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Resilience in supply networks: Definition, dimensions, and levels

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ABSTRACT

Oftentimes, seemingly robust systems fail, almost inexplicably, due to unforeseen events leading to disruption. Exploration and research of the mechanisms behind the failure of such systems have revealed that those capable of surviving are not robust, but resilient. This has spawned a stream of research on the resilience of different complex systems, from ecosystems, to the human body, to supply chains and communication networks. Supply networks are complex adaptive systems in which a subset of agents create flow and are required to deliver such flow to sink agents located at the other end of the network. Delivery of flow under pre-defined service conditions requires resilient design and operation protocols.

In this article, a supply network formalism is introduced, and the concept and dimensions of resilience in supply networks, explored. Five core components of resilience are derived from reviewed definitions; two resilience dimensions, structure and control protocols, and two resilience levels, agent and network level, are characterized based on insights from articles in literature. Finally, emerging trends in resilience research as well as current research gaps are presented and future work directions outlined.

1. Introduction

Over the last decades, the world has witnessed an exponential growth in the level of complexity and interconnection among systems, mainly fueled by advances in communication and sensing technologies, and the rapid development of smaller, more powerful computers. Physical and digital worlds are becoming increasingly intertwined, giving rise to cyber-physical systems with emergent complex interactions. As human development calls for more efficient and cost-effective systems, optimization of normal operating conditions undermines systems' protection against disruptions, affecting their capacity to anticipate, respond, and recover from these negative events. Furthermore, the increased dynamicity and complexity of modern supply networks renders robust supply network designs and strategies inapplicable, as they are static in nature. Therefore, design for resilience is becoming essential to enable systems to maintain an acceptable level of performance, even when challenged by unexpected events, and continuously adapt to a dynamic environment. To this end, researchers must elucidate: *What is resilience? Which aspects/components of complex systems need to be designed for resilience? Where do resilience mechanisms need to be placed?*

Supply networks (SNs) are a subset of all complex adaptive systems, in which a collection of agents interact to enable flow from source agents to sink agents. From this broad perspective, a SN may deliver physical products (e.g., supply chains), digital flow (e.g., sensor and communication networks), and/or resources and executed tasks (e.g., in service and maintenance systems). Although the aforementioned systems share a common abstract form, current literature lacks a generalized supply network formalism capable of encompassing all these systems. As a result, researchers in seemingly disjoint fields (e.g., supply chain management and sensor network design) work in silos to develop mechanisms that enable resilience in different types of SNs, failing to learn from, and leverage, each other's findings. Cross-comparison and complementarity among these various areas of resilience research can provide valuable insights, as well as outline current gaps in literature to be addressed by future work. To this end, this article contributes to current resilience literature by providing the first review of articles exploring resilience in different SN domains.

In order to close the gap among various streams of resilience research, this article reviews 92 works from various research fields, including supply chain management, sensor and communication networks, complex systems, organizational theory, and ecological systems. This literature review is not exhaustive but selective, intentionally to provide the necessary and sufficient spectrum of issues, highlights, and key objectives of previous relevant work, for the scope defined in the title. It is not an exhaustive collection of

Abbreviations: CEDP, Conflict and error detection and prognostics; LAN, Local area network; SC(s), Supply chain(s); SLA, Service level agreement; SN(s), Supply network(s); QoS, Quality of Service; WSN(s), Wireless sensor network(s).

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Nomenclature

a, i, j	Supply network agent
A	Set of supply network agents a
A^I	Set of source (input) agents
A^K	Set of kernel agents
A^O	Set of sink (output) agents
CL	Set of communication links $cl_{i\rightarrow j}$
$cl_{i\rightarrow j}$	Communication link from i to j
CN	Communication network (A, CL)
CP_a	Control protocols of agent a
FL	Set of flow links $fl_{i\rightarrow j}$
$fl_{i\rightarrow j}$	Flow link from i to j
FN	Flow network (A, FL)
L	Set of supply network links $FL \cup CL$
$QoS_{i\rightarrow j}$	QoS delivered to agent j by agent i
QoS_{SN}	QoS delivered by agents $i \in A^I \cup A^K$ to agents $j \in A^O$
R_a	Internal resources of agent a
$SLA_{i\rightarrow j}$	Service level agreement between agents i and j
SN	Supply network (A, L)
$\phi^k_{fl_{i\rightarrow j}}$	Attribute of flow link $fl_{i\rightarrow j}$
$\phi^h_{cl_{i\rightarrow j}}$	Attribute of communication link $cl_{i\rightarrow j}$

articles related to supply network resilience within a predefined publication period, but rather a selection of articles from various sources and domains. Articles were obtained from *Engineering Village*, a search engine comprising Compendex and Inspec databases, as well as Google Scholar, following the search methodology proposed by Webster and Watson (2002); search keywords include resilience, resiliency, supply chain, supply network, complex network (systems), agent, disruption, vulnerability, error/conflict, collaboration, topology, and combinations thereof.

Based on the above described review methodology, this article first develops a SN formalism capable of encompassing physical, digital, and service SNs. Review and analysis of 28 articles addressing supply chain definitions, the shortcomings of a "chain" paradigm, and the emergent notion of supply networks to model complex flow systems in digital, physical, and service domains provides sufficient evidence for the need of a unified SN formalism. Furthermore, the applicability of the SN formalism introduced in Section 2.2 is validated by a review of 26 articles from various domains, in which the SNs modeling approaches used are comprised within the unified SN formalism.

The overarching SN formalism provides a foundation to review and analyze further research articles from various fields, in search for a unified understanding of resilience in SNs. Building on the common aspects of the definitions of resilience found in 30 articles from previously disjoint research areas, resilience is characterized through a set of five fundamental concepts applicable to SNs in general. Further analysis of the reviewed articles suggest that design for resilience needs to address two dimensions, i.e., SN structure and control protocols, at two different levels, i.e., agent- and network-level.

The SN formalism and resilience fundamentals, dimensions, and levels provide a starting point for future work in SN resilience to create more connections among previously disjoint research fields. As gaps are closed, a unified understanding of SN resilience and its enablers will emerge, with extended applicability to multiple SNs types and combinations. The remainder of the article is organized as follows: Section 2 presents a supply network formalism and discusses necessary assumptions for the formalism to encompass various types of digital, service, and physical supply networks; Section 3 reviews definitions of resilience from various authors, extracts their main common concepts; Section 4 characterizes resilience dimensions and levels found in the reviewed definitions; and finally, Section 5 summarizes findings, shortcomings in current research and outlines future work directions.

2. Supply network assumptions and formalism

2.1. Supply chains… or supply networks?

By definition, a chain is a collection of elements that are connected to each other forming a line; each element is connected to, at most, two other elements. Initially, this notion of sequential connections provided a sound conceptual model for real-world manufacturing processes entailing the transformation of natural resources into finished products, giving rise to the idea of a Supply Chain (SC). Over time, researchers and practitioners introduced various definitions of SC, e.g., an integrated process to source, manufacture, and deliver products involving forward product and backward information flows (Beamon, 1998), a sequence of production and distribution activities (Stevenson & Spring, 2007), a system of firms that are linked via buyer-supplier relationships (Dass & Fox, 2011). Despite the increase in SCs' complexity, with growing number of participants and interrelations, the concept of SC as a sequence of stages is still in place, as evidenced, for instance, by the current version of the Supply Chain Operations Reference model (Huan, Sheoran, & Wang, 2004; Leukel & Sugumaran, 2013; Luck & D'Inverno, 2001; Supply Chain Council, 2010). This widely used framework, developed by the Supply Chain Council to model SCs, proposes a sequential model where a company will focus on its suppliers, internal processes, and customers, and may eventually include more distant participants upstream or downstream (e.g., the company suppliers' suppliers).

Formally, a Supply Chain can be defined as a set of agents arranged in sequential stages or, more traditionally, echelons, where physical flow occurs in one direction between connected agents in neighboring echelons, and information flow occurs in the opposite direction. The model is product (flow)-centric (Braziotis, Bourlakis, Rogers, & Tannock, 2013) and/or agent-centric (Christopher & Peck, 2004) in that the SC will contain enough information to fully describe the flow of one type of product or the flow relative to the transformation made by one agent. This representation of the interrelations among agents presents three main shortcomings: (a) incompleteness, (b) intransitivity, and (c) non-reversible flows.

Agents can be part of several SCs (Braziotis et al., 2013), nonetheless, connectivity of agents, beyond the focus of the SC under consideration, is not adequately represented (Dass & Fox, 2011). This incomplete representation of the interactions that are relevant to the SC focus in order to model the competition over upstream resources may lead to sub-optimal or even adverse decisions. For instance, consider Fig. 1(a) where the SC of agent A is depicted by grey circles in echelons −2 to +1. Agent B is a direct predecessor of A and is also part of a different SC with agents C and D. Although D and A may not compete over the same market, they are in direct competition for the resources of B and, therefore, the existence of a connection between B and D is relevant to A. Moreover, C is a predecessor of B whose actions can affect the decisions B makes regarding how it allocates resources to serve A and D (e.g., if C reduces the cost of a raw material B used to provide D, it could make it more desirable for B to allocate more capacity to D and less to A) and, therefore, it is of relevance to A.

Intransitivity refers to the inability of the SC model to include transitive relations among agents, where C is a predecessor of B and A, and B is a predecessor of A, as shown in Fig. 1(b). By constraining the SC agents to belong to sequential echelons and flow to occur between neighboring echelons, transitive relations must be modeled by replicating the predecessor common to two