Sustainability, resilience and complexity in supply networks: A literature review and a proposal for an integrated agent-based approach

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Abstract

Supply Networks (SN) can be seriously affected by unplanned disruptions producing important consequences on system's functioning. These alterations may have implications over dimensions of sustainability due to the re-adaptation of the network to cope with the disruptive event. In this sense, it is relevant to understand how sustainability can be measured while considering aspects like resilience and network's dynamism. This article presents a critical review to enhance the understanding of sustainability assessment of supply networks affected by disruptions under a CAS perspective. A non-systematic literature search was conducted where relevant studies were identified. The dissociation between sustainability and resilience observed in literature was discussed from motivational, temporal and methodological perspectives. The review led to the proposition of four principles that underpin the conceptual foundations that should guide the development of any complexity-driven sustainability assessment methodology (SAM). Moreover, using agent-based modelling as the core computational paradigm, a SAM framework was outlined as a first step to implement a functioning tool that embeds the new assessment approach. Finally, the article concludes that sustainability should adopt a complexity-oriented approach when analysing disruptions. Challenges for future research such as delimitation of sustainability boundaries and validation of models are also discussed.

Keywords— s ustainable supply network; simulation; agent based modelling; disruption mitigation; supply chain resilience

1 Introduction

A supply chain can be broadly defined as a system with parties that are involved in fulfilling costumer's orders, with the essential principle that each one of them aims to maximise profit or utility [20, 43]. System's parties require to interact constantly among them and with the environment to exchange materials, money, and information. However, the continuity of these interactions may sometimes be affected by disruptive phenomena such as natural disasters, pandemics or alterations in the logistic operations [60]. These unavoidable events are part of the inherent risks of supply systems [27], and are relevant issues to consider due to the important consequences they may have on system's functioning. Moreover, these disturbances may also have effects on different aspects of sustainability (e.g., environmental impacts), especially when the operational configuration of the system varies in order to re-adapt itself. The role of disruptions in supply systems is a subject under ongoing study that has gained more relevance, as it is reflected in the current literature [8, 56]. However, the implications that these disrupted interactions may have on the environment or society are yet to be fully understood [113].

~~Supply~~ Depending on the level of analysis, supply system's interactions are usually represented to consider only direct supplier-costumer relationships (i.e., dyad or firm), indirect relationships centred on a focal-firm (i.e., supply chain (SC)), or complete and non-focal relationships (i.e., supply network ~~SN~~(SN)) [80]. The selection of the adequate level of representation depends on the practitioner's desired scope and objectives. In this sense, in this review paper we focus on the latter, where the system is studied in a manner that many firms and their flows are represented as nodes and edges in graphs, and the focus is on the performance of the whole network. This broader representation expands the focal-firm centred SC scope in order to encompass the complexity of the system under study.

When focusing on disruptions, there is still no consensual definition of the characteristics of a SN in the literature. While most studies concur in modelling the system as a graph, they treat system complexity from different perspectives [8]. In this paper, we treat a SN as a complex adaptive system (CAS) that derives from the interactions among different individuals, processes, and resources. These interactions can involve financial, product and information flows between suppliers, manufacturers, distributors, retailers, costumers [107], and even stakeholders unrelated to the value chain. Choi et al. [19] were the first that suggested treating SN as CAS hinged upon the principles of complexity theory and analysing the intrinsic properties of a SN. They argued that a SN is emerging, self-organising, dynamic and evolving by nature [19]. Pathak et al. [90] extended this idea introducing the concept of Complex Adaptive Supply Networks (CASN) as an augmentation of CAS principles oriented to SNs. A CASN was defined as a ' system of interconnected autonomous entities that make choices to survive and that~~as collective~~ , as collective, evolves and self-organises over time', suggesting that a supply network can be ultimately interpreted as a complex web of decision making [90]. In practice, the ~~complex~~ network of decisions leads to a system with different layers of complexity that increase the difficulty of handling it. This occurs because ~~there is~~ the high interconnection of nodes ~~in the network representation~~ can become challenging to represent and solve computationally and mathematically (i.e., algorithmic complexity), it is difficult to set variables or equations to define the network evolution trajectory ~~during time~~ or future state (i.e., deterministic complexity), and because the network behaviour arises from local nodes interactions that are driven by heterogeneous motivations (i.e., aggregate complexity) [74].

The interest on treating a SN as CAS rose from the necessity of understanding phenomena that cannot be easily addressed with relational models that use variables to explain the changes in other group of variables [90]. A complexity-driven approach can be used to identify properties intrinsic to a SN, such as adaptability, robustness, resilience, or to observe the emergence of collective behaviours, such as system's sustainability. Effects from changes on different suppliers' layers or SN adaptability against disruptive events hardly follow a linear fashion and can only be identified when system's evolution or agents' independence are included in the SN model. As a consequence, the strategies meant to allow the achievement of society goals, such as sustainable development, should contemplate these effects.

Studies and reviews that focus on disruption mitigation methods [8, 117], social sustainability [30, 69], or sustainable behaviours transmission [112, 77] with a SN scope can be found in the literature. Particular aspects of a CAS, such as the aggregate complexity [110], or resilience [97] have also been analysed from a SN perspective with the aim of proposing strategies to achieve sustainability. ~~More specifically, resilience, or the capacity of a system~~ With respect to resilience, literature is extended regarding its meaning, especially because of the existence of perspectives when defining it, such as ecological, social, economic, and organisational perspectives [95]. Nevertheless, resilience can be broadly defined as the capacity of an entity to return to ~~its initial condition, is a relevant property of a CAS that~~ an initial state after the occurrence of a disruption. This property is relevant when studying a CAS and it has been constantly associated with sustainability from different perspectives. As ~~cited~~ discussed in [5], sustainability and SN resilience can be coupled considering resilience as a part of sustainability, sustainability as a part of resilience, or as independent concepts [71]. Studying sustainability as a whole adds an additional layer of complexity, especially because it requires to account material, information, and monetary flows if impacts to environment, society, and economy are meant to be calculated. Nevertheless, few studies have focused on coupling sustainability and resilience for SCs or SNs in a pragmatic or quantitative manner, whether it is using a Life Cycle Assessment (LCA) perspective [94, 24], mathematical optimisation ~~[37]~~[37, 42], simulation methods [49], or paradox theory [5].

~~It is indeed relevant to identify the difficulties for coupling sustainability concepts~~ In light of the absence of mainstream methodologies for assessing sustainability of systems with CAS properties~~such as resilience. Understanding~~, it is relevant to identify if there is any obstacle for that purpose. Moreover, understanding existing synergies and differences can later serve to set the basis of a sustainability assessment approach capable of integrating these concepts in a pragmatic manner. In this sense, our main objective is to define a conceptual framework where the development of a ~~sustainability assessment method~~ Sustainability Assessment Method (SAM) underpinned by the complex nature of SNs is possible. To this purpose, we conducted a non-systematic literature review ~~to identify~~ identifying the characteristics of current SAMs used for studying SN with special focus on disruptions as phenomenon of interest. We use our findings to later elaborate our conceptual proposal and to identify the requirements of the envisioned SAM. Thus, the contribution of this article is twofold: 1) it provides a comprehensive analysis of the literature linking sustainability and resilience of SN under the umbrella of complexity, and 2) it proposes a conceptual framework that can be used as a guideline to develop SAM to study complex SN.

Our critical review begins by identifying pertinent studies in Section 2. Sections 3.1 to 3.1 discuss the relation between SN structure, resilience, and sustainability, as well as dissociation and conceptual gaps. We describe the computational structure of most of SN models to later focus on complexity-oriented approaches in Section 3.1. In Sections 4, and 5 we present our vision and the principles of a SAM that can embrace the nature of a CAS and a framework to be used as the foundation of a practical and quantitative method. We finally present and summarise our conclusions.

2 ~~Literature review~~Methodology

~~The~~

Instead of focusing on a specific question or a narrow body of research (i.e., systematic review), the selected non-systematic ~~literature review~~ approach allowed us to address broader and less defined questions [25]. By using this approach, we focused on the exploration of notions and on the understanding of the literature regrading the topics of interest. In this sense, the purpose of this review orbited around two main questions:

Q 1 *How are sustainability, disruptions and resilience treated when studying a CAS?*

Q 2 *How do SAMs treat the complexity of a supply system in practice?*

The review consisted in the identification of relevant articles that were used to nourish the analysis and development of the conceptual framework. The ~~review~~ scope was on articles that ~~discuss~~ discussed disruptions or resilience of a SN considering a sustainability perspective, or vice-versa. In this manner, we covered the topics of sustainability, resilience, complexity and supply networks. We analysed the literature in two stages to first identify trends and a landscape (i.e., general review) and then focus our attention ~~in~~ on our specific research objective (i.e., detailed review).

~~List of words used for each set of selected descriptors~~ ~~**supply network resilience complexity sustainability**~~~~supply chain* resilience complexity leasupply network* disrupti* agent-based life cyclevulnerab*~~

~~agent based life-cycle criticali* topolog* sustainab* robust* complex adaptive system* life cycle assessment network* environment* network analysis~~

~~The review covers the topics of sustainability, resilience, complexity and supply networks.~~ For the general review, we selected a set of keywords that described each one of these topics (see Table 1). While our interest ~~is~~ was on studies with a network perspective, we also included keywords related with supply chains in the search because they ~~are~~ were sometimes used as synonyms. The aim of this stage was to obtain a broader notion of the relationship among these descriptors. ~~We~~ Thus, we performed search queries excluding one set of descriptors and combined the remaining in triads to create ~~a sub query~~ sub-queries using logic operators (i.e., AND, OR) where **supply network** was always present ~~.~~ (e.g., ("sustainability" OR "sustainable") AND (("vulnerability" OR "criticali*") AND ("supply chain"))).

Table 1: List of words used for each set of selected descriptors

supply network	**resilience**	**complexity**	**sustainability**
supply chain*	resilience	complexity	lca
supply network*	disrupti*	agent-based	life cycle
	vulnerab*	agent based	life-cycle
	criticali*	topolog*	sustainab*
	robust*	complex adaptive system*	life cycle assessment
		network*	environment*
		network analysis	

We used SCOPUS database to query the articles for every combination of descriptors, considering abstracts, titles, and keywords only. The search was limited to only include journal articles published after year ~~2000.~~ 2000 until March 2021. The three corpora had 11296 elements in total and resulted in a corpus of 9437 articles after merging and excluding duplicates (see DataS3 in Supplementary Material). A terms extraction algorithm was used to obtain the most relevant 200 terms present in the corpus. The parsing and computations were performed in the CorText Manager platform [26]. Terms were ranked and selected from a trade-off between their frequency at a sentence level (i.e., frequency equals to at least 3), and their specificity (i.e., χ^2 score as metric of co-occurrence)[1]. After indexing the terms to every article, a terms' co-occurrence network was built and different clusters were identified using the Louvain community detection algorithm already implemented in CorTexT Manager [9] (see Figure 1) (see DataS2 in Supplementary Material).

~~Network of co-occurrences of extracted terms in corpus of abstracts, titles and keywords~~

For the second stage, we performed a more specific query using the Web of Science (WoS) database in addition to SCOPUS. For this, we made a unique query of the four topics combined to obtain articles that considered aspects of resilience, complexity, sustainability, and supply networks. The search query delivered 985 and 1071 articles for SCOPUS and WoS, respectively, that resulted in 1346 articles after merging and eliminating duplicates. These articles were later scanned by title or abstract and most of them were discarded due to impertinence or not being relevant. Moreover, due to the non-systematic nature of our review we also considered works that were not detected by any of the search queries but were still pertinent in the context of our narrative. This resulted in a total of 116 articles that were read, analysed and used to elaborate our arguments. A detailed description article identification and selection can be found in Figure S1 of Supplementary Material.

[1] A more detailed description of CorTexT Manager methodology can be found in [73] and in https://docs.cortext.net/lexical-extraction/

3 Results and analysis

We used the graph in Figure 1 to identify trends in literature. In the network, nodes are the extracted terms, edges indicate co-occurrence in an article, and node size represents the frequency of that term in the corpus. The resulting clusters can be interpreted as different contexts where ~~the terms belong~~each term belongs. As observed in Figure 1, cluster of terms associated with sustainability assessment methods (e.g., life cycle, climate change, environmental impacts) can be differentiated from terms related with computational methods in supply systems modelling (e.g., chain network, integer linear programming, and sensitivity analysis). This implies that these terms do not appear frequently in the same article. Moreover, it is interesting to note that terms in the disruption-related cluster (e.g., natural disasters, risk assessment, chain disruptions) are not directly connected with sustainability assessment methods terms. In fact, the only common nodes between these communities belong to the chain management cluster (e.g., case study, chain management, chain performance), which has many edges connecting disruption-related terms. While not exhaustively, this may suggest that these two areas of study (i.e., sustainability assessment and disruptions) are not abundantly related in literature.

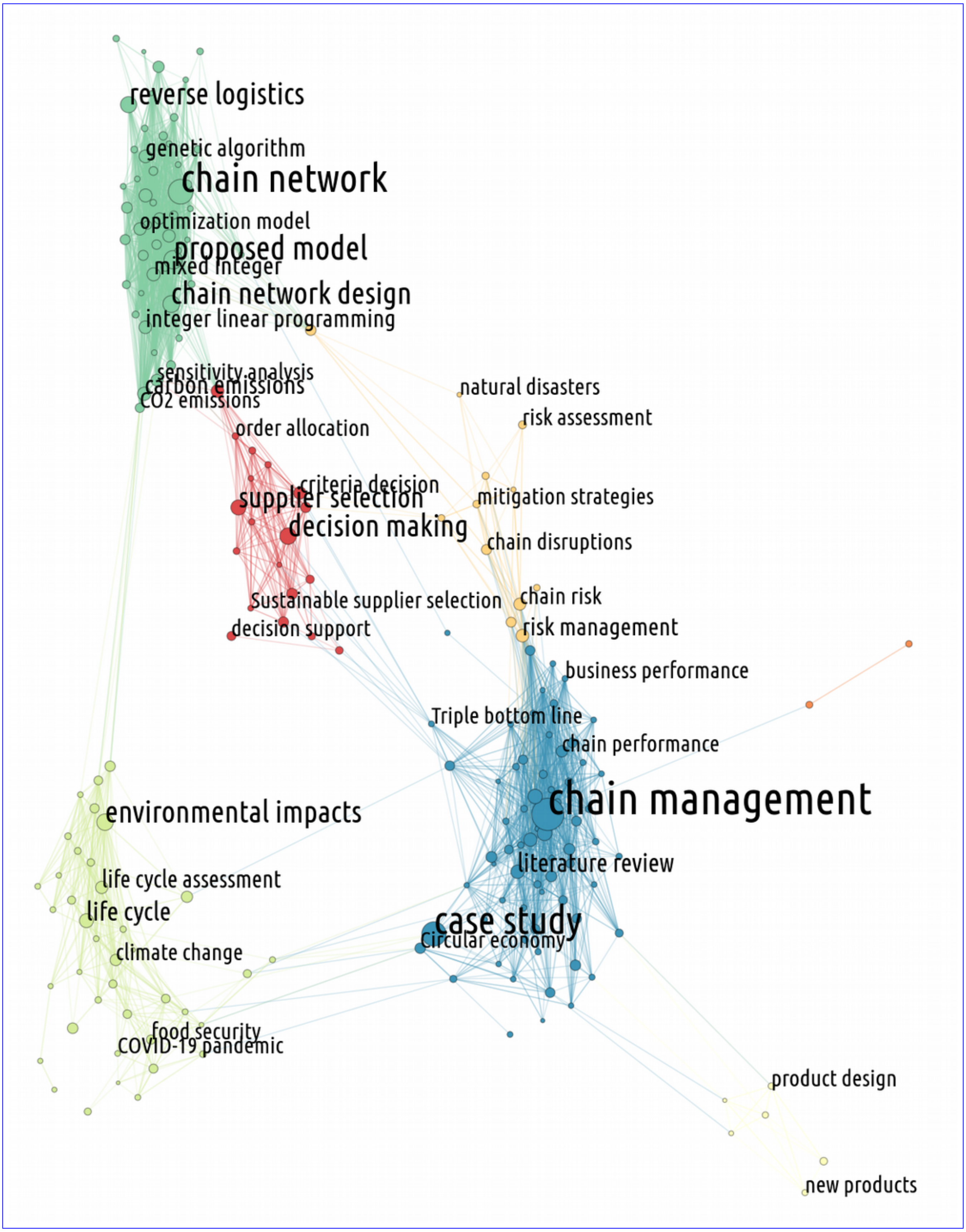


Figure 1: Network of co-occurrences of extracted terms in corpus of abstracts, titles and keywords

With respect to the detailed review, the scanning and abstract revision showed that only 69 articles were suited for revision considering the objectives of the study. Most of the discarded papers corresponded to articles not related to SNs, or that mentioned one of the keywords in a shallow manner. From these mapped articles, only 8 corresponded to studies that properly considered all topics of the query. In this sense, we had to include articles that were found in the general review, but did not pass the detailed review filter (See Figure S1 in Supplementary Material). Compared to the articles found in the general review, this lack of publications from the detailed query depicts an absence of studies that actually cover all of the presented topics. In most of the cases, one of the terms was mentioned anecdotally in the abstract or in the keywords. Despite of this, we found that the number of publications regarding these topics has been increasing in the last years (see Figure S2 in Supplementary Material). Table 2 shows the characteristics of most of the selected articles and relevant examples. This classification follows the criteria later used to conduct the analysis and discussion.

~~For the second stage, we refined the search criteria used previously on the SCOPUS database. We combined the four descriptors to obtain articles that were considering the aspects of resilience, complexity and sustainability. The search query delivered 1347 articles that were later scanned, analysed and selected for the purpose of our study. Furthermore, we identified and included additional relevant works that were not detected by the first search query. While our focus is on complexity and SN, we did not discard studies that we considered as important for the development of our arguments. Table 2 shows relevant articles that were later used as a substantial source for our analysis characterised using aspects that were later discussed in this paper~~A complete description of selected articles has been shared as an excel table Data S1 in Supplementary Material.

4 ~~Sustainability and SN structure~~

3.1 Sustainability and SN structure

We live in a constrained world, especially in terms of available natural resources, human and economic capital, and capacity of the biosphere to contain emissions and waste [23]. In this context, the definition of sustainable development arose as meeting the needs of this generation while letting future generations satisfy their necessities [87]. Among firms, the implementation of this concept has been translated into the evaluation of impacts at different dimensions such as the environment, economy, and society [36]. Nevertheless, it is not unusual to find several adaptations of this concept applied to other areas. Hassini et al. [43], for instance, define business sustainability as 'the ability to conduct a business with a long term goal of maintaining the well being of the economy, environment and society'. They introduced the definition of Sustainable Supply Chain Management (SSCM) as 'the management of supply chains operations, resources, information and funds in order to maximise profit, minimise environmental impact, and maximising social well-being'. Dyllick and Hockerts [32] define a more corporate oriented version of sustainability as "meeting the needs of a firm's direct and indirect stakeholders (e.g., shareholders, employees, clients, pressure groups and communities), without compromising its ability to meet the needs of future stakeholders as well". As it was noted, sustainability is broadly defined and it is susceptible to be interpreted in multiple ways. Because of this, firms aim to achieve sustainable outcomes by following different perspectives and strategies. In this sense, the complexity of a SN model can condition the approach adopted by the firm as well as the sustainable actions taken to fulfil the task.

At a dyadic level, implicit sustainable practices can be found during the purchasing process, which can require managers to follow codes and guidelines for selecting suppliers based on green and sustainable practices ~~[80]~~[80, 65, 103]. Similarly, a buying firm can select the supplier based on its involvement in social-responsible practices, or even condition it to be involved into social initiatives [16].

At a SC level, the scope is on a focal-firm and its direct and indirect suppliers and buyers. For this level, the pursuit of sustainable outcomes requires to consider firms beyond the first layer of stakeholders. Here, sustainability can be achieved not only trough an adequate selection of suppliers, but also by the incorporation of new production configurations and distribution schemes. This implies that

Table 2: Relevant articles that studied SC and SN considering sustainability, disruptions or complexity

~~Reference~~ **Focus**	~~**Methodological**~~ **Computational framework**	**Objective orientatio**
~~Derissen et al. [29]~~ D/F	~~-~~ C	~~SD R ≠~~
SC	FL + MOO	R ⊂ S
SN	NA + GM	R
~~Marchese et al. [71]~~ ~~*~~ SC*	~~SC~~ -	R + S
~~Rajesh [97]~~ SC*	~~SC~~ -	R ≠ S
SC	LCA + MCDA	R ≠ S
SC	LCA	R ⊂ S
SC	FL + MOO + NA	R ⊂ S
SN	ABM + NA	S ⊂ R
SN	ABM + DA	R
SC	ABM + NA	R
SN	SD	R ≠ S

* Review

SC: supply chain, **SN:** supply network, **D/F:** dyad/firm, **C:** conceptual , **FL:** fuzzy logic, **MOO:** multi-objective optimisation, **SD:** system dynamics, **MCDA:** multi-criteria decision analysis, **GM:** generative model, **LCA:** Life cycle assessment, **ABM:** Agent-based modelling, **NA:** network analysis ,**DA:** data analysis, **R:** resilience, **S:** sustainability

the assessment can include stages prior to the production phase, such as material extraction, or even beyond, like the end-of-life phase. This rationale fits the fundamentals of life-cycle thinking, which consider products as sources of impacts and organisations as responsible for their own impacts and those generated throughout the product life cycle [45]. At this level, LCA is the most selected methodological framework because it can represent in a simplified manner the topology of most SC models. In many LCA studies, the SC model depicts the state of the system under average performance or stable conditions. Moreover, it allows the quantification of impacts throughout multiple layers of suppliers and life cycle phases (e.g., cradle-to-gate, or cradle-to-grave). When the target is environmentally oriented, strategies such as eco-design [14, 12, 75], environmental product declarations [101] and eco-labelling [22] are commonly evaluated. These targets can be expanded to include economic aspects, leading to the implementation of eco-efficiency [57, 17] and circularity [44] strategies.

When modelling a SC, it is usually assumed that the focal-firm has the power to influence the topology of its network to reach target goals (e.g., environmental improvement, cost reduction). Nevertheless, a firm's capacity to shape its SC decreases the more intertwined and global the network becomes [92]. This aspect gains relevance when the achievement of a firm's sustainability goals relies on selecting adequate suppliers, especially because in real life these may have different motivations. The SN level expands the scope from a focal-firm oriented SC to a network of agents. At this level, a sustainable condition results from the complex interactions among the different stakeholders and it is not attributed to a firm or product, but to the whole network of stakeholders. Because sustainability is seen as a property of the system, studies focus on analysing policies, theories and firms' practices, and in understanding their effect on the sustainability of the network, rather than shaping it.

From a topological point of view, it can be noticed that a SN shall not be fundamentally different from a SC. The structure of a SC model can grow considerably until including many nodes and edges. For this, SC methods like LCA have been suited to by-pass the challenges of the resulting dense network [93]. However, the main distinction between SC and SN models is the scope considered in the analysis. When the sustainability of the SN is pursued it is required to represent the dependency among firms in terms of decision making that cannot be directly considered using a SC a scope [85]. The SN model assumes that nodes are intelligent and autonomous, and acknowledges that the network cannot be shaped to the will of the focal firm. This change on the scope requires the use of different methodological frameworks. In this sense, the assessment approaches used to study sustainability under this scope rely mostly on qualitative [76] and statistical methods [112] to obtain insights, and computational techniques when impacts quantification is sought [85, 61]. Many aspects of SN dynamism, resilience, network adaptation and temporal behaviours that are considered as coherent with the sustainability narrative [2, 34] cannot be easily represented in a straight-forward manner [94]. These aspects are particularly relevant in SCM when studying the SN's risk of being affected by disruptive events and its recovery capacity ~~[70, 54]~~[70, 54, 51].

4 ~~Disruptions and resilience in SN~~

3.1 Disruptions and resilience in SN

Disruptions and resilience are two concepts strictly related since the latter is a property that arises as a consequence of the risk of disruptive events. In SCM, risk can be defined as the 'expected outcome of an uncertain event' [70], and it is commonly classified as operational or disruptive. The former refers to high-probability-low-impact events (HPLI), while the latter to low-probability-high-impact (LPHI) events. On the one hand, operational risks are related to variations of the operation parameters during normal functioning of a system. These can lead to undesired phenomenon such as bullwhip effect, for instance, which stands for the propagation and augmentation of the HPLI effect upstream the focal-firm [62, 78]. On the other hand, disruptive risks are associated to events that affect the functioning of the nodes in the SN. In this case, a phenomenon called ripple effect may appear and generate the downfall of the rest of the nodes downstream of the disrupted firm [102, 50]. Phenomena generated due to operational risks such as bullwhip effect have been widely studied in the literature [78], while ripple effect and disruptive risks are topics currently under study [31, 53, 52, 48]~~.~~, especially when it refers to the environmental impacts that it may generate [119].

Disruptions can be originated from different sources, such as operational contingencies (e.g., critical system malfunctioning), natural hazards (e.g., earthquakes or climate change), political instability (e.g., terrorism or economic shocks) [60], or global pandemics (e.g., COVID-19 pandemic) [106]. These sources can also be denominated as drivers of risk, and they can be supplier-related (i.e., drop in supplier's capacity), costumer-related (e.g., sudden increase or drop in demand), and internal (e.g., unexpected failure at plant) [21]. Kim et al. [59] indicate that, in many cases, disruptions do not originate from focal firm's facilities, but from nodes located along SN. They argue that disruptions at a local level do not lead, necessarily, to a network-level disruption. In this manner, SN's topology has been studied to provide insights regarding the risk of disruptions and to determine resilience of the system [59, 10].

Disruptive events may have tremendous impacts in the economy, environment and human life-style, but their effects can easily propagate through the different components of society. For instance, after the Great East-Japan Earthquake in 2011, the estimated indirect losses as percentage of national GDP due to disrupted supply chains were higher than the direct losses due to the earthquake [109]. ~~Another example shows how~~ In the case of the COVID-19 pandemic~~affected food supply system, imposing new constrains in the manner how the system operates [99]. Regardless of the source or the~~ , the rapid contagion and severity of symptoms affected industries like apparel and food. Regarding the apparel sector, it suffered a triple hit because 1) there were direct supply disruptions, 2) the workforce was reduced due to contagions along the SC, and 3) the global demand experienced unprecedented variations [18]. Similarly, reports indicate that the pandemic had an important impact in the global food industry, especially to primary producers since the initial disruptive effects reduced farming supplies and increased their prices [6].

COVID-19 pandemic is the most recent and relevant example that shows how different components of a supply system may have different paces when it refers to adapting to changes. In the case of food supply, different reports suggest that major episodes of food shortage were not observed in 2020 as it was initially expected, most likely due to primary actors coping with the disruptive effects [6]. Likewise, changes downstream in consumers' behaviours (e.g., panic buy and stocking up) may generate alterations on demand that can force retailers to implement strategies to mitigate shortages [111]. In this sense, regardless of the location of the impact, disruptions will eventually have repercussions on society's well-being and adopting resilient practices becomes important.

In ~~this context, understanding properties such as resilience and robustness becomes a relevant task. Depending on the expected response mechanism to a disruptive event, resilienceand robustness can be characterised using notions from graph theory and network analysis [58, 10], or computational approaches [83, 96]. In the literature, resilience and robustness are~~ essence, the concept of resilience is related with the individual's ability of returning to an undisturbed condition. Nevertheless, this notion is also valid when expanding the scope to communities and organisations since it maintains its meaning [7]. These concept has different perspectives in its conceptualisation and it has been associated with matters such as ecological and social vulnerability, the psychology of disaster recovery, and risk management [95]. However, when it refers to the study of SCs, it can be observed that resilience has a significant economic component, which is coherent with the main motivation of companies.

This diversity is not only present in the perspectives that conceptualise resilience, but also in the levels of practical actions that can be taken to improve it. Rose [100] discussed a three level view of economic resilience: microeconomic level (e.g., firms, households and organisations), mesoeconomic level (e.g., sectors or markets), and macroeconomic level (i.e., individuals and markets combined). Increasing the inventory capacity, or considering substitution of imported products are firm-oriented and belong to the microeconomic level, while setting price mechanisms, or pooling resources are sector-oriented and correspond to the mesoeconomic level. Regarding the macroeconomic level, the inclusion of individuals and organisations into the same scope generates an intertwined system where the "resilience in one sector can be greatly affected by activities related or unrelated to the resilience in another" [100]. In this manner, the macroeconomic resilience results from the collective interaction and is not the added sum of individual actions [100], which can also lead to interpret resilience as an emergence property of the system. When compared with the levels of analysis of a supply system [80]

, mentioned in Section 1, it can be noted that the microeconomic, mesoeconomic, and macroeconomic levels are comparable to the dyad/firm, SC, and SN models, respectively. In this sense, enhancing a macroeconomic resilience would imply the consideration of a SN model.

Ponomarov and Holcomb [95] presented a definition that used a multidisciplinary perspective, in which resilience is 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'. Moreover, different concepts, such as robustness and flexibility, are also studied since they are aspects discussed when studying the resilience of a system. These notions, along with resilience, are associated with ideas like management strategies, self-organisation, and dependency among agents [2]. For instance, resilience and robustness are usually found as synonyms, but they describe distinct aspects of a SN's behaviour. On the one hand, resilience is defined as the capacity of a system to adapt and modify its configuration without losing its functionalities. Robustness, on the other hand, is not related to the adaptation mechanism but to the capacity of the SN to withstand damage without losing its basic functionality [92]. The identification and study of these aspects can be done in a theoretical or pragmatic manner. Regarding the latter, depending on the expected response mechanism to a disruptive event, resilience and robustness can be characterised using notions from graph theory and network analysis [58, 10], or computational approaches [83, 96].

~~Our~~ In this review, our focus is on understanding resilience and its integration with sustainability concepts. This is justified because a resilient network relies on the capacity of the nodes to reconnect and modify the ongoing configuration. ~~Moreover, it provides a broader notion to understand the adaptability of a SN, which is associated with management strategies, self-organisation, and dependency among agents [2]~~Furthermore, as argued by Ambulkar et al. [1], firms should learn to reconfigure their resources (e.g., adding new or shedding current) in addition to just ensuring the availability of them. From the sustainability point of view, ~~adaptability is relevant because firms~~ this implies that, after a disruptive events, firms will require to select new suppliers ~~after disruptive events, meaning that sustainability~~ or even modify their operational configuration in a context where sustainability-oriented policies and behaviours can influence ~~these decisions~~the decision process. There are methods that aimed at integrating resilience aspects with sustainability for SC models such as LCA [94]. These proxy methods are used to approach the complexity of a SN by using metrics that are representative of the structural characteristic of the network. However, they derive from static observations of the system and do not embrace the role of each node in the adaptability of the system nor the rationale behind it.

4 ~~Sustainability and resilience: two dissociated concepts~~

3.1 Sustainability and resilience: two dissociated concepts

The variety of interpretations of sustainability and resilience can be a source of confusion. Definitions used in studies might be too wide or too vague, especially when these two concepts share similar assumptions and goals, such as the aim of the system to survive [63]. In essence, these concepts are akin, but in practice they address research questions following different frameworks and methodologies. This disparity is depicted in the taxonomy of combinations identified in literature reviews. Depending on the research field, sustainability and resilience objectives can be used interchangeably, treated as dissimilar, or included into one of the two (i.e., sustainability as part of resilience or vice-versa) [34, 71]. In the case of studies and disciplines that treat one concept as a component of the other, it can be observed that frameworks are oriented on identifying how can the ultimate objective of the system be achievable if one the concepts is included. For instance, studies that consider resilience as a component of sustainability evaluate how increasing system's resilience can contribute to accomplish the main goal, which in this case is to achieve system's sustainability. For instance, Karmaker et al. [55] considers that SC sustainability can be achieved by promoting drivers that can improve properties such as agility and resilience. This logic is similar for the opposite case, where sustainability is considered as a component of resilience [49]. In the case of studies that treat these two concepts as different, it is acknowledged that they imply different objectives that may sometimes overlap, and that it is not always possible to deduct one concept from the other [29]. A more comprehensive discussion regarding the interpretation of these concepts in studies can be found in Marchese et al. [71].

Sustainability and resilience are used to describe any kind of system, whether it is extensive as a global economy or particular as the functioning of the human body [15, 71]. The sustainability target considered in the debate usually comes from disciplines like ecological economics, where it is linked to ecosystem services and the consequences that their affectation may have over society's well-being [29]. Nevertheless, few studies handle this discussion considering different dimensions of sustainability (e.g., impacts) [37] and the ~~CAS~~ complex nature of supply systems [49]. ~~While~~ For the latter, the inclusion of complexity into the modelling exercise responds to the necessity of bringing context to the study rather than following a particular motive. Moreover, while there may exist differences in the definition of the ultimate goal (i.e., whether a resilient or a sustainable SN) [71], it is clear that these two aspects ~~require to be addressed when the~~ are both valuable and important when studying and designing SNs. ~~In this sense, we analyse the fundamental aspects of sustainability and resilience with focus on how they are implemented in SC and SN modelling.~~ Indeed, we ~~identify~~ identified that mainstream methodologies for studying both of them ~~may~~ usually converge to the same principles, but are decoupled in terms of their practical ~~use~~implementation. We found that this dissociation can be discussed more easily from three points of view: motivational, temporal and methodological point of view.

Motivation decoupling. In literature, SC resilience is considered as an intrinsic and structural property of the system ~~[3, 108, 92]~~[3, 108, 92, 104], while sustainability is perceived as a consequent condition of the SC operation. Because resilience is oriented on SN's structure and sustainability on a desired objective, the former is usually inferred from topology, while the latter from accounting and characterising the flows. If we use eco-efficiency and redundancy as proxies of sustainability and resilience, respectively, it can be distinguished that they appear to be dichotomous measures. For instance, when the variety of suppliers of the same product is increased, the firm's productive configuration becomes more redundant, while at the same time production costs or environmental footprint may become sub-optimal and less efficient. This dilemma arises because LCA-based eco-efficiency methods envision sustainability as the main goal and they are not suited to explicitly account for system's resilience. Instead, they focus on measuring the intensity of flows rather than the structure resulting from firms interactions [94]. Under a SC scope, the interpretation of both concepts and the establishment of goals is constrained to the eyes of the focal company, which accentuates this duality. An attempt to integrate resilience objectives into the sustainability goal was published by Fahimnia and Jabbarzadeh [37], who used an optimisation approach to include different disruption scenarios where the expected SC cost, environmental and social performance where considered as optimisation targets. In this situation, managers will aim to maximise environmental performance and reduce disruption related costs, meaning that the only solution is to find trade-offs between both aspects.

Temporal decoupling. In CAS-oriented models, the study of disruptions usually relies on simulation methods. The resilient condition of a system is determined after observing the dynamism and adaptability of simulations of the SN in a period of time after the introduction of a disruption [83, 64]. Even when the analysis depends on the use of proxy network analysis metrics [108], or statistical approaches [3], the aim is to understand system's resilience acknowledging that the topology may change during time. On the contrary, most of SAM usually consider a snapshot of a SC model and use its impact over certain dimensions (e.g, environmental, social or economical) as proxies of sustainability. This snapshot is made with the average configuration of the network for a given period, despite the possibility of it of being a very dynamic system. This temporal stagnation does not usually represent an issue for many environmental impacts because most of them consider a long-term span in their evaluation (e.g., climate change). Nevertheless, some other social (i.e., job losses), economic and environmental (i.e., water consumption) impacts are relevant in the short-term and, if ignored, may have negative consequences to society. The negative short-term effects that are generated after disruptive events provide the main justification for seeking more resilient systems. Integrating both concepts into a temporally flexible framework would require to encompass the system structure during a whole time span (i.e., network evolution) and to acknowledge the different affectations under different temporal horizons (i.e., short- and long-term effects).

Methodological decoupling. As explained in Section 3.1, sustainability is commonly studied with methods that are based on analytic approaches, such as LCA. This method, which relies on linear algebra, has the adequate computational framework to account for the system's flows required to manufacture a given product. The environmental impacts are calculated on the basis of the resources extraction and emissions from and to the environment, respectively. This SAM is SC-oriented and assumes that all agents are going to satisfy the demand, depicts the system in a stable or average situation, and mainly focuses on the flow of products or money. By contrast, methods that aim to understand or quantify SN resilience not only rely on analytic approaches, but mostly on heuristics or computational techniques as core elements of their frameworks [98]. For instance, proxy methods based on graph theory not only focus on system's flows, but on network structure and its topological properties. Here, resilience is determined following heuristics that rely on network indicators that are calculated with the use of algorithms [64, 116]. In simulations, resilience is evaluated after observing SN's behaviour in a computational environment following the introduction of a disruption [48]. Some LCA studies incorporate resilience aspects into the evaluation by modelling resilient scenarios [94], or by discussing scenarios using multi-criteria decision analysis [24]. In studies that integrate these two concepts, we observe that sustainability and resilience are determined using different methodological assumptions and they are later integrated into a common assessment framework. ~~In the one hand,~~ Most of the studies use multi-objective optimisation methods and they represent the resilience target with proxy objective functions. For instance, Hasani et al. [42]'s optimisation model considered the maximisation of geographical dispersion of SC facilities as a positive indicator of resilience against disruptions. In a similar way, Fahimnia and Jabbarzadeh [37] introduced disruptions in an explicit manner as scenarios in a multi-objective optimisation framework. While there ~~are~~ were not exact measurements of resilience, this property ~~is~~ was embedded in the sustainability goal where the system ~~is~~ was expected to be sustainable under business-as-usual and disruptive conditions. ~~On the other hand~~Finally, Zahiri et al. [120] developed a mathematical model that minimised costs, environmental and non-resilient aspects of the network. Indicators such as node complexity and demand dissatisfaction were used as proxies of resilience, assuming that they ~~reflect~~ reflected how the system may respond under disruptions. In ~~this case, resilience is~~ these cases, resilience was incorporated as an additional and distinct objective that ~~requires~~ required the use of optimisation techniques to allow a common framework to analyse both aspects.

Motivational and temporal decoupling condition practitioners to select different methodological pathways (i.e., methodological decoupling) when studying supply system and disruptive events. We argue that these issues can be confronted by finding a common conceptual ground that shall lead to similar objectives and to a coherent methodology. When dealing with SNs, this aspect is more relevant because no CAS-oriented framework or implementation that deal with this two concepts has been identified. In this sense, it is important to understand the computational capabilities of current modelling techniques to then select an adequate method to be set as the core of a common assessment framework. We argue that any selected computational tool should be able to contemplate the characteristics of a SN, which implies embedding the CAS nature of the modelled system.

4 ~~Computational structure of SN models~~

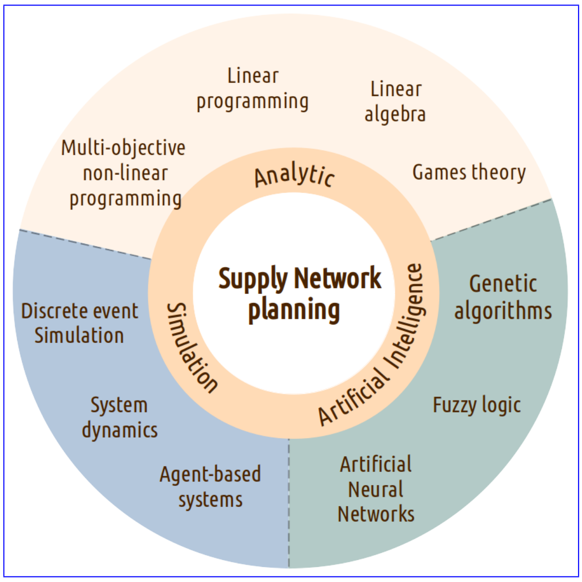
3.1 Computational structure of SN models

A CAS-oriented scope embraces the notion of adaptability of the network. Moreover, it leads to a common ground where both resilience and sustainability are not determined or calculated prior any event, but they need to be observed as emergent characteristics. These characteristics need to be tangible and measurable, for instance, practitioners should be allowed to observe the constant change in topology or in sustainability metrics in the SN model. When treated as a CAS, the sustainability state is observed during the same period of time as the disruption occurs. Moreover, because the initial and final state of the system are observed, more attention can be provided to those impacts that may be brief but with significant effects. This example shows the necessity of identifying an appropriate methodology to be set as a core tool for a SAM. In this sense, we explored current supply systems modelling techniques identified in the literature to later focus on the most suitable for our goal.

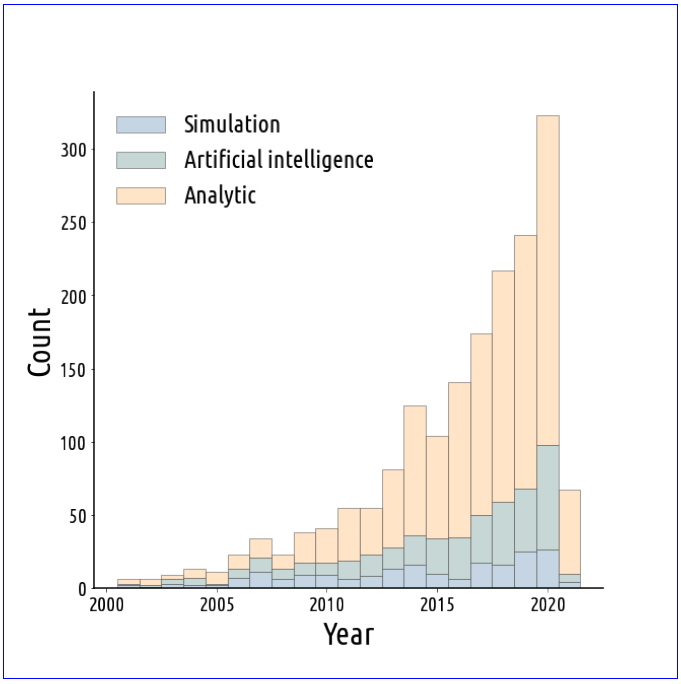
3.2 ~~Current computational frameworks~~

3.1.1 Current computational frameworks

Studies aim to identify the correct configuration that allows the flow of materials or information in a beneficial way. Planning involves beginning an endeavour or re-designing a SN. The taxonomy of models is not formally defined in literature, but we are basing ours on the classification proposed by Giannoccaro and Pontrandolfo [41], which fits most of the studies found in literature, as stated in Peidro et al. [91] (see Figure 2a). In this sense, a SN can be analysed using an analytic model (AM), an artificial intelligence model (AIM), or a simulation model (SM). AM use linear algebra, linear programming, games theory, and all the variants of mathematical optimisation methods. They use deterministic principles to model a SN usually seeking for the optimal configuration in terms of logistic, production, or environmental impacts ~~[39, 38, 81, 33]~~[39, 38, 81, 33, 42]. In the literature, studies that use AM are the most abundant, but in recent years an increase in SM and AIM has been observed (see Figure 2b [2]).



(a)



(b)

Figure 2: Taxonomy of modelling approaches for treating supply network planning, based on [41]

AIM and SM are models that use heuristics and algorithms to recreate the conditions of the SN. AIM rely on artificial intelligence algorithms and techniques such as reinforcement learning, genetic algorithms and fuzzy logic. For instance, Park et al. [89] implemented a genetic algorithm for the planning of a SN. In Nezamoddini et al. [86] a framework that integrated a genetic algorithm and neural networks was proposed to determine the adequate configuration of a SC. With respect to SM,

[2] This figure was elaborated using the extracted terms related with the taxonomy and the indexed articles identified in the *general review*

these methods involve the computational recreation of the functioning of the SN in discrete steps, such as discrete-event simulation (DES), dynamic system simulation, and agent-based modelling (ABM) [3]. DES is the most used and it proposes modelling systems where queues and flows are relevant and where events happen in a discrete manner. In DES, it is required to provide information regarding the logic rules that allow the flows through the whole system. ABM, on the other hand, differs from other simulation techniques because the system behaviour is not modelled a priori, but it emerges after observing the simulation [105]. This modelling paradigm allows the simulation of agent's interactions (i.e., individuals or organisations) and conclusions regarding the system functioning are drawn from analysing the final landscape [13]. Because of these features, ABM is usually selected as the modelling tool when a CAS-oriented analysis is sought [74, 90].

3.2 ~~Agent-Based modelling: a CAS-oriented tool~~

3.1.1 Agent-Based modelling: a CAS-oriented tool

As it was introduced before, ABM is a computational paradigm used for modelling complex systems where patterns emerge from the aggregation of agents' interactions in a bottom-up fashion, agent-by-agent and interaction-by-interaction [66]. Agents require to be explicitly programmed with particular rules that will command their actions in the simulation environment. In this sense, in an ABM, three main components can be distinguished: a set of agents, a set of relationships, and agents' environment [66]. Firstly, as presented by Macal and North [67], agents can be defined as autonomous, self-contained and interacting computational entities that have specific attributes, behaviours, and goals. Secondly, relationships are determined by defining the rules of agents-agents and agents-environment interactions, where the resulting layout is referred as the ABM's topology [66]. Finally, the environment provides the context and information (e.g., location, time) to be used by agents during the decision processes. The three components need to be explicitly programmed as part of a computational software. For this, the object-oriented programming (OOP) paradigm is commonly used. In OOP, the software is an implementation of a collection of real-world objects that will interact among them when the program is executed [40].

An ABM can be programmed to be as sophisticated as computational resources allow for. This implies that, in theory, it can be integrated with other methodologies. When it refers to sustainability, for instance, ABM simulations and LCA calculations can be integrated in the same computational framework. The degree of integration depends on the expected outcome and different classifications can be found in the literature. For example, Baustert and Benetto [4] classify the integration as unidirectional coupling and LCA/ABM symbiosis. A symbiosis occurs if, during run-time, LCA calculations have an effect on the ABM agents or environment, and the ABM results can influence the next step of the LCA calculations. When the ABM results feed an LCA framework, or vice-versa, the integration is considered unidirectional. Conversely, [79] proposed a taxonomy using the terms soft-, tight- and hard-coupling. The first two refer to cases where ABM results are used to perform LCA at the end of the whole simulation (i.e., soft-coupling) or at each time step (i.e., tight-coupling). Hard-coupling, similar to LCA/ABM symbiosis, implies the mutual influence of methodologies during run time.

Regardless the type of integration, literature shows that the use of ABM allowed to enhance studies that had a limited computational framework. For instance, Navarrete Gutiérrez et al. [84] developed an ABM in a case of the study that had previously been analysed using econometric and non-linear programming techniques. The ABM allowed them to model behaviours and interactions among farmers in maize production that could not have been represented with an analytic approach. Wu et al. [115] argued that ABM allowed them to include human behaviours in the construction of the Life Cycle Inventory (LCI), which is a relevant aspect when analysing the building industry. Another example can be found in Davis et al. [28], who proposed a soft-coupled framework that was used to understand the

[3]While Giannoccaro and Pontrandolfo [41] considers ABM as an AIM, we will refer it mostly as a SM because it has characteristics also proper that type of modelling.

environmental impacts of an evolving SN (i.e., bio-electricity production), where LCA computations were performed at every time step to assess the Global Warning Potential of the electricity mix. In this sense, it can be noted that ABM has been successfully used to deliver consistent foreground data during the construction of LCI [72].

As mentioned in Section 3.1, achieving a sustainable supply chain can have different meanings depending on the perspective of the stakeholder formulating the question [80]. When modelling an ABM, this conundrum is transferred to the agents when the assessment tools are integrated into the ontology of the agents. Because of this, it is important to consider the particular interpretation of sustainability that every agent might have (e.g., firm managers, producers, costumers), especially because practitioners may feel lured to impose their vision of sustainability during modelling. Sustainable purchasing behaviours, for instance, have been previously introduced in ABM whether as individual motivations (e.g., green-consciousness) [84] or as the result of imposed policies (e.g., carbon-taxes) [28]. Risks and disruptions can also have an influence on the decision making process of every agent, whether is directly or in a subtle manner. In a SN, disruptions have direct influence on firms' decisions, as well as the structural position of a firm may affect other companies' perceptions regarding its risk [114]. In this sense, ABM can be used to understand behaviours like trust and risk propagation through the SN to increase the resilience of the system [46]. Moreover, other phenomena studied in SCM, such as criticality identification, and supply and demand mismatches can also be analysed by using ABM as SN modelling framework [47, 118]. In all the cases, neither sustainability nor resilience are measured by observing an individual, but by assessing the performance of the overall system. This characteristic principle of complex systems leads to the dilemma of classifying sustainability and resilience as individual or collective properties.

ABM models were developed on the basis of the requirements of distinct resilience or sustainability assessment methods. There is still no evidence of an ABM implementation that integrates both notions from the conceptual foundations until the practical use of its outcomes. The construction of the ABM is flexible, but it requires a clear definition of the complex phenomenon that is under analysis. For this, it is important to define the ultimate research goal that will lead the modelling exercise. In this sense, we argue that a computational framework that integrates resilience and sustainability should be built underpinned by a robust and coherent conceptual framework.

4 A complexity-driven sustainability assessment approach

While the study of disruptions is leaning towards frameworks that contemplate SN complexity, most of SAM approaches still rely on the use of SC models and analytic frameworks to describe topology and to derive quantitative proxies of sustainability (i.e. impacts). These approaches encounter difficulties when integrating sustainability with resilience because they were initially conceived to be coherent with the nature of the SC-oriented scope [94]. In fact, to the best of our knowledge, even studies that employed complex modelling frameworks used LCA-oriented principles to answer question of system sustainability. From our point of view, this SAM scope seems narrow when we observe all the features that CAS-oriented frameworks can provide to the practitioner. In this sense, we argue that expanding the system modelling scope to a SN level also requires the expansion of the approach of the SAM so that it can be underpinned on the principles of a CAS.

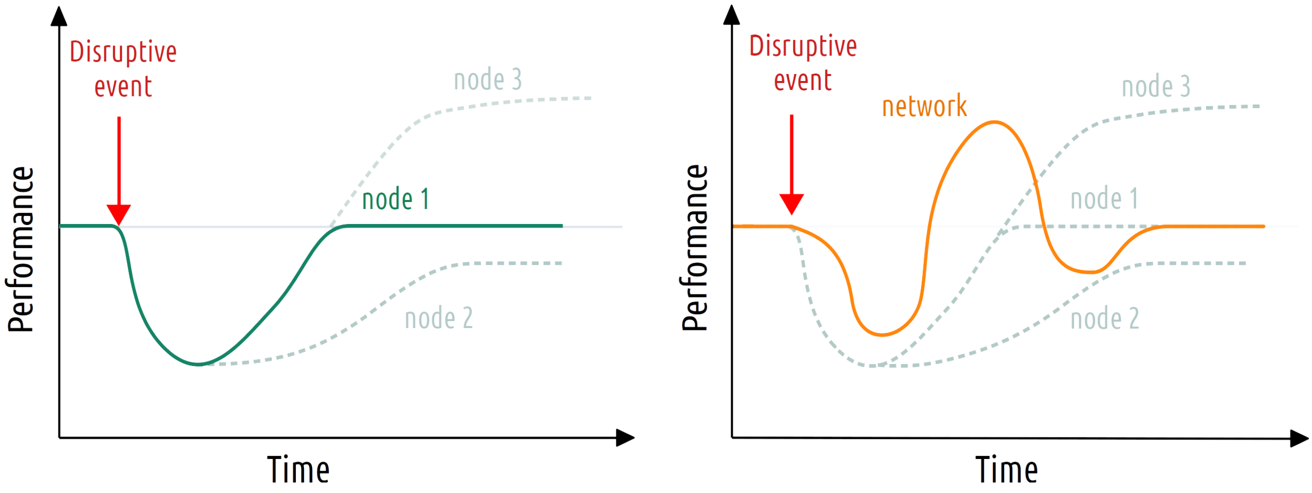
Aspects such as resilience and network dynamism do not reflect direct consequences to society, but provide insights of SN's capacity to achieve well-being goals even after sudden changes. We envision sustainability as the conceptual umbrella that embeds SN complexity. Thus, the sustainability assessment exercise should organically consider these aspects as well as environmental impacts, society development, and economic prosperity. There are aspects that can be directly and indirectly associated with dimensions of well-being in short and long term. For instance, undesired SN states in terms of unemployment and economic losses can be immediately observed after a disruption. Conversely, the effects that network re-adaptation can generate in global temperature cannot be perceived instantly, but they still have important consequences for future societies. In this sense, we consider that *a SN is sustainable if it is capable of contributing to the well-being of current and future societies while ensuring its own adequate functioning during its lifetime.* This vision emanates from the fact the real global SN fairly fits the CAS definition and the assumption that computational tools can serve as the operational framework to study SN's complexity. To this end, we consider ABM as the core of this sustainability assessment approach and we ground our sustainability vision on four principles described below.

1. *It does not focus on an optimal solution, but on delimiting sustainability boundaries.*

    By accepting that agents are intelligent and autonomous, finding the solution that optimises the SN configuration seems worthless if it requires us to explicitly modify the topology of the network and the operational configuration of every node. Independent agents may act in ways that are unpredictable and can only depend on the environment, other agents' context, or randomness. This means that the system is not deterministic, and we cannot know if an optimal and unique solution exists. In this situation, the 'most' sustainable solution is practically unreachable. Sustainability is a concept that tolerates nuances in terms of how much a system can improve, but is strict in terms of the limits that a system should not surpass. In this sense, it is more coherent to turn the focus on finding the boundaries in which the SN can still be considered as sustainable. Moreover, when we acknowledge the stochastic nature of the CAS, the analysis can be translated in the exercise of determining the probability of remaining (or becoming) sustainable. These *sustainability boundaries* can be established using well-known metrics (e.g., LCA metrics), but can also be delimited appealing to different indicators (e.g., economic and social metrics) that fit the requirements of the practitioner. In this sense, sustainability can be pictured as a region or regions located in a *multidimensional space* so a variety of different solutions can still be considered as sustainable. SN models designed with different parameters can still lead to sustainable outcomes, which implies that no solution is necessarily better than other as long as they remain in a target *sustainable region.* This region can be interpreted as the space where given societal expectations are fulfilled.

2. *Nodes achievements are irrelevant if they do not lead to system's success.*

    Macchion et al. [68] conducted a qualitative study on 18 firms in the apparel sector and they showed that structural complexity (also referred as static complexity) influences the adoption of sustainability practices at different levels of a SN. In this case, the first tier suppliers experienced difficulties when different sustainability strategies clashed among the focal-firm and the upstream suppliers. This occurs because practices and policies assumes the involvement of all the elements of the system. If we maintain the assumption of firm's leverage over the SN, the new network configuration can indeed lead to a state of sustainability from the firm's point of view. However, implementing this changes over a SC may have effects on the firms outside of the scope of analysis. In such way, we ask ourselves if it is reasonable to think that the addition of firms' sustainability states can indeed be equivalent to the sustainability of the network. Under the SC scope, the focus is on understanding the sustainability of a node and its supply chain, ignoring the performance of other nodes associated to the same network (e.g., competitors) (see Figure 3a). In contrasts, when analysing the SN, the attention relies on network's sustainability rather than specific nodes (see Figure 3b). Sustainability in a SN should not be evaluated at a micro scale without considering the macro consequences of the decisions. For instance, firms can implement sustainable practices in order to diminish their impacts and increase their profit, but at the same time they can influence the whole sector's footprint and economy [35]. One reason is that, while components of some dimensions (e.g., environmental and economical) can be conveniently observed from a micro perspective, others (e.g., biodiversity, cultural and social) necessarily require of a macro view to make sense from them.



(a) (b)

Figure 3: Variations on system's performance under a (a) focal-firm oriented supply chain and a (b) non-focal firm oriented supply network

3. *Shifts the interest from predicting the future towards understanding causalities.*

The SN model is CAS-oriented and the uncertainty of environmental stimuli and agents behaviours may lead to a chaotic system. In this case, attempting to predict a single point in a vast cloud of possible solutions is naive or even erroneous. In an ABM, every action of an agent can be traced back to its behaviour's definition. This means that the sequence of events that occurred during the simulation can be identified and analysed. The coherence among agents' decisions, network topology, and overall indicators must be verified, especially if the programmed rules are meant to be implemented in real life. The agreement between a real-world measurement and the system outcome does not necessarily ensures that the model represents accurately the SN [88]. In this sense, practitioners should not be concentrated on achieving the most accurate prediction because it may deviate the attention from the task of understanding agents' interactions. Because sustainability is now assumed as an emergent behaviour, the key of the assessment exercise is to determine what are the rules or policies that tend to lead to a sustainable system and why is that happening.

4. *It is dynamic and holistic by nature.*

Society's vision of well-being is not static. Our expectations and tolerances in terms of these *sustainability boundaries* are set on the basis of our appreciation of the current SN state. Hence, due to the network adaptability, some aspects of the state can dramatically change after perturbations as well as the way we value them. After experiencing a highly disturbing event, our main priority may no longer be the minimisation of environmental impacts, but the survival of the economic system and social fabric linked to the SN. This dilemma of objectives, however, should not imply prioritising one over the other, but ensuring the permanence of SN in the *sustainability region*, paying attention to the temporal appropriateness of the considered metrics. For instance, if the network reaches a future state within the expected yearly GHG emissions (i.e., long-term

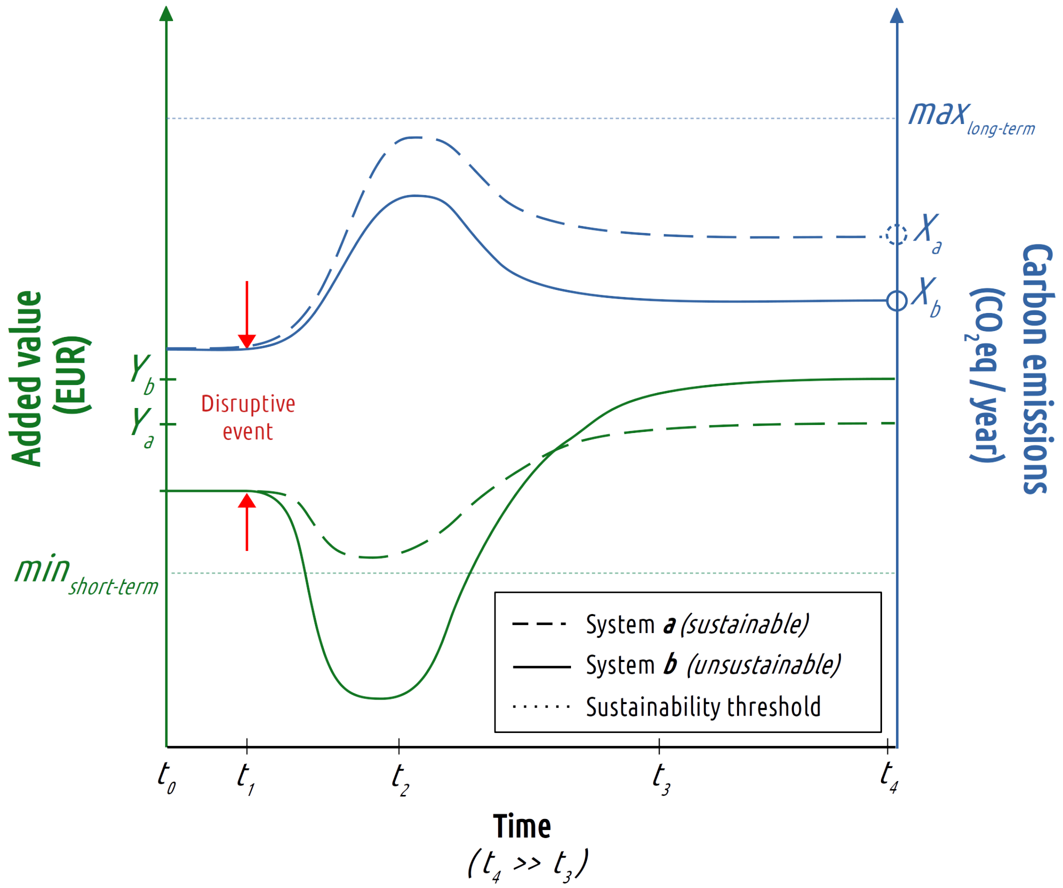


Figure 4: Performance of a sustainable (***a***) and an unsustainable (***b***) system under the evaluation of a short-term (added value) and a long-term (carbon emissions) sustainability indicator after a disruptive event.

target) without surpassing added value (i.e., short-term target) thresholds during the period of analysis, then we can say this SN is sustainable. In other words, the SN is contributing to the current well-being and ensuring its functioning while being capable of considering the well-being of future societies. On the contrary, if the system is inside this long-term target bounded space, but has highly decreased below any short-term target threshold, we can no longer consider it as sustainable because it cannot ensure its own survival nor its contribution to the economy. For instance, Figure 4 depicts two systems (i.e., ***a*** and ***b***), evaluated using two sustainability metrics after a disruption occurring at time t_1. System ***a*** is considered sustainable because it does not surpass the short-term (added value) and long-term (CO_2eq/year) imposed emission threshold, measured at t_2 and t_4, respectively. In contrasts, system ***b*** cannot be considered as sustainable because it surpasses the threshold in t_2, despite having a better performance in t_4 for both yearly emissions and added value indicators.

Under this approach, we do not need to use proxies to describe systems proneness to failure because we can observe explicitly how the network and metrics vary after the introduction of disruptive events. For this, metrics should be carefully selected so they can indicate if the SN is still functioning or has failed. In this sense, a SN can be called robust if it remains inside the *sustainable region* and does not experience dramatic changes during the whole simulation, implying that it has the capacity of coping with external disturbances. Similarly, a SN can be considered as resilient if it can return to a position distant from the *sustainability boundaries* after approaching them. This means that the SN has the capacity of returning to its initial state after being negatively affected by disruptive events. With this logic, a system that surpasses the imposed thresholds cannot be called as unsustainable even if it eventually returns to its initial condition.

It is important to notice that the main focus is not on finding a resilient or robust configuration because they are structural aspects embedded into the sustainability analysis process we propose. By embedding the short-term effects, the necessity of determining if a system is resilient or robust becomes overshadowed by the sustainability target.

5 Towards a new sustainability assessment framework

The proposed principles represent a conceptual basis that can be used as a compass to design an assessment method. Based on these, we identified a potential path to develop a complexity-driven SAM to be used when analysing disruptions or other complex phenomena in SN (see Figure 5) . The following set of stages describe a framework that should allow the modelling of a SN and potential disruptions, nodes' interactions, and should deliver enough information for decision making. This framework involves sequential steps and heuristics that provide the notions to couple SN topological aspects and sustainability principles in a practical manner during the computational phase and the decision making exercise.

Computational modelling of the supply network. The modelling stage should consist in representing the industrial sector we aim to evaluate as a network of agents. Ideally, agents should always depict real-world entities, meaning that firms as well as key stakeholders need to be included into the network. Moreover, aspects such as firm's production scheme and emission factors, selling and procurement behaviours, and managers' mitigation plans need to be considered. It is unpractical and sometimes unfeasible to collect detailed data of every firm. Thus, relevant companies need to be identified so they can be explicitly represented, while the remaining can rely on secondary data or experts opinions. Once the elements of the SN have been mapped, agents need to be represented as computational objects with attributes and functions. For this, any ABM tool can be used as long as it allows to program explicit agents' characteristics, account for interactions, consider current sustainability metrics, and treat the SN as a computational graph object. Finally, companies' characteristics will then be ingested as attributes and decision rules as functions.

Selection of parameters and events of interest. Once the computational engine of the simulation is set, the next step should be to identify the different parameters that will vary during each simulation. The logic behind considering more or less parameters responds to expected influence of those over the system behaviour. These influences are usually based on evidence or can be assumed a priori as part of the research hypotheses. Parameters such as production capacity, initial position of an agent in the network, emission factors, delivery time and efficiency tend to determine the performance of a company in the market. We label these as *endogenous parameters* because they are intrinsic to agents and vary according to firms' access to information. On the contrary, we label aspects such as market demand, environmental and anthropogenic disruptions, and public policies as *exogenous parameters* because they are context dependant and do not rely on a particular agent state or point of view (see Figure 5). Both of these parameters are meant to be set before the simulation run as initial conditions.

There may exist parameters from these two categories that are not expected to remain constant because of the uncertainty associated with them. In ABM exercises, it is usual to assign a probability distribution to these parameters to provide a computational source of randomness into the modelling. By this, real-world randomness can be measured and it promotes agents to encounter always different decision situations. In this sense, it is evident that multiple simulation runs with same initial conditions (e.g., Monte Carlo simulation) need to be performed to make sense of the stochastic nature of these parameters. In a similar way, events of interest (e.g., disruptions) are meant to be programmed and included into the model. For instance, natural phenomena can be introduced indirectly as slight variations in some environmental parameters used by agents, such as precipitation (i.e., required by farmers), or change in availability of a natural resource (i.e., fishes at the ocean). Other disruptions, like explosions or lock-downs, can be introduced as direct changes in network's topology, such as the

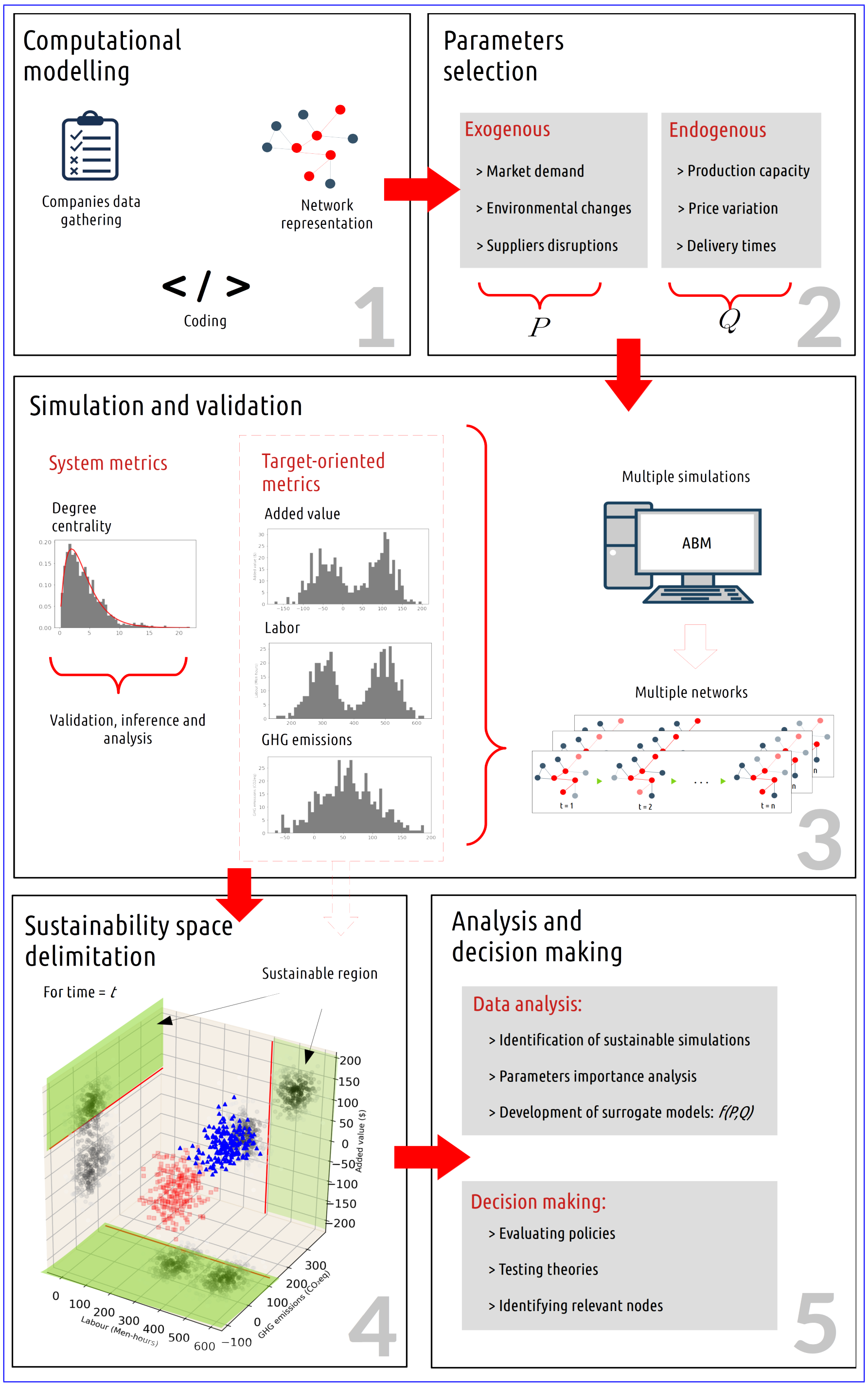


Figure 5: Required stages for a potential framework of a complex-oriented sustainability assessment method for supply networks.

deletion of nodes in a certain country or region or the instant variation in production capacity of certain firms. Moreover, the practitioner has to explicitly program the start and end of the exogenous disruptive events over the simulation environment so it can be executed during run-time. Finally, the combination of all the parameters and events of interest will set the conditions of the simulation which we can label as a *scenario*.

Validation and simulation of scenarios. A priori assumptions and model outcomes have to be verified and validated before using the model in any assessment exercise. For this, a set of indicators or metrics should be proposed so they can be interpreted as time dependant variables that represent the state of the SN in a given time step. The practitioner's task is to make sense from these metrics and validate or reject the SN topology and outcomes. There are multiple metrics that can be used to characterise the simulation results, but depending on the nature of the indicator, we can classify them into *system metrics* and *target-oriented metrics*. The former represent performance and structural properties of the system that can be used as proxies to describe network's topology, but cannot be explicitly related to a sustainability state. The latter are metrics that can be directly associated with society's vision of well-being and can be used as dimensions of the *multidimensional space*. On the one hand, network analysis indicators, such as centrality measures and their distributions, can be directly used as *system metrics* and they also serve to validate model's capacity of simulating a feasible SN topology. Moreover, indicators like betweenness or alpha centrality [11] can be used to identify relevant agents and to track their roles in the SN during the simulation. On the other hand, indicators used in LCA (e.g., global warming potential, water depletion), life-cycle costing (e.g., value added), or social LCA (e.g., direct employment) can be used as *target-oriented metrics*. For this kind of metrics, new indicators can be proposed as long as they can be calculated from the simulated SN and associated with dimensions of sustainability or society goals.

With the computational engine, parameters and metrics configured, the next step will be to run one simulation for each scenario, or multiple simulations if the scenario is bounded with uncertainties that are meant to be evaluated (e.g., Monte Carlo simulation). A simulation run for one scenario will generate a set of $\boldsymbol{t}$ graphs, and a set of $\boldsymbol{t}$ vectors of dimension $\boldsymbol{m}$ containing the network and the values of $\boldsymbol{m}$ *target-oriented metrics*, respectively, for every time step from 0 to $\boldsymbol{t}$ (see block 3 in Figure 5). The first set should be used to calculate all the *system metrics* and to understand the changes in the SN topology, while the second set can serve to position the SN state in the *m-dimensional space* conformed by every *target-oriented metric*.

Sustainability space identification. In this stage, *sustainability boundaries* can be introduced as upper or lower thresholds for every *target-oriented metric*. For instance, in a three-dimensional space the thresholds can be graphically represented and the *sustainability region* can be intuitively distinguished (see block 4 in Figure 5). In this sense, the sustainability of a SN state is determined by the location of its coordinates in the *multidimensional space*. When the stochastic nature of the parameters is considered by performing a Monte Carlo simulation, for instance, the multiple simulations will lead to a cloud of points. In this case, the interpretation cannot be dichotomous anymore (i.e., it is or not sustainable), but it has to consider the distributions of the simulations for every dimension (i.e., the probability of staying in the sustainable region).

It is not practical to perform this graphical analysis of the SN state and the *multidimensional space* $\boldsymbol{t}$ times. Because of this, the ABM should be equipped with tools to automate the process of calculating the distance of a point to the boundaries in an *m-dimensional space*.

Analysis and decision making. This stage should be used to interpret the simulations and to generate knowledge from it. The type of analysis may vary depending on the objective of study. For instance, when designing a SN it is relevant to explore and identify the operational configuration most likely to lead to a sustainable state. If the goal is to explore the effects of disruptions then it will be important to identify the nodes that play crucial roles in sustainable or unsustainable SN states. If the objective is to test new policies, theories or rules, node interactions and cause-effect chains can be examined step-by-step to make sense of the action mechanism that lead to the final state.

The simulations create a synthetic database that can be also used with data analysis purposes. For example, the influence of certain initial parameters in the sustainability state can be studied. Moreover, surrogate models that map initial conditions to the likelihood of remaining in the *sustainable region* can be developed using statistical or machine learning approaches. The objective of this modelling strategy is to avoid the necessity of running simulations if the influence of certain parameters in the final outcome have been identified and validated.

Finally, this stage does not represent utterly the final phase because it can be in the middle of multiple iterations steps in the process of achieving the right model. Validation, verification and calibration processes may require to traverse all the different steps presented before.

6 Conclusions and ~~future steps~~implications

In this paper we conducted a critical review based on a non-systematic literature search. At the best of our knowledge, this review is novel in discussing the methodological impediments and advances when modelling complex SNs and assessing sustainability of SNs. Trends regarding modelling approaches in SN, sustainability, complexity and disruptions were also explored in order to identify relevant perspectives. ~~While dissecting concepts such as resilience and sustainability, important conceptual dissociations were distinguished. We~~ Additionally, we identified that the differences in the selection of methodological pathways in SN modelling can be influenced by differences in the motivations and the temporal scope of the study. ~~In this sense, we presented ABM as an adequate tool to facilitate the development of the conceptual foundations of a CAS-oriented methodology~~Moreover, based on our findings, we provided a more integrated vision of sustainability that is consistent with methods used in the study of complex systems, namely ABM.

We have put in evidence that an appropriate assessment method that is coherent with the selected SN modelling approach is required in order to be useful in practice, whether it is for designing or improving a sustainable SN. The necessity of considering actors' agency to achieve sustainability as an emergent norm has also been acknowledged in other studies since businesses actions respond to motivations beyond utilitarianism [82]. While an ongoing trend on developing frameworks to mitigate disruptions effects on SNs [8, 56] has been observed, similar efforts to enhance SAMs to consider the complex nature of a SN are still missing. Our point of view is consistent with the conclusions drawn by [8], where methods to mitigate disruptions were reviewed and a more complexity-oriented SN agenda was proposed.

We suggest that sustainability assessment approaches should also evolve in a conceptual and methodological manner to consider multiple aspects of a CAS, such as resilience, adaptability and the dynamism of network's topology. We have elaborated four theoretical principles that we consider should guide the development of any complexity-driven SAM. The principles concur to the notions of treating sustainability as a multidimensional space, and acknowledging the relevance of ~~temporality~~ time for both network's evolution and metrics selection. Under this vision, resilience objectives are embedded into the sustainability target, which can provide a common framework for analysis.

The assessment framework that this review suggests has been built on the basis of the proposed principles. Steps that depict data acquisition, computational modelling, *sustainability region* delimitation and decision making have been outlined to portray the desired characteristics of an operational SAM. Substantial part of the framework has been built taking stages of the conventional ABM paradigm, meaning that challenges associated with this modelling approach will also come along in the SAM. ~~In spite of not being discussed thoroughly in this paper, the validation step in the model construction is very important and it may imply a significant effort, especially while selecting the adequate validation approach and calibrating the model.~~

The fact the our framework relies on the delimitation of the *sustainability region* also represents an important challenge. Selecting the appropriate sustainability dimensions (i.e., *target-oriented metrics*) is not trivial and it is a task that should be based on science but also on understanding societal and industries goals. Likewise, establishing *sustainability boundaries* requires the quantification of these limits. This may represent an issue for environmental dimensions where a consensual objective is not yet defined, or where it is difficult to allocate global targets to specific sectors (i.e., GHG emissions reduction plans). While the establishment of *sustainability boundaries* is conditioned by practitioners' objectives, it is still important to ~~provide~~ pay attention to the development of comprehensive and consistent sustainability metrics. ~~Finally, we argue that these considerations and the notions of the framework provided in this review can facilitate the setting up of an operational complexity-drive SAM~~

This article provides a first attempt to set conceptual principles to guide the construction of CAS-oriented SAMs, presenting ABM as the adequate tool to facilitate the future development of a methodology. Since supply systems are becoming more complex and intertwined than ever, it is important constantly evaluating if current methodological tools are comprehensive enough to address these complex systems. In this sense, we consider that future practitioners can rely on our findings to discuss current methodologies or to provide robustness to their methodologies when assessing and modelling SNs.

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