC as well.

Organisational and processes' platforms: Platforms are an important practice to reduce the complexity of the internal SC's organisational design and processes structural complexity. These are teams that lie at the core of each SC area (e.g. planning or logistics) and that define the common architecture of processes, tools and solutions for the given area. Platforms play an important role in "establishing commonalities" in the organisation, as they develop solutions for all teams that perform certain activities and define standardised processes that contribute to reduce the variety of processes and of tools employed in different territories or by teams responsible for different businesses. A SC manager describes the consolidation of processes undertaken by the planning platform as follows:

> "There is a part of planning which is specific to the type of component. But we also have a common area, that is the planning platform, and that is where we look to provide with planning tools, to drive process and continuous improvement… where

we look for the improvements that are common for all [planning] businesses" [Percomp, CS]

Rationalisation of partners and strategic partnerships: Partner rationalising is used in conjunction with the development of strategic "gain and pain" [Percomp, PL] partnership relations to consolidate partners; hence, reducing the structural complexity that stems from the variety of service providers involved in SC activities. In doing so, this consolidation can partially offset the complexity drawn by outsourcing. In this vein, managers explain that by establishing long-term (i.e. stable) win-win relationships with partners they can reduce the variety of partners and focus on fewer relationships to cover the full geographic span of the network. The implementation of a robust "data strategy" (i.e. comprehensive and structured information data flows) that can counteract for the lack of proximity and interactions (formal and informal) with the rest of the organisation is posed as a critical need to allow for these partnerships to be effective.

SC project management office: A project management office (PMO) is defined as part of the support SC function. This office plays a central role in the management of dynamic complexity in the SC, especially that related to activities in the strategic time frame. More precisely, project and program managers are responsible for the management of the previously discussed "SC transformation" which encompasses rationalisation of SC facilities, implementation of standard and premium SC delivery models and reconfiguration of flows in the network (e.g. countries that served from the central DC instead of a country warehouse).

The overarching purpose of the PMO is to reduce as much as possible the intrinsic uncertainty that these changes to the SC network entail for managers and to facilitate the transitions, reducing the cost of these activities and its negative impact on SC performance. In order to do so, the PMO systematically structures and monitors the progress of these activities and seeks to achieve the necessary coordination within the various teams and functions involved.

Multiple-stage transitions and management of change: The management of change is presented to underpin the impact of some dynamic complexity factors on SC performance. In particular, the management of change is raised as a relevant issue in connection to the uncertainty driven by strategic and tactical SC activities that alter the extant SC design and thus render obsolete managers' preconceived models about the status quo (e.g. PMO projects, implementation of the product-centric organisational design for the planning group, etc.). Transitions in these activities are structured in several stages to bind the uncertainty that these entail for managers, avoid overwhelming them and reduce total adaptation time.

External SC complexity management

Five practices serve to reduce the negative impact of customer- and supplier-stemmed complexities on SC performance: (1) outsourcing, (2) customer requirements rationalisation, (3) simulation, (4) cross-functional performance reporting, and (5) supplier obsolescence management practices.

Outsourcing: Outsourcing emerges as one of the most extensively leveraged approaches to manage structural complexity. In fact, its use goes beyond supplier and customer base complexities and regards product portfolio and internal SC complexities as well. In this vein, all procurement-related activities for segment A components, all SC activities for the consumer segment, and non-core activities (e.g. facilities management, logistics, component repair) are outsourced to service providers and partners. Moreover, this is a practice that is similarly adopted in the firm's main manufacturing SC, in which, for instance, all assembly and manufacturing activities are outsourced. Despite the effectiveness of outsourcing to reduce the variety of suppliers, customers, parts and SC activities that Percomp must manage, managers highlight some aspects of outsourcing that increase the complexity in the internal SC. For instance, as discussed in the previous section, managers find the large variety of partners that results from outsourcing a critical structural complexity factor. In addition, outsourcing is presented to aggravate some of the mechanisms through which structural and dynamic complexity factors jointly hinder SC performance. This phenomenon is discussed in more depth in the forthcoming section.

Customer requirements rationalisation: Managers underline the link between the variety of customer requirements from end-customers and customer interaction channels and the structural complexity of the internal SC. Indeed, managers note that "*it is the variety of interaction channels with customers that makes us have very complex processes in which we must collaborate with many different teams*" [Percomp, CS]. Two approaches are adopted to rationalise the variety of requirements from customers within the SC and lessen the effect that this variety has on its structural complexity. First, managers strive to find commonalities within requirements, as this allows the SC to leverage common processes and infrastructure for a variety of customers, thus driving scale and efficiency. Secondly, customer requirements are bound by setting limits for customer specific solutions and clear priorities within requirements. Moreover, designing appropriate limits for customer requirements can also be used to reduce operational dynamic complexity related to customer demand.

Simulation: Simulation is employed to aid managers make decisions regarding the management of the dynamic complexity of SC operations. In particular, the SC has developed their own tools to allow managers foresee the implications of potential changes in the network such as the increase of average customs time for a given country or the increase of demand variability in a given location in the network of facilities. These bespoke tools are developed by platform groups (e.g. planning platform) and fall outside the scope of the main IT infrastructure, as "*changing IT infrastructure is something very* *heavy that takes a lot of time and a lot of money, and usually it's very difficult for the IT infrastructure to follow business process evolution*" [Percomp, PL]. As explained by a manager, these tools allow to exploit the data that is available in the SC's main IT infrastructure (e.g. in ERPs) to enhance decision making:

> "You have everything in there, all the data is in there, but can the ERP with one click of a button tell you what will happen in South Africa if you increase your custom time from three to ten days? No, it cannot" [Percomp, PL]

Cross-functional performance reporting and KPIs: Cross-functional reporting metrics and KPIs are employed to enable managers to better understand customer behaviours as well as foster collaboration with front-end teams. Establishing these links between functions is critical to manage dynamic complexity. As illustrated by a manager:

> "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" [Percomp, PL]

Supplier obsolescence management practices: Supplier obsolescence stands out as the most critical dynamic complexity factor associated to the supply base. In the past, Percomp had managed these events mainly through Last-Time-Buys (LTBs), in which SC managers purchased the expected required amount of the obsolete-to-be component to support the remaining of Percomp's affected product LC. However, due to the high costs of LTBs (e.g. LTBs account for about 50% of segment B inventories), the SC has devised some practices to better cope with supplier obsolescence including component repair strategies, improved product LC curve models, and, more recently, the development of product upgrading.

[…]

4.3 Auto within-case analysis

4.3.1 Introduction and background

Auto is a leading manufacturer of wheels in the automotive industry. The company produces steel wheels for passenger cars and light commercial vehicles and spoke wheels for motorcycles. Auto is part of a larger group whose main businesses regard the distribution of steel and manufacturing (other) components for the automobile industry.

The company currently employs about 1,500 employees and is the leading European steel wheel producer, with a yearly turnover of approximately €200M. It is active in two markets: direct sales to automotive OEMs and the after-sales market, for which the company employs a dedicated sales network. In addition to its dense European footprint, the firm has in the last decade expanded its global presence through a number of acquisitions and joint ventures. As a result, the company now boasts production facilities in Asia, Central America, Africa and Europe.

The case study examines the structural and dynamic complexity factors and management practices that regard the firm's entire internal SC activities. Because an official SC function does not exist in the organisation's tree, the data collection and analysis has taken into account the perspectives of managers that perform SC activities, which include purchasing, logistics and manufacturing managers both based in the firm's various production facilities as well as in its headquarters (HQ).

4.3.2 Structural and dynamic complexity

Product design and portfolio complexity

The breadth and size of the firm's product portfolio and, more importantly, the degree of uniqueness of products (i.e. product specificities) arise as the most relevant product-related structural complexity factors. Likewise, the addition of a 'stylish wheels' product line to the portfolio and the development and introduction of new products are presented as critical dynamic complexity factors for Auto's SC managers.

The size and span (i.e. breadth) of the product portfolio emerges as a source of structural complexity for Auto SC managers. The firm's product portfolio is comprised of more than 150 wheel models in the segments of passenger cars (PCs), motorcycles and light commercial vehicles (LCV)s. The production of PCs and LCVs' wheels mostly relies on similar manufacturing processes and materials. However, motorcycle wheels differ significantly from the former segments in terms of their underlying components, materials, design methods and limitations and production processes. Therefore, motorcycle wheels pose a different set of requirements and constraints on SC activities. Moreover, passenger car and commercial vehicle wheels are divided into two product lines (traditional and stylish) that require different production technologies, procedures and equipment as well as product design and development processes.

Furthermore, managers underline the large number of product specificities (i.e. product particularities or characteristics that differentiate it from others in the portfolio) as a major structural complexity factor. In particular, the degree of uniqueness of products in the PC and LCV portfolio segments is presented as a more critical source of complexity than the breadth of the portfolio or the sheer number of products in it. Managers explain that in general terms "*each automobile model requires one or more unique wheel models*" to be manufactured [Auto, ED]. In fact, it is not uncommon that a single vehicle requires of three models of wheels: front, back and spare wheels. Factors such as the wheels' dimensions and tolerances (which are dependent on the remaining wheel components such as breaks), aesthetic design, intended vehicle weight and the use of flow-formation (to improve material's mechanical properties and reduce thickness) contribute to render each wheel model unique. Above all, managers note that it is the differences between customers and each one's diversity of requirements that drives product specificities:

> "It's the demand of customers that pushes us to define diverse products. There are so many requirements: geometry, stiffness, fatigue resistance… so many details that lead us to conceiving products in different ways even if to reach similar goals. It's customer product concept, which is influenced by its history, that makes products incompatible [with one another]" [Auto, ED]

The introduction of stylish wheel models as a new product line (NPL) in the product portfolio is a major source of dynamic complexity for the internal SC. Stylish wheels were first introduced three years back as a "*commercial strategy*" [Auto, SD] to cope with the continuously decreasing size of the market for steel wheels, especially in Europe. These wheel models seek to imitate the lighter-looking and more open geometries and designs that are typical of aluminium wheels, which in Europe already account for more than 50% of all original equipment wheels in LCV and PC vehicles. Stylish wheels can be offered to automobile OEMs as a less costly alternative to aluminium wheels due partly to the difference in cost between raw materials (i.e. steel vs. aluminium) and, thus, can aid Auto retain market share, especially for low-segment and fleet-oriented auto models.

Nonetheless, despite the potential commercial benefits of stylish wheels, these introduce a number of challenges for SC activities, as they require technologies that lie "*beyond the mature, standard steel wheel technologies that have been consolidated for decades*" [Auto, PD]. The uncertainties and dynamics related to the addition of this NPL mainly concern product and production process design activities. In the same vein, managers highlight the difficulties of adapting production lines to make them compatible with stylish wheels. Managers describe these adaptations as resource-hungry and uncertain, especially as "*if the plant is equipped from the beginning to only produce standard wheels, then it is complicated to re-orient the plant to the new production process*" [Auto, GMD]. Extensive testing is necessary to determine the changes to extant equipment that could potentially render the production of these models feasible. In addition, certain solutions can entail longer cycle times, higher scrap ratios and additional operations, which can degrade the performance of a whole production plant due to the synchronisation that exists between the various production lines in a single facility.

New product development (NPD) and introduction (NPI) is a second critical dynamic complexity factor. These are posed as intrinsically uncertain activities in which iteration plays a necessary role, and that yield learning curves in a variety of SC areas (e.g. purchasing, logistics, manufacturing), therefore jointly involving a variety of teams within the internal SC. The need of upgrading and incorporating new machines to the production line is a key aspect underpinning the dynamic complexity of NPD activities, and in fact managers often aim for customers to bear the costs of production line upgrades as part of the associated production costs for the specific product. Moreover, the cost breakdown in the preliminary offer only includes rough estimates of the cost of the new equipment and its installation, as direct and indirect suppliers have not been involved at this point. Thus, if the customer accepts the offer, the process of implementing these changes to the lines to arrive at a consistent manufacturing of the product is uncertain, and may require teams to alter the originally intended product designs and equipment. This variability is underlined by a purchasing manager:

> "Basically, industrial projects [i.e. NPI] are different every time. Each time we make our engineers come up with a totally new specification, and practically each time different suppliers are involved" [Auto, PM]

In addition, the introduction phase is also linked to increased uncertainty and variability in several aspects, including demand variability from customers and production quality issues that can underpin internal operational dynamics. Lastly, managers note that the lower production line speeds that are often adopted due to the modifications to production lines compromise performance and can further complicate the management of these operational dynamic issues.

Internal SC design complexity

The differences between SC facilities, the interactions with other functions and facilities and the variety and fragmentation of processes are presented as relevant structural complexity factors. In addition, managers underline continuous improvement practices, machine breakdowns and production quality issues, and mergers and acquisitions as sources of dynamic complexity.

The large differences that exist between the firm's manufacturing plants are a critical structural complexity factor that is detrimental for activities that require the involvement of the firm's HQ or of several plants, and that therefore hinders Auto's SC performance. The differences between facilities span three areas. Firstly, manufacturing plants differ in terms of their physical layout and equipment. Plants can handle different ranges of wheel dimensions and are unequally suited to produce some portfolio lines (e.g. stylish wheels) or to perform technical processes such as flow-formation. Secondly, and more importantly, facilities adopt different organisational designs. In this vein, the activities that SC teams are responsible for change within plants and, also, the activities that are performed locally or by the HQ differ per facility. Thirdly, plants employ different managerial tools and present disparate levels of adoption of IT systems. For instance, while one of Auto's most prominent facilities extensively leverages an integrated ERP system for a range of SC activities (e.g. production planning, direct material purchasing, etc.); SC managers in a different territory rely mostly on basic office software packages to perform these same tasks. In the same vein, managerial tools (e.g. 5S) are adopted and implemented by some plants only.

Moreover, managers underline a series of aspects that, in addition to each plant's type of customers (i.e. OEM vs. after-sales customers), differ between plants' locations and that underpin their heterogeneity. In particular, the countries' cost of labour, local culture and level of education affect the plant's competences, the adoption of certain production technologies (e.g. automation) in the plant, and, ultimately, firm's customer demand allocation decisions. The plant's historical background is presented to play a key role in shaping plant's specificities as well as the difficulty to homogenise these.

A second structural complexity factor is functions' need to interact with the other functions and facilities which are involved in SC activities. As exemplified by a manager:

> "The complexity comes from interfacing the other functions: commercial and quality for product design aspects, industrial investments and purchasing regarding improvements or changes to production equipment. […] Then there are the connections to manufacturing facilities, that are also involved in the definition of products and equipment. All functions are scattered and we need to achieve coordination from the HQ" [Auto, ED]

More precisely, the difficulties in communicating and coordinating with a variety of functions prevents the exchange of relevant information and compromises functions' ability to leverage each other's knowledge, resulting in hindered decision making and SC performance. Moreover, the fact that Auto lacks a formally defined SC director and function implies that SC activities are spread within several functions and that there is no "*unique figure or team which is able to manage the entire [internal] chain*" [Auto, PD]; therefore accentuating the relevance of these interactions. In the same vein, managers underline the variety and fragmentation of SC processes as related sources of structural complexity.

Continuous improvement practices emerge as a major source of dynamic complexity for Auto's managers, as these result in frequent changes to managerial processes and to production line equipment and procedures. Production lines may be modified to increase the range (i.e. dimensions) of wheels that can be produced or to reduce change over time between models, hence minimising production batches and stocks. Similarly, improvements can be made to the integration and use of systems and IT tools to increase the efficiency of SC activities (e.g. purchasing). Some aspects of continuous improvement practices are consolidated and standardised in the SC, and the variety of themes these investigate relates to internal benchmarking activities or to direct customer suggestions. Nonetheless, because most of the introduced changes have implications for the definition of products, the involvement of the HQ is required. In addition, continuous improvement practices' uncertainty requires of testing and iteration. Therefore, managers note the high frequency at which continuous improvement practices disrupt nominal operations, increasing the complexity of internal operational dynamics. As described by a manager:

> "Perturbations to production [related to continuous improvement practices], occur almost daily. Because you put together the list of corrective actions, and then during the month we have to implement such corrective actions, the majority of which typically relates to production processes. So you have to disrupt the production process to try the corrective actions and understand the efficiency of such actions" [Auto, GMD]

Mergers and acquisitions (M&A) are a source of dynamic complexity for Auto's SC managers, especially for HQ-based managers. Indeed, M&A are instrumental to the global development strategy the firm has adopted in response to the increasing penetration of aluminium wheels in European countries, causing the market for steel wheels to decrease year on year. The company has in recent years acquired three production facilities in African, Asian and American countries. Managers underline the resources required and the length of the integration of the acquired firms, which is managed by the HQ. The need to establish and manage new relationships with distant local managers and the process of understanding local specificities and harmonising, unifying and rationalising suppliers and processes are highlighted to underpin the uncertainty and complexity of the integration. Lastly, managers note the need to minimise the changes to the organisation that these activities can incur, since "*customers in this industry are sensitive to organisational changes. They are not keen on revolutions, but rather prefer to really know the organisations they work with*" [Auto, SD].

Lastly, managers underline the internal operational dynamics triggered by unexpected machine breakdowns and production quality problems as "*one of the main causes of month to month degraded performance*" [Auto, GMD]. This dynamic complexity factor affects all SC areas beyond production, as it requires increasing customer and supplier stocks and forces managers to incur in additional costs beyond those of standard procedures (e.g. by negotiating the urgent delivery of a tooling piece that may be required to resume production).

External SC complexity

With regards to the customer base, managers present the diversity and breadth of customer requirements as a critical structural complexity factor while underlining the addition of new customers, short- and long-term demand uncertainty and customer's reduction of technical competences as sources of dynamic complexity. Structural complexity from suppliers is mainly driven by the large variety of materials and parts that need to be procured. Raw material delays from suppliers contribute to the overall dynamic complexity of SC operations.

Auto's customer base spans two different markets. The company provides OEMs with first equipment wheels for the production of new automobiles, and also produces wheels for the after sales (AS) market, in which case the customers are mainly local dealers. First equipment sales have traditionally generated the most revenue for the firm, but the AS's sales have become increasingly important in the face of recent economic trends and as a means to overcome the decreasing size of steel wheels' market (still, the current percentage of first equipment wheels sold per plant varies between 50% and 95%).

The existent difference between the two markets increases the variety of requirements for SC activities. For instance, while the demand from OEMs is relatively stable and can thus be accurately forecasted, after sales demand is seasonal and is strongly influenced by factors that can be difficult to predict such as weather conditions. This, together with the different legal requirements of OEM and after sales dealers, drives Auto to in turn employ different teams for both forecasts as well as planning procedures and stock management policies. In addition, first equipment and after sales wheels feature different technical and packaging requirements as well.

In addition to this, the breadth of requirements from OEM customers is presented as a predominant structural complexity factor for managers. Auto manufactures wheels for twelve large OEMs in the LCV and PC segments. However, and despite the reduced number of individual customers, managers unanimously highlight the large span of customer requirements, which results in compromised SC performance in terms of cost, speed and quality. For instance, OEMs employ completely different mechanical tests and criteria to ensure the security of steel wheels. Table 4.5 (in the next page) summarises the key areas that are constrained by customer requirements.

Overall, the breadth and diversity of customer requirements increases the rigidity of Auto's SC design as well as reduces the firm's ability to respond to operational dynamics. For instance, a manager explains that it would at least take six months to be start serving a customer from a different facility in the network, and that the customer's homologation process would account for about four months of these. In the same vein, the relationships with these customers that are stable and consolidated, since "*it requires a lot of time to become a supplier to an OEM, due to security, and once inside the supply base it is very rare to be removed from their supplier panel*" [Auto, SD].

Table 4.5: *Areas spanned by OEM customers' requirements.*

Area	Description
Production processes	Customer demand bespoke visual quality controls and additional production operations. Each customer has a distinct boundary book of accepted defects. Production processes are "untouchable" without customers issuing an authorisation.

Supplier management	Customers place requirements on supplier management processes and demand the certification and homologation of suppliers.
Management processes	Customers can impose the adoption of managerial tools and influence management policies.
Shipping and packaging	Customers demand a variety of transportation and liability agreements and customised packaging solutions (i.e. beyond standard packaging). One single reference is shipped in thirteen different types of packaging according to the shipment's destination plant.
SC network of facilities	OEMs often demand their suppliers' manufacturing plants to be close to theirs so as to make payments in local currency and minimise SC risk, transportation costs and working capital.

Demand uncertainty is presented as a relevant customer-related dynamic complexity factor, which increases SC costs. In particular, the variability and lack of accuracy of the short and long term forecasts provided by customers are a critical source of complexity. Likewise, at an operational level, a manager explains that, some of the customers' demand forecasts its plant receives can vary by up to 80% from one week to another, making demand variability a significant "*part of the complexity of the business*" [Auto, LM]. Moreover, managers also note that delays of raw materials from suppliers contribute to the operational dynamic complexity of SC operations.

In addition, managers note trends in customer's competences that increase the complexity of SC activities. More precisely, customer's continuous loss of technical skills makes interacting with them more complex, since *"this entails great difficulties to negotiate, for example, an authorisation to deviate from obsolete standards that may be inaccurate or too restrictive*" [Auto, ED].

With regards to supplier-related structural complexity, managers place the emphasis on the large variety of parts that purchasing teams must manage, increasing the cost of safety stocks and the size of the overall supply base. Managers underline that product specificities, driven by customers' diverse requirements, underpin this variety of parts and materials. As a result of this, a plant manufacturing less than 30 wheel models can account for as many as 1200 high rotation and 7000 total materials. In the same vein as with the customer base, the need to homologate suppliers and materials fosters the stability of the supply base and prevents the firm to switching within suppliers. As explained by a manager,

> "Changing suppliers is costly and risky. We have to, following automobile industry rules, inform all our customers if we wish to change suppliers. We also have to redo the homologation of all related products, which incurs in serious costs, time and risk. For instance, we may have to incorporate the new requirements of a customer which may have changed and become more restrictive" [Auto, PD]

4.3.3 Complexity management practices

Product design and portfolio complexity management

Various management practices are employed to lessen the effects of product design and portfolio complexity on SC performance: (1) product platforms and standards, (2) anti-mixing systems and practices, (3) design carry-over, (4) project management practices, and (5) simulation and customer offer development software tools.

Product platforms and standards: The definition of product platforms and standards is presented as an effective practice to reduce the variety and specificities of products. However, attempts to define these must be guided by customers in order to be successful. For instance, a customer has recently successfully defined product platforms for its spare wheels, rendering these models common for a large range of vehicles. In a similar manner, other automakers are developing standards for different parts of vehicles (e.g. of the suspension group in the case of wheels). As described by a manager,

> "We have to make customers understand that some platform and standards can be defined if planned in advance. […] Otherwise, we can do very little if they do not pursue that direction" [Auto, ED]

A major drawback in the effectiveness of product standards to reduce structural complexity in the SC is the lack of platforms and standards that are shared by more than a single automaker. As managers explain, such cross-automakers standards "*are very rare, and, even when feasible, there often lacks interest in achieving these [standards]. Also because it can lead to problems related to security or to the legal rights to using a specific technology*" [Auto, SD].

Anti-mixing systems and practices: The firm has established a series of practices that are to be implemented in all manufacturing plants to reduce product mixing. These issues are linked to the variety of SKUs managed in manufacturing facilities and, in particular, to the high number of different packaging types used for each wheel model. To this end, bespoke containers have been designed (i.e. kitting trolleys) to supply specific packaging types to the packaging line, both reducing line supplying time and the number of packaging mixing issues. In addition, logistics teams have adopted the lean management tool 5S to improve the organisation of the workspace, introducing visual cues that differentiate otherwise similar packaging types and defining fixed roads for material handling. Lastly, the packaging line and the warehouse have been electronically linked. In addition to improving the synchronisation between activities, the system also provides with distinctive visual cues to avoid supplying the lines with an incorrect packaging type. Overall, managers note that these practices reduce material handling costs as well as product mixing induced quality issues.

Design carry-over: Auto leverages several practices and tools to manage the dynamic complexity that stems from the introduction and development of new products. Design carry-over is presented as a key approach to reduce the uncertainty that new product designs bring to the SC. Despite the differences between wheels, the maturity of the product facilitates that models already in production (or at least some of its underlying components) can be slightly modified and adapted to satisfy the new requirements of a customer offer. In fact, as explained by a manager, carry-over is the setting point for all NPD activities:

> "Each time we try to simplify, to unify: starting with the product design phase we try to use the same materials that we have, and if possible the same thickness, same dimensions and same grade […]. For sure, the first point for the design office and for us [(i.e. production plant)] is to see what we have today, and see if we can adapt it and use it directly and not to create something new which will be specific for the single product" [Auto, GMD]

Project management practices: The project management team, part of the engineering function, plays an important role in minimising the dynamic complexity of NPI and its effect on SC performance. It is also involved in the management of continuous improvement activities and other activities that entail changes to production equipment.

Concerning NPI, the team follows a five-stage gated process that structures all activities that regard the definition and design of the product, the design of production process and equipment and its implementation on the production facility. Deliveries, timing and costs for each stage are set in advance to minimise the uncertainty for managers. In addition, the firm has recently included measures for the number of changes performed to the product design throughout the life of the project as well as the resulting performance of the production line (mostly efficiency and quality indicators) as performance measures for projects.

Simulation and customer offer development software tools: Auto SC managers leverage software tools to better cope with the dynamic complexity of NPIs. In particular, the firm has developed a series of simulation tools as part of its innovation strategy that allow managers to better predict the behaviour and properties of potential wheel designs and hence reduce the number of design changes as well as of the interactions with production facilities and customers during the NPD process.

In addition, the SC has adopted a bespoke communication software tool that facilitates and accelerates the exchange of information between HQ and plants and within the various functions involved in the development of the preliminary offer for customers. Therefore, the use of this software tool aids managers cope with both the dynamic complexity of NPIs and the structural complexity of the organisation, by allowing facilities and functions better communicate and interact with each other. The implementation of the tools has also fostered the standardisation of the NPD process and led to the development of a digital archive of previous offers for OEM customers.

Internal SC complexity management

Three management practices are used to mitigate the effect of internal SC design complexity on the performance of the internal SC: (1) process standardisation, (2) *benchmarking activities, and (3) specific training.*

Process standardisation: Auto strives to unify and standardise production processes in attempt to reduce the variety of processes within the various firm facilities and some of the differences that exist between them. In particular, HQ's managers define "*general rules that derive either from best practices or consolidated techniques for the management of activities and flows within manufacturing facilities*" [Auto, PD]. In this regard, managers present the adoption of lean practices as a way to manage production-related activities similarly across the firm's plants. Nonetheless, managers note that the differences in equipment, resources and layout between plants limits the SC's ability to unify processes and leads to the introduction of exceptions and variations. For instance, in standardising the wheel's disc production process, the different types of presses employed in each facility has forced managers to standardise several sequences of operations that are to be used.

Benchmarking activities: Benchmarking activities are used to "*transfer solutions adopted by a single plant to other plants*" [Auto, ED] and are an important practice to manage some structural and dynamic complexity factors. First, benchmarking activities help plants cope with the dynamic complexity of novel requirements from new customers by relying on the know-how and experience of other plants that have already served those customers. In addition, these activities perform a homogenisation role between plants, as they are used to "*turn improved solutions into standards that are then applied to other plants when applicable*" [Auto, ED]. In the same vein, other managers describe these activities as "*copy-pasting*" [Auto, LM] solutions that have been introduced by other facilities. Thus, in this respect benchmarking activities reduce the structural complexity related to the differences between facilities.

In order to perform benchmarking analyses, manufacturing facilities utilise a dedicated scorecard system and generate monthly performance reports that are shared with central management and all other plants using regular spreadsheet software and shared folders. Plants are predominantly autonomous and mostly take the initiative to investigate performance differences and set collaborations with other leading facilities to understand the root causes behind these. In addition, managers from quality, engineering and industrial investments functions are involved to aid in the implementation of solutions, monitor extant performance and suggest directions for further improvement accordingly.

Two main limitations to the effectiveness of benchmarking are highlighted. The first is that the differences between plants hinder the comparative analysis. For instance, a manager explains that even if the performance areas in the report are common, each plant may utilise specific KPIs that are in line with the plant's particularities. Secondly, managers note that the cost associated to the implementation of the shared solution, together with each plant's objectives and priorities, often imply that solutions are made available for all but only implemented in a few facilities, hence compromising the potential homogenisation effect of benchmarking.

Specific training: The mentality of employees and the management of change is presented as one of the elements that hinders the development and implementation of projects (e.g. NPIs, product line upgrades, adoption of new managerial processes and tools), and that thus aggravates the effects of dynamic complexity on SC performance. Managers note that specific training can accelerate the implementation of these changes and alleviate the effect of the associated transitions on performance by accelerating employees' learning curves and also helping them understand the reasons underpinning the changes in the way a SC activity is accomplished to alleviate opposing mentalities.

External SC complexity management

Several practices serve to reduce the negative impact of customer- and supplier-related complexities on SC performance: (1) cross-market unification of requirements, (2) organisational buffers, (3) unique customer interfaces, (4) supplier development initiatives, (5) integrated ERP systems and automation, (6) centralisation and localisation of purchasing and (7) vendor rating tools.

Cross-market unification of requirements: Auto SC managers partially unify the different requirements from the after sales and first equipment markets to reduce the variety of requirements for SC activities (i.e. structural complexity). This is facilitated by the fact that the requirements for the former market are, in most instances, less restrictive than those posed by OEM customers. As a consequence, the SC can unify these requirements whilst leveraging the after sales market to maximise economies of scale and the utilisation of production capacities. This approach allows managers to partially reduce the structural complexity of producing for two markets and to maintain the diversity in those few instances in which it benefits performance.

Organisational buffers: Organisational redundancies or buffers are employed to reduce managers' exposure to structural complexity. More precisely, the SC relies on additional independent organisations to handle the structural complexity that stems from producing for the after sales and first equipment markets, from the motorcycle portfolio segment and from M&A and global expansion of the firm. While this approach appears effective in reducing the variety Auto's SC managers must cope with, it entails additional costs in the form of additional human resources and prevents the optimisation of the SC as a whole. In line with this, Auto is investigating the feasibility and benefits of leveraging its NPI tools and practices (e.g. simulation tools, project management, etc.) for motorcycle products too, to maximise resource utilisation and performance.

Unique customer interfaces: Due to the high variety of requirements that OEM customers place on a range of SC activities, the SC defines management roles that act as unique interface for specific OEM customers. These managers are referred to as Key Account Managers (KAMs) and are responsible for interfacing the customer in all customer-specific operational or strategic activities. As described by a manager,

> "Customers require an interface that is able to understand their needs, requirements and procedures worldwide. Someone that can manage the customer in the different territories it is present and can coordinate all of Auto's activities with customers: technical aspects, quality aspects, etc." [Auto, SD]

KAMs are also involved in the management of customer-driven operational dynamic complexity. For instance, they are responsible for customers' demand and play a key role in the generation of monthly forecasts. Likewise, they are also central in managing any type of disruption that may affect the customer by managing communications between Auto's functions and the customer and providing the latter with direct on-site support.

Supplier development initiatives: Auto has developed a series of processes to foster the development of suppliers and aid SC managers better cope with the variety in the supply base and with supplier-triggered operational dynamics. These initiatives span three areas: supplier managerial processes and certification (especially focused on the ISO technical specification ISO/TS 16949 for the automotive industry), supplier production equipment and the development of communication processes between firms (critical in the management of operational dynamics).

Integrated ERP systems and automation: the adoption of integrated ERP systems in some of Auto's facilities poses as a major aid for SC managers with operational dynamic complexity. In particular, these integrated systems facilitate the communication and coordination between the different functions involved in SC processes. In addition, they improve the real-time visibility functions have of the progress and deviations of operations, and offers them with enhanced data to support decision making (e.g. more robust and comprehensive historic data of similar events). Lastly, these systems allow for a better integration with suppliers' ERP systems, allowing for the automation of certain tasks (e.g. automatic purchase requests for direct materials). Automation of these tasks does not only aid in the management of dynamic complexity, but reduces the variety of parts that needs to be directly managed, hence partially offsetting the effects of structural complexity on managers' focus and decisions.

Centralisation and localisation of purchasing: the centralisation of purchasing activities allows the SC to reduce the size of the supply base despite the large variety of materials and parts that have to be procured.

Central purchasing teams manage the supplies for key direct and indirect materials (e.g. tooling, welding materials, etc.) to aggregate volume for these parts and thus gain negotiation power with suppliers. This allows Auto to secure better deals for these materials but also to establish longer relations with fewer and larger suppliers that can supply most of Auto's facilities. Hence, key materials are provided by less than thirty global suppliers. In addition, centralisation fosters the unification of materials across plants, which according to managers facilitates knowledge sharing in the firm as well as potential demand relocations in the network by reducing the time and cost of homologations and learning.

On the other hand, the purchase of other materials is rather localised to benefit from the lower lead times and higher flexibility and responsiveness that local suppliers can offer. While these characteristics can reduce the complexity of managing single suppliers, this approach results on much larger supply base and compromised negotiation power (e.g. some of Auto's plants have more than four-hundred local suppliers). For this reason, most plants rely on local suppliers for cheaper materials such as packaging. Nonetheless, this approach has been adopted for the purchase of key materials in territories in where the deliveries of central suppliers were not reliable enough (e.g. steel purchasing in countries where customs' authorities may be especially uncertain).

Vendor rating tools: Vendor rating systems are presented by managers as useful tools to better cope with the SC's variety of suppliers. Data on supplier's certification level, in-bound material quality and on-time delivery rates is collected by local purchasing managers and shared with central management. This aggregated information helps SC managers monitor supplier performance to prioritise, set corrective actions, negotiate with and change suppliers, to improve the quality and costs of supplies.

Stocks: Auto's SC managers underline the use of stocks in the SC as a key practice to cope with the operational dynamic complexity driven by customer, supplier and internal uncertainties (e.g. demand variability, raw material delays and machine breakdowns). Manufacturing facilities produce for stock both to account for these uncertainties and due to the short lead times demanded by customers. In addition, managers note that these stocks are further increased when facing events that underpin demand variability such as NPIs.

While stocks allow the internal SC to handle unexpected changes in demand, managers note that excessive reliance on stocks can lead to quality problems in addition to extra costs, as production materials' and products' properties may be compromised by long warehousing times. This is an especial concern for low rotation parts and models, which may require quality controls to be performed twice (at reception or production and prior to shipping or feeding into the lines).

[…]

4.4 Defence within-case analysis

4.4.1 Introduction and background

Defence is an Italian and UK-based high-tech company and a key player in the Defence, Aerospace and Security industries, in which the company offers an extremely diversified range of products and solutions to both military and civil markets, including aircrafts, sensors, systems, infrastructure and weaponry.

Defence was first founded in the 1950s and has since grown into a truly global organisation. Today the company employs more than forty-five thousand employees worldwide and sells its products in more than a hundred countries. Moreover, Defence leverages a global manufacturing footprint, with close to two-hundred facilities, a strong presence in Poland and the US as well as in Italy and the UK and operations in more than fifteen countries. The firm is organised into seven divisions, each with a largely independent SC, and has a yearly revenue of approximately €12,000M.

The case study analyses the complexity factors and management practices encountered in the internal SC of the Airborne and Space systems division in the UK. This division designs, develops and produces a wide range of solutions for aircraft platforms, such as radars and sensors, simulation systems and aerial target systems. The division approximately generates 20% of the company's revenues. The analysis of the collected data reveals significant differences between the product portfolio and organisational design adopted by the division in other key territories. For this reason, the review of factors and practices presented in the case study is not in principle generalisable to the rest of the division.

4.4.2 Structural and dynamic complexity

Product design and portfolio complexity

The complexity of Defence's products and the breadth of its portfolio (i.e. variety of distinct product segments) drive structural complexity for managers. In addition, the development and introduction of new products is an uncertain and iterative process and a critical dynamic complexity factor.

The design of products is a relevant source of complexity for Defence SC managers. The complexity of products stems from their number of underlying components and, more importantly, from their technological edge. Indeed, as illustrated by the manufacturing and SC director,

> "We deal with very complex products, and in all cases we are pushing the boundaries of technology together with our suppliers" [Defence, SCD]

Moreover, due to the long product lifecycle and service life (in some instances products may remain in service for as much as forty years), while some products leverage state-of-the-art signal processing and software technologies, others' underpinning technologies date back to the second world war, thus resulting in a significant technological spectrum.

In addition, the company holds a broad product portfolio that consists of six product segments: lasers, electro-optics, micro-electronics, defensive aid systems, EW tracking systems and radars, which is in turn divided into surveillance radars and fire control radars. Managers underline the detrimental effect that portfolio breadth can have on the performance of the internal SC. Indeed, "*if your product portfolio is too broad and therefore volumes of everything are reduced, which is going to increase your unit cost*" [Defence, HP] as well as reduce the leverage you can exert on suppliers and can increase product quality issues. In the same vein, the division of effective resources against too many products can make it difficult to maintain speed.

With regards to dynamic complexity, new product introductions (NPIs) arise as a critical complexity factor. To this regard, the development of products and their transition from engineering into stable manufacturing is presented as an uncertain and iterative process that underpins dynamics in the internal SC. Managers underline the limited extent to which the uncertainty of these lifecycle phases may be reduced by acting upon product designs in advance, as even though "*we specify the design to take account of the variability, that does not mean we capture all of it*" [Defence, HSC]. Moreover, the often low production volumes and technological nature of products underpin the uncertainty of NPIs, and entail that "there will be changes that we find as we enter into manufacturing" [Defence, HSC].

Furthermore, arising change proposals during the NPI may entail the involvement of suppliers or customers as these "*may mean amendments to specifications, returning material to suppliers or it may mean concessions to be negotiated with the customer*" [Defence, HSC]. This can result in added pressure of customers, who may request to place their people in the manufacturing site. This potential involvement of customers further contributes to the complexity of these dynamics.

Internal SC complexity

The low number of SC facilities and their independency makes the network of facilities of the internal SC a minor structural complexity factor. Nonetheless, interactions between functions and teams are a relevant source of structural complexity for managers. The extent and high frequency of organisational restructuring activities stands as a critical dynamic complexity factor.

The structural complexity of the internal SC is not a major concern for SC managers. Indeed, the division's network of facilities consists of two different sites in the United Kingdom that respectively employ about one and three thousand people. Facilities' operations are largely independent from each other. The fact that each site focuses on different product portfolio segments further contributes to this independency. Despite the straightforwardness of Defence's network of facilities, the dependencies and interactions between functions poses as a relevant source of structural complexity. In this line, tasks such as the management of product export licenses, which requires the interaction with commercial functions, or the implementation of continuous improvement practices, which are owned by the SC and manufacturing team but often demand the involvement of other functions (e.g. engineering) and of suppliers, are underlined as some of the most complex tasks for the SC function. In addition, the need to ensure security standards around specific products can force Defence to employ bespoke procedures in the sourcing, material picking and dispatching of these products, thus contributing to the variety of processes in use in the internal SC.

Organisational restructuring is a source of dynamic complexity for SC managers. The company has undergone a series of organisational restructuring processes in recent years, the latest of which consisted of dividing the extant holding of companies into divisions to adopt a standard divisional organisational design. Indeed, in line with the high frequency of these organisational changes managers to state that "*we live in a world of continuous organisation restructuring*" [Defence, HSC]. Managers note that the top down imposition of these designs can be severely detrimental to SC performance, as the lengthy process of establishing the new organisation "*affects practical things such as name changes, which affect the IT systems, which affect the commercial systems, which may mean that you cannot ship the product or have a product be delivered to you and pay your suppliers back*" [Defence, HSC]. Likewise, these dynamics have a negative effect on the perceptions of employees, who must adjust and come to terms with the changes. In this respect, in spite of the clarity that these modifications may bring to the organisation, the frequency of organisational restructuring has made the workforce, to a certain degree, unsusceptible to the organisation around them, which can not only undermine their performance but also hinder the development of a common shared manner of working in the organisation (i.e. organisational culture).

External SC complexity

The customer and supply base are critical sources of both structural and dynamic complexity. The breadth of requirements and the involvement of a large variety of customers is major structural complexity factor. On the contrary, the management of the relations and dependencies with a reduced number of suppliers challenges procurement managers in securing the technological solutions Defence products need at an adequate cost. Customers and suppliers are also important sources of uncertainty and drive operational dynamic complexity in the internal SC.

Managers highlight the criticality of the diversity and breadth customer requirements as structural complexity factors. This diversity is partly underpinned by the variety and different types of customers Defence delivers its products to. The division sells its products directly to the military and ministry of defence of a number of countries in Europe, North America and Asia. In other territories, however, Defence deals with customer integrators, which manage and aggregate the demands of typically smaller customers in a specific geographic area (e.g. bureaus and detection agencies). In addition, the division manufactures its products for both small and large platform integrators, supplying equipment and systems unto the platforms developed by these organisations. Furthermore, requirements from customers are not only diverse but broad, as they span a wide range of aspects beyond product characteristics or features (e.g. support, shipping, contracting and security requirements). For instance, despite the division's efforts to consolidate on a single carrier, international customers often request the use of specific freight carriers, simultaneously increasing direct shipping costs and reducing the extent to which Defence can manage delivery performance. Likewise, customers may have specific packaging requirements or demand re-usable packaging. Even though the division does not offer bespoke packaging, "*these are just part of the contracts that we accept from our customers*" [Defence, HSC].

Customer involvement appears to underpin the breadth of such requirements. Moreover, managers underscore that the tendency of large and very demanding customers to intervene in Defence operations translates into not only additional requirement breadth (i.e. structural complexity) but also more complicated operational dynamics, as such customers can demand regular reports and meetings to closely monitor the project's progress as well as take part in decision making.

The supply base is a relevant source of structural complexity for Defence managers. However, complexity does not stem from excessive variety but from the dependencies and interactions with them, which are rendered critical by the extensive use of outsourcing and the technological nature of products. As underlined by the division's SC director,

> "The complexity comes in where we are dealing with cutting edge technology and we have to develop our suppliers to perform at the level that we require, and where we need to make sure our engineers teams are defining where the critical features in their design are to ensure that it works and point them out to the suppliers" [Defence, SCD]

With respect to dynamic complexity, supplier obsolescence is a major concern due to the length of service and support (usually of about twenty-five years) of Defence's products. Managers underline the impact that these events can have on the performance of the internal SC and note that obsolescence is often not triggered by a supplier who decides to upgrade or stop manufacturing a component, but rather related to shifts in the commercial market that may in turn affect suppliers (e.g. forcing them to adopt a new standard or suddenly putting them out of business). For this reason, supplier obsolescence is hard to predict in spite of the writing of obsolescence plans and the use of tools to monitor products through their lifecycle.

Lastly, the irregular pace of operations emerges as a critical dynamic complexity factor negatively affecting the performance of the internal SC. Unexpected demand increases, material delays or quality issues and failing test equipment or facility actions that can disrupt the planned flow of production. These dynamic events can require a significant amount of the internal SC's resources as "*regularly we [managers] revolve around the progress of production*" [Defence, HSC]. The relevance of operational dynamics is highlighted by the head of SC and manufacturing:

> "It's the operations, the operations movement and the dynamics of it that are bringing most of the complexity. Because we deal with things that are as big as these two tables, to things that are individual items. So scale, size, the complexity of shipping the product is not something we are not in line with: it's the instability and drumbeat and rhythm that is a difficulty" [Defence, HSC]

4.4.3 Complexity management practices

Product design and portfolio complexity management

A series of practices are employed to reduce and accommodate the structural and dynamic complexity of products and the product portfolio. Outsourcing, cellular manufacturing, portfolio rationalisation, traceability, and anti-mixing systems mainly focus on structural complexity. The implementation of a cradle-to-cradle style lifecycle management process and carry-over of product design features predominantly aim at dynamic complexity factors.

Outsourcing: the division leverages on outsourcing to be able to cover the full technological spectrum of their products. Indeed, with the exception of some product segments that are a key part of the division's identity and competitive advantage (e.g. micro-electronics), in the majority of products Defence focuses on the final acceptance and integration of components and on product testing in-house. However, managers reinforce the need to establish a proper balance between outsourcing and in-house expertise, as outsourcing renders the relations with suppliers critical and can yield the internal SC vulnerable to supply risk. As briefly put by the head of procurement, "if you do more in the SC you got to retain enough intellect locally to control that supply. You can't procure a product that you don't understand" [Defence, HP].

Cellular manufacturing and product technology groups: Another measure that the firm adopts to accommodate the breadth of the portfolio and technological edge of products is breaking down manufacturing into technology groups around products, and setting these up in the best way to manufacture each product segment. Thus, manufacturing is organised into large cells and a different manufacturing technique can be adopted within each cell depending on the product. For instance, "*if it is a one-of product or if it is a flow, you will probably have a one-piece-flow type of coordination within that large cell*" [Defence, SCD]. In addition, this design allows the development of specialist skills and knowledge. However, managers note that, in doing this, it can restrict the flexibility of the workforce, which are dedicated to their cell.

Portfolio rationalisation: rationalisation of the product portfolio is presented as a means to reduce structural complexity in the internal SC while enhancing overall performance by "*typically removing products that were making a loss*" [Defence, SCD]. In this regard, rationalisation allows the division to "*make the space for new products and focus our efforts on the ones that are driving sales*" [Defence, HP]. In addition to freeing up resources and enhancing management focus, the reduction of product variety is argued to improve efficiency and reduce internal variability, and hence quality issues.

Traceability and anti-mixing systems: A series of practices are employed to reduce the detrimental effects that the variety of products and components have on the performance of in-bound and out-bound logistics activities. A bespoke logistics facility has been designed for all warehousing and goods receiving and dispatching activities. The facility employs two shuttles that are eight meters tall to generate the equivalent of a thirty thousand square foot storage in a very compact facility. Materials coming in are logged into a system solely through barcode readers so as to enhance speed and avoid typographical errors. The system is fully integrated with Defence's main ERP, providing complete visibility of materials six minutes after data is inputted. Real time visual feedback on how in-bound and dispatching orders are meeting their service level agreements is also provided to the workforce both inside and outside the ERP (e.g. through a traffic-light colour code in the facility). Product-specific trolleys to pick up the materials are used, which are comprised of various drawers for the product specific parts to be arranged in sequence. Likewise, the main products utilise bespoke containers for their bolts, screws and other smaller components, which are integrated with suppliers and are automatically topped up in kits when necessary.

These systems and tools have together resulted in a significant reduction of the resources employed for material-handling activities. For instance, the head of SC illustrates the speed increase as "*it has reduced the time to get orders out from days to hours*" [Defence, HSC]. Moreover, the systems enhance traceability, which provides with responsiveness to potential supplier issues, and minimise the probability of mixing and internal errors, thus partially mitigating the effects of variety on the performance of these activities.

Lifecycle management process: The lifecycle management process (LCMP) is a central practice allowing the internal SC to deliver consistently despite the large variety of products and customer requirements. It consists of a formalised gated process that sets the foundations for managing all products and through which all projects are run. Hence, the LCMP defines unique criteria for all products to advance through its lifecycle, ensuring that all customer requirements are met and setting the requirements for all internal SC activities from scheduling and planning to sourcing.

In addition to accommodating product and customer variety and reducing internal SC structural complexity by establishing commonalities between all projects, the LCMP touches all facets of products and aids managers manage dynamic stages of their lifecycle such as NPIs or supplier obsolescence. Indeed, the LCMP demands different plans and criteria that foster the interaction between functions and that reduce the uncertainty of some product lifecycle events. For instance, aspects regarding the reuse of a product's design and tools to partially eliminate the uncertainty of NPIs have been introduced into the LCMP. Another of its main beneficial outcomes is that it fosters lesson learning, which is, for example, central in the management of supplier obsolescence. Hence, the LCMP poses as a critical tool in managing both structural and dynamic complexity in Defence's internal SC.

Design carry over: one aspect that is integrated with the LCMP and managers underline is the reutilisation of previous product design elements when upgrading or designing new products. In particular, managers emphasise that, despite the need to keep up with the fast pace of technology, the development of new products "*is usually [about] evolution, rather than revolution*" [Defence, HP]. The fact that new products still bring forward elements of previous products reduces the uncertainty and dynamics of NPIs. For instance, it enhances supplier manufacturability and allows Defence to perform little modifications to the extant supply base, reducing the instability of operations and number of changes to the product design or manufacturing processes to be dealt with during this product lifecycle phase. In a similar manner, carry over allows Defence managers and workforce to leverage as much as possible on the specialised expertise the integrated product teams have acquired on the preceding products.

Internal SC

Internal SC complexity is significantly less critical than product design and portfolio or external SC complexity. However, two practices are employed to facilitate the interaction between functions as well as organisational restructuring. The adoption of integrated product teams is a key measure in managing not only the interactions between functions but also product design structural and dynamic complexity. In addition, the use of incremental organisational changes, together with intensive training and communication throughout the organisation (i.e. inside and outside the internal SC) can help reduce the effects of these dynamic factors on SC performance.

Integrated product teams and project management: one of the main measures adopted to facilitate the interactions between functions while accommodating the breadth of the product portfolio is the definition of integrated product teams (IPTs). These are teams that comprise of procurement, engineering and manufacturing and SC personnel who work physically together on a daily basis, and are collocated with products and dedicated to their specific manufacturing cell. Hence, the head of procurement reinforces that "*in the day to day I do not see my managers, they are all working with the product teams*" [Defence, HP].

In addition, because Defence runs its operations employing a project-based model such that "*each project typically delivers a product to a customer*" [Defence, HP], each project manager has an IPT whose members are responsible for interfacing with their respective functions and bringing in the necessary resources for the product and project. The fact that Defence is both "*product-focused and project-focused*" [Defence, HP] also facilitates the customisation of products to meet the requirements of each customer. Managers underline the relevance of "*getting right the interface point*" [Defence, HP] with the IPTs. Careful attention is paid to foster a direct and physical interaction and communication between IPT and function managers (e.g. avoiding the definition intermediate roles).

IPTs enable the physical integration between functions involved in SC activities. This fosters comprehensive solution development and decision making. In addition, the product-centricity of IPTs implies that these teams run through the entire lifecycle of products, maximising team member's learning. This allows Defence to benefit both from the cross-functional collaboration and coordination, and from the specialised product knowledge during the management of dynamic complexity factors such as NPIs or supplier obsolescence.

Incremental organisational changes: even though managers struggle to pin point individual practices that effectively address the dynamic complexity of organisational restructuring, they underline some guidelines followed to alleviate the effects of these dynamic complexity factors on SC performance. In this vein, managers underscore the importance of seeking to mostly rely on minor improvements and small scale incremental changes to the organisation, hence dividing a significant transformation into successive smaller steps. In addition, bespoke training programs and striving to effectively communicating change can accelerate the transitions. These general guidelines are also for key processes. For instance, in the rolling out of a new version of the LCPM managers emphasised the evolutionary nature (i.e. small scale improvements) of the changes made, the use of training, and its incremental implementation and adoption in the organisation.

External SC

In line with the relevance of external SC complexity, Defence employs a range of practices to mitigate the effect of these factors on the performance of its internal SC. The unification of customer requirements, decentralisation of procurement, category management, and modular design and software customisation predominantly focus on structural complexity. Supplier collaboration and development, flexible workforce, split of sourcing responsibilities and supply-demand reconciliations mainly aim at dynamic complexity factors.

Unify customer requirements: Defence strives to find and establish commonalities within the variety of customer requirements to reduce the variety of product parts (i.e. structural complexity) in the internal SC. As illustrated by the SC director,

> "Customer requirements are hugely different, and it is our job to try and find some commonality so that we are not reproducing the wheel at each time that we deal with a new customer" [Defence, SCD]

Furthermore, managers underline the need to align the design of the organisation with this purpose. For instance, a challenging case was defining common processors for the radar lines as "*we had numbers of different requirements and a number of engineering teams wanting to drive their own requirements*" [Defence, SCD]. This was finally solved by setting "*one [bespoke] single team that pulled together all those requirements and put a root map in place for that product*" [Defence, SCD] rather than leveraging on the individual product teams.

Procurement decentralisation: the decentralisation of procurement activities is presented as a key measure to enable the effective management of the relationships and interactions with the supply base. In fact, managers explain that in other countries where Defence has adopted centralised designs, procurement managers struggle to manage the complexity in the supply base. The close relationships with suppliers that are enabled by the decentralisation of procurement allows Defence to "have the right conversation early about how to design and manufacture the products" [Defence, HP]. In this vein, it is the complexity and nature of products (as well as outsourcing) that imposes the need to closely manage supplier relationships, and therefore prevents from centralisation.

Category management: a category management approach is implemented in the procurement function to group similar components and parts and reduce the effect that the diversity of these has on Defence's bargaining power with suppliers as well as on procurement decision making. As described by the head of procurement:

> "Even if parts are not identical, they belong to the same category. Therefore, you have common suppliers and technologies even if the item itself is not exactly the same, and you can start to apply some leverage on the market" [Defence, HP]

Similar components are grouped under a unique category, which is managed by a category team that is part of the procurement function. In addition to aggregating volumes "*each category has its own strategy [that defines] what is the business plan, who are the* *key suppliers, what is our approach with them, how much leverage do we have with them, etc.*" [Defence, HP]. The discussion of category strategy is centralised, so that information is shared across geographies to ensure that the right strategy is implemented for each category. Hence, categories facilitate strategic decision making with regards to procurement activities despite the wide variety of product parts.

Modular design and software customisation: the use of modular product designs and of software customisation is presented as central in jointly accommodating the diversity of requirements from customers. These two practices have been increasingly embraced during the last decade to adapt product's functionality to the needs of individual customers while minimising the resulting product variety and its effects on SC performance. Indeed, they allow Defence to quickly and flexibly tailor a solution for a customer whilst counterbalancing the reduction of volumes driven by the variety of products and reducing manufacturing and procurement costs by enhancing scale. Ultimately, it enables the division to "*drive more revenues and sales with the same capacity of engineers and personnel*" [Defence, HP].

Supplier collaboration and development: Collaborating and developing suppliers aids Defence SC managers manage the relationships with suppliers and the technological edge of products. Indeed, the close relationships with suppliers allows managers understand and expand suppliers' capabilities, which allows to not only push the technology embedded in products but also to ensure that product design have an adequate manufacturability for suppliers. For this end, suppliers are involved in the development of new products and their input is considered "*from the very beginning of the design process*" [Defence, HP].

The benefits of improving the manufacturability of product parts for suppliers is twofold. On one hand, it translates into more predictable and stable operational dynamics on the job floors, as it reduces the variability of testing and manufacturing processes. On the other, by avoiding too specific and complicated solutions from suppliers, procurement managers can maximise the competition between suppliers and thus exert further leverage on the market.

Flexible workforce: the flexibility of personnel in the SC and manufacturing function is enhanced to maximise management's ability to deal with the instabilities and perturbations of operations. For this purpose, a reduced group of employees are trained with the necessary skills to be able to work across a range of manufacturing cells, allowing management to respond and adapt to external (i.e. suppliers and customers) or internal (i.e. testing and manufacturing) uncertainties. Seeking to balance costs and benefits that derive from this enhanced flexibility of resources, about 10% of personnel involved in manufacturing and testing activities on the job floor are part of this initiative. These are moved across product lines once approximately every three months so as to maintain their varied skill-sets up to date and effective.

Split of sourcing duties: The operational responsibility to manage suppliers is split between manufacturing and procurement teams in order to aid with the management of product portfolio structural and dynamic complexity. More precisely, the SC and manufacturing group is responsible for managing the stable phases of procurement for regular (i.e. non-sensitive) components, whereas procurement handles the operational sourcing of especially complex product parts and of all parts during non-stable product phases. Therefore, this reduces the dynamic and structural complexity that SC and manufacturing managers must cope with and allows procurement managers to further specialise on these issues.

Supply-demand reconciliations: managers employ a range of meetings at different fixed time intervals and organisational levels to adapt to the dynamics of customers and suppliers and ensure the continuous alignment between supply and demand. Daily and weekly “drumbeat” meetings are held by all IPTs, focusing on the daily progress of production and incorporating updated feedback from procurement regarding potential supply issues. Monthly “hard supplier reviews” meetings sit together procurement, manufacturing and project management managers to prevent and discuss any potential mismatches between supply and demand. Lastly, demand and supply sides are strategically aligned via the integrated business plan, which establishes the goals for procurement and commercial functions for the following five years.

Appendix C: Summary matrix of findings

The summary matrix of findings, represented in Figure 1 and discussed in Chapter 7, matches complexity management practices, on the rows, and supply chain resilience constituents, on the columns. Positive (i.e. increasing) and negative (i.e. decreasing) effects on resilience are reported separately. In each cell, the complexity drivers intermediating the relationship and linking the two dimensions are reported.

		Flexibility		Visibility		Velocity		Collaboration	
		Increase (+)	**Decrease (-)**	**Increase (+)**	**Decrease (-)**	**Increase (+)**	**Decrease (-)**	**Increase (+)**	**Decrease (-)**
Variety reducing practices	**Accessory-based customisation**	Product var. and spec.				Product var. and spec.			
	Product platforms and standards		Product var. and spec.			Product var. and spec.			
	Product portfolio rationalisation	Product LC events Demand/supply dynamics				Product var. and spec. Product LC events Demand/supply dynamics			
	Product-centric organisational design	Portfolio breadth Product var. and spec. Variety customer requires Product LC events Demand/supply dynamics Differences between facilities	Product var. and spec. Variety customer requires		Variety customer requires	Product LC events Demand/supply dynamics Differences between facilities	Product var. and spec. Variety customer requires	Portfolio breadth Product var. and spec. Variety customer requires Demand/supply dynamics Differences between facilities	
	Platform teams								
	Rationalisation of SC facilities		N. and layers SC				N. and layers SC		
	Process standardisation					Differences between facilities			
	Unification of customer requirements							Variety customer requires	
	Centralisation of purchasing	Differences between facilities		N./var. of partners				Differences between facilities N./var. of partners	

(continue)

		Flexibility		Visibility		Velocity		Collaboration	
		Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
Confinement and decoupling practices	**Outsourcing**		Portfolio breadth Product var. and spec. Variety customer requires		N./var. of partners Variety customer requires				
	Customised distribution channels								
	Modular design and software customisation	Product var. and spec. Variety customer requires							
	Category management			N./var. of partners				N./var. of partners	
	Localisation of activities	Product var. and spec. Variety customer requires Demand/supply dynamics				Demand/supply dynamics			
	Additive manufacturing postponement	Product var. and spec.				Product var. and spec.			
	Organisational buffers								
	Split of sourcing activities								
	Flexible workforce	Demand/supply dynamics							
	Stocks	Demand/supply dynamics				Demand/supply dynamics			
	Intermediate interface teams							Demand/supply dynamics	

(continue)

		Flexibility		Visibility		Velocity		Collaboration	
		Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
Coordination and collaboration practices	**Decentralisation of procurement**							N./var. of partners	
	Global SC forums							Differences between facilities	
	Integrated product teams					Product LC events Demand/supply dynamics		Portfolio breadth Variety customer requires Demand/supply dynamics	
	Strategic relations with partners and suppliers		N./var. of partners New customers/suppliers Product var. and spec.	N./var. of partners		N./var. of partners Product LC events Demand/supply dynamics		N./var. of partners Product var. and spec. Demand/supply dynamics	
	Integrated ERP systems		Product var. and spec.	N. and layers SC		N. and layers SC Demand/supply dynamics		Portfolio breadth Product var. and spec. N. and layers SC Demand/supply dynamics	
	Benchmarking							Differences between facilities Demand/supply dynamics	
	Coll. with prod. design/front-end teams								
	Project management			Reconfig. SC Improvements M&A		Product LC events Reconfig. SC Improvements M&A		Portfolio breadth Product var. and spec. Variety customer requires M&A	
	Cross-functional KPIs								
	Multi-level supply-demand reconciliations							Demand/supply dynamics	
	Unique customer interfaces					Demand/supply dynamics		Variety customer requires Demand/supply dynamics	
	Supplier development			N./var. of partners		Product LC events Demand/supply dynamics N./var. of partners	Product var. and spec.		

(continue)

		Flexibility		Visibility		Velocity		Collaboration	
		Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)	Increase (+)	Decrease (-)
Decision support and Knowledge generation	**Forward-looking forecasting**								
	Cellular manufacturing and product tech. groups		Product var. and spec. Portfolio breadth			Product var. and spec.			
	Product segmentation and specialised teams								
	Automation		Product var. and spec.			Demand/supply dynamics			
	Traceability and anti-mixing systems	Portfolio breadth Product var. and spec. Demand/supply dynamics				Demand/supply dynamics			
	Multi-Echelon ERPs and optimisation IT tools	Portfolio breadth Product var. and spec. N. and layers of SC		N. and layers of SC		N. and layers of SC		Portfolio breadth Product var. and spec. N. and layers of SC	
	Product lifecycle mgmt processes and tools					Product LC events Demand/supply dynamics			
	Vendor rating tools			N./var. of partners				N./var. of partners	
	Specific training					Product LC events Reconfig. SC Improvements M&A			
	Product design carry-over					Product LC events			
	Simulation								

Figure 3: *Summary matrix of findings, matching complexity management practices and supply chain resilience constituents.*