Chapter 2
Supply Networks

Real-world systems are inherently complex, formed by a large number of self-governing interconnected agents which dynamically update their behavior rules and connections based on context and environment changes. In order to model and understand the basic properties of these systems, it is necessary to start from a common definition of their components and main evolution processes.

In this chapter, the foundations introduced by Reyes Levalle and Nof (2017) to model supply networks as complex adaptive systems are presented. The traditional (linear) supply chain model is discussed and contrasted with a more advanced formalism, i.e., supply networks. Supply network components, agents and links, as well as basic network structure dynamics, formation and reconfiguration, are defined based on the notion of autonomous agents and graph theory. The concepts introduced in the following sections will provide the theoretical basis for supply network modelling and analysis, and for the discussion of supply network resilience, throughout this book and in future research efforts in the field.

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.:

R. Reyes Levalle, *Resilience by Teaming in Supply Chains and Networks*,
Automation, Collaboration, & E-Services 5, DOI 10.1007/978-3-319-58323-5_2

(1) An integrated process to source, manufacture, and deliver products involving forward product and backward information flows (Beamon 1998)
(2) A sequence of production and distribution activities (Stevenson and Spring 2007)
(3) A system of firms that are linked via buyer-supplier relationships (Dass and 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 (Luck and D'Inverno 2001; Huan et al. 2004; Supply Chain Council 2010; Leukel and Sugumaran 2013). 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 et al. 2013) and/or agent-centric (Christopher and 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 and 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. 2.1a where the SC of agent A is depicted by grey circles in echelons −2 to +1.

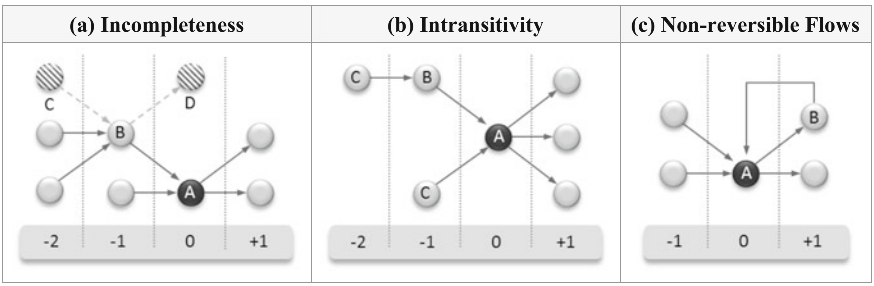

Fig. 2.1 Main shortcomings of the supply chain concept

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. 2.1b. 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 or more agents, potentially overlooking the effects of correlation. For instance, in Fig. 2.1b a disruption in C will directly affect A, but it will also affect B which, in turn will affect A.

The notion of sequential flow between neighboring stages also constraints the modeling of reverse flows, necessary for re-manufacturing and recycling as well as for returns of flow that did not met the service level agreement (SLA) between two agents. These needs led to the relaxation of the sequential flow constraint and gave rise to the concept of "closed-loop" SCs as an extension of traditional SCs (see Stindt and Sahamie (2012) for a review on closed-loop SCs).

Although the SC model could be further relaxed and modified to include new extensions and overcome some of its inherent limitations, the introduction of a new paradigm to describe relationships among agents, free from the SCs shortcomings, seems more suitable. As argued by Fiksel (2003), it is not possible to model complex non-linear systems by connecting a series of fragmented linear models; these models oversimplify and distort the reality of real-world systems (Hearnshaw and Wilson 2013).

Lately, researchers have been increasingly embracing the notion of Supply Network (SN) to describe the complex interrelationships among agents (Lamming et al. 2000; Harland et al. 2001; Christopher and Peck 2004; Thadakamalla et al. 2004; Pathak et al. 2007; Stevenson and Spring 2007; Dass and Fox 2011; Nair and Vidal 2011; Corominas 2013; Hearnshaw and Wilson 2013); nevertheless, there is no unified definition for SNs. Flow in SNs is not necessarily restricted to physical goods; it can also involve services (Lamming et al. 2000; Harland et al. 2001; Cui et al. 2010; Corominas 2013; Hearnshaw and Wilson 2013) or tasks (Moghaddam et al. 2016). Moreover, the supply of digital flow, e.g., signals, digital information, and/or data in communication and sensor networks, can also be described under the paradigm of a SN.

Despite the differences among physical, digital, and service SNs (or any combination thereof) it is possible to develop a unifying framework for their design, operation, and performance analysis. The advantage resides in that the framework will leverage the complementarity of previous research focused solely on physical, service, or digital SNs; care must be taken to evaluate whether certain assumptions pertaining one network type invalidate the use of some approaches from a different domain or, conversely, to examine which changes need to be made to methodologies proven effective in one domain to also be beneficial in other domains.

2.2 Supply Networks: An Introductory Definition

In general, a supply network can be defined as a collection of interconnected agents that interact via communications and flow exchanges to fulfill their individual objectives and/or a set of common goals. In order to formalize a definition and model for SNs that encompasses physical, digital, and service SNs, it is required first to characterize its two principal components: SN agents and SN links.

2.2.1 Supply Network Agents

Lately, engineering and science research has been increasingly focusing on problems concerning the interaction of multiple entities which make decisions with some degree of decentralization. The advent of multi-agent systems theory has led to the introduction of various definitions of the term *agent*; nonetheless, several attributes and components are common to most variants. Agents, which can be physical (e.g., humans, robots, sensors, manufacturing facilities) or intangible (e.g., software programs) entities, must be (1) autonomous—able to control their own actions and internal resources, (2) goal-oriented—capable of making rational decisions leading towards the achievement of their own goals, and (3) interactive—able to communicate with other agents and to react to changes in the context or environment (Franklin and Graesser 1997; Luck and D'Inverno 2001; Nof 2003; Allwood and Lee 2005; Velásquez and Nof 2009; Wooldridge and Jennings 2009).

Based on the aforementioned characteristics of agents, a SN agent (a), Fig. 2.2, can be defined as:

> An autonomous entity with self-interested goals comprising (1) a set of internal resources R_a capable of processing input into output and (2) a collection of control protocols CP_a which coordinate collaboration among internal resources and regulate communication and interactions with other agents.

2.2.2 Supply Network Links

SN agents interact to enable physical (e.g., products), digital (e.g., signals), and/or service (e.g., tasks) flow among their internal resources and to exchange information via control protocols. Flows and information exchanges form unidirectional

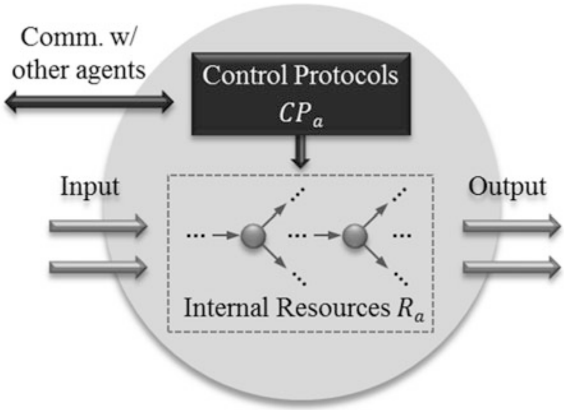

Fig. 2.2 Supply network agent

associations, i.e., in the direction of flow or communication, between SN agents; these associations can be formally characterized as links.

A flow link $(fl_{i \to j})$ is formally defined as:

> A connection between the internal resources of SN agents i and j which enables flow from i to j.

Every flow link has a set of time-dependent attributes $\Omega[fl_{i \to j}]$, e.g., capacity, status, which fully describe the interaction between i and j at time t.

Communication links, on the other hand, are part of the SN control structure and enable interaction between two agents. Formally, a communication link $(cl_{i \to j})$ is:

> A connection between the control protocols of SN agents i and j which enables information to be sent from i to j.

As in the case of flow links, every communication link has a set of time-dependent attributes $\Omega[cl_{i \to j}]$, e.g., capacity, status, which fully describe the interaction between i and j at time t.

Whenever two agents i and j form an association, the direction of the link $i \to j$ determines precedence; therefore, i is a predecessor of i and, conversely, i is a successor of i. Each link between any two agents i and i comprises a service level agreement $(SLA_{i \to j})$, in which, limits and valid ranges for relevant flow and communication link attributes are defined. Then, at any time t, the quality of service provided to agent i by agent i, $QoS_{i \to j}$ can be expressed as a function of $SLA_{i \to j}$, $\Omega[fl_{i \to j}]$, and $\Omega[cl_{i \to j}]$.

$$QoS_{i \to j}(t) = f\left(SLA_{i \to j}, \Omega\left[fl_{i \to j}\right], \Omega\left[cl_{i \to j}\right]\right).$$

2.2.3 Supply Network Definition

Agents and links are the building blocks of Supply Networks (SNs), which can be formally defined as:

> A collection of autonomous agents with self-interested goals that interact to enable physical, digital or service flow through a series of links.

SN agents' interactions constitute a form of e-work, defined by Nof (2003) as any collaborative, computer-supported and communication-enabled productive activities in highly distributed organizations of humans and/or robots or autonomous systems.

2.3 Graph Theory-Based Formalism for SNs

Consider a set $A = \{1, \ldots, a\}$ of supply network agents which form associations by establishing flow and communication links, and let $FL = \{fl_{i \to j} | i, j \in A \text{ and } i \neq j\}$ and $CL = \{cl_{i \to j} | i, j \in A \text{ and } i \neq j\}$ be the set of flow links and communication links, respectively. Then, from a mathematical perspective, a supply network SN can be represented by a directed graph with nodes $a \in A$ and arcs $l \in L = FL \cup CL$. Lee II et al. (2007) use a similar approach to model interdependent network flows by introducing a layer (network) for each type of flow and adding constraints on flows at nodes common to several networks to account for interdependences. It can be argued, though, that each layer in the interdependent network is either a flow or communication network and that interdependency constraints are part of the SN agents' control protocols CP_a.

Based on the links formed by agents in A, the latter can be classified as source (or input) agents, kernel agents, and sink (or output) agents. A source agent $a \in A^I \subseteq A$ is a SN agent that lacks input flow links. Formally,

$$A^I = \{a \in A | \nexists fl_{i \to a} \in FL,\ i \in A\}$$

A sink agent $a \in A^O \subseteq A$ is a SN agent that lacks output flow links. Formally,

$$A^O = \{a \in A | \nexists fl_{a \to j} \in FL,\ j \in A\}$$

A kernel agent $a \in A^K \subseteq A$ is a SN agent which has at least one input and one output flow link with other agents in A. Formally,

$$A^K = \{a \in A | \exists fl_{i \to a} \in FL \text{ and } \exists fl_{a \to j} \in FL, \quad i, j \in A\}$$

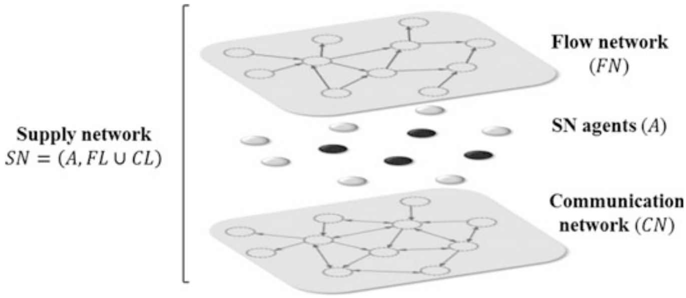

Fig. 2.3 Supply networks: a combination of flow and communication networks

Therefore, from a functional viewpoint, a supply network $SN = (A, L)$ can be formally defined as:

> The conjunction of a flow network $FN = (A, FL)$ and a communication network $CN = (A, CL)$ through which agents in A interact in order to fulfill their individual objectives and/or a set of common goals (Fig. 2.3). Interactions enable input from source agents $A^I \subset A$ to flow through kernel agents $A^K \subset A$ and reach sink agents $A^O \subset A$.

The objective of the SN is to provide sink agents in A^O with an adequate QoS based on their individual service level agreement (SLA) with agents either in A^K or A^I. Then, quality of service at network level can be measured by aggregating local QoS values as follows

$$QoS_{SN}(t) = f\left(SLA_{i\to j}, \Omega\left[fl_{i\to j}\right], \Omega\left[cl_{i\to j}\right]\right), \quad \forall\, i \in A^I \cup A^K \text{ and } j \in A^O.$$

2.3.1 *Supply Network Dynamics*

Several authors have studied the mechanisms behind network evolution over time from a structural perspective (the reader is referred to Albert and Barabási (2002) for a summary of previous research in this area). Despite the variety of processes that can shape a SN's structure, these can be clustered in two main categories: formation and re-configuration.

Formation is the process by which a supply network $SN^* = (A^*, L^*)$ is obtained from $SN = (A, L)$ by (1) adding a set of agents A^+ and links L^+ to, and/or (2) removing a set of agents A^- and links L^- from SN.

Formally, let A, A^+ and A^- be sets of agents such that $A^+ \cap A = \varnothing$ and $A^- \subseteq A$; then, $A^* = A^+ \cup (A \cap A^{-c})$. Moreover, let L^+ be the set of links between agents i and j such that $i \in A$ and $j \in A^+$, or $j \in A$ and $i \in A^+$, and let L^- be the set of links between h and k such that $L^- \subseteq L$ where at least one element in $\{h, k\} \in A^-$. Then, $L^* = L^+ \cup (L \cap L^{-c})$

Reconfiguration is the process by which a set of agents in A create a set of links L^+ and/or eliminate a set of links L^- with other agents in A, transforming $SN = (A, L)$ into $SN^* = (A, L^*)$.

Formally, let L^+ be a set of links between agents $i, j \in A$ such that $L^+ \cap L = \phi$ and L^- be a set of links between agents $h, k \in A$ such that $L^- \subseteq L$; then, $L^* = L^+ \cup (L \cap L^{-c})$.

2.4 Examples

The formalism introduced in the previous section is independent of the real-world realization of agents, their objectives, the type of information exchanged, and the flow/s which are central to the supply network; therefore, it can be used to conceptualize and model physical, digital, and service supply networks. Table 2.1 presents a summary of the examples described in the next paragraphs along with the main findings of this section.

Digital supply networks involve a set of interconnected agents responsible for generating, storing, transforming, transmitting, and receiving signals or information, e.g., sensor networks (Colbourn 1993; Liu and Nof 2004; Jeong and Nof 2009; Erdene-Ochir et al. 2010), and computer and communication networks (Colbourn 1993; Faloutsos et al. 1999; Tangmunarunkit et al. 2002; Sabella and Iovanna 2006; Lau et al. 2008; Pereira and Neumann 2009). In sensor networks, agents include sensing devices, computational processors of intelligent sensors, base stations, and external processing units, and, links, both for flow and communication, comprise physical or wireless connections among agents. Similarly, in computer and communication networks, e.g., Internet or a LAN, agents involve routing devices, servers, databases, user interfaces, and field devices (sensors and actuators), and links include all physical, e.g., cable, fiber optic, and wireless, e.g., radio frequency, Wi-Fi, communication channels. The common characteristic among digital supply networks is that *FN* and *CN* share a single physical/wireless network, i.e., communication messages among agents are transmitted through the same physical network used for signal transmission.

In physical supply networks, agents are also responsible for generating, storing, transforming, delivering, and receiving flow, but in the form of physical products. Physical SN agents include (but are not limited to) production equipment, manufacturing facilities, warehouses, power generation plants, pumping stations, water treatment plants, cross-docking facilities, and ports, among other. Examples of physical SNs include production and manufacturing networks (Paquet et al. 2004, 2008; Adenso-Diaz et al. 2012; Hu et al. 2013), logistics and transportation networks (Meepetchdee and Shah 2007; Kaluza et al. 2010; Baroud et al. 2014), and utility networks, e.g., water (Todini 2000) and power generation/distribution grids (Rosas-Casals 2010; Zio and Piccinelli 2010; Zio and Sansavini 2013).

Table 2.1 Summary of supply network examples

SN domain	Agents (A) and links (L)	Example(s)
Physical	**A:** Equipment/facilities that generate, store, transform, and deliver, flow of physical products **L:** Conveyor belts, roads, pipes	Production networks (Paquet et al. 2004, 2008; Adenso-Diaz et al. 2012; Hu et al. 2013) Transportation networks (Meepetchdee and Shah 2007; Kaluza et al. 2010; Baroud et al. 2014) Utility networks (Todini 2000; Rosas-Casals 2010; Zio and Piccinelli 2010; Zio and Sansavini 2013
Digital	**A:** Devices that generate, store, transform, transmit, and receive signals or information **L:** Cables, optic fiber, radio frequencies	Sensor networks (Colbourn 1993; Liu and Nof 2004; Jeong and Nof 2009; Erdene-Ochir et al. 2010) Computer and communication networks (Colbourn 1993; Faloutsos et al. 1999; Tangmunarunkit et al. 2002; Sabella and Iovanna 2006; Lau et al. 2008; Pereira and Neumann 2009)
Service	**A:** Resources that execute tasks, e.g., operators, software agents, processing units **L:** Logic sequence of steps required to execute a workflow	Product development projects (Lee and Suh 2008) Workflow management systems (Cao et al. 2004) Collaborative networked organizations (Moghaddam et al. 2016)
Combined	**A, L:** Any combination of physical, digital, and service agents/links	Equipment maintenance (Mahulkar et al. 2009) Power generation/distribution (Lee II et al. 2007) Integrated business process management and manufacturing networks (Luo et al. 2001; Dotoli et al. 2006; Zhang et al. 2010)

Service networks involve the flow of tasks between agents which are responsible for their execution. Upon receiving a task from a predecessor, an agent must process it using its internal resources. Once processing is completed, an agent can send additional tasks to other agents within the service network. Workflow networks, e.g., product development projects (Lee and Suh 2008) and software workflow management (Cao et al. 2004), in which activities or tasks need to be executed by various agents to complete a project or request are examples of service networks.

Oftentimes, physical supply networks need to interface with service networks (Cui et al. 2010) or other physical networks. In these interactions, the primary physical network requires specific flow from the secondary physical network or the execution of tasks or allocation of resources from a service network. Examples of these interactions are (1) equipment maintenance, where a crew is responsible for performing maintenance tasks on the resources of a set of processes which are part of a physical supply network (Mahulkar et al. 2009), (2) power generation/distribution, in which a set of agents is responsible for providing the physical supply network agents with energy to function (Lee II et al. 2007), and integrated business process management and manufacturing networks, where business management agents make decisions affecting the operation of manufacturing agents (Luo et al. 2001; Dotoli et al. 2006; Zhang et al. 2010).

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http://www.springer.com/978-3-319-58321-1

Resilience by Teaming in Supply Chains and Networks
Reyes Levalle, R.
2018, XII, 150 p. 42 illus., Hardcover
ISBN: 978-3-319-58321-1