Steering supply chains from a complex systems perspective

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Abstract
Purpose – The purpose of this research is to systematically review the properties of supply chains demonstrating that they are complex systems, and that the management of supply chains is best achieved by steering rather than controlling these systems toward desired outcomes.

Design/methodology/approach – The research study was designed as both exploratory and explanatory. Data were collected from secondary sources using a comprehensive literature review process. In parallel with data collection, data were analyzed and synthesized.

Findings – The main finding is the introduction of an inductive framework for steering supply chains from a complex systems perspective by explaining why supply chains have properties of complex systems and how to deal with their complexity while steering them toward desired outcomes. Complexity properties are summarized in four inter-dependent categories: Structural, Dynamic, Behavioral and Decision making, which together enable the assessment of supply chains as complex systems. Furthermore, five mechanisms emerged for dealing with the complexity of supply chains: classification, modeling, measurement, relational analysis and handling.

Originality/value – Recognizing that supply chains are complex systems allows for a better grasp of the effect of positive feedback on change and transformation, and also interactions leading to dynamic equilibria, nonlinearity and the role of inter-organizational learning, as well as emerging capabilities, and existing trade-offs and paradoxical tensions in decision-making. It recognizes changing dynamics and the co-evolution of supply chain phenomena in different scales and contexts.

Keywords Supply chain, Complexity, Complex adaptive systems, Organization, Management, Steering

Paper type Research paper

Introduction
The desired outcomes of managing supply chains or networks have been cited in several papers in the literature. Managing interactions among the value-adding business/work processes, organizational resources, and ties and relationships can lead to the following: optimize the configuration and utilization of resources; facilitate access to scarce inter-organizational resources, capabilities, knowledge, skills, experience, infrastructures, markets, capital and innovation; reduce transactional and total costs; increase effectiveness, efficiency and profitability; improve overall performance; align operations and strategies; match supply with demand better; improve visibility; safeguard property rights; increase customers’ satisfaction as well as service levels; share risks; and minimize uncertainties (Mentzer et al., 2001; Christopher, 2005; Greer and Lei, 2012; Dubey et al., 2020; Bowman and Collier, 2006; Huggins, 2010; van Fenema and Keers, 2018).

Although supply chain management (SCM) is underpinned by a desire for interacting and integrating (Mentzer et al., 2001; Stock and Boyer, 2009; Lambert, 2006; Drake and Schlachter, 2008;
Simchi-Levi et al., 2004), it is simplistically treated in both theory and practice, given the following: the emergent properties that arise from interactions over time; improper handling of proximities, feedbacks, nonlinearities, transformation (Ojha et al., 2018), ambidexterity (Turner et al., 2013), dynamic capabilities (Ambrosini and Bowman, 2009; Vogel and Güttel, 2013), learning processes (Chiva et al., 2010), adaptive, absorptive- and desorptive capacities (Dobrzykowski et al., 2015; Roldán Bravo et al., 2020), viability properties (Ivanov and Dolgui, 2021a), resistance, conflicts, paradoxical tensions (Nielen and Stefan, 2019), path dependencies, contingencies (Bowman and Collier, 2006) and changing organizational-ownership, structure, culture, behavior (Larentis et al., 2019), identities, citizenship, power and politics; or when the extent and context dependencies of interactions are neglected.

It is also simplistic to assume that all stakeholders ranging from way upstream suppliers to far downstream customers/consumers can be correctly identified, objectively prioritized and truly integrated with error-free flows of products (goods and services) and information, due to the fact that the boundaries of control are limited to one organization and not to the end-to-end chains/networks. Furthermore, there is lack of research-based understanding regarding when or how dis-integration, re-integration or re-configuration occurs or should occur in supply chains (SCs). This could also imply challenges in data analytics (Ivanov and Dolgui, 2021a), as it is vague what is or should be included in big data, the best way to detect their anomalies, how they should be semantically interoperated and interpreted (Datta, 2015, 2017), who owns or is in charge of them, where and how long they should be stored and remembered, or how they are transformed over time.

Understanding SCs from the perspective of complex systems and their general properties can be beneficial for explaining even complex SCs, whereby the perspective explains why SCs behave as they do in reality. Complex systems are open systems which operate under quasi-equilibrium conditions (Gell-Mann, 1995), whereas their states are determined by the values of their inputs and outputs (Cilliers, 2005), resulting from the interactions of interconnected subsystems, with interactions being highly sensitive to the history of the subsystems and to their current context (McMillan, 2006; Hogue and Lord, 2007; Hoogeboom and Wilderom, 2020; Asthana et al., 2020). In addition, complex systems possess the capacity to respond to their environments in more than one way (Allen and Strathern, 2003).

A complex systems perspective can also facilitate the understanding of how SCs are more effectively managed, i.e. directed, assessed, improved and transformed toward desired outcomes. This perspective achieves this understanding by challenging simplistic, superficial and positivistic approaches, techniques, assumptions or mindsets in SCM – some examples include: objective reality, deliberate design, reductionism, uniformity, determinism, stability, rationality, equilibrium, linearity, symmetry, order, hierarchy, centralization and controllability.

The purpose of this research is to systematically review the complexity properties of SCs by demonstrating that SCs are complex systems and that the management of such systems is best achieved by steering or coaxing them. Accordingly, in order to fulfill the research purpose, the research question to be answered is: Why do SCs have properties of complex systems and how to deal with them while steering them toward desired outcomes?

By answering the research question, this study aims to theoretically introduce an inductive framework for steering SCs from a complex systems perspective by transforming their multidisciplinary conceptual understanding and research paradigm. It also aims to guide practitioners as well as decision-makers by critically challenging some of the simplistic, taken-for-granted assumptions in SCM and by recognizing supply chain systems open structures and their dynamics and behavioral patterns and also multi-scale and multi-contextual interactions while transforming them toward the desired outcomes over time.

The next sections provide an overview of the methodologies for collecting, analyzing and synthesizing data, as well as the measures for increasing the quality of research. These are followed by a findings section, followed by complementary reflections, the presentation of the
inductive framework for steering SCs away from a complex systems perspective as well as the identification of research gaps in the discussion section. The paper ends with concluding remarks, possibilities for further research and critical reflections regarding research limitations.

Methodology

The research study was designed as both exploratory and explanatory (Saunders et al., 2009), in order to clarify the understanding of properties and dealing mechanisms of complex SC systems, and also to establish relationships among them, respectively. As summarized in Figure 1, the research methodology was inspired by the Sven-Step Model for a Comprehensive Literature Review (CLR), presented by Onwuegbuzie and Frels (2016).

Step 1: Exploring Beliefs and Topics

Our ontological and epistemological stance in this research was mainly that of constructionism and interpretivism, respectively (Bryman and Bell, 2007), as these better reflect the subjectivity, interactions, nonlinearities, dynamic capabilities and transformative changes that exist in management of complex SC systems over time.

Step 2: Initiating the Search

To systematically review the literature, Scopus was searched by [complex* AND {supply chain}*] in title or abstract or keywords of the documents. By limiting the search into the peer-reviewed journal articles, written in English and published until end of 2019, 4,279 hints of articles were identified. Afterward, abstracts of all the identified articles were read, from which 304 articles were determined as pertinent within the scope of this research study.

Step 3: Storing and Organizing Information

In the next step, the bibliometric information as well as access links of the pertinent articles were saved in a cloud-based version of RefWorks and considered for further investigation.

Step 4: Selecting/Deselecting Information

By skimming the whole body of the pertinent articles, 99 articles (see the “systematic literature review (SLR) references” list) were selected as relevant. To judge the relevance of the articles, their main bodies had to incorporate foundational, explicit and worthy information (such as meta-reflection, in-depth analysis, critical thinking and reflexive practices) about the complexity properties of SC systems and mechanism(s) for dealing with the complexity of SCs. Furthermore, we found that the number of relevant articles was sufficient for data saturation and for identifying the emergence of the patterns of complexity properties and dealing mechanisms. Other pertinent articles were either considered as supplementary for possible use or deselected as not useable for answering the research question in this research study.

Step 5: Expanding the Search

In parallel with the SLR, a narrative literature review (see the “narrative literature review (NLR) references” list) was performed in order to increase research authenticity by collecting further supportive references from well-established manuscripts – articulated in complexity science discipline – which address properties of complex systems in general terms than complex SCs in specific terms. The bibliometric information as well as access links of the narratively reviewed literature were also saved in the RefWorks.

Step 6: Analyzing and Synthesizing Information
Step 1 - Exploring Beliefs and Topics
- Formulating the research question
- Clarifying the ontological, epistemological and theological standpoints

Step 2 - Initiating the search
- Searching Scopus by relevant phrases
- Identifying 4279 hints of articles
- Selecting 304 pertinent articles

Step 3 - Storing and Organizing Information
- Saving bibliometric information and links of the pertinent articles as well as the narratively reviewed literature in RefWorks

Step 4 - Selecting/Deselecting Information
- Selecting 99 relevant articles
- Selecting supplementary potential articles

Step 5 - Expanding the Search (MODES)
- Narrative literature review

Step 6 - Analyzing/Synthesizing Information
- Analyzing data in open-, axial- and selective coding stages
- Explaining and synthesizing relationships among the complexity properties and dealing mechanisms

Step 7 - Presenting the CLR report
- Increasing authenticity and trustworthiness of the research
- Auditing, quality checking and proofreading several drafts of the article before journal submission

Figure 1. The seven-step model for a comprehensive literature review (CLR) inspired by Onwuegbuzie and Frels (2016)
Inspired by the “grounded theory” approach discussed in Strauss and Corbin (1990, 1998), Saunders et al. (2009) as well as Bryman and Bell (2007), data were analyzed in three stages: open-, axial- and selective coding. In the first stage, i.e. the open coding stage, while reading the selected articles and manuscripts, data about complexity properties of SC systems as well as mechanisms for dealing with them were chunked and grouped into smaller segments or meaningful conceptual units and given a descriptive label or code. In the axial coding stage, relationships or similarities between the open codes were identified in order to arrange and explain them into clusters of categories. This was developed to a selective coding stage, where categories were linked and integrated to form the emerged themes or what we call properties and dealing mechanisms in this research study.

Relationships among the emerged complexity properties and dealing mechanisms were further re-evaluated (Alvesson and Sandberg, 2020) and analytically synthesized (Breslin and Gatrell, 2020), based on accumulated experience, insights and wisdom (Saunders et al., 2009) during the research study. This led to generation of an inductive, conceptual framework (Post et al., 2020) for steering SCs from a complex systems perspective.

Step 7: Presenting the CLR Report

Once the first full draft of the CLR report was written, it was audited, quality checked and proofread several times before journal submission. To judge research quality, two criteria were taken into account: authenticity and trustworthiness. To increase the authenticity of the CLR, Scopus was used to select a sufficient number of relevant peer-reviewed literature which had relevance for the notion of the complexity of SCs qualitatively and/or quantitatively.

To increase trustworthiness, the systematically collected data, memos from the grounded theory and also research diaries were registered in a common database which was shared by the authors. The work-in-process text was also circulated among a number of scholars in the field, in order to align interpretations and understand data during the entire research process. Accordingly, although there is subjectivity about how the collected data was interpreted and codified, which is common in constructive anti-positivistic qualitative research, the data collection process is transparent and replicable.

Findings

The results of the analysis reveal the complexity properties of SC systems, as well as mechanisms for dealing with the complexity of SCs.

Complexity properties of supply chain systems

SCs have properties of both complicated and complex systems. As a result, SCM should go beyond silo or atomic analysis of its constituent subsystems, such as goods, services, organizational resources and stakeholders. This section presents a synthesis of such properties which have been categorized into four categories abbreviated to “SDBD properties”: Structural properties, Dynamic properties, Behavioral properties and Decision-making properties.

The SDBD properties arise from a subjectively defined “complexity profile”. A complexity profile is related to the scale of the system (i.e. the unit of analysis) and describes in detail the system and its subsystems, as well as the context in which the system operates. Scale of the system is subjective (Casti, 1994), ranging from micro (SC of a focal organization, business unit or individual) to meso (SC among clusters of organizations or industrial/economic segments) and ultimately macro (SC in the aggregate economy). Details in describing the system and its subsystems also depend on the observer, since the details reflect the interests of the observer. Context of operation is inclusive, ranging from local, urban and regional to
national, multinational, continental or global. A description of those SDBD properties that could arise in every scale and context of observation from our subjective point of view is detailed below.

**Structural properties.** Structural properties delineate relatively static heterogeneous subsystems of SCs, shaping their nodes or vertices. As summarized in Table A1 in the Appendix, complexity arises due to the number, size, variety, extent and echelons/tiers of relatively static physical/tangible resources or components of SCs at each scale or context and the information or time required for the description of subsystems.

**Dynamic properties.** Dynamic properties delineate dynamic heterogeneous inter-flows and inter-processes of SCs, shaping their edges or connections or links. As summarized in Table A2 in the Appendix, complexity also arises due to the number, volume/degree, frequency, variety and extent of multiple flows of products (goods, services), movable physical/tangible-, human-, informational-, and financial resources; as well as value adding business/work processes that circulate among subsystems or are transformed by them.

**Behavioral properties.** As summarized in Table A3 in the Appendix, behavioral properties delineate the macro characteristics in SCs which originated from complex subsystems of the SCs and their interactions. Some of the properties which were adapted from the properties of complex adaptive systems (CAS) and are highlighted in this paper including: emergence due to interactions among subsystems and their nonlinearities over time; self-organization due to their openness and autonomy; and adaptive and evolutionary capacities of their agent-based subsystems.

**Emergence.** Complexity also arises on account of the degree and extent of interactions among the subsystems, i.e. the degree and extent of the effects on other subsystems while changing structural or dynamic properties of a subsystem. These interactions – which are sensitive to the history of the subsystems and to their current context (Hogue and Lord, 2007) – can lead to both linear and nonlinear behaviors in complex systems. Examples of nonlinearity can be found in system dynamics, nonlinear programing or modeling-related literature or those which reflect Forrester’s flywheel effect and bullwhip effect caused by the amplification of demand distortion, rationing and shortage gaming, order batching and price fluctuations (Wilding, 1998; Wycisk et al., 2008; Surana et al., 2005; Ouyang and Li, 2010; Ma et al., 2019; Serdarasan, 2013; Tu et al., 2019), among others.

Due to the changes in the complexity profile of the system and the degree, extent, frequency and nature of its interactions, the holistic system has a dynamic macroscopic property or collective behavior (Gell-Mann, 1995) that differs from the microscopic properties or behavior of its subsystems. In other words, the whole is more than (and different in kind from) the sum of its parts (Holland, 1995; Letiche, 2000; Reitsma, 2001; Cilliers, 2005; Merali, 2006; Choi et al., 2001). Due to the presence of linearity in complicated systems, these show a simple emerging (emerging simplicity) property that makes them deterministic. Due to both linearity and nonlinearity in complex systems, they have a complex emerging (emerging complexity) property that makes them probabilistic or stochastic (Bar-Yam, 1997), with existing uncertainties and indeterminism (Nilsson and Gammelgaard, 2012), such as in the case of demand, delivery time windows, lead times, quality or quantity by suppliers, processing and manufacturing schedules and employees’ behavior (de Leeuw et al., 2013; Serdarasan, 2013; Bozarth et al., 2009; Milgates, 2001; Wilding, 1998). This means that complex systems are not completely or deterministically predictable (Gershenson and Heylighen, 2004; Casti, 1994; McMillan, 2006).

As Holland (1992) and Kauffman (1995) put forward, complex systems’ behaviors are semi-predictable, as they reveal underlying patterns of behavior over time, such as the business cycle exemplified by Choi et al. (2001). In managing SCs, the patterns of emergent properties of the system – what we call its capabilities – can be identified and learned. According to Olavarrieta and Ellinger (1997, p. 563), capabilities are “complex bundles of
individual skills, assets and accumulated knowledge exercised through organizational processes that enable firms to co-ordinate activities and make use of their resources.” Capabilities should be directed toward the fulfillment of shared values and behaviors that lead to the emergence of desired outcomes in SC systems. With regards this, as highlighted in Abbasi (2014), in order to study SC performance and capabilities, the holistic assessments of the system – with different complexity profiles, i.e. different scales as well as contexts – must go beyond the assessment of the performance and capability of each subsystem in isolation.

Adaptation and self-organization. CAS learn from the patterns of emergent properties and react to changes based on their schemata (values, rules, norms, beliefs, assumptions, mental models and images) over time.

The schemata influence the behavior of agents [the subsystems that populate a complex system, partake in the process of spontaneous change in such a system and are able to interact meaningfully in the course of events (Choi et al., 2001)] of CAS while they are reacting to changes in their environments or creating their local surroundings. While the patterns of emergent properties and schemata are interpreted and learned over time, agents behave by self-organizing (Gershenson, 2007) based on the feedback that they receive by spontaneously rearranging their interactions with each other in the quest to optimize their overall fitness, without the need for an internal or external controller (Kauffman, 1995).

SCs are CAS because they have some subsystems with agency characteristics (e.g. intelligent goods and resources [humans, machineries, organizations]) that are able to intervene meaningfully in the course of events, or, as Bruzzone et al. (2005) highlight, because they sense and re-act to external stimuli. Complex adaptive SCs, or networks, are comprised of heterogeneous interacting agents that work under quasi-equilibrium (Li et al., 2010) and a combination of regularity and randomness (Surana et al., 2005). They show properties such as the ability to learn the patterns, self-organization, autonomy and emergent behaviors. Schemata in complex adaptive SCs should be in favor of fulfilling desired outcomes such as financially and institutionally-driven values, rules and norms which are expected to be shared among the agents throughout the system.

To adapt to the schemata, the “agency” characteristics of SCs need to increase, in order to: intelligently save, process and analyze the changes over time; identify the patterns; learn; and have the capacity to decide de-centrally. However, giving more freedom and a higher degree of autonomy to the agents can increase resilience (Casti, 1994) as well as the probability of emergence of innovative [desirable or acceptable] properties.

Self-organization and autonomy also enable the SCs to add or delete relations between agents, shift strategies in different markets (Fisher, 1997; Chand et al., 2018), adapt to different legislations (Statsen etc, 2018; Li et al., 2010) or adapt their forms of inter-relationships – in the scale and context where they operate –, such as: vertical; horizontal; arm’s length/transactional; cooperative; collaborative; competitive; coopetitive; operational; tactical; strategic partnership; joint venture; foreign direct investment (FDI); franchising; outsourced; alliance building and clustering; joint research and development; collaborative planning, forecasting and replenishment (CPFR); vendor-managed inventory (VMI); integrated product/process development; mergers and acquisitions; and joint action arrangements.

To self-organize, agents need to be open-minded and have sufficient autonomy to interact with other agents of their networks outside their functional boundaries. Ideal SCs adapt to the schemata by organizing themselves based on feedback (Choi et al., 2001; Varga et al., 2009), without an internal or external controller or a centralized decision-maker (Touboul et al., 2018). However, opportunistic behavior, bounded rationality, lack of know-how or skills, market imperfection, asset specificity, subjectivity and asymmetry in information and also interpretation can hinder the perfect adaptation to the schemata and exclusion of control or orchestration in SCs. That is why discussion about self-organization and adaptation, which
originated from natural sciences, requires more research in social sciences and applications such as SCM.

When analyzing adaptability, some papers reviewed in the literature highlight “resilience”. Hearnshaw and Wilson (2013) differentiate resilience from adaptability by relating the former to the capacity to carry out functions despite disruptions or damage by disturbance, that is, the capacity to resist change and preserve connectivity after nodal removal. The latter is then related to the capacity to adapt to novel and unexpected changes, the capacity to self-organize and reconfigure the structure and behavior to satisfy new conditions.

Other authors find overlaps between resilience and adaptability. Datta et al. (2007) define SC resilience as being not only the ability to maintain control over performance variability in the face of disturbance, but that it is also a sign of being adaptive and is capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands. Accordingly, a resilient system is expected to return to its original state or a better state after turbulence and disruption (Olivares Agulia and ElMarapgy, 2018). Asokan et al. (2017) identify three different articulations of resilience, namely: “engineering resilience”, which is the same as the term of elasticity and emphasizes the time a system takes to return to equilibrium or a steady state; “ecological resilience” accepts the presence of multiple stability regions and measures the amount of perturbation which the system can absorb; whereas “adaptive cycle of resilience” captures the concept of continuous change, which has four stages, namely: exploitation (r), conservation (K), release (Ω) and reorganization (α).

Asokan et al. (2017) argue that robustness (i.e. maintaining some level of functional parts and pathways or the ability to run the system at different output levels, or the ability to cope with errors during execution, according to Olivares Agulia and ElMarapgy (2018)) and transformation (facilitating interactions, expanding capacity and capability when needed) are two parameters that are crucial for a resilient system. Flexibility can lead to both robustness and transformation in times of stress, shock or strain. Further mechanisms for increasing SC resilience have been highlighted by Datta et al. (2007), Hearnshaw and Wilson (2013) and Ma et al. (2014), which include, among others: a hybrid balanced flexibility and redundancy; timely information sharing; agility and responsiveness by regular sensing; visibility; decentralized structure providing autonomy and good coordination; a high level of collaboration with key suppliers, including monitoring their financial and operational health and even working with them to reduce their vulnerabilities; flexibility to produce on demand, based on global and local information, rather than fixed monthly plans; and informed coordinated decision making that constitutes institutional memory and intelligence. According to Birkie et al. (2017), at a higher level of complexity, resilience capabilities lead to more performance benefits when compared with situations with a lower level of complexity.

Evolution. Evolution is related to gradual change or development in complex systems over time. As Gell-Mann (1995, p. 244) highlights, “evolution proceeds by steps, and at each step, complexity can either increase or decrease, but the effect on the whole set of existing species is that the greatest complexity represented has a tendency to grow larger with time.” Accordingly, the capacity of a complex system to interact, learn, adapt and self-organize can change over time. As stated by Bar-Yam (1997, p. 538–539), “the theory of evolution is based upon two processes, mutation and selection, that are assumed to give rise to incremental changes in organisms.” Mutation is related to heritable variations, mainly through changes in the genome from generation to generation, while selection (Lewontin, 1970) is related to differential reproduction.

Building upon these two processes, Abbasi (2014) highlights how SCs can increase probability of their sustainability and gradually developing their behavioral capacities over time by: replicating heredity by, for example, transferring and transforming memory of the
generations of the system in time; selecting co-operatively by, for example, letting the subsystems democratically decide, select and constructively compete; having enough variety and diversity by, for example, keeping back-ups from the subsystems, double sourcing, and diversifying the agents, products, processes, and markets.

Pathak et al. (2009) elaborate upon evolutionary role of intelligent agents that dynamically adjust both their overall and local fitness in their surrounding contexts. As Li et al. (2010) put forward, the evolution of complex adaptive supply networks is a function of its structure and fitness. Structure is related to the collection of nodes and edges, and the weight of the edges, whereas fitness is defined as a process of matching the environmental and internal factors. The results of their study show, on the one hand, that government regulations, demand and market structure are the external environmental factors that have the most impact on the evolution of complex adaptive supply networks. On the other hand, firm strategies, product structure complexity, technological complexity and organizational considerations are the predominant internal factors that influence the evolution of complex adaptive supply networks. When analyzing the evolutionary properties and models of SCs, Rose-Anderssen et al. (2009) refer to the method of cladistics in the cases of commercial aerospace SCs, for visualizing evolutionary timelines based on variation in the traits of a SC and the co-operative selection in the environment. Nair et al. (2009) highlight the reciprocity theory based on the PD (prisoner’s dilemma) game and the tit-for-tat strategy (TFT) when discussing the evolution of cooperation between agents. According to Hearnshaw and Wilson (2013), on the one hand, scale-free networks with power-law distributions are likely to improve their fitness and acquisition rate for connections, as are firms that form tightly coupled partnerships with other firms for their exchange strategies. On the other hand, firms that continue to carry out an arms-length transaction will not.

Decision-making properties. As summarized in Table A4 in the Appendix, decision-making properties denote the capacity of multiple-criteria decision making and also of dealing with paradoxical tensions and exogenous effects.

As complex systems are interwoven systems which include interactions in several scales and contexts, decision making by optimizing one parameter can lead to restrictions or conflicts with the other parameters (Serdarasan, 2013; de Leeuw et al., 2013). As a result, decision making in complex systems requires the capacity to semi-optimize the system as a whole when making perfectly isolated decisions. Some parts of sub-systems might attempt to be optimized, however this can lead to the sub-optimal performance of holistic systems. This results from limited and local knowledge as Cilliers (1998, p. 4) states: “each element in the system is ignorant of the behavior of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element ‘knew’ what was happening to the system as a whole, all of the complexity would have to be present in that element.”

The rationale for the extensiveness in complexity theory is based on the notion of paradoxes which are apparent in complex phenomena. Paradoxes can be a state in which two apparently contracting or conflicting, yet interrelated, elements appear to exist simultaneously, neither of which can be eliminated or resolved (Stacey et al., 2000). According to Smith and Lewis (2011), such elements seem logical when considered in isolation, yet irrational, inconsistent and absurd when juxtaposed.

Nilsson and Gammelgaard (2012) reflect upon the rationale for the existence of paradoxes and transformative theology when explaining the properties of complex logistical and SC systems from CAS and complexity thinking (CT) approaches. Some examples of paradoxical properties that may coexist in SCM are stabilizing price movement with suppliers in order to minimize complexity while increasing manufacturing flexibility to embrace growth in the product portfolio (Turner et al., 2018); coopetition or horizontal collaboration (Nilsson, 2005; Surana et al., 2005); organizational ambidexterity by reconciling ‘exploitation’ (refining and
using existing knowledge) and ‘exploration’ (innovation, problem solving and creating new knowledge) (Turner et al., 2018); increase in the self-regulatory survival capacity through an increment in variety, which is also a hindrance to rapid adaptation (Ramirez, 2012) and organizational unity and integrity. Abbasi (2014) further the list by highlighting: developing core competency/division of labor/division of perception and knowledge, while being multi- and interdisciplinary/holistic; the centralization of decision-making to increase efficiency as well as encouraging its decentralization to make SCs democratic, resilient and robust; increasing freedom and autonomy for the sake of self-organization and creativity, while establishing restrictions and regulations for the sake of controlling work routines, giving preferences, management and governance, or taking advantage of capabilities that emerge from the bundling of resources.

**Exogenous effects.** CAS have reflexive relationships with their surrounding natural, business/economic, institutional and socio-political environments or that which is defined as being outside of their boundaries. Changes in the system both shape and are shaped by changes in the surrounding environments. Dynamic interactions between the system and its environment – in addition to dynamic interaction among the subsystems (Bar-Yam, 1997) – take us from issues of simple adaptation and evolution to issues of co-adaptation and co-evolution (Merali, 2006). Schemata of CAS co-adapt and co-evolve with the schemata of their surrounding environments.

Supply and demand for goods and services in the surrounding environments shape the SC systems. However, changes in SC systems, such as launching new products, re-engineering the processes or the emergence of inter-organizational resources reshape existing environments. SC systems dynamically co-adapt with emerging infrastructures, technologies, values, norms, cultural as well as with juridical rules and regulations in their surrounding natural, business/economic, institutional and socio-political environments in different contexts. Experimenting with changes to the degree and diversity of mutual interactions between the CAS and their rugged and dynamic (Capaldo and Giannoccaro, 2015; Choi et al., 2001) or harsh and mild (Pathak et al., 2009) environments can open doors to co-evolution.

**Mechanisms for dealing with the complexity of supply chains**

With regards the mechanisms for dealing with the complexity of SCs, five mechanisms were inductively conceived from the systematic literature review, namely: classification, measurement, modeling, relational analysis and handling.

**Classification mechanisms.** As summarized in the former section, almost all of the systematically reviewed literature elaborates on complexity classification by revealing one or two of the properties of the complexity of SCs. However, as illustrated in Tables A1–A4 in the Appendix, structural as well as dynamic properties were discussed much more than behavioral and decision-making properties.

**Modeling mechanisms.** Table A5 in the Appendix provides an overview of the modeling mechanisms, which can be summarized as: simulation-based, swarm intelligence, network dynamics, evolutionary game theory, mathematical statistics and miscellaneous models.

**Simulation-based** models were dominant among the systematically reviewed literature and are mainly represented by “agent-based modeling”, which offer promising approaches for understanding the dynamic, behavioral and decision-making properties of complex adaptive SCs by simulating how each agent autonomously makes decisions based on its interactions with the environment and other agents. According to Surana et al. (2005), agent-based modeling is a bottom-up approach which simulates the underlying processes that are believed to be responsible for the global pattern, by enabling the evaluation of which mechanisms are most influential in producing the emergent pattern in question.
Another simulation-based model was “system dynamics”, which is deterministic and does not require multiple iterations (Barbosa and Azevedo, 2017, 2019; Pathak et al., 2007). The drawback of system dynamics models is that the structure has to be determined before starting the simulation (Surana et al., 2005). “Scenario analysis”, “discrete event simulation” and “cellular automata” were also carried out among the systematically reviewed papers in the literature. According to Nair et al. (2009), cellular automata are discrete dynamical systems where space, time and the states of the system are all discrete. Other simulation-based models are based on “evolutionary algorithms”, in particular “genetic algorithms” and “evolving hypergraphs”. Swarm intelligence was represented by the artificial bee colony (ABC), which offer heuristic multi-objective optimization algorithms.

Network dynamics models shed light on the properties of the dynamical patterns of network topologies, such as: the “clustering coefficient” [that expresses network transitivity, which is the average probability of two neighboring nodes that are connected to a given local node being connected to each other], “path length” [the distance between any two nodes chosen at random], “degree distribution” [the average number of connections possessed by each node in the network], “degree of centrality” [which represents the range size of a node control, whereby the higher the degree centrality of a node, the more neighbor nodes are associated with it in the network], “betweenness centrality” [the number of shortest paths from all vertices to all the others that pass through that node] and “network density” [the number of edges of a node, divided by the total possible edges that a node could have].

According to Hearnshaw and Wilson (2013), the key properties of efficient SCs are a high clustering coefficient, a short characteristic path length and a power law connectivity distribution. Two topological models that have particularly been proposed in the systematically reviewed literature were the Watts-Strogatz (WS) model and the Barabási-Albert (BA) model, which have topologies that fall between the regular and the random network models (Surana et al., 2005; Hearnshaw and Wilson, 2013; Ma et al., 2014; Zhang and Liu, 2013; Wang et al., 2018). WS exhibits a high clustering coefficient and the small-world property, i.e. a short characteristic path length, whereas each node has roughly the same number of connections. These findings render WS topology appropriate for establishing the trade-off between reducing transaction costs and improving the decentralized synchronization of SC and efficiently transferring the flows across the system. BA exhibits a low clustering coefficient, a short characteristic path length and power law connectivity distribution (which is known as “scale-free”), all of which indicates the presence of a small number of highly connected nodes or hub nodes, and a large number of nodes with a low number of connections. BA provides improved economic performance, especially regarding a lower transaction cost, over the WS model. BA also improves the synchronization of SCs, as well as the robustness and resilience of the system against the removal of nodes, although it is fragile in respect of the specific removal of the most highly connected nodes. As Statsenko et al. (2018) posit, if a sufficient network density exists, then this is a sign of its responsiveness and adaptability. Inspired from network dynamics, neural networks were highlighted in Pathak et al. (2007) and Surana et al. (2005), as well as in McKelvey et al. (2009).

Evolutionary game theory models investigate the evolutionary dynamics of strategy choices. Mathematical statistics models apply probability theory and statistical models for decision-making support. Originating from strategic and performance management jargon, situation-actors-process (SAP)-learning-action-performance (LAP) or SAP-LAP is a qualitative model that captures the managerial insights and learnings of complex situations and it tends to be dynamic in nature. According to Kavilal et al. (2018) and also Piya et al. (2019), interpretive structural modeling (ISM) is a methodology designed for identifying interdependence among specific items in a complex system by creating a distinguishable hierarchical model, which in turn defines a problem or an issue. Design
structure matrix (DSM) is a square matrix which investigates the relationships between the elements of a system. Finally, coupled map lattice (CML) is a branch of dynamical systems, where space and time are discrete and its state is continuous. CML models the behavior of a nonlinear system.

Measurement mechanisms. Measurement mechanisms provide several numerical means for quantifying the complexity of SCs. Entropy-based measures, mathematical optimization or mathematical programming measures, multi-criteria decision-making approaches and indices all emerged from the systematically reviewed literature (see Table A6 in the Appendix).

The first group is constructed based on entropy or Shannon’s information entropy, i.e. the amount of information needed to describe or monitor the static/structural or dynamic/operational state of a system, which is a measure of the dimension of variety, disorder and uncertainty. With its origin in operations research, mathematical optimization or mathematical programming provides numerical analytical methods for optimal decision making, mainly by taking the static aspects of the SCs into consideration. Multi-criteria decision-making approaches are represented by the analytic hierarchy process (AHP), and also by the rough set theory (RST) in the systematically reviewed literature. The last group are indices, which mainly provide indicators of SC structural and/or dynamic complexity, inspired by network topology and graph theory.

Relational analysis mechanisms. The fourth group includes those mechanisms that elaborate on the relational analysis between the complexity properties of SCs and different variables, such as flexibility, resilience, responsiveness, adaptability, integration, disruptions, risk, costs, innovation and performance. As summarized in Table A7 in the Appendix, the resultant relational mechanisms can be classified as positive direct relations, negative direct relations, positive moderating relations and negative moderating relations. One of the studies highlights quadratic relations.

Handling mechanisms. The last group highlights mechanisms for handling the complexity of SCs, which can be summarized as mitigating and accommodating strategies (Table A8 in the Appendix). Mitigating strategies highlight the handling of structural and dynamic properties of the complexity of SCs, while accommodating strategies mainly concern the handling of the behavioral and decision-making properties of the complexity of SCs.

Mitigating strategies. The first type of mitigating strategies elaborate on the managing of variety reduction in the following ways by: removing low-volume or low-contribution products from offerings; reducing duplication and redundancy; focusing on a narrower range of elements (e.g. products, suppliers, customers, shipping points, distribution centers, outsourcing partners, geographies); the rationalization of SKUs and modular product architecture or, as Fernández Campos et al. (2019) suggested, by establishing commonalities among the elements, which thus reduces internal diversity while minimizing the effect of this diversity on the extent of the firms’ businesses, for instance, by deploying platform teams which seek to define a common internal architecture of processes and tools for SC activities across businesses and geographies.

The second type of mitigating strategies highlights optimal SC configuration by, for example: allocating effective suppliers, partnering firms, or bespoke distribution channels to contain the complexity within a reduced domain, where specialized resources can be leveraged; reducing non-value-added steps and processes; and decoupling practices such as assembly sequence planning and postponement by narrowing the range of activities that must bear structural and dynamic complexity in SCs while preserving firm responsiveness.

The last type of mitigating strategies emphasize exercising tighter control and intervention, which, in turn can include the following: detailed interface management, sub-tier intervention, tight planning and control of many first-tier suppliers, as well as detailed...
multi-level contracting and risk taking; process standardization and partitioning among the multiple players; tighter integration and relationship management by rigidly systematizing information collection and tangible knowledge management (documentation, organization and storage of business-process information, managerial and group experiences) and by building long-term relationships with key channel partners.

Accommodating strategies. Accommodating strategies are dominant by those that work on managing interrelationships and reciprocal interdependencies, including the following: pay-offs from cooperation; coordination and collaboration among stakeholders, such as suppliers, customers and service providers; decision support through the sharing of information and [both tacit and explicit] knowledge; communication, synchronization and alignment between learning teams, processes and functions, both inside and outside the internal SC; intelligent monitoring, connectivity, clustering, pattern recognition, end-to-end visibility and transparency, by using big data as well as neural network monitoring and smart parts; joint consortiums/alliances and partnerships; and delegated responsivity and risk sharing, such as VMI agreements.

Other accommodating strategies include flexibility and resilience, which highlight the capability of a firm to gain a competitive advantage by quickly realigning its resources and responding faster to unpredictable changes in demand and business model, as well as adjusting to influences of the external environment, regulations and institutions. In this regard, other authors suggest the following: providing a hedge against operational, demand and other environmental uncertainties by building redundancy and buffers, such as extra or adaptive capacity (such as labor, space, machinery, equipment, systems, time, multi-sourcing, outsourcing) and inventory (raw material, semi-finished and finished goods) all of which have the effect of shortening the planning and forecasting horizons; process redesign; periodic batch control; and relying upon flexible workforce, organizational structure and resources.

The last type of accommodating strategies concerns the following: managing by positive feedback; increasing dimensionality, autonomy and improvisation; adopting an ambidextrous approach; co-evolutionary decision making in alignment with contextual conditions at the time; and handling trade-offs. Wilding (1998) and de Leeuw et al. (2013) exemplify trade-offs that exist between having additional buffer stocks in order to reduce uncertainty and increasing costs or demand amplification. As Nilsson and Gammelgaard (2012) state, CAS and CT assume the simultaneous existence of order and unorder, subjectivity, conflicts, power and the emergent indeterminable future of living with, rather than attempting to remove them.

Discussion
Figure 2 illustrates the interrelationship between the emerging dealing mechanisms, which is a continuous process for the classification of complexity in SCs and modeling, measurement, relational analysis and handling over time. Juxtaposing and putting together the potential complexity properties of SCs reveal and explain the clusters of the patterns of their emergent properties without being reductionist. Patterns are dynamic, whilst being subject to evolutionary, revolutionary and exogenous changes over time.

On the one hand, modeling tools can be beneficial for revealing the emergent patterns or collective states of behavior which emerge from the interactions of subsystems over time, while on the other hand, measurement tools can be beneficial as a decision-making support while analyzing emergent patterns. Accordingly, patterns have to be saved in the memory of the system and learned. Pattern learning is a topic that is missing in the mainstream field of SC (complexity) management. Handling complexity goes hand in hand with complexity relational analysis, in order to judge whether mitigating and/or accommodating complexity leads to desired outcomes and creates a foundation for re-classifying complexity over time.
It is very common in different scientific and nonscientific jargons to talk about the necessity of “simplifying” complexity. As explained in the findings section, from a complex systems perspective, complexity is not an unpleasant property that can always be discarded, ignored or oversimplified, but rather it can enable co-evolution with the market or institutional needs as well as the emergence of new properties, such as systemic resilience, robustness and acceptable innovation. Some of the literature refers to this as the “complexity zone” or “edge of chaos”, i.e. a place where components of the complex system never quite lock into place, and yet never quite dissolve into turbulence either, according to Waldrop (1992). The edge of chaos is a constantly shifting battle zone between stagnation and anarchy and is the one place where a complex system can be spontaneous, adaptive and alive.

Among other studies, Dittfeld et al. (2018) for instance refer to this phenomenon when highlighting how one of their case studies within the food processing industry uses differences in demand patterns – associated with high detailed complexity (as a function of numerous and variety) – to achieve better production planning, increased utilization rates and less uncertainty at the plant level. In another study, Birkie et al. (2017) explain that the structural complexity of SCs (as a function of variety and dependencies within system components) is found to have a significant positive relation with performance improvement after disruption, together with resilience capability. When analyzing the trade-offs between structural complexity vs cost and robustness vs cost in a case study setting, Olivares Agulia and ElMarapgy (2018) suggest that complexity (in terms of the number of components and interactions between them) is necessary to achieve robustness and an increase in cost is required to attain a balanced level of complexity and robustness.

Ivanov (2021) elaborates on how some leading firms rely on adaptation strategies (namely, scalability (by expanding network size and capacity), repurposing (by process and product flexibility), substitution (by structural reconfiguration such as usage of backup suppliers, redundancy or product substitution) or intertwining (by fostering collaboration among different economic segments)) to achieve SC viability in responding to the COVID-19 pandemic. The authors provide some insights about how to estimate different thresholds for adaptation investment, preparedness, intensity and impacts, while deploying the different adaptation strategies.

Sharma et al. (2019) conclude that horizontal and vertical complexity (represented by the number of direct suppliers and the number of Tier-2 suppliers per Tier-1 supplier, respectively) in the supply network have a nonlinear relationship with the innovation performance of a firm, which is moderated by a firm’s strategic emphasis on value creation (i.e. to find the emphasis on whom) and its influence over the network. Choi and Krause (2006) also propose that although a reduction in complexity may lead to lower transaction costs and increased supplier responsiveness, in certain circumstances this can also increase supply risk and reduce supplier innovation. Therefore, reducing supply base complexity in general could
be a cost-efficient approach, although blindly reducing this base could potentially decrease the purchasing company’s overall competitiveness.

In contrast to Giannoccaro et al. (2018), who show that the dimensions of complexity (number of firms and level of interrelationships among firms) are negatively related to supply network performance – although moderated by the scope of control – in their field study and survey of 274 apparel manufacturers and their suppliers in Bangladesh, Chowdhury et al. (2019) propose that SC network complexity (NC) can improve supply chain resilience (SCRE) and, as a result, SC performance (SCP) also, if the NC acts as a buffer in improving flexibility (e.g. by using multiple suppliers, buyers, markets, and alternative transportations which all lead to an increase in flexibility and a reduction in supply risk), as well as a reduction of a SC’s vulnerability during supply disruptive events in the SC. Such flexibility in the network leads to higher SCP and, as NC is increased with the increase in SC relational performance (SCRP), the effect of SCRE on SCP is increased. However, as Yang and Yang (2010) investigate, there is a trade-off between redundancy (such as multiple sourcing) and flexibility, where it can be expected that adding redundancy and building flexibility can increase complexity to such a point that an increased exposure of the SC to risk occurs.

As Choi et al. (2001) and Li et al. (2010) posit, when managing supply networks, managers need to appropriately balance how much to control [by deterministically reducing dimensionality and through negative feedback] and how much to allow to emerge [by increasing dimensionality and through positive feedback]. For imposing too much control detracts from innovation and flexibility, and, conversely, too much emergence can undermine managerial predictability and work routines. Giannoccaro et al. (2018) further suggest that scope of control is nonlinearly related to supply network performance, whereby as the scope of control increases, supply network performance initially increases, but then decreases. In other words, the relationship between scope of control and supply network performance follows an inverted-U shape. It is important to bear in mind that complex systems possess behavioral and decision-making properties and that oversimplifying may destroy them, or even produce models that severely misrepresent the original system. In other words, there is a limit to which systems and their control models can be simplified, as these have to satisfy Ashby’s law of requisite variety. As Einstein supposedly said when asked how complex a system should be: “everything should be made as simple as possible, but not simpler”.

“Steering”, rather than “controlling” SCs better grasps the evidence of emerging phenomena from the dynamics of interconnected complex systems, as well as gradual/evolutionary, radical/nonlinear/revolutionary and co-evolutionary changes, subjectivity, contextuality and self-organization in managing complex systems. Steering SCs involves adaptability in a dynamically changing environment, where the future is unknown, and is thus semi-predictable, based on trajectories of behavioral patterns. Figure 3 summarizes the learning from this paper regarding the steps for steering SCs as complex systems, which includes defining a complexity profile, classification, measurement, modeling as well as a relational analysis of the complexity properties of SCs and explains how to deal with them over time.

This study also reveals the identification of some research gaps. The authors argue that the science of complexity is relevant and useful for the science of SCM. SCs are not the only social systems which are complex, and that organizational and institutional complexity, that is, the perspective that organizations and institutions are complex systems, is already understood. Therefore, exploring emerging and innovative properties of diverse inter-flows, value-adding processes, tangible as well as intangible organizational resources, ties and relationships all deserve further research from both theoretical and empirical perspectives. Another avenue for further research is the investigation of the co-adaptation and co-evolution of exogenous properties due to governmental, institutional, social and market intervention in
Defining complexity profile
- Describe scale of the system (micro, meso, macro)
- Define details in describing the system and its subsystems
- Describe context of the system (from local to global)

Complexity classification

Structural properties
- Investigate value-adding static heterogeneous resources or components

Dynamic properties
- Investigate flows of value-adding products (goods and services)
- Investigate flows of value-adding human resources
- Investigate flows of value-adding informational resources
- Investigate flows of value-adding financial resources
- Investigate flows of value-adding business work processes

Behavioral properties
- Investigate degree, extent and nonlinearity of interactions among the subsystems
- Adaptation and self-organization:
  - Store and learn patterns of emergent properties, i.e., capabilities over time, in memory of the system
  - Compare schemata with emergent properties and feedbacks from self-organization
  - Adapt to the updated schemata
- Evolution:
  - Transfer memory of the system over time
  - Consider variety and diversity in the system to create complex structures/forms over time
  - Select competitively by letting the fitted structures/forms to further develop
  - Increase capacity to learn and adapt

Decision-making properties
- Investigate effects, degree and diversity of changes in the surrounding environments on SC system
- Investigate effects, degree and diversity of changes in SC system on the surrounding environments
- Investigate and decide upon trade-offs
- Investigate and deal with paradoxes

Evolution
- Integrating patterns over time
- Learning from the patterns over time
- Complexity modeling
- Complexity measurement

Complexity relational analysis
different scales and contexts. Once one accepts that SCs are complex systems, it is possible to use achievements in dealing with complex systems from other fields to achieve a better understanding of complex SCs.

Another opportunity for further research is to investigate the effects of structural and dynamical changes (for example, in the aftermath of a pandemic such as COVID-19, or the ripple effect) (Ivanov and Dolgui, 2020, 2021b) on behavioral and decision-making properties and how to model, measure or handle these changes over time.

The above-mentioned classification of the complexity of SCs represents powerful tools for the identification and classification of the agents of agent-based models. Intelligent SCs based on agent-based systems and intelligent flows are powerful tools for accommodating complexity, as are value-adding processes in the system. The analysis and traverse of different parts of intelligent agent-based SCs (such as smart products, IoT (Datta, 2015), cyber-physical systems, digital twins (Datta, 2017; Ivanov and Dolgui, 2021a), robotic and autonomous processes, cognitively intelligent production and distribution systems, clusters of organizations) as well as their application in developing sustainable supply chains would be of great interest.

Conclusion
The main finding in this study is that complexity properties can be summarized in four interdependent categories, which we have abbreviated to “SDBD properties”, namely: Structural, Dynamic, Behavioral and Decision making, all of which enable the assessment of SCs as complex systems. The dealing mechanisms framework consists of five steps: classifying complexity, modeling complexity, measuring complexity, relational analysis of complexity and handling desirable/undesirable complexity.

The main contribution of this research is the emergence of the inductive framework for steering SCs from a complex systems perspective, through explaining why SCs have properties of complex systems and suggesting how to deal with their complexity while steering them toward the desired outcomes.

The results suggest that the classification of complexity properties of SCs is a substantial precedent for the modeling, measurement, relational analysis and handling of the complexity of SCs. Complexity classification entails the exposure and assessment of the various components and sub-systems of SCs, which could be complex systems in their own right. Classification also provides knowledge regarding emergent patterns from behaviors and interactions which, in turn, create emergent phenomena which describe not only desirable qualities of the SCs but also the risk of the system.

The inductive framework can be valuable from a pedagogical, research and scientific point-of-view. It has the potential to systematically develop the building blocks of a formal theory (Bryman and Bell, 2007) and to generate a novel perspective or conceptual understanding (Post et al., 2020; Alvesson and Sandberg, 2020; Breslin and Gatrell, 2020) in steering supply chains as complex systems. It could also possibly shift the research paradigm, as well as the classical boundaries of knowledge (Post et al., 2020) in SCM by critically analyzing (Breslin and Gatrell, 2020) and creatively synthesizing (Alvesson and Sandberg, 2020) inter-organizational and institutional insights.

Furthermore, this research – by critically challenging certain taken-for-granted assumptions – can guide both practitioners and decision-makers in understanding why SCs are difficult to manage and control, and subsequently suggest opportunities to steer, or coax them toward the desired outcomes. Recognizing that SCs are complex systems enables a better grasp of the effect of positive feedback on change and transformation, as well as the interactions leading to dynamic equilibria, nonlinearity and the role of learning and innovative capacities, trade-offs and of paradoxical tensions, while also recognizing changing dynamics and the co-evolution of SC phenomena in different scales and contexts.
The limitations of the contribution of this study concerning the methods used include: the choice of database for literature review, the criteria for selection and inclusion and the subjective classification of the literature. While much transparency is in evidence, it is likely that alternative classifications will arise over time with the inclusion of researchers who possess different historical experiences. That is not to say that the above-presented classification is wrong, but rather that there are other alternative valid classifications, as described by Richardson (2004, p. 76) “for complex systems (by which I really mean any part of reality I care to examine) there exists an infinitude of equally valid, non-overlapping, potentially contradictory descriptions.”

In terms of next steps, we propose the testing of the inductive framework, as well as the SDBD properties, which will include case studies in different industries, scales and contexts of SCs. A catalogue of schemata could be developed with contextual information, management interventions and the emergent properties of the SCs over time, which would help build a robust library of SCs patterns and related phenomena, mediated by context and management behaviors.

A further literature review is planned, to include the use of mixed methods to make it possible to also compare and contrast the findings on the complexity of SCs with other types of networks, organization, institutional regime, and market, etc. Both the application of quantitative and qualitative work in network theory on network topology is also of interest, as is research regarding high reliability organizations and regimes for which public policy makes way for diverse interpretation, and, finally, the study of markets in which competition and collaboration are equally desirable.

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### Structural properties of supply chains complexity

| Selective coding: step 3 | Axial coding: step 2 | Open coding: step 1 | Supportive references |
|--------------------------|----------------------|---------------------|-----------------------|
| **Structural properties**| Topology of relatively static heterogeneous resources or components | - Number, size, variety, extent and echelons/tiers of involved static subsystems in the transformation of goods and services such as: focal organization, business unit or individual, idiosyncratic suppliers and customers, distribution centers (such as terminals, hubs, consolidation centers), warehouses, retail outlets, service providers, etc.  
- Number, size, variety, extent and echelons/tiers of involved static resources such as buildings/offices; fixed working stations, assembly lines, machineries and equipment; as well as static supportive energy, water, sewer, communication infrastructures and technologies inside each static subsystem | Gerschberger et al. (2012), Modrak and Marton (2014), de Leeuw et al. (2013), Zhang and Liu (2013), Posey and Bari (2009), Bode and Wagner (2015), Caridi et al. (2010), Ma et al. (2014), Chen and Lin (2012), Sentarussan (2013), Bocarh et al. (2009), Manaj and Sahin (2011), Choi and Krause (2006), Skilton and Robinson (2009), Kavikal et al. (2018), Chand et al. (2018), Barbosa and Arcevedo (2019), Dittfeld et al. (2018), Jiang et al. (2019a, b), Modrak and Semanco (2011), Asmussen et al. (2018), Birkie et al. (2017), Kriheli and Levner (2018), Suo et al. (2018), Bai and Sarkis (2018), Gerschberger et al. (2017), Sharma et al. (2019), Fernández Campos et al. (2019), Rodevald et al. (2016), Hamta et al. (2018), Turner and Williams (2005), Shamsuzzoha (2018), Yang and Yang (2010), Hu et al. (2008), Johnsen et al. (2019), Chowdhury et al. (2019), Gunaselaaran et al. (2015), Wang et al. (2018), Giannaccaro et al. (2018), Wanke and Corrêa (2014), Atken et al. (2016), Hearnshaw and Wilson (2013), Wu et al. (2007), Sivadasan et al. (2006), Cheng et al. (2014), Vachon and Klassen (2002), Day (2014), Migeat (2001), Surana et al. (2005), Blome et al. (2014), Wong et al. (2015) |
| Dynamic properties | Inter- | Heterogeneous | Number, volume and variety of the products (goods and services) as well as their specifications, SKUs, batches, cycle/work-in-process inventories and materials, modules and architecture, BOMs, levels in the BOMs, shorten product lifecycle, etc. |
|---------------------|--------|---------------|----------------------------------------------------------------------------------------------------------------------------------|
| Movable heterogeneous resources + Human resources | Inter- | Number, volume and variety of movable physical/tangible resources such as packages, unit loads, cargo carriers, vehicles, movable machineries, equipment; as well as dynamic supportive energy, water, sewer, communication infrastructures, human resources, diversity of skills and know-hows, etc. |
| Informational resources | Value adding processes | Magnitude, frequency, transfer methods, distortion, variation, asymmetry or invisibility of data and information about goods, services, resources, stakeholders, contracts, etc. |
| Financial resources | Value adding processes | Different and varying: price tags, tariffs, import quotas, transfers, transactions, monetary resources: bonds, stocks, intellectual properties; currency exchange rates and fluctuations, payment methods, receipts, (re) funds, etc. |

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| Systemic properties | Emergence | Behavior properties of supply chains complexity |
|---------------------|-----------|------------------------------------------------|
|                     |           | Steering complex supply chain systems |

**Selective coding: step 3**

**Axial coding step 2**

- Consequences of interactions among subsystems and their nonlinearities over time
- Macroscopic patterns of behavior

**Open coding: step 1**

**Supportive references**

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**Adaptation and self-organization**

- Acting on learned feedbacks
- Monitoring continuous improvement
- Adaptation due to interventions while allowing to self-organize
- Reconfiguring the inter-relationships

**Evolution**

- Redundancies in the system
- Fitness of subsystems and supply chain ecosystem
- The ability to absorb and deal with new schemata
- Dynamical patterns

Gell-Mann (1995), MacIntosh and MacLean (1999), Bar-Yam (1997), Lewontin (1970), Rose-Anderssen et al. (2009), Nair et al. (2009), Asokan et al. (2017), Li et al. (2009, 2010), Touboulic et al. (2018), Pathak et al. (2009)
| Selective coding: step 3 | Axial coding: step 2 | Open coding: step 1 | Supportive references |
|--------------------------|----------------------|---------------------|----------------------|
| Decision-making properties | Semi-optimal, instead of perfect, decision making | Optimizing/balancing the system as a whole | Cilliers (1998), Serdaran (2013), Jiang et al. (2019a, b), Bai and Sarkis (2018), Sayed et al. (2017), Sharma et al. (2019), Yang and Yang (2010), Nair et al. (2009), Aitken et al. (2016), de Leeuw et al. (2013) |
| Paradoxes | Accepting tensions if it can lead to a semi-desired than undesired outcome | | Stacey et al. (2000), Smith and Lewis (2011), Nilsson (2005), Ramirez (2012), Nilsson and Gammelgaard (2012), Surana et al. (2005), Sayed et al. (2017), Turner et al. (2018) |
| Exogenous effects | Interactions with surrounding environments | | Bar-Yam (1997), Merli (2006), Capaldo and Giannoccaro (2015), Pathak et al. (2007, 2009), Kinra and Kotzab (2008), Nilsson and Gammelgaard (2012), Wanke and Corrêa (2014), Day (2014), Wycisk et al. (2009), Giannoccaro (2015), Omar et al. (2012), Bai and Sarkis (2018), Touboul et al. (2018), Nair and Reed-Tsochas (2019), Chowdhury et al. (2019), Nair et al. (2009), Varga et al. (2009), Manuj and Sahin (2011), Mc Kelvey et al. (2009), Li et al. (2010), Statsenko et al. (2018) |
| Selective coding step 3 | Axial coding: step 2 | Open coding: step 1 | Supportive references |
|-------------------------|----------------------|---------------------|----------------------|
| Complexity modeling     | Simulation-based     | Agent-based modeling| Barbosa and Azevedo (2017, 2019), Bruzzone et al. (2005), Ge et al. (2015), Kim (2009), Mertens et al. (2018), Li et al. (2009, 2010), Zhao et al. (2019), Datta et al. (2007), Nilson and Darley (2006), McKelvey et al. (2009), Pathak et al. (2007), Surana et al. (2006), Giannoccaro et al. (2018), Giannoccaro (2015), Capaldo and Giannoccaro (2015) |
| System dynamics         | Scenario analysis    | Discrete event simulations, Cellular automata, Genetic algorithms, Evolving hypergraphs | Barbosa and Azevedo (2017, 2019), Pathak et al. (2007), Surana et al. (2006) |
|                         |                      |                     | Ekinr and Baykasoglu (2019), Drzymalski (2015) |
|                         |                      |                     | Barbosa and Azevedo (2017, 2019), Turner and Williams (2009), Nair et al. (2009), Chen and Liu (2012), Wu et al. (2007), Pathak et al. (2007), Surana et al. (2006) |
|                         |                      |                     | Suo et al. (2018), Zhang and Liu (2013), Pathak et al. (2007, 2009), Surana et al. (2006), McKelvey et al. (2009) |
| Evolutionary game theory|                      |                     | Jiang et al. (2019a) |
|                         |                      |                     | Jiang et al. (2019b) |
|                         |                      |                     | Surana et al. (2006), Hermath and Wilson (2013), Ma et al. (2014), Zhang and Liu (2013), Wang et al. (2018), Statsenko et al. (2018), Pathak et al. (2007), McKelvey et al. (2009) |
| Mathematical statistics |                      |                     | Ma et al. (2019) |
|                         |                      |                     | Tu et al. (2019) |
|                         |                      |                     | Pathak et al. (2009) |
| Miscellaneous           |                      |                     | Pathak et al. (2007) |
|                         |                      |                     | Chand et al. (2018) |
|                         |                      |                     | Pathak et al. (2007) |
|                         |                      |                     | Kavilal et al. (2018), Piya et al. (2019) |
|                         |                      |                     | Wang et al. (2018) |
|                         |                      |                     | Surana et al. (2006) |

Table A5. Summary of the reviewed complexity modeling mechanisms

Steering complex supply chain systems
| Complexity measurement | Mathematical optimization or mathematical programming | Mathematical decision-making |
|------------------------|--------------------------------------------------------|------------------------------|
| Entropy-based          | Propose assembly sequence planning and optimal assembly SC configuration as two measures of assembly systems and SCs complexity | Propose a graph-theoretic approach (GTA) to quantify SC complexity by a single numerical index considering the interdependence and the inheritance of the SC complexity driven by topological structures between SC network nodes |
| Entropy-based measures of static/structural or dynamic/functional state of complexity | Demonstrate how the optimal assembly supply network is obtained by comparing the total complexity values of the feasible configurations | Propose an entropy-based measure of supply network complexity considering the interdependence and the inheritance of the SC complexity driven by topological structures between SC network nodes |
| Mathematical optimization or mathematical programming | In a case study testing, rely upon mathematical programming to find the optimal product mix for the value chains such that the contribution margin KLM is maximized. | Mathematical optimization or mathematical programming based on the number of feasible sequences in a graph; as well as an aggregate measure of process complexity (AC) based on the number of virtual arcs and the number of upstream suppliers, regardless of whether they are physical or virtual arcs. |
| Mathematical decision-making | In a second step, another nonlinear mathematical programming model (referred to as cost allocation model [CAM]) is used to allocate the costs of the optimal product mix for individual products. | A unified measure of complexity by integrating both product variety and assembly process information |
| Propose a unified measure of complexity by integrating both product variety and assembly process information | Refer to Hamta et al. (2010), Isik (2010), Kriheli and Levner (2008), Nair and Reed-Tsochas (2019), Cheng et al. (2016), Oliveira Aguida and EBner-Engelhardt (2018), Robel et al. (2016), Hentschel et al. (2016), Modrak and Marton (2014), Snellenburg et al. (2009), Hu et al. (2008), Hamann et al. (2016), Christofides (2006), Bai and Sarkis (2018), Olivares Agulia and ElMarapgy (2018), Kinra and Kotzab (2008), Surana et al. (2005), Kavilal et al. (2018), Modrak and Semanco (2011), Musso (2009), Modrak and Marton (2014), Hu et al. (2008), Wu et al. (2007), de Leeuw et al. (2013), Dzirnyakis (2015), Wang et al. (2016). |
### Selective coding: step 3

#### Complexity analysis
- Positive direct relations:
  - Positive direct relationships among horizontal, vertical and spatial SC complexity and their synergies with frequency of SC disruptions
  - SC structural complexity is found to have a significant positive relation with performance improvement after disruption, along with resilience capability
  - SC complexity and supplier disruptions
  - SC complexity and SC performance
  - SC complexity and supply chain decision-making complexity
  - SC complexity and cost estimation accuracy
  - SC complexity and supply chain decision-making complexity
- Negative direct relations:
  - Negative relation between supply chain complexity and transaction cost
  - Supply base complexity and transaction cost
  - Nonlinear relationship between both horizontal complexity and vertical complexity with respect to innovation performance
  - Under high product complexity, firms need to implement internal and supplier integration, while product complexity does not have a direct impact on customer integration
  - Positive relation between SC structural complexity and information sharing within the SC
  - Positive relationship between supply base complexity and transaction cost
- Positive moderating relations:
  - Positive moderating effect of product complexity on the link between SC adaptability and cost performance as well as operational performance
  - Positive moderating effect of product complexity on the relationship between competitive advantage and supply chain coordination
  - SC structural complexity positively moderates the resilience-performance link
  - Supply chain structural performance (SCSP) in terms of SC performance and SC adaptation and network complexity (NC) [as a function of the number of nodes in the network, interconnections between nodes and the geographic spread of the network] as well as network resilience (NCR) [which consists of flexibility, redundancy, visibility and collaboration dimensions] and supply chain performance (SCP) .
- Negative moderating relations:
  - Negative moderating effect of product complexity on the relationship between SC integration and SC performance (in terms of innovation and flexibility)
  - Product complexity has a negative moderating impact on the relationship between SC integration and SC performance (in terms of innovation and flexibility)
  - Product complexity has a negative moderating impact on the relationship between SC integration and SC performance (in terms of innovation and flexibility)

### Axial coding: step 2

#### Open coding: step 1
- Positive direct relations:
  - Positive direct relationships among horizontal, vertical and spatial SC complexity and their synergies with frequency of SC disruptions
  - SC structural complexity is found to have a significant positive relation with performance improvement after disruption, along with resilience capability
  - SC complexity and supplier disruptions
  - SC complexity and SC performance
  - SC complexity and supply chain decision-making complexity
  - SC complexity and cost estimation accuracy
  - SC complexity and supply chain decision-making complexity
- Negative direct relations:
  - Negative relation between supply chain complexity and transaction cost
  - Supply base complexity and transaction cost
  - Nonlinear relationship between both horizontal complexity and vertical complexity with respect to innovation performance
  - Under high product complexity, firms need to implement internal and supplier integration, while product complexity does not have a direct impact on customer integration
  - Positive relation between SC structural complexity and information sharing within the SC
  - Positive relationship between supply base complexity and transaction cost
- Positive moderating relations:
  - Positive moderating effect of product complexity on the link between SC adaptability and cost performance as well as operational performance
  - Positive moderating effect of product complexity on the relationship between competitive advantage and supply chain coordination
  - SC structural complexity positively moderates the resilience-performance link
  - Supply chain structural performance (SCSP) in terms of SC performance and SC adaptation and network complexity (NC) [as a function of the number of nodes in the network, interconnections between nodes and the geographic spread of the network] as well as network resilience (NCR) [which consists of flexibility, redundancy, visibility and collaboration dimensions] and supply chain performance (SCP) .
- Negative moderating relations:
  - Negative moderating effect of product complexity on the relationship between SC integration and SC performance (in terms of innovation and flexibility)
  - Product complexity has a negative moderating impact on the relationship between SC integration and SC performance (in terms of innovation and flexibility)
  - Product complexity has a negative moderating impact on the relationship between SC integration and SC performance (in terms of innovation and flexibility)

### Supportive references
- Birkie et al. (2017)
- Chen et al. (2018)
- Gushchinger et al. (2017)
- Novak and Kepkeger (2001)
- Assunção et al. (2018)
- Imran and Bremenfield (2014)
- Wu et al. (2017)
- Poer and Jr. (2009)
- Choi and Koo (2009)
- Sharma et al. (2019)
- Burchart (2009)
- Assunção et al. (2018)
- Musso (2019)
- Giannoccaro et al. (2019)
- Milpate (2011)
- Vachon and Kim (2012)
- Choi and Koo (2009)
- Shin and Robinson (2013)
- Sharma et al. (2019)
- Eidstein et al. (2014)
- Wong et al. (2013)
- Birkie et al. (2017)
- Chowdhury et al. (2015)
- Giannoccaro et al. (2012)
- Giannoccaro et al. (2012)
- Poer and Jr. (2009)
- Sharma et al. (2019)
- Bhaye et al. (2016)
- Giannoccaro et al. (2010)
- Giannoccaro et al. (2010)
- Choi and Koo (2009)
Table A8: The influence of supply chain complexity on management practices

| Complexity handling | Reactions | Separation references |
|---------------------|----------|-----------------------|
| Supplier 1          | Supply chain redesign | Ferreras et al. (2013) |
| Supplier 2          | Supply chain redesign | Ferreras et al. (2013) |
| Supplier 3          | Supply chain redesign | Ferreras et al. (2013) |
| Supplier 4          | Supply chain redesign | Ferreras et al. (2013) |
| Supplier 5          | Supply chain redesign | Ferreras et al. (2013) |

Note: The table above summarizes the influence of supply chain complexity on management practices. The complexity handling column lists the specific supplier numbers involved, while the reactions column includes the strategies applied. The separation references column provides the sources for further reading.