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LOGISTICS AND SERVICE OUTSOURCING: ADVANCED MODELS AND TOOLS FOR SUPPLY CHAIN MAPPING

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LOGISTICS AND SERVICE OUTSOURCING: ADVANCED MODELS AND TOOLS FOR SUPPLY CHAIN MAPPING

BY

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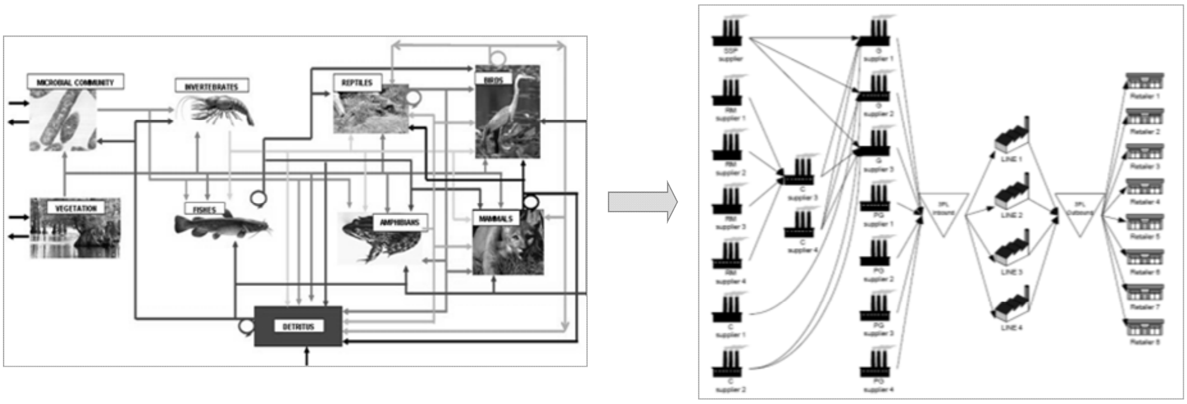

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ABSTRACT

The present Ph.D. thesis comes from the consideration that distribution networks and logistics networks urgently require new and efficient logistics management strategies to preserve their competitiveness, increase the level of organization and control the increase of system complexity, at the same time. The research explores the fundamental theories concerning Distribution Network Optimization in the presence of Logistics Outsourcing and analyzes the complexity of Supply Networks with a quantitative approach, by proposing new techniques to study specific aspects of a complex logistics network and emphasizing the importance and the need for new systemic approaches in the development of these particular disciplines.

The main objectives of the present thesis are:

1. Demonstrate the effectiveness of a new theoretical model of Supply Network Analysis (SNA), derived through a multidisciplinary approach, to study logistics networks, whose basic principles are borrowed from the information theory (Shannon) and the ecological systems theory (Ulanowicz).

2. Show how the design of efficient and durable Supply Networks should be supported by appropriate mathematical models and not only semi-quantitative procedures.

3. Analyze the performance of a Supply Network in the presence of logistics and service outsourcing, with deep insight into the role and the strategic impact of the service providers involved.

4. Develop and validate a new and integrated model for Network Analysis using virtual case instances and real case studies, based on the concept of "information entropy" (Shannon, 1948) and entropic complexity indexes derived by ecology, as a tool that supports mapping and rating activities of a logistics network, decision-making, alternative scenarios analysis and design and reengineering of supply chains.

These accomplishments are associated with an appropriate software application.

This work, conducted with a profitable interdisciplinary collaboration with the Department of Ecology and Evolution at the University of Chicago, is devoted to investigate goods distribution in supply networks, especially characterized by logistics outsourcing, and to develop better theories on the supply network mapping problem and its application to industrial contexts.

INTRODUZIONE

La presente tesi di dottorato nasce dalla convinzione che le reti distributive e i network logistici richiedano urgentemente nuove ed efficienti strategie di gestione per preservare la loro competitività, aumentare il livello di organizzazione e controllare al tempo stesso l'incremento di complessità dei sistemi. La ricerca analizza le teorie fondamentali riguardanti l'ottimizzazione dei network distributivi (Distribution Network Optimization) in presenza di outsourcing logistico (Logistic Outsourcing) e affronta l'analisi della complessità di un Supply Network (Supply Network Complexity Analysis) con approccio quantitativo, proponendo nuove tecniche per studiare aspetti peculiari di una rete logistica complessa e sottolineando l'importanza e la necessità di nuovi approcci sistemici per favorire lo sviluppo futuro di queste discipline.

Il lavoro si pone quattro obiettivi principali:

1. Dimostrare l'efficacia di un approccio metodologico di tipo multi-disciplinare allo studio delle reti logistiche, sviluppando efficacemente i principi di base derivanti dalla teoria dell'informazione (Shannon) e dalla teoria dei sistemi ecologici (Ulanowicz).

2. Mostrare come la progettazione di Supply Network efficienti e longevi da un punto di vista logistico debba essere supportata da modelli matematici adeguati e non soltanto da procedure semi-quantitative.

3. Analizzare la performance del Supply Network in presenza di outsourcing di servizi e attività logistiche, comprendendo a fondo il ruolo e l'impatto strategico dei service providers appartenenti alla rete.

4. Sviluppare un nuovo modello organico e integrato di Network Analysis (supportato da un adeguato strumento di calcolo) e validarlo mediante casi studio reali. Il modello, basato sul concetto di "entropia dell'informazione" (da Shannon, 1948) e sulle misure entropiche della complessità delle reti, risulta uno strumento in grado di supportare le attività di mappatura e rating di una rete logistica, coadiuvando così il decision making, l'analisi di scenari alternativi e il supply chain mapping e reengineering.

Questi traguardi sono associati allo sviluppo di un opportuno strumento di calcolo per l'applicazione del modello teorico.

Il lavoro di ricerca è stato sviluppato grazie ad un'efficiente collaborazione interdisciplinare con il dipartimento di Ecologia ed Evoluzione dell'università di Chicago e, fin dall'inizio, si è posto l'obiettivo di investigare i flussi logistici caratteristici di un Supply Network in presenza di outsourcing della logistica e, più in generale, di fenomeni di integrazione e centralizzazione di rete, apportando un'innovazione sia nella base teorica riguardante la progettazione dei network logistici, sia nella conseguente applicazione pratica in contesti industriali a noi contemporanei.

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First of all I would like to express my huge gratitude to my PhD program supervisor, prof. Daria Battini, for her constant example of professionalism, expertise and friendship. She was also the one who told me about the chance to take the challenge and who has believed in me from the beginning.

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I'm also very grateful to all my research group colleagues, who have shared this journey with me, but most of all welcome me in the group since the beginning and shared with me their expertise: Fabio Sgarbossa, Maurizio Faccio, Giorgia Zanin and Mauro Gamberi.

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I can't forget Stefano Allesina, a brilliant researcher of the Chicago University, who was the first, together with prof. Daria Battini to brilliantly accost ecological network and industrial network. I thank them to have welcome me on board years ago, sharing with me ideas and encouraging me through the development of this successful interdisciplinary collaboration.

Moreover, I would like to greet Prof. Alberto Regattieri, for his profitable collaboration, comments and criticism during the papers writing and revision.

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Thanks to the colleagues of the "ING-IND/17" group, especially to those who offered me professional enrichment and to those with whom I shared hearty laughs during the last three summer schools.

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Above all, I thank my husband Simone for his love, encouragement and sharing: without him behind me, I would never be able either to finish or to start this adventure.

Finally, thanks to our four gorgeous rogues... and thanks to the sincere laughs they offered me in many occasions. I'd like to report two sentences of my two older children, which are pretty representative of how they went through this journey with me: 1) "*Mum, why are you asking me everyday how was school? I'm not going to be able to hold on until my PhD if you continue bothering me like that!*"; 2) "*Mum, are you thinking to be able to read all this staff without figures?!? I'm pretty sure I'm gonna die before you finish it!*"

Thanks to you all.

Vicenza (Italy), January 2012,

Anna Azzi

To Simone and “the four little rascals”

...and to my dear grandma

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"If you have an apple and I have an apple and we exchange these apples, then you and I will still each have one apple. But if you have an idea and I have an idea and we exchange these ideas, then each of us will have two ideas"

George Bernard Shaw

1

Introduction

This section is dedicated to describe the main goals of the present PhD thesis, as well as its outline, and it briefly describes the scientific contributions developed and studied for this research purposes (their full version is also enclosed and it can be found at the end of the thesis).

1.1 Purpose

Industrial organizations supply a variety of products and services, meet the multiple expectations of different customer, and cope with the consequences of the globalization of world markets, all of which are producing significant levels of complexity. To ensure growth and survival in today's business environment, supply chains need to supply the desired product, in desired quantity, in the desired place at the desired moment, at a reasonable price, hence, accuracy, flexibility, agility, cost reduction and control, all play a key role. The only way to achieve such goals is by improving processes both internally and externally.

At the same time, modern supply chains are certainly longer and more fragmentised than they used to be: the walls of the enterprise continue to move out. Businesses are outsourcing more and more, and partnerships and organizations are reaching out to one another. This is leading to an increasing need for integration and complexity management, strategies implementation such as outsourcing, centralization and share of recourses and services.

Over the years, Third-party logistics (3PL) has been adopted by companies with the objective of helping organizations with their value chain activities and hence to be competitive, flexible and responsiveness to dynamic market requirements.

Again, according to literature and practice, what is produced in outsourcing logistics has effects not only on the parties directly involved, but also on other relationships and organizations within the network in which the relationship is established. Up to now, 3PL outcomes from the point of view of the parties directly involved (shipper, manufacturer and logistics service provider) are often addressed in literature, while the "external outcomes" experienced at the supply chain level need further analysis.

Three main considerations can be derived by an exhaustive literature review on logistics outsourcing:

- The explosion of the phenomenon and the importance and relevance of the topic is supported by a vast literature, for the most part recent, which emphasizes the increase in the diffusion of outsourcing across industries worldwide (e.g. Carter and Yan, 2007, Gunasekaran and Sarkis, 2008).
- A lack of theoretical contributions and mathematical models, versus empirical researches and descriptive studies, as supported by state of art surveys (e.g. Marasco, 2008; Selviaridis and Spring, 2007).
- A lack of holistic approaches to the study of logistics outsourcing: despite the fact that logistics providers are often required to offer skills and services linked to supply chain management, literature does not tackle this issue (few exceptions are related to qualitative contributions, e.g. Ellram and Cooper, 1990, Aas et al., 2008). Existing literature offers merely dyadic approaches and the very few studies of logistics triads and networks do not seem to add any supra-dyadic information (Aas et al., 2008; Selviaridis and Spring, 2007).

The present study has a simple aim: to research the phenomenon of logistics outsourcing with the application of innovative advanced models and tools to support the efficiency of this widespread phenomenon in an industrial context characterized by high complexity.

The research project analyzes fundamental theories concerning Distribution Network Optimization in case of Logistics Outsourcing or Service Sharing, and analyzes the complexity of a Supply Network with a quantitative approach, by proposing new techniques to study specific aspects of a complex logistics network, and emphasizing the importance and the need for new systemic approaches (supported by appropriate software tools) to facilitate the future development of these disciplines.

The work has four main objectives:

1. To demonstrate the effectiveness of a new theoretical model to study logistics networks, obtained through a multidisciplinary approach. Basic principles are borrowed from information theory (Shannon) and the ecological systems theory (Ulanowicz) and effectively developed to reach a well-established Supply Network Analysis (SNA).
2. To show how the design of efficient and durable Supply Network from a logistical point of view should be supported by appropriate mathematical models and not only semi-quantitative procedures.
3. To analyze the performance of a Supply Network in the presence of logistics and service outsourcing, with deep insight into the role and strategic impact of the service providers involved.
4. To develop and validate a new and integrated model for Network Analysis using virtual case instances and real case studies. The model, based on the concept of "information entropy" (Shannon, 1948) and complexity entropic indexes derived by ecology, is a tool that supports the mapping and rating activities of a logistics network, thereby assisting decision-making, the analysis of alternative scenarios and supply chain design and reengineering.

In conclusion, this work investigates the consequences on the supply network structure of outsourcing logistics activities and provides a useful tool for supply chain analysis and mapping. The new theoretical model, properly developed to investigate forward and reverse logistics flows, provides a diagnosis of supply chains structure. In particular, the research provides a set of entropic measures useful to study the quantity of information required in a network, able to quantify the level of complexity that characterizes it. Moreover, cycling logistics flows are analysed through SNA, offering a picture of their characterization and nature through the quantification of the so called Logistics Cycle Indexes (LCIs): this is crucial to understand the causes of increasing network complexity and eventually assess a quantification of network sustainability.

The developed theoretical models, some extracts of which have already been published in two different international journals, will be described extensively in this work.

This research work was developed thanks to an efficient interdisciplinary collaboration with Prof. Stefano Allesina (University of Chicago), with focus on implementing really innovative solutions in both the theoretical sector, concerning the design of logistics networks, and the practical application in contemporary industrial environments.

1.2 Thesis outline

The thesis is organized as follow:

Section 2 presents a literature review, where background on logistics outsourcing and supply chain characterizing trends and evolution are provided. Section 3 describes the new model for supply chain analysis and mapping: the Supply Network Analysis (SNA). To test and validate the developed methodology, the model was applied to some real world settings, as illustrates in Section 4. Section 5 investigates the implications of outsourcing logistics activities on the supply network structure from a complexity point of view. Finally, section 6 discusses findings, identifies the research limitations and makes suggestions for further research.

1.3 Summary of the papers

The last part of this thesis consists of two papers, the first on Supply Network Analysis and the computation of eight performance indexes based on information entropy, while the second addresses the issue of investigating the implications of outsourcing logistics activities on the supply network structure in terms of complexity.

I have had the privilege of co-authoring all the included papers, with Doctor Stefano Allesina (University of Chicago) and Prof. Alberto Regattieri (University of Bologna), for the first paper, Prof. Alessandro Persona, coordinator of my research group, and Prof. Fabio Sgarbossa, for the second. Finally, the whole research has been co-authored with my PhD supervisor, Prof. Daria Battini.

PAPER 1:

- ✓ Allesina S, Azzi A., Battini D, Regattieri A (2010). "**Performance Measurement in Supply Chain: New Network Analysis and Entropic Indexes**". *International Journal Of Production Research*, vol. 48 (8); p. 2297-2321.

Starting from the preliminary intuition published by Battini et al. (2007), this paper develops a new quantitative measurement of the complexity for industrial supply network based on Network Analysis (NA), which is often used to study natural ecosystems, focusing in particular on the concept of entropy of information. This new interdisciplinary approach takes advantage of eight new entropic indexes to map the exchanges of goods between different actors in a complex supply chain (the suppliers, manufacturers, distributors, customers, etc.). These measures provide a meaningful analysis of the level of complexity in the whole supply network, in mapping the exchanges of goods between different actors in the network. The impact of possible modifications in the structure can easily be anticipated using these tools, providing a simple evaluation of the different scenarios. The proposed methodology offers a holistic way to undertake the problem of supply network optimisation. A real world application of the developed methodology is presented to support the theoretical part of the study.

PAPER 2:

- ✓ Azzi A., Battini D, Persona A, Sgarbossa F (2010). "**Decreasing Network Complexity with Logistics Outsourcing: An Entropic Approach**". *International Journal Of Procurement Management*, vol. 3 (4); p. 339-360.

This work investigates the implications of outsourcing logistics activities on the supply network structure, by employing a set of entropic measures useful to study the quantity of information required in a network.

The research has three primary goals:

1. To help clarify the current state of the art on logistics outsourcing;
2. To present and apply 'Supply Network Analysis' (SNA), demonstrating the correlation between logistics outsourcing and supply chain complexity;
3. To overcome the dyadic approach frequently taken by the outsourcing literature.

This work investigates the implications of outsourcing logistics activities on the whole supply network structure through the utilization of SNA, useful to study the quantity of information required in a network. As Karp and Ronen's purpose (Karp and Ronen, 1992) was to show that a well-managed transition from large- to small-lot production brings a decrease need for information, this contribution aims to show that resorting to a 3PL brings decrease need for information as well. Moreover, applying 'Supply Network Analysis' (SNA), allows to highlight how networks can be much more organized when inbound and outbound logistics are outsourced, since complexity levels decrease. Thus, this research shows that a well-managed transition from a self managed structure to third-party logistics arrangement brings with it, if correctly managed, a decrease need for information and consequently a reduction in supply network complexity levels.

Two further contributions developed from this research are currently under review.

"We are close to know just about everything there is to know about the pieces: but we are as far as we have ever been from understanding nature as a whole"

Albert Barabasi

2

Literature review

This section is dedicated to describe the state of the art relative to logistics outsourcing: according to literature and practice, what is produced in outsourcing logistics has effects not only for the parties directly involved, but also for other relationships and organizations within the overall network in which the relationship is established, emphasising the need of a new integrated and holistic approach for supply chain mapping and engineering.

2.1 Logistics outsourcing

The term Logistics encompasses all the information and material flows throughout an organization (Gunasekaran and Ngai, 2003), hence , a third-party logistics (3PL) provider involves using external companies to perform logistics functions which have been conventionally operational within an organization (Işıklar et al., 2007). Some of the logistics activities are related to transport, trans-shipment, inventory maintenance , and assembling or reconditioning of products. Logistics processes and related activities may also involve order fulfillment processes, customer relationship management, customer service, and procurement such as demand management.

Today’s business environment has grand expectations for the actors of the supply chain due to the great dynamism and uncertainty of the market: pressure is on cost efficiency and customer responsiveness, so that processes need to be improved both internally and externally. Across the globe, competitive pressures and the need for performance improvement are driving an increase in the magnitude of outsourcing across industries worldwide (Carter and Yan, 2007). Over the years, 3PL has been adopted by several companies, with the objective of helping organizations with their value chain activities and hence to be competitive, flexible and responsiveness to dynamic market requirements (Gunasekaran and Sarkis, 2008; Yanxia et al., 2008). 3PL experienced an explosive growth, becoming a common practice. Keeping into account the growing trend of logistics outsourcing, many providers are now offering a variety of services (Jharkharia and Shankar, 2007), with significant consequences on global competition’s intensification, de-regulation of the transportation industry, customer expectations, focus on core competencies, increasing popularity of just-in-time (JIT) policies, and information and communication technology, leading to a stronger integration of modern supply chains (e.g. Gunasekaran and Sarkis, 2008; Lewis and Talalayevsky, 2000, Yan et al, 2006). Research in third-party logistics (3PL) has expanded rapidly as well, providing a significant amount of empirical and survey-based 3PL research (Maloni and Carter, 2006).

2.2 Pros and cons

Logistics outsourcing is an emerging trend in the global market (Işıklar et al., 2007) and several recent studies deal with the topic of 3PL’s market penetration, suggesting that an always increasing number of companies across industry sectors use 3PLs for the management of their logistics operations (e.g. Lieb and Bentz, 2004; Lieb and Bentz, 2005; Lieb and Miller, 2002). The functions performed by logistics providers can include the entire logistics process or selected activities such as inventory management, warehousing operations, consolidation and packaging, transportation and logistics information systems. Ashenbaum et al. (2005) estimated that from 1996 to 2004 market penetration for logistics outsourcing in general, measured in percentage of companies outsourcing, has increased from 5 to 8 percent annually.

Researchers have extensively discussed the relevant topics of 3PL in different perspectives and the principal benefits coming from logistics outsourcing. For example, the evaluation criteria used in the selection problems have been widely examined in many studies (e.g. Aguezzoul et al., 2007; Yan et al., 2003; Chen et al., 2006; Işıklar et al., 2007; Jharkharia & Shankar, 2007; Liu and Wang, 2009).

When successful, 3PL relationships can give both parties a competitive advantage in the marketplace (Tate, 1996) due to the ability to turn fixed costs into variable costs, achieving economy of scale and economy of scope, focusing on core competencies and capabilities, and accessing both the know-how and fresh ideas (e.g. Bask, 2001; Bowersox, 1990; Carter and Yan, 2007; Vasiliauskas and Jakubauskas, 2007; Yan et al., 2003). Again, increasing managerial incentives (Xiao et al., 2007) and acquiring tacit knowledge from outsourcing partners (Li et al., 2008) are empirically validated as some of the motivations for outsourcing, while some drawbacks and risks of this ever more common practice are described as well in some literature. Contracts and negotiation costs, increasing costs in relationship management, possible loss of internal competences, employee resistance and unrealistic understanding of the job,are all drawbacks well described by Bowersox (1990),Ackerman (1996), Harland et al. (2005), and Tsai et al. (2008).

From the literature review it was possible to identify four main topic to be dealt with by a company who is seriously evaluating the trade-off between logistics outsourcing and logistics self management. Articles are classified according to these four themes that are obviously recurring in existing literature. The outcome of this survey can be considered as a “pros and cons” list drawn by the state of the art on 3PL’s scientific literature.

In spite of the fact that some differences of opinion over whether logistic outsourcing outcomes are to be considered beneficial or detrimental, Table 1 summarises the main results of the review. The first theme focuses on pros and cons related to costs. The second dimension deals with competences. The third is about personnel reactions and behaviours. The final subject of the framework reflects benefits and risks concerning relationship management and supply chain management.

	Self management	***Outsourcing***
Cost	↓ difficulty to identify every cost ↓ high asset investment, high labour and equipment maintenance costs ↓ higher cost to access advanced technologies ↓ large hidden costs	↑ 3PL's achievement of economies of scale, economies of scope and experience serving multiple customers ↑ attracting more investment to the sector anddevelop customer markets ↑ higher return on investments ↑ reduced capital investment in facilities, equipment and manpower ↑ spreading and reducing financial risk ↑ turning fixed cost into variable costs ↓ additional cost burden of managing the outsource relationships ↓ contracts and negotiation costs ↓ increased costs in relationship management
	References: Ackerman (1996), Andersson (1995), Bask (2001), Ballou (1999), Bardi and Tracey (1991), Bowersox (1990), Carter and Yan (2007), Daugherty et al. (1996), Ellram and Cooper (1990), Harland et al. (2005), Hsiao et al. (2010), Larson and Gammelgaard (2001), Lieb and Bentz (2005), Vasiliauskas and Jakubauskas (2007), Wilding and Juriado (2004), Yan et al. (2003), Zineldin and Brendenlow (2003).	

Notes: pros/benefits (↑) and cons/risks (↓) of logistics outsourcing

	Self management	***Outsourcing***
Competences	↑ realistic understanding about job to be done ↑ retain skills and competencies ↓ difficult to develop and maintain all competences equally well ↓ difficulty to focus resources on core activities	↑ access to 'fresh ideas' and new opportunities ↑ access to advanced logistics services ↑ access to best in class skills and capabilities ↑ access to international distribution networks ↑ coordination of several customers at the same time (due to 3PL's ability to adapt to the individual customers their products and systems) ↑ easier access to logistics information systems (LIS) ↑ enable organisations to focus on core activities ↑ greater growth opportunities ↑ higher range of services ↑ improved access to and application of technology ↑ improvement of service level and end-customer satisfaction ↑ increased flexibility to meet changing market needs ↑ possible increasing of credibility and image by associating with well-known providers ↑ synergy obtained by working together ↓ 3pl's necessity of greater effort to understand the business ↓ necessity of information sharing (they might be private or related to core competencies) ↓ risk of loss of internal competence, skills and learning relating to outsourced activities ↓ risk of degradation of customer services and loss of contract with the customers (in case of failure to manage outsourcing relationships properly)
	References: Ackerman (1996), Andersson (1995), Ballou (1999), Bask (2001), Bhatnagar and Viswanathan (2000), Bowersox (1990), Boyson et al. (1999), Carter and Yan (2007), Cheong (2004), Daugherty et al. (1996), Ellram and Cooper (1990), Gunasekaran and Sarkis (2008), Harland et al. (2005), Hertz and Alfredsson (2003), Hsiao et al. (2010), Işıklar et al. (2007), Laarhoven et al. (2000), Larson and Gammelgaard (2001), Li et al. (2008), Lieb and Bentz (2005), Lounsbury (1987), Lynch (2004), Mohammed and Chang (1998), Sink and Langley (1997), Skjoett-Larsen (2000), Tsai et al. (2008), Vasiliauskas and Jakubauskas (2007), Wong et al. (2000), Yan et al. (2003).	

Notes: pros/benefits (↑) and cons/risks (↓) of logistics outsourcing

	Self management	***Outsourcing***
Personnel	↑ greater motivation for internal improvement ↑ greater sense of membership ↓ lower logistics skills	↑ improved employee morale ↑ promotion of a positive climate for learning and innovation ↑ skilled personnel ↓ employee resistance ↓ risk of demotivation and hidden desire to see relationship with the 3pl fail (due to fear of losing the job
	References: Ackerman (1996), Bowersox (1990), Daugherty et al. (1996), Ellram and Cooper (1990), Larson and Gammelgaard (2001), Lieb and Bentz (2005), Panayides and So (2005), Tsai et al. (2008)	
Relationship management and supply chain management	↑ greater sense of control ↑ independency ↓ inadequacy to manage market's higher logistics requirements	↑ concentration on a relationship continuum instead of a series of single transactions ↑ facilitates supply chain restructuring (by allowing greater changes to be made more quickly and with less investment) ↑ greater experiences ↑ maximization of supply chain efficiency and improvement of the competitive position of the entire supply chain ↑ necessity of establishing clear target, clear roles and laying down firm rules ↑ possibilities to expand geographical boundaries ↓ availability of some information may become more critical ↓ loss of control on the outsourced activities ↓ need of suitable control systems, performance measures and metrics ↓ need to develop new management competencies ↓ relationship risks such as 'vendors opportunism', 'contractual violation, 'poor communication', 'lack of shared goal'
	References: Ackerman (1996), Bask (2001), Bowersox (1990), Cheong (2004), Daugherty and Dröge (1997), Gentry (1996), Gunasekaran and Sarkis (2008), Harland et al. (2005), Hofenk et al. (2011), Kopczak (1997), Lieb and Bentz (2005), Lounsbury (1987), Panayides and So (2005), Tsai et al. (2008), Vasiliauskas and Jakubauskas (2007), Xiao et al. (2007).	

Notes: pros/benefits (↑) and cons/risks (↓) of logistics outsourcing

Table 1. Summary of a literature review: pros/benefits (↑) and cons/risks (↓) of logistics outsourcing

2.3 Dyadic approach

In spite of the great interest about logistics outsourcing and the large amount of papers on this topic, literature review reveals a relative lack and weakness of theoretical work on 3PLs (Marasco, 2008; Selviaridis and Spring, 2007) when compared with exploratory and descriptive studies (mainly surveys and empirical studies based on interviews and data collections). The theories frequently adopted to explain logistics outsourcing are transaction cost economics (TCE) and resource-based view (RBV), but still, there is a large portion of literature without proper theory basis.

Current literature seems to have largely neglected the analysis of “external outcomes” experienced at the supply chain level (Marasco, 2008). Aas et al. (2008) argue that the evolution of gradually more complex supply chains makes the logistics outsourcing decision more difficult, and that the dyadic approach frequently taken in the outsourcing literature is insufficient to provide adequate decision support in outsourcing. According to Håkansson and Snehota (1995) what is produced in outsourcing logistics has effects not only for the parties directly involved, but also for other relationships and organizations within the network in which the relationships are established. To further emphasize this idea, relationships between buyer and logistics provider falling under the denomination of 3PL are often characterized by a broad range of services, a long-term duration, joint efforts to develop cooperation, the customization of the logistics solution, and a fair sharing of benefits and risks, suggesting that 3PL incorporates strategic implications and not just tactical implications (Skjoett-Larsen, 2000): thus, 3PL is an entity that truly changes the morphology of the supply network, not a “once in while” transaction of some kind.

2.4 Supply chain mapping

Increased globalisation and continued outsourcing in various sectors have caused industry and organizations to function and compete on a supply chain level and/or interwoven demand networks’ level (Seuring er al., 2008). A generic supply chain usually provides very complex inter-correlations between its various actors: suppliers, manufacturers, distributors, customers, etc., not only based on material flows, but also on data and financial flows.

The links and the constraints on actors are numerous and mutually interdependent, with the traditional approach providing research into optimal local work conditions: each actor aims at obtaining best performance for his own local system. Consequently, optimal effectiveness in a global logistic network is not usually reached: undoubtedly, nowadays, success is not tied-up just in processes of one focal company, but in processes of all its value chains and network. Thus, the best approach is to obtain optimal performance throughout the entire network system: this is the fundamental challenge for Supply Chain Management (SCM).

According to Bowersox (1990), the overall performance is improved by 'supply chain collaboration' which facilitates the cooperation of participating members along the supply chain. This idea is stressed even more by Manzoni et al. (2006): companies cannot afford to remain isolated as their survival depends on their ability to organise an efficient supply chain, able to develop value for all participants.

For all these reason, Supply Chain mapping methodologies are gaining great importance and attention from both industry and academia. Citing Gardner and Cooper (2003) "*a supply chain map is a representation of the linkage and members of a supply chain along with some information about the overall nature of the entire map*". Increased interest upon this topic is driven by the belief that quantitative understanding through configuration analysis (i.e tier structure, dynamics, relationships/partnering models, logistics flow characteristics etc.) is very important for both measuring the effects of the actual distribution network configuration and assessing the impact of different configuration of supply networks, thus understanding possible future capabilities and performances.

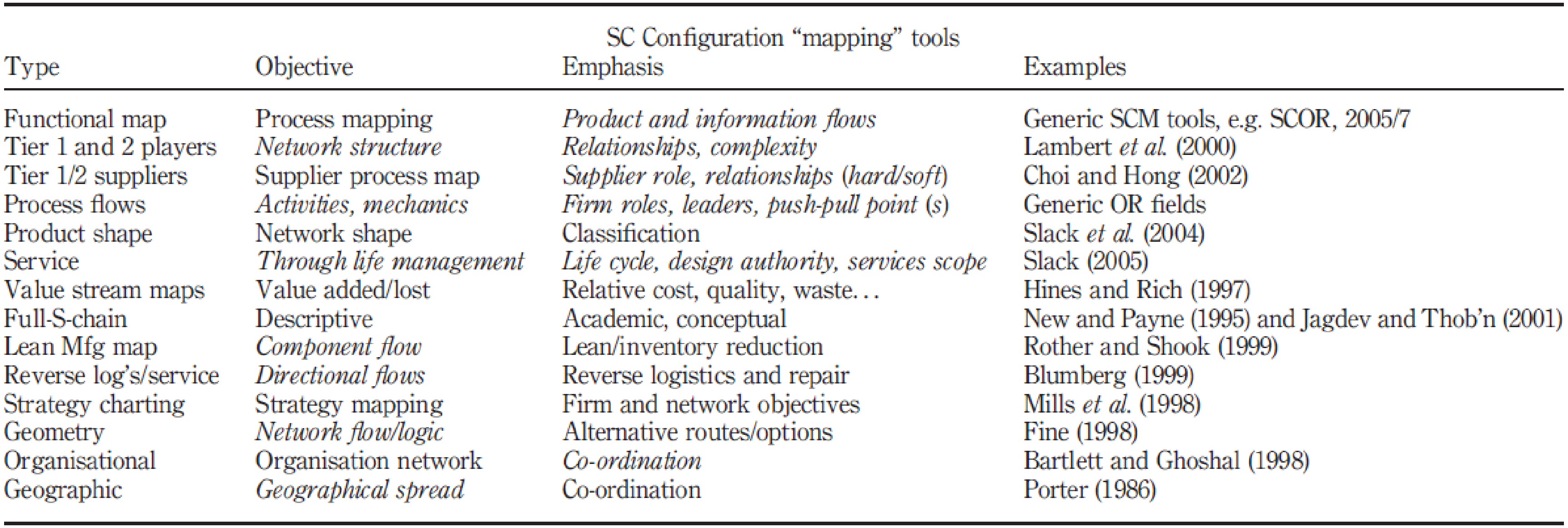
One interesting contribution on this topic is proposed by Srai and Gregory (2008), who provide a supply network configuration perspective on international supply chain development, introduce an interesting review on this topic, which is summarized in table 2, with specific examples. The principal objective of any Supply configuration mapping tools is typically to assess the impact of configuration on supply network capability and performance. Quantitative understanding through configuration analysis can be also strategic on driving recommendations on future supply network development. Gardner and Cooper (2003) launch a discussion of the alternative approaches possible for supply chain mapping, without a universal set of mapping conventions. Moreover, they recall the principle reasons driving the creation of supply chain maps:

- To link corporate strategy to supply chain strategy.
- To alert supply chain managers to possible constrains in the system.

- To help picturing the supply chain, identifying areas in need of further analysis and giving evidence for unclear inefficiencies by studying just a segment of the whole supply network. Quoting Gardner and Cooper (2003) "*with a good map rationalizing the supply chain becomes easier*".
- To offer a basis for supply chain redesign or modification (maps can be descriptive, i.e. "as is" supply chain map, or prescriptive, i.e. "to be" supply chain map).
- To help defying the perspective of the supply chain integration effort.
- To facilitate a common understanding of the supply chain, thanks to both the process of creating the map and the process of disseminating the map.
- To provide communication tools to reach across supply chain members and corporate units.
- To evaluate the progress of possible supply chain redesign goals.
- To assist tracking industry dynamics and emergencies.
- To direct individuals or firm in their role within the supply network.
- To provide guidance toward an improved supply chain management procedure.

To summarize, it can be said that supply chain mapping is strategically bonded to the decision making process, especially when it comes to supply chain configuration and performance, therefore, a key consideration in the decision making process, is how the map will be employed in conjunction with the company's strategic planning and supply chain strategic planning (Kaplan and Norton, 2000).

From this global point of view, system management is confronted by great complexity, hence optimal measurement and management of complexity is a strategic advantage. Consequently, a thorough study of the literature on this subject is beneficial. The following section is dedicated to presenting a brief review of the literature focusing on supply chain management and on the measurement of network complexity.



SC Configuration "mapping" tools			
Type	Objective	Emphasis	Examples
Functional map	Process mapping	*Product and information flows*	Generic SCM tools, e.g. SCOR, 2005/7
Tier 1 and 2 players	*Network structure*	*Relationships, complexity*	Lambert *et al.* (2000)
Tier 1/2 suppliers	Supplier process map	*Supplier role, relationships (hard/soft)*	Choi and Hong (2002)
Process flows	*Activities, mechanics*	*Firm roles, leaders, push-pull point (s)*	Generic OR fields
Product shape	Network shape	Classification	Slack *et al.* (2004)
Service	*Through life management*	*Life cycle, design authority, services scope*	Slack (2005)
Value stream maps	Value added/lost	Relative cost, quality, waste. . .	Hines and Rich (1997)
Full-S-chain	Descriptive	Academic, conceptual	New and Payne (1995) and Jagdev and Thob'n (2001)
Lean Mfg map	*Component flow*	Lean/inventory reduction	Rother and Shook (1999)
Reverse log's/service	*Directional flows*	Reverse logistics and repair	Blumberg (1999)
Strategy charting	Strategy mapping	Firm and network objectives	Mills *et al.* (1998)
Geometry	*Network flow/logic*	Alternative routes/options	Fine (1998)
Organisational	Organisation network	*Co-ordination*	Bartlett and Ghoshal (1998)
Geographic	*Geographical spread*	Co-ordination	Porter (1986)

Table 2. Supply configuration mapping tool. Source: Srai and Gregory (2008)

2.5 Complexity analysis and control

As previously highlighted, recent literature shows that companies are taking a growing interest in the global supply network, from raw materials to final products, so it becomes intrinsically more important to consider company performance by correlating it strictly to its global supply chain performance that covers suppliers, production system and distribution network. For this reason, from a holistic point of view, system management is confronted by great complexity, and optimal measurement and management of complexity are strategic advantages.

In recent years several authors have proposed different approaches to supply chain management techniques and to supply network complexity computation, considering both internal chain and external chain aspects (Harland 1996), which are summarized in Table 3.

Literature divides complexity into three types – first, 'static complexity', i.e., linked to system structure, second 'dynamic complexity', i.e., related to the material and data flows between different actors, and third 'decisional complexity', created by the managerial choices required.

Four types of approaches can be identified:

- Introductions and/or general studies. The whole problem of supply chain performance management and control is presented and the complex features of a modern supply network are underlined, with a large set of supply chain performance indexes and software packages being introduced to support the decision making and mapping of the supply network (i.e., Huan et al. 2004, Tan and Platts 2004).
- Statistical approaches. Analysis of the correlation between qualitative measurements of complexity and general supply chain performance indexes (i.e., Milgate 2001, Perona and Miragliotta 2004).
- Entropic models. Mathematical models derived by the 'entropy of information' (developed during WWII for measuring and separating information codes, (Shannon and Weaver 1948) that quantify the complexity of supply chain and manufacturing systems (i.e., Frizelle and Woodcock 1995, Calinescu et al. 1998, Sivadasan and Efstathiou 2002).
- Surveys. Mills et al. (2004) proposed and discussed several methods that provide support to companies in a complex supply chain, populated by numerous actors. The authors, however, did not discuss the problem of complexity in the supply chain, but rather

emphasised the need for studies on this important topic, justifying and validating the aims and objectives of the present research.

Many authors have examined the relationship between performance/flexibility and complexity (Calinescu et al. 1998, Milgate 2001, Arteta and Giachetti 2004, Perona and Miragliotta 2004), the results are however insufficient to validate a robust relationship. Nevertheless, it is extremely important to find the best trade-off between these parameters since poor control of complexity can produce poor performance and poor quality, generating significant additional costs. This is a substantial challenge, and Helo et al. (2006) elaborated on the topic, asserting that a supply chain may be too complex and too difficult to analyse, exceeding human information-processing capabilities.

After applying this principle, Meijer (2002) proposed an organisation design methodology based on the development of different alternative solutions and then reducing the number of alternatives until only the best alternative is left. Similarly Tan and Platts (2004) developed software to support managerial decisions, while several authors (Bullinger et al. 2002, Huan et al. 2004) accepted the SCOR model (supply chain operation reference model) developed by the Supply Chain Council (SCC).

Perona and Miragliotta (2004) defined the skill of managing supply chain complexity as strategically fundamental to modern organisations, since complexity is always transferred between actors in a supply chain (Sivadasan and Efstathiou 2002), and empirical evidence shows that companies usually manage complexity in four ways (Sivadasan et al. 2003):

- by exporting operational complexity to other actors on their own supply chain;
- by charging in the attempt of coping with imported complexity;
- by investing in precautionary systems that work to avoid complexity generation;
- by investing in resources to absorb complexity.

The most important activities in addressing complexity are to understand it, and above all, to measure it. People generally have an intuitive understanding of complexity, but experience great difficulty confronting it rigorously, according to Arteta and Giachetti, (2004), or, according to Bullinger et al. (2002), ‘only something that can or has been measured improves, and only an holistic approach prevents the adoption of sub-optimal decisions’. Also, in the literature it is possible to find several methodologies to measure and reduce complexity; some are either models based on graph theory (Seese and Schlottmann 2001), or statistical models (Beamon and Chen 2001, Milgate 2001, Blackhurst et al. 2004); others exploit entropic measurements (information entropy).

The concept of entropy was introduced by Shannon and Weaver (1948) to measure the level of uncertainty (or the information level) found in an unclear signal. Since complexity produces uncertainty in flows (materials and information), increases lead times, and may result in unreliable operations, entropy of information is a valid system for the measurement of complexity in an industrial system, and can specifically be used to measure the complexity of a global supply chain (Frizelle and Woodcock 1995). Karp and Ronen (1992) proposed entropic indexes to demonstrate that decreasing batch dimensions and that the use of just-in-time (JIT) solutions require less information, which means that the level of uncertainty is less critical.

Frizelle and Woodcock (1995) defined a measurement of the first type of complexity (static) and introduced a definition for the second type of complexity (dynamic), that deals with the uncertainty found in material and data flows, which mainly evidences itself in supply chains with queue formation in input from and/or output to different participants (Sivadasan and Efstathiou 2002). While Deshmukh et al. (1998) expanded this approach by considering the relationship between resources, the concept is further developed by Shih and Efstathiou (2002), who proposed an algorithm to analyse the effects of different manufacturing network configurations, and Calinescu et al. (1998) who put forward two complementary methodologies to estimate the complexity of a production system: the entropic procedure introduced by Frizelle and Woodcock (1995), and a similar method named MFC proposed by Meyer and Foley Curley (1995). Efstathiou et al. (2002) proposed a web-based expert system that mainly focuses on a third kind of complexity (organisational), and is based on measurement of the entropy generated by information transfers. They defined ‘decision making entropy’ as the level of entropy (organisational entropy) required for decisions to be taken correctly, and Fujimoto et al. (2003) published a very practical application of complexity measurement for which they use an entropic approach to evaluate the complexity of an assembly line.

A new measurement of complexity at the business process level of an organisation was developed by Arteta and Giachetti (2004) by creating a Petri net model of the system, in order to obtain a probabilistic analysis. They argued that less complex processes are easier to change and thus more agile, but much more extensive validation and exploration of the link between agility and complexity is required.

Deshmukh et al. (1998) tried to take the fundamental step of introducing a potential link between complexity and performance of a production system. Sivadasan et al. (2003) applied this approach to different real world cases so as to check its validity, while Wu et al. (2001) used simulation to carry out a similar validation, and Battini et al. (2007) demonstrated the potential of using the average mutual information (AMI) index to classify the level of organisation (the opposite of complexity) in a supply chain, by applying an entropic parameter in measuring material flows to a real supply network.

In the belief that information entropy is a very promising indication of supply chain complexity, this work presents the theory and then applies a new approach that can be viewed as a logical extension of the above mentioned studies on manufacturing system complexity.

		Targets										
		Complexity analysis internal supply chain			Complexity analysis external supply chain				Supply chain management			
Year	Author(s)	Static complexity	Dynamic complexity	Decisional complexity	Static complexity	Dynamic complexity	Decisional complexity	Performance indexes	Operative planning	Tactical planning	Strategical planning	Methodologies
1992	Karp and Ronen		×									Entropic model development
1995	Frizelle. and Woodcock	#	#									Entropic model development
1998	Calinescu *et al.*	#	#									Entropic model development
1998	Deshmukh *et al.*	V										Entropic model development
2001	Beamon and Chen							×				Statistical model and simulation
2001	Milgate				×	×		×				Entropic model development
2001	Seese and Schlottmann			V								Graph theory
2002	Wu *et al.*				#	#						Simulation and entropic parameters
2002	Albino				#	#			#	#		Linear programming model
2002	Bullinger *et al.*						V	V			V	Decision making model
2002	Efstathiou *et al.*	V	V	V								Software development and entropic parameters
2002	Makui and Aryanezhad	V										Entropic model development
2002	Meijer	V		V								Theoretical model
2002	Shih and Efstathiou	X										Entropic model development
2002	Sivadasan and Efstathiou		×			×			×			Entropic model development
2003	Sivadasan *et al.*								V			Theoretical model
2004	Arteta and Giachetti				#			#				Petri net model

(*continued*)

Table 3. Literature review matrix

		Targets										
		Complexity analysis internal supply chain			Complexity analysis external supply chain				Supply chain management			
Year	Author(s)	Static complexity	Dynamic complexity	Decisional complexity	Static complexity	Dynamic complexity	Decisional complexity	Performance indexes	Operative planning	Tactical planning	Strategical planning	Methodologies
2004	Blackhurst *et al.*				#	#			#	#		Statistical model and Petri net model
2004	Blecker *et al.*				V	V					V	Theoretical model
2004	Huan *et al.*						V	V			V	Decision making model
2004	Mills *et al.*				–	–						Survey
2004	Perona and Miragliotta	#	#		#	#						Complexity index development
2004	Tan and Platts			#								Software development and entropic parameters
2006	Battini *et al.*				#	#		#	#	#	#	Entropic model development
2006	Helo *et al.*				×			×	×	×		Software development
2006	Laumanns and Lefeber				×	×			×			Numerical model
2006	Manzoni and Islam							×				Performance index model

Notes: Legend
V: theoretical approach;
–: survey;
×: numerical application;
#: case study.

Table 3. Continued.

2.6 Discussion

Competitiveness has forced many manufacturing companies to outsource their logistics service, leading to the growth of 3PL.

Based on an insightful literature review, three main conclusions can be drawn:

- Several recent studies deal with the topic of 3PL’s market penetration, suggesting that a increasingly greater number of companies across industry sectors use 3PLs for the management of their logistics operations [e.g. Lieb and Miller, 2002 Lieb and Bentz, 2004-2005]. Thus, logistics outsourcing practices are experiencing an *explosive growth*.
- Many contributions are exploratory and descriptive in nature (mainly surveys and empirical studies based on interviews and data collections), thus, the state of the art is characterized by a *lack and weakness of theoretical work* on 3PLs [Selviaridis and Spring, 2007; Marasco, 2008].
- Approaches belonging to expanding literature are merely dyadic and the very few existing studies of logistics triads and networks do not seem to add any supra-dyadic insights (Aas et al., 2008; Selviaridis and Spring, 2007). Therefore, scientific literature is basically characterized by a *dyadic approach*, and only few researchers studied the phenomenon considering the supply chain as a whole [e.g Skjoett-Larsen, 2000].

This underlines the importance of the present topic and, at the same time, the need for new theoretical studies of the phenomenon, possibly overcoming the frequent dyadic approach revealed by the literature.

These considerations can be even better understood if we consider that logistic providers are usually called to demonstrate expertises and skills related to supply chain management, and they urgently require new efficient management strategies to preserve competitiveness, increase level of organization and control, at the same time, the amplification of system complexity, to optimize their distribution and logistics networks. Thus, the present research comes from the conviction that logistic providers and their supply networks are in need of innovative advanced models and tools for supply chain mapping and complexity analysis.

The next section is entirely dedicated to the description of a new procedure, whose methodology, which is been called Supply Network Analysis, is been derived through a multidisciplinary approach.

"My greatest concern was what to call it. I thought of calling it 'information', but the word was overly used, so I decided to call it 'uncertainty'. When I discussed it with John von Neumann, he had a better idea. Von Neumann told me, 'You should call it entropy, for two reasons. In the first place your uncertainty function has been used in statistical mechanics under that name, so it already has a name. In the second place, and more important, nobody knows what entropy really is, so in a debate you will always have the advantage."

Claude Elwood Shannon

3

Supply Network Analysis

As mentioned in the introduction, the theories illustrated in this part develop a new quantitative assessment of the complexity of supply networks, based on Network Analysis, which is often used to study natural ecosystems, focusing in particular on the concept of "entropy of information". The research reports advances in both theory on Supply Network Analysis problem and on its application to industrial context. This new interdisciplinary approach draws on eight different entropic indexes to map the exchanges of goods between different actors in a complex supply chain and measure its complexity and organization level. Moreover, ten different Logistics Cycle Indexes (LCIs) are developed: they are meant to identify complexity drivers and quantify supply chain sustainability. These accomplishments are associated with an appropriate software application.

3.1 Introduction

A modern supply network provides very complex inter-correlations between its various actors (i.e., the suppliers, manufacturers, distributors, customers, etc.) based on material, data and financial flows (Harland 1998). This work focuses on the complex supply network (which is the 4th level supply chain, as defined by Harland (1996), where logistics activities are partially or completely outsourced, concentrating not only on the materials and information flow analysis, but also on the network structure development and re-design. We can generally distinguish two types of supply network optimization problems:

1. Network flow optimization: in this case we consider a pre-designed or existing distribution network, and we want to optimize the flow of goods/information/money through the network, without changing its structure (number of layers, depots, warehouses, etc.).
2. Network design or re-design: in this case we want to find the best configuration of facilities and relationships in order to satisfy the goals of the company and reduce the complexity of the network structure.

As previously extensively discussed, due to optimization or design purposes, it is necessary to truly know and understand the structure of the supply chain and its related logistics flows. For this reason, methodologies of supply network analysis and mapping are exceedingly important to optimize existing distribution network or to conduct scenario analysis evaluation (e.g. extension of the supply chain with new partners, supplier reduction, outsourcing policies). This research addresses in particular this issue.

The links and the constraints on actors within a network are numerous and mutually interdependent, with the traditional approach-providing research into optimal local work conditions: each actor aims at obtaining the best performance for his own local system, consequently, optimal effectiveness in a global logistic network is not usually reached. One of the fundamental challenges for supply chain management (Harland 1998, Tapscott et al. 2000) is to achieve optimal performance for the whole network from a holistic point of view as clearly stated in Manzoni and Islam (2006). Companies cannot afford to remain isolated, as their survival depends on their ability to organize an efficient ‘supply web’ that brings value for all participants.

This work deals with supply chain complexity analysis, proposing a new methodology for supply network structure optimization and monitoring, based on a new methodology employing eight different entropic performance measures, able to quantify network complexity and provide information about the network structure, and ten different Logistics Cycle Indexes (LCIs), assessing motivation for complexity and quantifying supply chain sustainability.

Monitoring supply chain complexity is very important for two reasons. First, the information obtained results in a good understanding of the global system, and offers a clear definition of the causes and effects of the problems. Second, it supports the research towards the best solutions for a network by comparing the various possible alternatives for objective and quantitative analysis.

Specifically, this study looks deeply into natural ecosystems, following the idea that there is a great morphological analogy between ecosystem networks and industrial supply networks, and, because of these analogies, several innovative concepts and methodologies successfully applied in natural systems can be adapted to industrial supply networks, as further discussed in the next section.

This work represents a second phase of the research initiated by Battini et al. (2007), whose fundamental development is a new set of quantitative measures that can be used to analyze supply networks and to assess their performances in terms of complexity and development within the network structure, as well as supply chain sustainability. In the present section, these are introduced and discussed theoretically.

3.2 From ecosystems to industrial systems

The key idea of the proposed methodology, which will be presented in the present section, lies on the analogy of ecological systems and industrial systems.

Food Webs and Ecological Networks utilize graph-theory to describe ecosystems by means of nodes-species and edges-trophic relations. The former illuminates the feeding relations among species in a qualitative (presence/absence) fashion; by the latter, it is possible to quantifies the magnitude of interactions occurring in the ecosystem, specifying the amount of matter or energy exchanged in a given time period. Food webs theory is rooted in the history of ecology (the idea was already present at the end of nineteen century - Camerano, 1880).

Ecological Network Analysis (ENA) consists of a set of tools for examining ecosystems, and it is based on the assumption that topology (statistical graph configuration associated to trophic links between species) reveals much about history, current status and function of ecosystems. At a very first glance ENA looks at ecosystems trying to answer two questions: a) Who eats whom? b) At what rate? Once these preliminary issues have been resolved, ENA allows researchers to perform procedures aimed to test the ecosystem's grade of organization, analyze the pathways occurring in the system, evaluate the number of trophic levels, estimate indirect effects and much more. The analysis of networks of ecological trophic transfers is a useful complement to simulation modeling in the quest for understanding whole-ecosystem dynamics. Trophic networks can be studied in quantitative and systematic fashion at several levels. The core of ENA was derived from economics, i.e. the structural analysis of Leontief (1963) and the generalization made by Augustinovics (1970), while the first attempt to translate these concepts in ecological terms was made by Hannon (1973). In a few years the technique was expanded to include more ecologically significant results thanks to the excellent contributions of Finn (1976), Ulanowicz (1980), Patten (1982), Szyrmer (1984) and many others.

The Supply Network Analysis (SNA) is a new and promising methodology to analyze a supply chain by means of its complexity, i.e. the structure of its logistics flows. The method deeply investigated and described by Allesina et al. 2010, starts from a preliminary intuition: that there are substantial similarities between ecological systems and industrial systems (Battini et al. 2007). In fact, while Ecosystems are collections of plant and animal species organized in complicated web-like structures by which energy and matter are transferred and transformed, a Supply Chain consists of different companies organized in complicated web-like structures by which energy, information, services and goods are likely transferred and transformed. In both supply chains and ecological systems this web-like structure is described by a network, and again, in both cases, the performance of the whole system is strongly dependent on the uncertainty of flows, on the number of partners involved (‘network nodes’) and on the quantity, typology and magnitude of exchanges that happen (‘network edges’).

Thus, since Ecological Network Analysis (ENA) (Ulanowicz, 1986; Baird and Ulanowicz, 1989; Fath and Patten, 1999) is a well consolidated methodology to study ecological system, why not to investigate it and model a new Network Analysis inspired by the ENA and opportunely developed to support the study of logistics networks?

Three kinds of similarities between industrial and ecological networks can be underlined to support this new approach:

- *Similarity in network structure*. Ecosystems are collections of plant and animal species organized in complicated web-like structures by which energy and matter are transformed and transferred. Analogously, the supply chain of a company consists of different departments, ranging from procurement of materials to customer service, and comprises a number of socio-economical activities that transform and transfer energy, information, goods and services; these processes create functional connections that link the activities to one another in a web-like structure. In both supply chain and ecological systems such web-like structures can be pictorially described by a network, which is necessary to make the system function.

- *Similarity in flow*. Flows exchanged inside the two kinds of networks are of various and different natures, for example, ecological systems are usually described in terms of exchange of energy and matter, industrial supply chains exchange goods, money, unit loads etc. In both cases the performance of the whole system is strongly dependent on the uncertainty of flows, on the number of nodes and edges and it is important to understand the trade-off between network complexity and network organization of the structure. In fact, maximum efficiency (minimum complexity) for the network often means maximum vulnerability and less flexibility to sudden changes. On the other hand, high redundancy and complexity of nodes and edges-links increase the total costs and reduce system performance.
- *Similarity in nodes*. Species inside an ecosystem are in relation with other species through a dependence relationship. In the same way, partners in a supply network have different roles inside the chain and are in a supplier-customer relationship with each other, with more or less dependence. In both cases it is important to measure how much a node is dependent on another node and how many links are redundant.

The following two illustrations compare ecosystem network structure and supply network structure: the analogy existing between them allows to apply ecological methods to study and measure the complexity of industrial supply network.

Innovative concepts and methodologies have been successfully applied in natural systems and can be adapted to optimize manufacturing systems with interesting results. The fundamental development is a new set of quantitative parameters that can be used to analyse supply chains, providing a diagnostic report related to forward and reverse logistics flows.

In the present section the SNA is introduced and discussed theoretically.

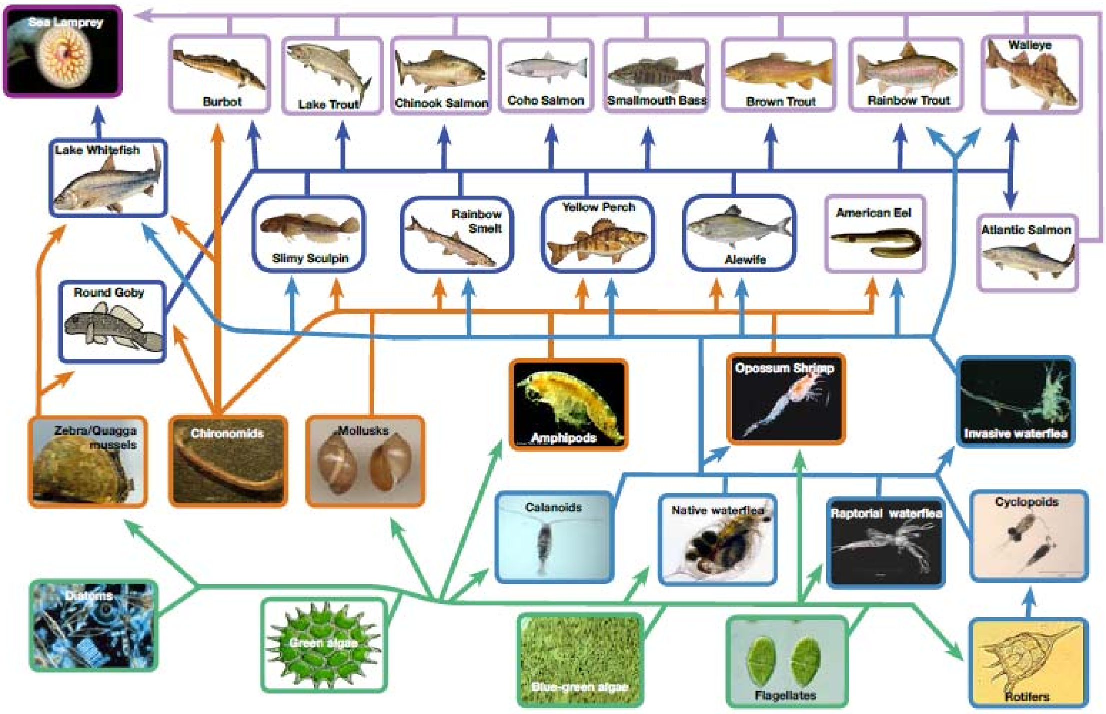


Figure 1. Example of ecological network: Lake Ontario Food web, Source: www.glerl.noaa.gov.

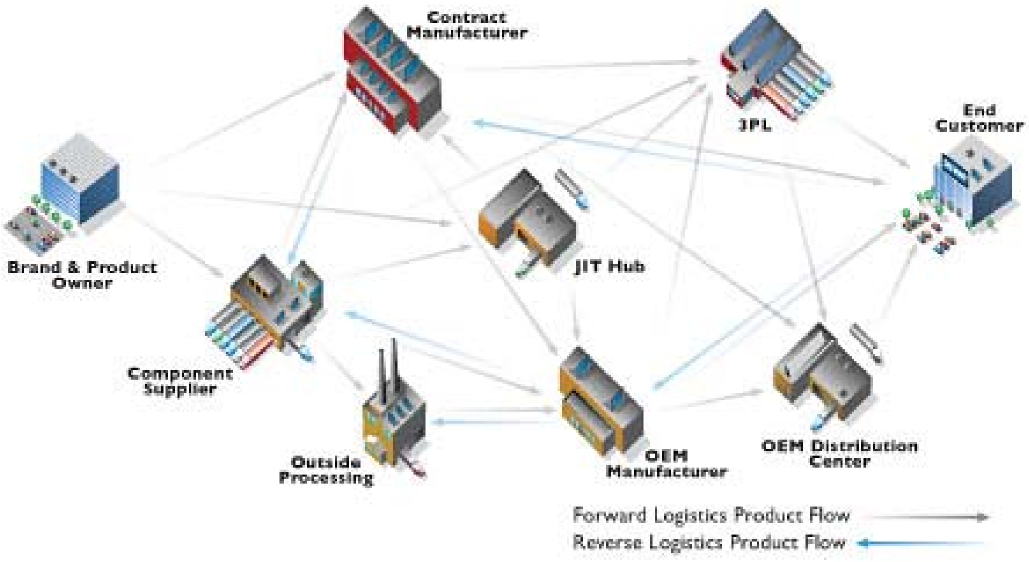


Figure 2. Example of Supply Network. Source: www.clearorbit.com.

3.3 Supply chain mapping and quantification of flows

As mentioned above, a system can be described as a network, which can be represented using nodes, corresponding to the main areas of the network and arrows, which symbolize the relationships between supply chain companies and between these and the external environment. Thus, the knots represent the system components (nodes) and arrows (edges) describe the flows between the various entities. Using $e_{i,j}$ for the edge linking node, i and j for the nodes, and $t_{i,j}$ for the material flow related to the edge $e_{i,j}$, a simple network with two element is shown in figure 3, together with related flows.

The flows can be categorized under the following four classes:

1. Input flow (coming from the external environment);
2. Internal flow, depicting flows between supply chain members;
3. Output flow (leaving the network toward the external environment);
4. Dissipation, or flow representing losses, waste and defeat.

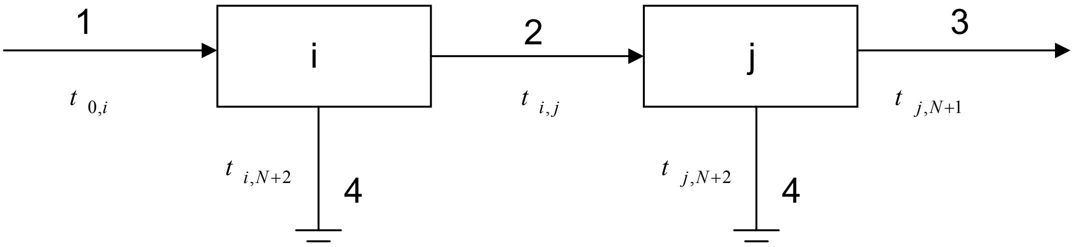


Figure 3. Example of a simple network with two elements (node i and node j).

The component i is affected by the inflow indicated by $t_{0,i}$, where the notation "0" refers to the external environment, which then lies beyond the borders of the analyzed system, thus behaving as a donor. At the same time, $t_{i,N+2}$ denotes dissipations in i: these kinds of flow, representative of waste and losses, converge to the virtual node *n+2*. Moreover, all exchanging flows with the generic supply chain member j are represented with the following notations: $t_{i,j}$ or $t_{j,i}$, depending on who is the donor and who is the receiver. Finally, $t_{j,N+1}$ identifies outflows, coming from *j* toward the outside of the supply network.

In other words, the fluxes can be divided into two main categories:

In the first categories are those flows that cross the interface between the supply chain and the surrounding environment, including imports, exports and dissipations (dissipated fluxes). Their individual magnitudes are arrayed as vectors.

The second category takes into account all fluxes between compartments, that are summarized in a $N \times N$ matrix, where N is the number of supply chain members. Thus, ecological networks can be summarised using vectors and matrices. A network is composed of a triplet G (V;E;W), where V represents the nodes and E the edges (arcs, arrows) associated with weights W.

To help understand and illustrate the methodology, a simple industrial example involving a small supply network of seven different partners (compartments) is presented in Figure 4. The network consists of three plants manufacturing electronic equipment, one 3PL, two retailers and a recovery product centre.

First of all, a unit of measurement needs to be selected in order to express flows between partners in the network, i.e., goods exchanged in tons/year. Then the inputs from outside the system into each compartment in the given period need to be measured, that means, for example, raw materials coming from the environment outside the network. This will form the import vector, called ‘X’. The flows exiting the system can be divided into reusable material, exports, called ‘E’, and dissipations, called ‘D’ (that means for example production losses):

$$X = \begin{bmatrix} 150 \\ 78 \\ 136 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad E = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 103 \\ 187 \\ 0 \end{bmatrix} \quad D = \begin{bmatrix} 16 \\ 9 \\ 12 \\ 3 \\ 18 \\ 0 \\ 16 \end{bmatrix}$$

Following a matrix of the goods transferred between partners, inside the system, called the transfers matrix *T*, can be set up, and an extended transfers matrix *T** can be associated with the oriented graph, to report all information about exchanges occurring in the network (Figure 5). The extended transfer matrix *T** in Figure 6 includes all the flows inside the system and all the exchanges with the external environment, as shown in Figure 4.

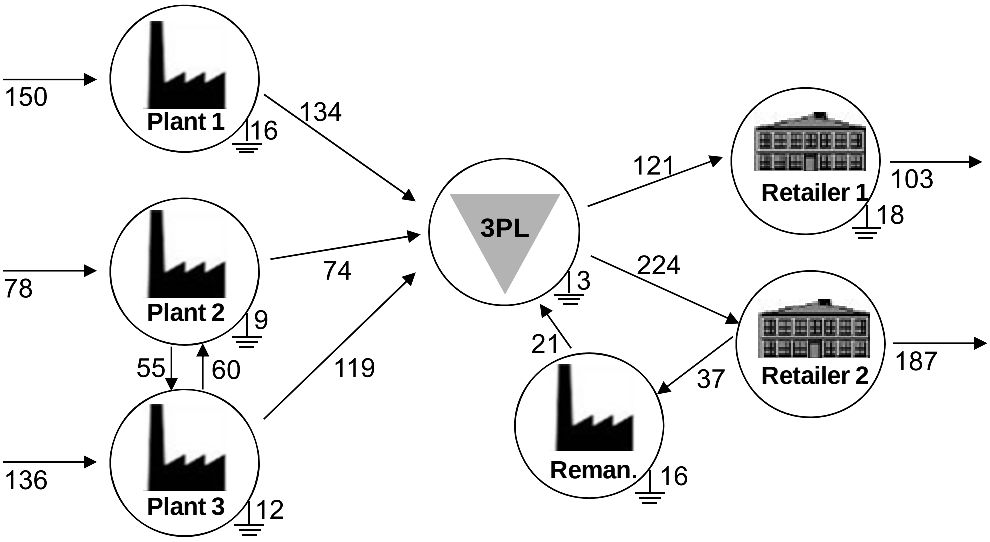


Figure 4. Example of an industrial supply chain.

If mass balance is met for the system, then:

$$\sum t_{0,i} + \sum t_{j,i} = \sum t_{i,j} + \sum t_{i,n+2} + \sum t_{i,n+1}$$

The same formula written in compact notation for each compartment i is:

$$T_{.i} + X_i = T_{i.} + E_i + D_i$$

where the 'dot' stands for sum across the whole row/column. Because of the complex procedure of network construction, the rough data is unlikely to be balanced (steady state). If steady state is achieved, then mass balance exists around every node (incoming edges perfectly balance outgoing ones). In order to achieve steady state condition in ecological networks, researchers change the coefficients as seldom as possible. It is worth noting that, while mass balance plays a fundamental role in some of the procedures sketched above, it is not as important when dealing with information indexes (Ulanowicz 2004). We can therefore assume without loss of generality that the networks are in steady state. The results will also extend to the non-stationary case.

	0	**1**	**2**	**…**	**N**	**N+1**	**N+2**
0	**0**	**Input [X]**				**0**	**0**
1	**0**	**Transfers between compartments [T]**				**Export [E]**	**Dissipation [D]**
2	**0**						
…	**0**						
N	**0**						
N+1	**0**	**0**	**0**	**0**	**0**	**0**	**0**
N+2	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Figure 5. Extended transfer matrix *T**.

	X	**P1**	**P2**	**P3**	**3PL**	**R1**	**R2**	**PR**	**E**	**D**
X		150	78	136						
P1					134					16
P2				55	74					9
P3			60		119					12
3PL						121	224			3
R1									103	18
R2								37	187	
PR					21					16
E										
D										

Figure 6. Extended transfer matrix *T of network in Figure 4.**

3.4 System descriptors and information theory

In thermodynamics, entropy is a state function introduced together with the second law of thermodynamics and is interpreted as a measure of disorder of a physical system or, more generally, the universe. Based on this definition, we can say that when a system goes from an ordered state to a disordered one, its entropy increases. Solids, for example, which are typically ordered on the molecular scale, usually have smaller entropy than gases, whose molecules' location is characterized by an high degree of uncertainty.

Information Entropy has a similar conceptual and intuitive meaning: it quantifies the uncertainty involved in predicting the value of a random variable. For example, stating the outcome of a coin flip (two equally expected results) provides less information (lower entropy) than specifying the outcome from a roll of a die (six equally expected results). Information theory was developed by Claude E. Shannon to find fundamental limits on signal processing operations such as compressing data and on reliably storing and communicating data, but its inception it has broadened to find applications in many other areas. Network Analysis has a strong linkage with Information theory. Thus, the present section is devoted to give an insight upon this foundation.

Boltzmann's famous definition of surprise helps placing the second law of thermodynamics on a statistical basis:

$$s = -k \log(p)$$

where s is one's surprise at seeing an event that occurs with probability p, and k is an appropriate (positive) scalar constant.

Because the probability p, is normalized to a fraction between zero and one, most offhandedly conclude that the negative sign is a mathematical convenience to make s work out positive (and that may have been Boltzmann's motivation). But one can also read this equation as defining s to gauge what p is not. That is, if p is the weight we give to the presence of something, then s becomes a measure of its absence. If p is very small, then the ensuing large magnitude of s reflects the circumstance that most of the time we do not see the event in question.

The product of the measure of the presence of an event i, $p(i)$ by a magnitude of its absence $s(i)$ yields a quantity that represents the indeterminacy $h(i)$ of that event,

$$h(i) = -k \cdot p(i) \cdot \log p(i)$$

When $p(i) \approx 1$, the event is almost certain, and $h(i) \approx 1$; then when $p(i) \approx 0$, the event is almost surely absent, so that again $h(i) \approx 0$. In other word, entropy has been employed as a measure of the degree of ignorance about the true state of a system. It is only for intermediate, less determinate values of $p(i)$ that $h(i)$ remains appreciable, achieving its maximum at $p(i) = 1/e$.

To make things simpler, it is possible to see information entropy as the amount of "surprise" that the realization of an event provides: whenever an event is certainly present or definitely absent, our “surprise” will be null such as the entropy. At the same time, if it decreases the probability that an event occurs, the surprise increases in its occurrence and so does entropy.

According to Shannon (1948) the logarithmic measure was chosen, since considered more convenient for various reasons:

(1). It is practically more useful. In engineering, parameters tend to vary linearly with the logarithm of the number of possibilities.

(2). It is nearer to our intuitive feeling as to the proper measure. This is closely related to (1) since we intuitively measures entities by linear comparison with common standards. One feels, for example, that two punched cards should have twice the capacity of one for information storage, and two identical channels twice the capacity of one for transmitting information.

(3). It is mathematically more suitable. Many of the limiting operations are simple in terms of the logarithm, but would require clumsy restatement in terms of the number of possibilities.

The choice of a logarithmic base corresponds to the choice of a unit for measuring information. If the base 2 is used, the resulting units may be called binary digits, or more briefly *bits,* a word suggested by J. W. Tukey. We can say that a ‘‘bit’’ is the amount of information required to resolve one binary decision. Thus, a device with two stable positions, such as a relay or a flip-flop circuit, can store one bit of information. N such devices can store N bits, since the total number of possible states is 2^N and $\log_2 2^N = N$ (Shannon, 1948).

Taking into account the entire collection of events X, the aggregate systems indeterminacy can be computed:

$$H_X = \sum_{i \in X} h(i) = -k \sum_{i \in X} p(i) \log p(i)$$

Dwelling on the significance of $p(i)$, one can say that event i indeterminacy, which corresponds to intermediate values of $p(i)$, leads to think that the event i is both present frequently enough and has sufficient potential for change to be an important player in system change or evolution (Ulanowicz et al., 2009).

Taking into account the entire collection of events X, whether system change will be coordinated or wholly stochastic depends upon whether or not the various events i are related to each other and by how much. In order for any change to be meaningful and directional, constraints must exist among the possible events (Atlan, 1974).

In order better to treat relationships between events, it is helpful to consider bilateral combinations of events. Accordingly, we will define $p(i,j)$ as the joint probability that events i and j co-occur. Boltzmann's measure of 'surprise' (i.e. measure of the absent of both events combination) becomes:

$$s(i,j) = -k \log p(i,j)$$

If events i and j are completely independent of each other, the joint probability, $p(i,j)$, that they co-occur becomes the product of the marginal probabilities that i and j each takes place independently anywhere. Now, the marginal probability that i occurs for any possible j is $\sum_j p(i,j) = p_{i.}$, while the likelihood that j occurs regardless of i is $\sum_i p(i,j) = p_{.j}$. Hence, whenever i and j are totally independent, $p(i,j) = p_{i.} p_{.j}$. Here the assumption is made that the indeterminacy $s(i,j)$ is maximal when i and j are totally independent. The difference between this maximum value (which we call $s^*(i,j)$) and $s(i,j)$ then becomes a measure of the constraint that i exerts on j, call it $s_{i|j}$, where

$$s_{i|j} = s^*(i,j) - s(i,j) = -k\log(p_{i.}p_{.j}) - [-k\log p(i,j)] = k\log\left(\frac{p(i,j)}{p_{i.}p_{.j}}\right) = s_{j|i}$$

As shown by the formula, $s_{i|j} = s_{j|i}$, thus this measures also represents the constraint that j exerts on i. Accordingly we can say that the expression above is a measure of events mutual constraints.

In order to calculate the Average Mutual Constraints, which will be called AMC, concerning the whole system, each $s_{i|j}$ should be weighted by the joint probability that i and j co-occur and sums over all combinations of i and j:

$$AMC = \sum_{i,j}\left[p(i,j)s_{i|j}\right] = k\sum_{i,j}\left[p(i,j)\log\left(\frac{p(i,j)}{p_{i.}p_{.j}}\right)\right]$$

Thanks to logarithm convexity (Abramson, 1963) and the nature of probability, which ranges from 0 to 1, one can easily affirm that:

$$H \geq AMC \geq 0$$

This is saying that entropy of the whole system is an upper bound on how much constrain (i.e. organization, order) can appear in the system.

Most of the time $H > AMC$: the difference is called “Conditional Entropy” (CE) and it represents what is not constrained, thus the irregular, disorderly, incoherent and inefficient behaviours of the system.

$$CE = H - AMC = -k\sum_{i,j}\left[p(i,j)\log\left(\frac{p^2(i,j)}{p_{i.}p_{.j}}\right)\right] \geq 0$$

Expressing the same formula in terms of indeterminacy:

$$H = AMC + CE$$

This expression makes a very important statement: it expresses the capacity for evolution or self-organization (H) as the sum of two terms, one representative of what is constrained, organized and ordered, the other representative of what is disordered, irregular, complex.

Up to this point, we have spoken only vaguely about events i and j. Without loss of generality, we now narrow our discussion to consider transfers or transformations, within a supply network. That is, event i will signify that some product or, more generally, some "quantum" leaves or disappears from component i. Correspondingly, event j will signify that a quantum enters or appears in component j.

The Extended Transfer Matrix T* previously presented includes all flows inside the system and all exchanges with the external environment. Thus, we now identify the aggregation of all quanta both leaving i and entering j during a unit of time – or, alternatively, the flow from i to j – as $T^*_{i,j}$. Thus, $T^*_{i,j}$ might represent a logistics flow from point i to point j.

The probability of a product (unit of load, work piece, truck, ton of materials, etc...) moving from compartment i to compartment j is assumed to be proportional to the flow from i to j:

$$p_{O,I}(i,j) = \frac{T^*{}_{ij}}{T^*{}_{..}}$$

As previously described, the entropy is the sum of the probabilities of each possible outcome i times the logarithm of the associated probability:

$$H_X = -\sum_{i \in X} p(i) \log p(i)$$

A supply chain network can be deemed as a collection of transition probabilities (i.e. the probability of finding a “quantum” of the exchanged goods or product pieces moves from a certain node to another at any time), and the entropy of the system computed ($p \cdot \log(p)$) by considering inputs to any node and outputs from any node.

In particular, the network is represented as a matrix (T*) and the entropy associated with row sums (probabilities of leaving the boxes) and column sums (probabilities of entering the boxes) is computed. If, at any given time, a product travelling in the system is marked at random, the probability associated with the event “the product is moving from compartment *i* to compartment *j*” will be found, and this quantity is the probability associated with the arrow from i to j.

The entropy associated with events such as “a product is leaving compartment i and entering compartment j” is usually called the joint entropy $H_{I,O}$:

$$H_{I,O} = -\sum_{i=0}^{N+2}\sum_{j=0}^{N+2} p_{I,O}(i,j) \log p_{I,O}(i,j) = -\sum_{i=0}^{N+2}\sum_{j=0}^{N+2} \frac{t_{ij}}{t..} \log \frac{t_{ij}}{t..}$$

The entropy associated with outputs from compartments will therefore be:

$$H_O = -\sum_{i=0}^{N+2} p_O(i) \log p_O(i) = -\sum_{i=0}^{N+2} \frac{t_{i.}}{t_{..}} \log \frac{t_{i.}}{t_{..}}$$

and the entropy associated with inputs into compartments will be:

$$H_I = -\sum_{j=0}^{N+2} p_I(j) \log p_I(j) = -\sum_{j=0}^{N+2} \frac{t_{.j}}{t_{..}} \log \frac{t_{.j}}{t_{..}}$$

These quantities will be positive or null, and will possess all the properties of entropies. In the sample network, the contribution of each coefficient to the joint entropy is $-\frac{t_{ij}}{t..} \cdot \log\left(\frac{t_{ij}}{t..}\right)$

The joint entropy is obtained by summing all contributions (Figure 7):

$H_{I,O} = 3.825$ bits.

	X	P1	P2	P3	3PL	R1	R2	PR	E	D
X		0.323	0.215	0.305						
P1					0.303					0.067
P2				0.169	0.207					0.043
P3			0.180		0.282					0.054
3PL						0.285	0.400			0.017
R1									0.258	0.074
R2								0.127	0.365	
PR					0.083					0.067
E										
D										

Figure 7. Matrix of joint entropy contributions.

In the same way:

$H_I = 2.952$ bits

where $-\frac{t_{.j}}{t_{..}} \log \frac{t_{.j}}{t_{..}}$ represent the contribution of every node to the input entropy H_I :

X	P1	P2	P3	3PL	R1	R2	PR	E	D
0.000	0.323	0.308	0.369	0.481	0.285	0.400	0.127	0.450	0.207

Figure 8. Contribution of every compartment to the input entropy H_I .

and $H_O = 2.783$ bits

where $-\frac{t_{i.}}{t_{..}}\log\frac{t_{i.}}{t_{..}}$ represent the contribution of every node to the output entropy H_O :

X	P1	P2	P3	3PL	R1	R2	PR	E	D
0.489	0.323	0.308	0.369	0.481	0.285	0.400	0.127	0.000	0.000

Figure 9. contribution of every compartment to the input entropy H_O

Conditional probabilities and entropies associated with events of the form “a product that is now in compartment i moves to compartment j” can be defined. In this case it is known that the product is currently in compartment i, but the uncertainty associated with the next destination needs to be measured. The associated entropy is:

$$p_{I|O}(j \mid i) = \frac{p_{I|O}(i \mid j)}{p_O(i)} = \frac{t_{ij}}{t_{i.}}$$

In the same way, conditional probabilities and entropies associated with events of the form “a product that is now in compartment j moves to compartment i” can be defined as:

$$p_{O|I}(i \mid j) = \frac{p_{I|O}(i \mid j)}{p_I(j)} = \frac{t_{ij}}{t_{.j}}$$

The associated total entropy is:

$$H_{I|O} = -\sum_{i=0}^{N+2} p_{I|O}(j \mid i)\log p_{I|O}(j \mid i) = -\sum_{i=0}^{N+2}\sum_{j=0}^{N+2}\frac{t_{ij}}{t_{..}}\log\frac{t_{ij}}{t_{i.}}$$

$$H_{O|I} = -\sum_{i=0}^{N+2} p_{O|I}(i \mid j) \log p_{O|I}(i \mid j) = -\sum_{i=0}^{N+2}\sum_{j=0}^{N+2} \frac{t_{ij}}{t_{..}} \log \frac{t_{ij}}{t_{.j}}$$

Results related to the simple distribution network under study are the following:

$H_{I|O}$ =1.042 bits

This is obtained by summing all contributions (Figure 10):

	X	P1	P2	P3	3PL	R1	R2	PR	E	D
X		0.323	0.215	0.305						
P1					0.303					0.067
P2				0.169	0.207					0.043
P3			0.180		0.282					0.054
3PL						0.285	0.400			0.017
R1									0.258	0.074
R2								0.127	0.365	
PR					0.083					0.067
E										
D										

Figure 10. Contribution of every compartment to the conditional entropy $H_{I|O}$.

$H_{O|I} = 0.873$ bits

This is obtained by summing all contributions (Figure 11):

	X	P1	P2	P3	3PL	R1	R2	PR	E	D
X			0.041	0.042						
P1					0.117					0.022
P2				0.063	0.105					0.017
P3			0.046		0.117					0.020
3PL										0.009
R1									0.098	0.023
R2									0.075	
PR					0.054					0.022
E										
D										

Figure 11. Contribution of every compartment to the conditional entropy $H_{O|I}$.

The following identity will be used to define Average Mutual Information:

$$H_{I,O} = H_I + H_{O|I} = H_O + H_{I|O}$$

This identity shows that the joint entropy is equal to the sum of the entropy associated with Inputs (Outputs) plus the conditional entropy on Outputs given the Inputs (Inputs given the Outputs).

$$H_{I,O} \leq H_I + H_O$$

The "Average Mutual Information" (AMI) is defined as:

$$AMI = H_O - H_{O|I} = H_I - H_{I|O} = H_O + H_I - H_{I,O}$$

This formula explicitly states that the information is equal to the decrease in entropy associated with inflows once the outflows are known (or the decrease in outflow entropies once the inflows are known), and that AMI possesses symmetry.

The AMI index of the network model in Figure 4 is:

$$AMI = H_O + H_I - H_{I,O} = 2.783 + 2.952 - 3.825 = 1.91$$

In a network of exchanges, many configurations are compatible with the same Throughput level (TST). More constrained topologies are those in which a restricted number of flows exist so that the medium is forced to move along a limited number of pathways. This occurs when compartments in the system are more functionally specialised or several constraints are on the medium, as measured by the AMI index. The two entropies are represented as areas (Figure 12):

their joint entropy *H(x;y)* is represented by the area in the bottom left-hand corner. The AMI is the overlap of the two areas and is the measure of how constrained the material flows are. When each compartment is connected with every other compartment and the flows are all the same, the AMI is 0 (the two areas are disjoint). In other words, the fact that a product exits in a certain compartment provides no information on the next destination. The opposite case is represented by the complete overlap of the two areas. In this situation knowing that a product is in a certain compartment implies that it will enter another known compartment. The flows are completely constrained.

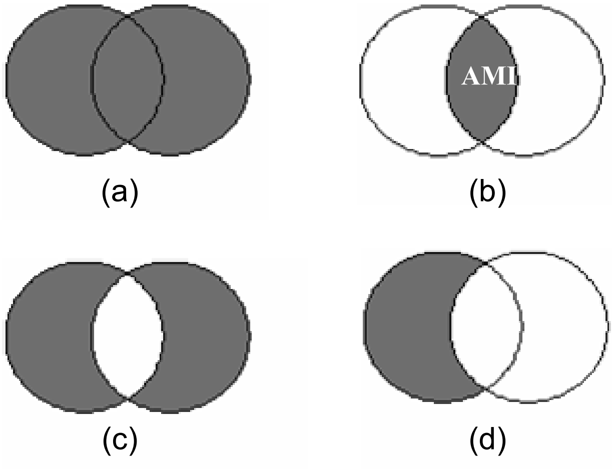


Figure 12. Venn diagrams expressing the relations between entropies and information.

H_I and H_O are sketched as circles that intersect. (a) The joint entropy expressed as the union of the two circles; (b) Average Mutual Information expressed as the intersection between the two circles; (c) the sum of the conditional entropies expressed as the union minus the intersection of the two entropies; (d) the conditional entropy $H_{I|O}$ expressed as the union minus the output entropy.

3.5 Entropic indexes

In this section, eight new indexes are presented:

1. Total System Throughput (TST);
2. Capacity (C);

3. Ascendancy (A);
4. Overhead (Φ);
5. Overhead in INPUT (Φ_I);
6. Overhead in EXPORT (Φ_E);
7. Overhead in DISSIPATION (Φ_D);
8. Redundancy (R).

These indexes, based on Information Theory and Ecological Network Analysis, are successfully applied to the study of Supply Network, to provide consistent measures to rate supply network structure in terms of size, organization, and complexity as well as quantifying the beneficial reserves of complex system in its response to disturbance (this last topic is further discussed at the end of section 4).

3.5.1 Total System Throughput

The Total System Throughput is simply the sum of all coefficients i.e. the “size” of the system or the total amount of the medium (goods, product pieces, product tons, money, etc...) flowing through the network.

$$TST = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} = t_{..}$$

Follows contractions are used to shorten the formulas, and $t_{..}$ means sum across all rows (first dot) and columns (second dot). Similarly, $t_{i.}$. is the sum of the *ith* row, and $t_{.j}$ the sum of the *jth* column.

Consequently, the TST for the network in Figure 4 can be computed as the sum of all flows:

TST = 1573 tons/year

This index quantifies the growth of the network because it is based on the number of nodes and the quantities transferred in the system; however, it does not provide information about the distribution of the flows inside the system.

3.5.2 Ascendancy, Capacity and Overhead

Because AMI is a-dimensional, Ulanowicz and Kay (1991) proposed to scale it for the sum of all TST flows, to combine the size of the system (TST) with its degree of organisation/development (AMI). Such combined measurement is called Ascendancy. Ascendancy is defined as the product of AMI and TST:

$$A = TST \times AMI = \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} t_{ij} \log\left(\frac{t_{ij} t_{..}}{t_{i.} t_{.j}} \right)$$

Ascendancy is a measure of how developed a system is and it considers both the size of the flows (the TST) and their organisation (the Average Mutual Information Index, AMI).

The sum of all the flows in a network yields the total amount of goods, money, information that flows through the industrial system. This quantity estimates the level of activity pertaining to the supply network, in other words the level of activity that quantifies the size of the network. The process that is directly linked with size is growth, therefore the growth of a supply network could be quantified by measuring TST, which depends on both magnitude of flows and number of partners involved. Growth pertains to the “extension” of a system, but does not provide details about how material and money are distributed within the network. It is possible for supply chain with the same TST to be characterised by totally different flow configurations. As shown above, higher values of AMI pertain to flow structures that are maximally constrained in terms of goods movement within the system. Consequently, supply networks are highly organised when distribution of goods takes place along few efficient routes and consequently the cost of managing the whole system decreases. It follows that highly redundant flow networks are considered to be less organised and they possess lower AMI values. In other word, Supply Chains, just as in ecological ecosystems, should develop in the direction of a more organised structure of exchanges, and development is identified by any increase in the mutual information of the exchange configuration. AMI therefore quantifies development for ecosystems.

Ascendancy measures the fraction of goods, money, and information that a supply network distributes in an efficient way. By combining system activity and organisation, it provides a unique measurement of growth and development. “In ecology, high values for ascendancy represent a mature food web, where species are specialised, exchanges are structured, and internal cycle and transfer are efficient. Should an ecosystem be developed and organised to its fullest potential, the ascendancy equals the Development Capacity, which forms the upper boundary of the ascendancy” (Allesina, 2004). If Supply Network life could be subdivided into four stages of a) introduction b) growth c) maturation d) decline, such as in the life cycle of a product, it is likely that increase in activity would dominates the first two stages, to decline as the ecosystem becomes more organised. “In this latter phase, the throughput accumulated at the beginning is redistributed and organised so that the mutual information of flows increases” (Allesina, 2004). By scaling the joint entropy using TST, the maximum development capacity of the system is obtained:

$$C = TST \times H_{I,O} = \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} t_{ij} \log\left(\frac{t_{ij}}{t_{..}}\right)$$

The development capacity is calculated by multiplying the TST by the entropy generated by the flows (i.e. how different compartments are used as inputs by other living compartments). The total Capacity C represents the maximum potential of a system and what can be used to achieve further development, as it is the upper limit for ecosystem organisation. The capacity is then partitioned into organisation of flows (Ascendancy A) and redundant, non-organised flows (Overhead Φ). The amount of the Development Capacity remaining non-organised is called Overhead and this is equal to the differences between C and A:

$$\Phi = C - A = TST \times (H_{I,O} - AMI) = TST \times (H_{O/I} + H_{I/O}) = -\sum_{i=0}^{N+2} \sum_{j=0}^{N+2} t_{ij} \log\left(\frac{t_{ij}^2}{t_{i.} t_{.j}}\right)$$

The overheads can be partitioned into four different contributions: Overhead on Imports, Exports, Dissipations and Redundancy. All four contributions are usually expressed by ecologists as a percentage on the capacity of the system: this aspect is useful as it allows different networks to be compared one with another. High values of Redundancy reflect a high proportion of parallel pathways in the system. The first three components are based on the exchanges with outside the system, while the latter pertains to the functional overlap of the pathways in the system.

Φ_I represents the Overhead in Input, Φ_E the Overhead in Export, Φ_D the Overhead in Dissipation, and R the Redundancy. Table 4 reports all principal system entropic indexes introduced in this paragraph and numerical values for the sample network in Figure 4. It is interesting to note that these four contributions are usually expressed by ecologists as a percentage on the Capacity of the system: this aspect is useful as it allows different networks to be compared one with another.

As Bullinger et al. (2002) state in their paper, to achieve logistic excellence in such complex and highly dynamic supply chains requires continuous in-depth analysis of the entire network reality, supported by measurements and a holistic point of view. In agreement with this point of view, the quantitative measurements presented in this chapter provide a picture of the complexity and the organisation level of the whole supply network.

The structure of the entropic model approach is described by the scheme of Figure 13. The presented quantitative parameters results in robust and meaningful analysis and optimization, a simple measurement of the level of complexity in the global supply network that rapidly evaluates the impact of modifications, which can then guide the choice of the best solution among all those available. The proposed method takes a global point of view, aiming to reach total optimization, thereby overcoming the problem of continuous research demanded by the constant need to find many possible local best solutions.

Indexes	Value	Percentage
$TST = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} = t_{..}$	1573.0	
$C = TST \times H_{I,O} = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} \log\left(\frac{t_{ij}}{t_{..}}\right)$	6016.1	100.00%
$A = TST \times AMI = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} \log\left(\frac{t_{ij} t_{..}}{t_{i.} t_{.j}}\right)$	3004.7	49.94%
$\Phi_I = -\sum_{j=1}^{N} t_{0,j} \log\left(\frac{t_{0,j}^2}{\sum_{i=1}^{N} t_{ij} \sum_{j=1}^{N} t_{0,j}}\right)$	3011.4	50.06%
$\Phi_E = -\sum_{j=1}^{N} t_{i,N+1} \log\left(\frac{t_{i,N+1}^2}{\sum_{j=1}^{N} t_{ij} \sum_{i=1}^{N} t_{i,N+1}}\right)$	344.8	5.73%
$\Phi_D = -\sum_{j=1}^{N} t_{i,N+2} \log\left(\frac{t_{i,N+2}^2}{\sum_{j=1}^{N} t_{ij} \sum_{i=1}^{N} t_{i,N+2}}\right)$	404.6	6.72%
$R = -\sum_{i=1}^{N}\sum_{j=1}^{N} t_{ij} \log\left(\frac{t_{ij}^2}{\sum_{j=1}^{N} t_{ij} \sum_{i=1}^{N} t_{ij}}\right)$	1572.8	26.14%

Table 4. Entropic Indexes (Ascendancy, Capacity, and Overhead) for the supply chain analysed.

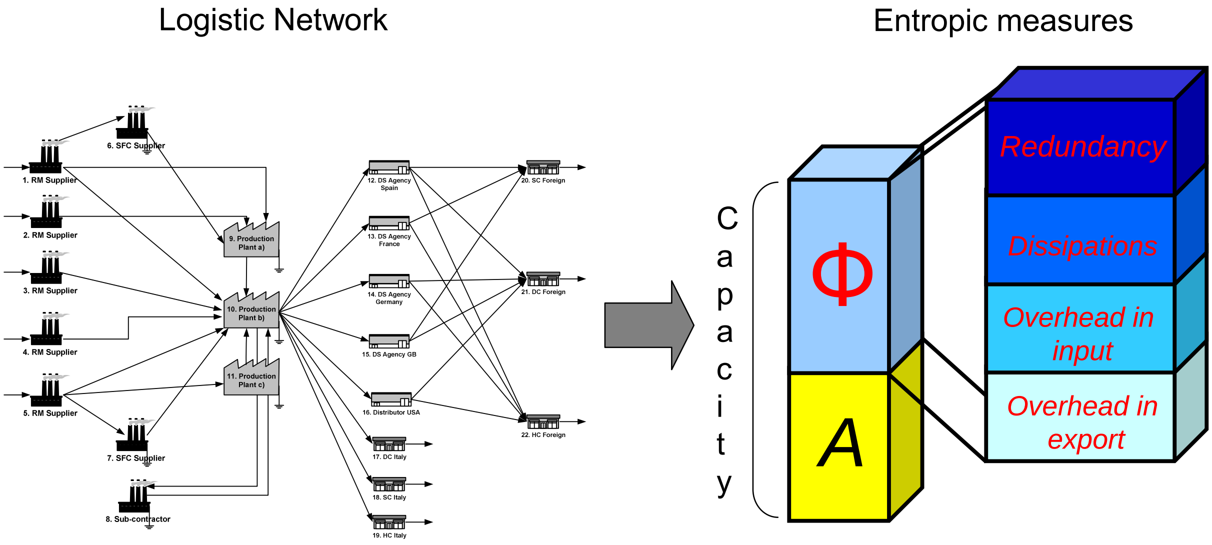


Figure 13. Structure of the entropic model approach

3.6 Cycling in industrial network

Through the study of several dummy networks and the application of the SNA to real case studies (some of which are presented in chapter 4), it became apparent how the methodology was excellent to grasp the degree of complexity of the industrial network under study, but it was not always capable of highlighting the reasons related to this complexity. In fact, as previously described, Overhead is featured by four different components which emphasize how input and output logistics flow, and how dissipations and multiple pathways contribute to system complexity. However, nothing more can be told about the nature of these flows. For instance, considering the whole product life cycle and all the relative logistic flows (forward and reverse), i.e. production, distribution, warranty, remanufacturing, recycle, disposal, etc., the adverse effects are quite considerable on the structure of the network. For this reason, these aspects should be considered in network design (Faccio et al., 2011). In other words, it is rather intuitive to understand how reverse logistics flows, for instance, may certainly cause an increment of complexity, but no entropic index is able to represent this information.

3.6.1 Cycling categories

Manufacturing industry has evolved considerably since the industrial revolution, leading our society to place emphasis on consumption and to a dramatic increase in volume and variety of inexpensive products available in our daily lives. Unfortunately, this is juxtaposed with excessive consumption of resources used in producing raw materials, which is bound to cause severe shortages. Moreover, improper waste management can lead to hazardous consequences for the environment and human health (Shah et al. 2010) at the end of a product's life,. For these reasons, reverse logistics is a hot topic, which has had a significant economic impact on industry as well as society (Krumwiede and Sheu, 2002), and its function in supply chain management has received great attention in recent years due to increased awareness and implementation of legal requirements (Guide and Wassenhove, 2009; Simpson, 2010).

Traditionally, reverse logistics has been perceived mostly as practices related to recycling goods and resources, but the technical definition is ever changing, depending on what company or segment of industry is attempting obtain (Krumwiede and Sheu, 2002): from the process of returning products from a customer to a vendor (Rowley, 2000; Wheatley, 2002; Mukhopadhyay and Setoputro, 2004), where new trends, like the growth of the internet and home shopping, has determined a rise in the volumes of products being returned, or a way to get defective products or reusable containers back from the user.

More generally, reverse logistics can intend any process related to flow of raw materials, in-process inventory, finished goods from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal, and refers to the distribution activities involved in product returns, source reduction/conservation, recycling, substitution, reuse, disposal, refurbishment, repair and remanufacturing (Min et al., 2006).In this thesis the concept is extended even further overcoming the insightful meaning of reverse logistics and extending our arguments to all possible cycling flows which can occur in a supply network, not necessarily related with the reuse or proper disposal of resources.

Government legislation in several countries is charging manufacturers with responsibility for the entire products' lifecycle, including their safe disposals (Kusumastuti et al., 2004); take-back and recovery obligations have been enacted for a number of product categories, such as the WEEE directives of the EU (i.e. European Union WEEE Directive, 2007), certainly creating important incentives for companies to engage in remanufacturing (Francas, D., Minner, S., 2009). Of course, the reverse logistics is now viewed not only as part of a legal requirement, but more importantly, to recover the economical as well as ecological value of used products, components and materials.

According to Simpson (2010), motivations for companies to become involved in reverse logistics activities include:

- legal requirements (end-of-life or packaging laws);
- economic convenience (re-conditioned goods for sale or recyclables with a reuse value);
- ethical motivation (recalls because of a product defect);
- environmental awareness (reduced waste to landfill and industrial ecology);
- customer service (after-sale repair or returns under warranty).

Transportation, storage and/or handling of returned goods have different characteristics compared to outgoing goods both in terms of complexity and cost of operations (Efendigil et al., 2008). Due to these complexities, many businesses prefer allocating their resources to core competency areas and choose to outsource their partial or overall reverse logistics processes to third-party logistics providers (3PLs) (Jeung Ko and Evans, 2007; Cottrill, 2000; Krumwiede and Sheu, 2002; Efendigil et al., 2008). At the same time, as cost pressures continue to escalate in the competitive logistics industry, a growing number of 3PLs have begun to explore the possibility of managing product returns in a more cost-efficient manner (Min and Ko, 2008). The importance of third-party logistics companies in managing forward and reverse logistics, especially for handling complex networking needs, has been widely discussed by many authors (e.g. Krumwiede and Sheu, 2002; Sarkis et al., 2004 e Min and Ko, 2008).

Last, although the reverse supply chain of returned products represents a sizeable flow of potentially recoverable assets, only a relatively small portion of the value is currently extracted by manufacturers, while a large proportion of the product value erodes away because of long processing delays (Kusumastuti et al. 2004). Although manufacturers show a growing interest in extracting value from product returns, the need to make the appropriate reverse supply chain design choices, has not inspired much research (Guide et al., 2006) . Starting from this perspective, the opportunity to develop a methodology to analyze and compare these kinds of network, make the topic even more challenging.

As previously mentioned, the purpose is not just to extend SNA to the analysis of reverse logistics flows, but in a broader sense, to include every cause of cycling inside a supply network, which cause an increase of logistics complexity.

From a literature review, ten different categories of logistics flows have been identified, and summarized in table 5 together with a sample of related references.

In particular, logistics cycling options can be distinguished in:

1. ***Maintenance***, meaning the returns of products or spare parts for predictive/preventive maintenance, typically due to prevent product abnormality before the abnormality occurs.
2. ***Reuse/resale***, meaning a product return, followed by a situation where the product is used again, perhaps to be resold or rented, continuing to exploit its economic value (i.e. second-hand goods or cascading, systems for borrowing of books, video tapes or sport equipment etc.).
3. ***Subcontracting part processing*** (i.e. outward processing, partial subcontracting, third party manufacturing…), meaning outsourced jobs, which imply batches to be transported back to the firm. Subcontractors' strategies, development and role within the supply system is a research topic located at the crossroads of a multiplicity of managerial and economic disciplines, such as strategic management, operations and supply chain management, organizational design, organizational behavior and industrial organization. In this research work, subcontracting is seen from a new perspective: a mean to create loop logistics flow, due to part processing externalization.
4. ***Non-conformity***, meaning materials returned into supply chain sites following deliveries of non-conforming or defect materials or products. Non-conformity can be related to poor quality, to an excess or lack of product and, more generally, to rather every reverse logistics flow due to poor practice within the forward supply chains.
5. ***Returnable goods***, meaning the reuse of products, transportation items or returnable packaging without an economic transaction of any kind, including returnable transportation items or returnable packaging materials, such as containers, pallets, slipsheets, totes, trays, kegs, trolleys, bins, RFID tags and so on. Some categories of reusable products also fall into this group (e.g. products to sterilized surgery instruments, wheel chairs or other types of medical equipment lent by National Health Services to

patients, service tools required to perform maintenance actions that are borrowed from a central unit, etc.).

6. ***Repair***, meaning returns with the purpose of restoring a product to working order. This alternative is common in several industries, such as the automotive industry.
7. ***Refurbishing***, meaning reverse logistics flow which result in refurbishment processes, i.e. products restore to original specifications or product upgrade to a specified, but less-than-new quality. It involves repairing only few (i.e. one or two) defective components in the product. Many electronic marketplaces offer refurbished products.
8. ***Remanufacturing***, meaning returns resulting in remanufacturing processes, aiming to bring the product to an "as good as new" quality state. Remanufacturing involves not only the repair of all the defective components, but an overhaul and upgrade of the entire product assembly. It involves disassembly of the products into individual spare parts, upgrading the performance of the defective components (overhaul), and then re-assembling the modules to replicate the product. For example, telecommunication providers offer remanufactured cellular phones in their service packages.
9. ***Cannibalization*** (i.e. parts retrieval), meaning flows of returned products to extract parts for reuse, as an alternative to new parts.
10. ***Recycling***, meaning returns with the intent of recycling products (or parts of them) to their raw material state from which they can be reused. An example of recycling is melting a used gear, or bearing, to obtain steel, which is then reused. A wide variety of industrial sectors, including consumer electronics, automotive, and carpet sectors, as well as metals, paper, and plastics industries, are involved in this process, even if it may concern just a small fraction of the overall material flowing (e.g. packaging recycling).

Figure 14 represents a draft generalization of possible logistics flow that involves cycling. Of course it is not to be intended as a hard configuration, but rather a theoretical and conceptual framework of real flows; in other word, supply networks are neither necessarily characterized by every possible cycling flow nor portrayed by flows having exactly the schematized paths. The aim is rather to be comprehensive of all possible cycling categories previously detailed.

CYCLING CATEGORIES	*REFERENCES (A SAMPLE)*
Reuse/Resale	Gungor and Cupta, (1999), van Hillegersberg et al. (2001), Thierry et al. (1995), Dekker et al. (2004), Srivastava and Srivastava (2006), Srivastava (2008), Min et al. (2006), Tomiyama (1999)
Maintenance	Fleischmann et al. (1997), Autry et al. (2001), Bernon et al., 2011
Subcontracting[1]	van Weele, A. (2002), Safaei and Tavakkoli-Moghaddam (2009), Svensson (2000), Qi (2008)
Non-conformity	Srivastava (2008), Amaro and Barbosa-Póvoa (2009), Bernon et al. (2011)
Returnable goods	Kroon and Vrijens (1995), Chan (2007), Hellström and Saghir (2007), Rudi et al. (2000), Young et al. (2002), Yuan et al. (1998), Vliegen and Van Houtum (2009), Carrasco-Gallego et al. (2009), Rudi et al. (2000)
Repair	Jayaraman (2006), Krumwiede and Sheu (2002), van Hillegersberg et al. (2001), Thierry et al. (1995), Van Nunen e Zuidwijk (2004), Srivastava (2008), Shah et al.(2010), Min et al. (2006)
Refurbishing	Jayaraman (2006), Krumwiede and Sheu (2002), Kusumastuti et al. (2004), van Hillegersberg et al. (2001), Thierry et al. (1995), Van Nunen e Zuidwijk (2004), Srivastava and Srivastava (2006), Srivastava (2008), Shah et al.(2010), Min et al. (2006)
Remanufacturing	Savaskan et al. (2004), Jayaraman (2006), Gungor and Cupta, (1999), van Hillegersberg et al. (2001), Thierry et al. (1995), Van Nunen e Zuidwijk (2004), Srivastava and Srivastava (2006), Srivastava (2008), Shah et al.(2010), Min et al. (2006)
Cannibalization (parts retrieval)	Jayaraman (2006), Krumwiede and Sheu (2002), van Hillegersberg et al. (2001), Thierry et al. (1995), Dekker et al. (2004), Srivastava and Srivastava (2006)
Recycling	Jayaraman (2006), Gungor and Cupta (1999), van Hillegersberg et al. (2001), Thierry et al. (1995), Moyer and Gupta (1997), Van Nunen e Zuidwijk (2004), Pagell et al. (2007), Srivastava and Srivastava (2006), Srivastava (2008), Shah et al.(2010), Min et al. (2006)

Table 5. Categories of logistics cycling flows, identified by the literature review.

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[1] Part processing subcontracting is usually not seen as a mean of cycling since reverse logistics is, for definition, related to the aspiration of recapturing products or act for proper disposal. However, with SNA the perspective is all new: in fact, due to the characteristics of the presented model, able to analyze cycling flows in networks, highlighting this particular kind of flows is particularly important and helps in having a better understanding of the distinctiveness of the industrial network under study. Thus, the references in the framework represent a portion of the state of the art dealing with the phenomenon of manufacturing subcontracting and its related benefits and drawbacks.

As illustrated in figure 14, customers may return products to the renter or reseller for several reasons: in such a case products are returned to the forward distribution channel. In some cases, diagnostic tests are performed to determine what action would recovers the most value from the returned product: this is done also in case of product returns due to defects or failures.

Returns from costumers may also be related to maintenance tasks, for repairing and refurbishing. Cannibalizing and remanufacturing are activities that may be conducted in common plants or structures that pool all remanufacturing activities in a separate plant. Remanufactured products may be sold in the same market or in a secondary markets, often to a marketing segment unwilling or unable to purchase a new product. At last, returns may also be used to recover spare parts for warranty claims, to reduce the cost of providing these services for customers.

Products which are not either partially reused or remanufactured are designated for scrap or recycling, usually after physically destroying the product. Reverse logistics flows headed for recycling may also come directly from a municipal waste collection or a third party recycler. Other possible logistics cycling, feasible at every supply chain tier, are those related to returnable goods, such as returnable transportation items, returnable packaging materials and certain categories of reusable products.

At the same time, at every tier, supply chain members can be part of materials and products cycling due to returns for non-conformity (both related to quantity and quality). Last, but not least, logistics cycling may be related to part processing subcontracting.

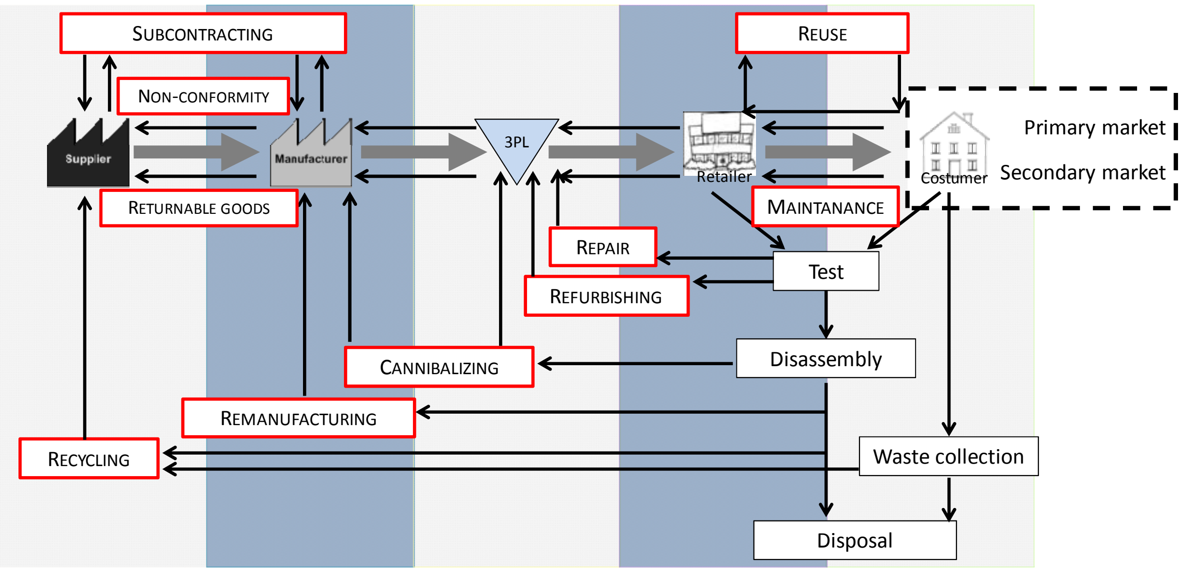


Figure 14. Logistics cycling categories framework.

3.6.2 Finn Cycling Index

Of course, energy and matter cycle. A cycle is defined as a path, through which energy and matter flow through the chain to return to the starting point, and is often examined in ecosystem ecology, especially as it relates to the behavior of autonomous systems, i.e. characterized by reduced dependence on external energy absorption.

Although the presence of trophic cycles was discovered and reported early in ecological studies (Hutchinson, 1948), the first model aiming to quantify the amount of cycling occurring was not proposed until the end of the nineteen-seventies, by Finn (1976), in the context of Ecological Network Analysis (ENA).What became known as Finn's cycling index (FCI) accounts for the percentage of all fluxes that is generated by cycling, and has been applied in a wide range of ecological studies (e.g. Kay et al. 1989; Bodini and Bondavalli, 2002; Allesina and Ulanowicz, 2004).

The chief advantage of FCI has been its simplicity, as its computation requires but a single matrix inversion, and its dimensionless, a feature that allows ecologists to directly compare diverse ecosystems.

Before giving a deeper dissertation of Finn's model and its development and computation, we should take a back step, since Finn's methodology starts by employing the so called "Input-Output" technique to quantify the amount of recycling in ecosystems. In economics, an Input-Output model is a quantitative economic technique that represents the interdependencies between diverse branches of the national economy or between branches of different, and even competing economies. Wassily Leontief (1905-1999) was credited with Nobel Memorial Prize in Economic Sciences for the development of this model. The method consists in the construction of a matrix reflecting the economic structure of inter-branches flows in an economic system, aiming to estimate the amount of raw materials and services required to produce a certain quantity of goods. Input-Output analysis of ecosystems (Hannon, 1973; Finn, 1976; Szyrmer and Ulanowicz, 1987) is an ecological adaptation of the original Input-Output analysis proposed by Leontief (1963) and can be considered the starting point for Finn's methodology.

Given a matrix of exchanges T, one can normalize its columns by dividing each coefficient $T_{i,j}$ by its corresponding inflow $S_{i,}$.

$$S_i = T_{.i} + X_{i.}$$

or, in other words, defining a fractional inflow matrix, [G],where [G] are obtained from the elements of the flow matrix, [T], and the input vector, (X), by normalizing the inter-compartmental exchanges using the total input to the receiving node, j,

$$g_{i,j} = \frac{t_{i,j}}{\sum_k t_{k,j} + X_i}$$

Element $g_{i,j}$ represents the fraction of j's inflows that is comprised by i. Reading column j of [G], information about the percentages for each logistics flow coming from i and entering a node j, which constitutes of the full intake by j.

For example, in the very simple network in figure 4, the nine non-zero values of $T_{i,j}$, generate corresponding nine elements in the matrix [G]:

$$G = \begin{vmatrix} 0 & 0 & 0 & g_{14} & 0 & 0 & 0 \\ 0 & 0 & g_{23} & g_{24} & 0 & 0 & 0 \\ 0 & g_{34} & 0 & g_{34} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & g_{45} & g_{46} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & g_{67} \\ 0 & 0 & 0 & g_{74} & 0 & 0 & 0 \end{vmatrix}$$

$$G = \begin{vmatrix} 0 & 0 & 0 & 0.385 & 0 & 0 & 0 \\ 0 & 0 & 0.288 & 0.213 & 0 & 0 & 0 \\ 0 & 0.435 & 0 & 0.42 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.060 & 0 & 0 & 0 \end{vmatrix}$$

Multiplying the matrix $[G]$ ($[G]\times[G]=[G]^2$)the following result is obtained:

$$G = \begin{vmatrix} 0 & 0 & 0 & 0 & g_{14}\cdot g_{45} & g_{14}\cdot g_{46} & 0 \\ 0 & g_{23}\cdot g_{34} & 0 & g_{23}\cdot g_{34} & g_{24}\cdot g_{45} & g_{24}\cdot g_{46} & 0 \\ 0 & 0 & g_{34}\cdot g_{23} & g_{34}\cdot g_{24} & g_{34}\cdot g_{45} & g_{34}\cdot g_{46} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & g_{46}\cdot g_{67} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & g_{67}\cdot g_{74} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & g_{74}\cdot g_{45} & g_{74}\cdot g_{46} & 0 \end{vmatrix}$$

$$G^2 = \begin{vmatrix} 0 & 0 & 0 & 0 & 0.385 & 0.385 & 0 \\ 0 & 0.125 & 0 & 0.098 & 0.213 & 0.213 & 0 \\ 0 & 0 & 0.125 & 0.093 & 0.342 & 0.342 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.060 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.060 & 0.060 & 0 \end{vmatrix}$$

The reader's attention is drawn to the fact that each of the non-zero elements of $[G]^2$ corresponds to the collection of pathways of length 2 that connect i with j. For example, the 1–5 element of $[G]^2$ reveals how much gets to 5 from 1 over the two step pathway 1→4→5, i.e. plant1→3PL→retailer 1.

Multiplying $[G]^2$ by $[G]$ once more yields the matrix $[G]^3$,

$$G^3 = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0.385 \\ 0 & 0 & 0.036 & 0.027 & 0.098 & 0.098 & 0.213 \\ 0 & 0.054 & 0 & 0.043 & 0.093 & 0.093 & 0.342 \\ 0 & 0 & 0 & 0.060 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.060 & 0.060 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.060 \end{vmatrix}$$

Again, non-zero elements of $[G]^3$ correspond to the three step pathways in the graph. For exemple, 1-7 element of matrix $[G]^3$ match with the path 1→4→6→7, i.e plant 1→3PL→retail 2→recovery product plant (remanufacturing). Thus, the *m*th power of [*G*] contains contributions from each and every pathway of exactly length *m* in the graph. The sequence of powers of $[G]$ truncates with $[G]^k = [0]$, whenever there are no pathways $> k$ in the network. When logistics cycling flows are in the network, the sequence of power of $[G]$ does not vanish, though growing progressively smaller.Recalling that the geometric series:

$$\sum_{n=0}^{\infty} q^n = 1 + q + q^2 + q^3 + q^4 + \ldots = \frac{1}{1-q}$$

Whenever $-1 < q < 1$, it is possible to demonstrate (Higashi et al., 1991) that, whenever $0 \le G_{ij} \le 1$, then

$$\sum_n G^n = I + G + G^2 + \ldots G^n \rightarrow [I\text{-}G]^{-1}$$

Where $\left[I\right]$ is the identity matrix (i.e. it consists of ones along its diagonal and zeroes elsewhere.)

This limit, $\left[L\right]=\left[I-G\right]^{-1}$ is called the Leontief structure matrix.

,

$$\left[L\right]=\left[I-G\right]^{-1}=\begin{vmatrix} 1 & 0 & 0 & 0.410 & 0.410 & 0.410 & 0.410 \\ 0 & 1.143 & 0.329 & 0.378 & 0.378 & 0.378 & 0.378 \\ 0 & 0.497 & 1.143 & 0.528 & 0.528 & 0.528 & 0.528 \\ 0 & 0 & 0 & 1.064 & 1.064 & 1.064 & 1.064 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0.064 & 0.064 & 1.064 & 1.064 \\ 0 & 0 & 0 & 0.064 & 0.064 & 0.064 & 1.064 \end{vmatrix}$$

The i–j^{th} component of [L] provides the fraction of the total input to *j* from *i* over all pathways of all lengths per unit of final demand, which plays a key role in economic theory. The discovery of the [*S*] matrix enabled economists to estimate the necessary production in various economic sectors in order to satisfy any vector of final demands. The Leontief matrix can be interpreted as follows: the number of times a quantum entering i^{th} will visit i^{th} compartment (the diagonal elements) is at least 1, where any coefficient greater than unity indicates that the compartment participates in the cycles.

The Finn cycling index (Finn, 1976) utilizes the Leontief matrix to assess the amount of material cycling within the supply chain. The formula, derived from the inverse matrix *L* is straightforward and simple:

$$FCI=\sum_{i=1}^{N}\frac{S_i}{TST}\frac{l_{ii}-1}{l_{ii}}$$

where l_{ii} is the i^{th} coefficient along the diagonal of the Leontief matrix, TST is the Total System Throughput $TST = T_{..} + X_{.} + E_{.} + D_{.}$ and S_i is the total inflow to the i^{th} supply chain member, where $S_i = T_{.i} + X_{i.}$

The FCI related to the simple distribution network under study turns out to be:

$$FCI = 0.0495$$

meaning that the 4.95% of logistics flow are due to cycling.

3.6.3 Logistics Cycle Indexes

Up to here, it is clear how SNA is successful in highlighting the complexity of a logistics network, however, what is not obvious is how to discriminate this complexity and how to relate it to the proper kind of logistics flows, since cycles certainly increase network complexity and FCI is capable of measuring the amount of material and product cycling within a supply network.

As extensively discussed in section 3.6.1, there are specific reasons for goods and materials to be along cyclic paths within a supply chain, however, those reasons may greatly differ from each other. Thus aggregating homogeneous information into a single index such as FCI may not be very significant and may perhaps even result misleading: relating complexity growthto recycling activities and related logistics flows, for instance, is rather different that relating it to returns of defective products.

Based on these considerations, therefore, a methodology to identify which fraction of FCI can be ascribed to a category of cycling rather than another is proposed. These “fraction” are called Logistics Cycle Indexes (LCIs) and are named after the typology of cycling flows involved, i.e. Reuse LCI, Maintenance LCI, Subcontracting LCI, Non-conformity LCI, Returnable goods LCI, Repair LCI, Refurbishing LCI, Remanufacturing LCI, Cannibalization LCI, Recycling LCI.

The flow chart describing the computation procedure is illustrated in figure 15, together with a very simple example.

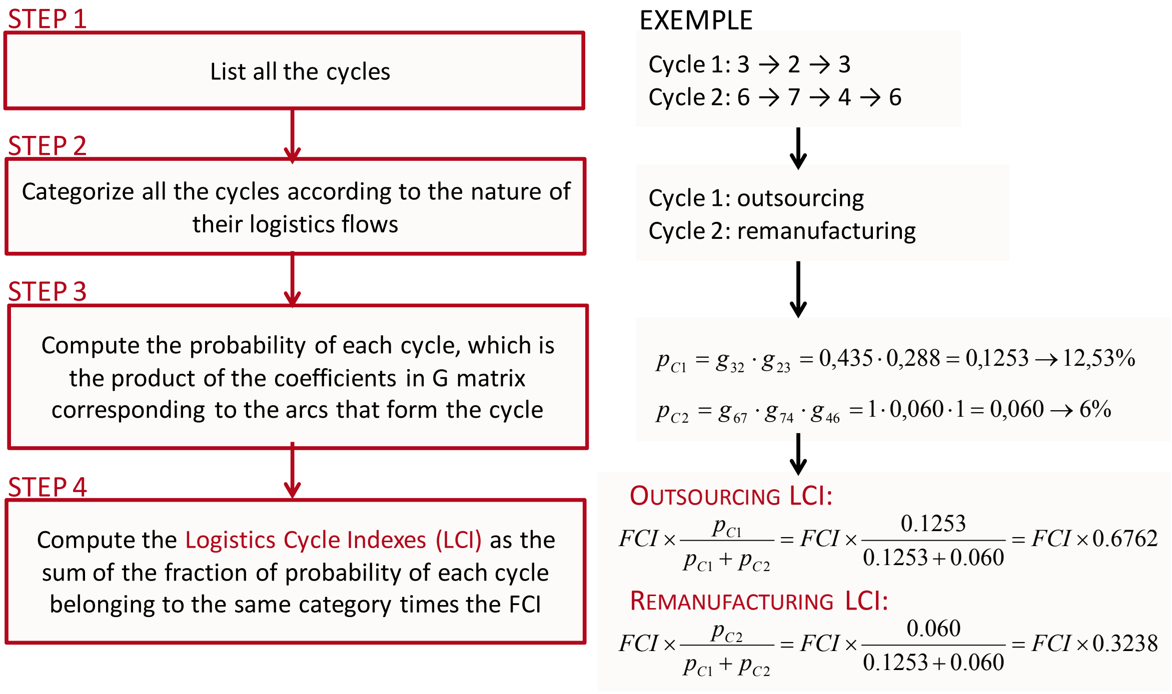


Figure 15. LCIs computation: procedure flow-chart.

The procedure includes the following steps:

1. List all the cycles belonging to the distribution network under study;
2. Categorize all the cycles according to the nature of their logistics flows;
3. Compute the probability of each cycle, which is the product of the coefficients in G matrix corresponding to the arcs that form the cycle;
4. Compute the Logistics Cycle Indexes (LCI) as the sum of the fraction of probability of each cycle belonging to the same category times the FCI

In the analyzed network, 2 kinds of logistics cycle can be identified:

- Plant 3 → Plant 2 → Plant 3, in case of subcontracting;
- Retailer 2 → Recovery product plant → 3PL → Retailer 2, in case of remanufacturing.

Then, the probability of each cycle, which is the product of the coefficients in G matrix corresponding to the arcs formed by the cycle, can be computed.

In this case the first cycle's probability is

$$p_{C1} = g_{32} \cdot g_{23} = 0.435 \cdot 0.288 = 0.1253 \rightarrow 12.53\%$$

While the second cycle probability is:

$$p_{C2} = g_{67} \cdot g_{74} \cdot g_{46} = 1 \cdot 0.060 \cdot 1 = 0.060 \rightarrow 6\%$$

The fraction of probability of each cycle is

- $\dfrac{p_{C1}}{p_{C1} + p_{C2}} = \dfrac{0.1253}{0.1253 + 0.060} = 0.6762 \rightarrow 67.62\%$
- $\dfrac{p_{C2}}{p_{C1} + p_{C2}} = \dfrac{0.060}{0.1253 + 0.060} = 0.3238 \rightarrow 32.38\%$

Therefore, LCIs can be computed as follow:

$$OutsourcingLCI = 0.6762 \cdot FCI = 0.03347$$

$$\mathrm{Re}\, manufacturingLCI = 0.3238 \cdot FCI = 0.01602$$

It is evident how, coupling these measures with complexity network analysis, can lead to many information about the distribution network studied. Following the example , it can be said, that about 3.35% of the logistics flows of the network is related to part processing subcontracting, while 1.6% is attributable to product recovery activities. Again, focusing on cycling inside the network, it can be stated that 67.62% of cycling logistics flow is due to outsourcing, while 32.38 % is due to remanufacturing activities.

Thanks to this procedure, forward and reverse logistics is truly under x-ray, giving an insightful understanding of the supply network structure and the distribution network complexity, and revealing strategic levers capable of increasing/decreasing complexity.

However, as it can be observed from the flow chart in figure 15, this procedure is by no means trivial, and it actually reveals to be very onerous if not computer-assisted. In fact, the method is not very intuitive and requires computer aid since the mere activity of listing all the cycle is not simple nor fast when conducted manually. For this reason, a software application to support research was developed in MATLAB environment, aiming to enable both an intuitive graphical mapping of a distribution network given as input a transfer matrix compiled in Excel, and the automatic and immediate computation of the main SNA indicators, such as the entropic indexes, the FCI and the LCIs.

3.7 A Matlab user-friendly tool for SNA

The program has been developed in Matlab environment.

In particular, an Excel compiled transfer matrix T is given as input to the software, which will quickly process data to map the supply chain, estimate and graph the entropic indexes, and perform a cycle analysis. Thus, the new tool represents a useful instrument for SNA, through three main accomplishments:

- Supply Chain Mapping through oriented graph: the Matlab code is meant to interpret the transfer matrix, proposing a first graphical result. If the user is not satisfied with the visual results, he can change it himself thanks to a Matlab interface, which dialogues with the user, allowing to move nodes, as well as extend or compress distances between supply chain tiers, to make the graph more representative and readable. Nodes can be labeled and replaced by other icons, arrows have different colors according to the related flow sizes, to make the results clear and visually satisfying.
- Estimate the Entropic indexes and graph them through a pie chart. These indexes describe the size and the developmental stage of the supply chain and constitute the principal SNA metrics used to compare different distribution networks.
- Perform Cycles analysis: the program will enumerates all supply chain cycles, recording their structures, before computing the FCI. After a categorization of all cycles costume made by the user, through a Matlab interface with multiple choices, the LCIs are calculated as well.
- Results related to information and system-level indexes as well as cycle analysis are obtained through the automatic compilation of an excel sheet file.

The graphical results are twofold: 1) to sketch a Supply Chain map and 2) to draw a diagram of entropic indexes through a pie chart. For a graphical Supply Chain map, the program implements a recursive procedure that, by exploring all the nodes in sequence (i.e zero and non-zero elements of the transfer matrix), finds the longest path: the number of supply chain members who made up that path will be the number of supply chain tiers in the graph. The other actors are incorporated, one at a time backward in the graph, starting from the last level (the customer) and up to the first level (providers), as long as they have predecessors. As already mentioned, if the results are not satisfactory, the user can interface with the tool and customize the map to his/her needs.

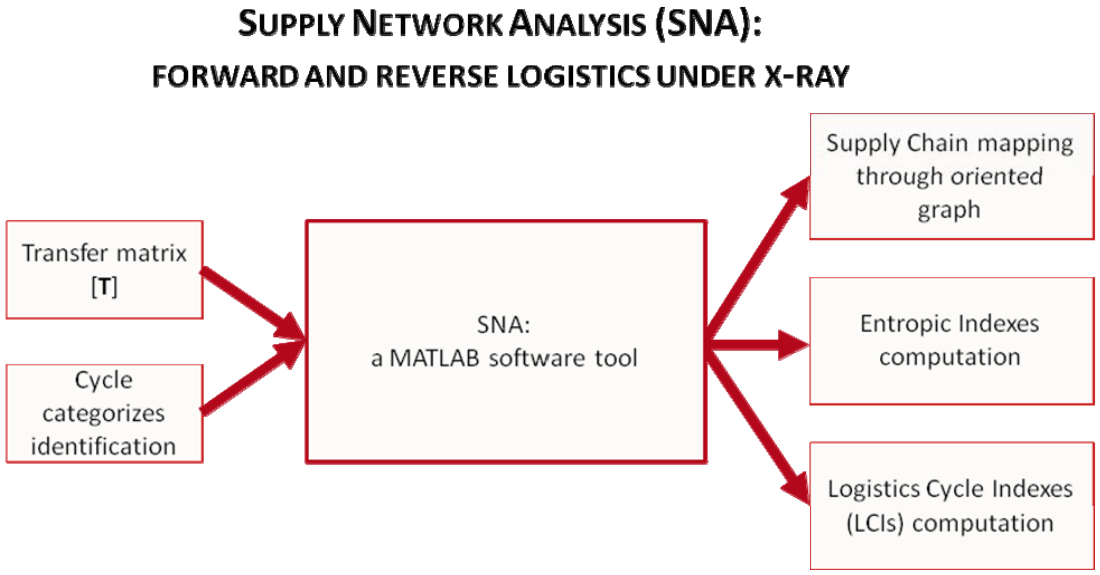


Figure 16. SNA software tool, explicating necessary input and obtainable output.

Accomplishing to map a distribution network means having a visual tool that can effectively communicate information about the complexity of the network itself, which may not necessarily be obvious by looking at the extended matrix. At the same time, the ability to automatically and rapidly return a first representation of the entire network, from a complex supply chain; to deal with a large number of actors and flows, and to map the entire network helps a great deal.

The great effectiveness of the tool is made even more user-friendly by making data very easy to handle, thanks to its familiar Excel format.

3.8 Conclusions

The Supply Network Analysis (SNA) is a new and promising methodology to analyze a supply chain from its complexity, i.e. the structure the of its logistics flows. In fact, by measuring flows of goods and interaction costs between different sectors of activity, within the supply chain, a network of flows can be empirically built and successively investigated by SNA, a tool derived by ecosystem ecology. The results of this study support the idea that an ecosystem approach can effectively provide an interesting conceptual perspective of the supply chain.

The methodology presented, and thoroughly investigated and described by Allesina et al. 2010, starts from a preliminary intuition: that there are substantial similarities between ecological systems and industrial systems (Battini et al. 2007). In fact, while ecosystems are a collections of plant and animal species organized in complicated web-like structures by which energy and matter are transferred and transformed, Supply Chains consist of different companies organized in complicated web-like structures by which energy, information, services and goods are likely transferred and transformed. In both supply chains and ecological systems this web-like structure is described by a network. Again, in both cases the performance of the whole system is strongly dependent on the uncertainty of flows, on the number of partners involved ('network nodes') and on the quantity, typology and magnitude of exchanges ('network edges').

Thus, since Ecological Network Analysis (ENA) (Ulanowicz, 1986; Baird and Ulanowicz, 1989; Fath and Patten, 1999) is a well consolidated methodology to study ecological system, it seems obvious to investigate the possibility to apply ENA to the study of logistics networks. Such a study produced eight indexes, based on information entropy (Shannon, 1948) and ecological theory (Ulanowitz); they were presented, providing a meaningful analysis of the level of complexity in the whole supply network:

1. ***TST*** (Total System Throughput): a measure of the magnitude of the logistics network, simply computed by summing of all logistics flows.
2. ***AMI*** (Average Mutual Information): a measure of how constrained the logistics flows are, equal to the decrease in entropy associated with inflows and known outflows (or the decrease in outflow entropies once the inflows are known).
3. ***C*** (Capacity): the maximum degree of organization a network can achieve, which can be measured by scaling the joint entropy (i.e. statics that summarize the degree of

dependence of uncertain input logistics flows on uncertain output logistics flows) using TST.

4. ***A*** (Ascendency): a quantification of both size and organization; it is obtained by subtracting the actual ecosystem's information entropy from the maximum possible entropy for the system, thus the upper boundary of the Ascendency is represented by the Capacity.
5. ***Φ*** (Overhead): the amount of Capacity remaining non-organized, given by the conditional uncertainty for the system's size; it can be computed simply estimating the differences between Capacity and Ascendency.
6. Φ_I (Overhead in INPUT): the fraction of complexity related to logistics flows entering into the system, thus the overhead in input.
7. Φ_E (Overhead in EXPORT): the amount of complexity ascribable to logistics flows leaving the supply network, thus the overhead in export.
8. Φ_D (Overhead in DISSIPATION): the complexity due to waste, disposal and dissipation flows in general.
9. ***R*** (Redundancy): the amount of complexity ascribable to the presence of multiple or parallel pathways among the components of the network, i.e. the measure of the uncertainty associated with the presence of the effective multiplicity of parallel flows.

To reach a complete comprehension of the complexity dimension, as well as to extend the analysis to reverse logistics, SNA has been extended to the study of logistics cycling, with the introduction of one additional index: the Finn Cycle Index or ***FCI.*** The Finn Cycle Index is the fraction of logistics flows within the distribution network which are due to cycle.

A procedure to compute ten new Logistics Cycle Indexes depending on their nature is also presented:

1. ***Maintenance LCI***: the amount of flows related to returns for maintenance activities, typically due to prevent product abnormality .
2. ***Reuse LCI***: the amount of flows related to product return followed by a situation where the product is used again.
3. ***Outsourcing LCI***: the amount of flows related to subcontracting part processing (i.e. outward processing, partial subcontracting, third party manufacturing…).

4. ***Non-conformity LCI***: the amount of flows related to products and material returns attributable to poor practice within the forward supply chain.
5. ***Returnable goods LCI***: the amount of flows related to the reuse of products, such as transportation items, returnable packaging and reusable products without an economic transaction of any kind.
6. ***Repair LCI*** : the amount of flows related to returns with the purpose of restoring a product to working order.
7. ***Refurbishing LCI*** : the amount of flows related to reverse logistics flows, which result in refurbishment processes.
8. ***Remanufacturing LCI*** : the amount of flows related to product recovery activities aiming to bringing the product to an "as good as new" quality state.
9. ***Cannibalization LCI*** : the amount of flows related to parts retrieval.
10. ***Recycling LCI*** : the amount of flows related to recycling.

Cycling indexes also enable the analyzer to acquire a measure of the supply network sustainability, thanks to the possibility to quantify logistics flow amounts ascribable to system autonomy behavior (e.g. the magnitudes of imports reflects the self-reliance of a system, i.e. the higher these values, the more dependent the system becomes on external exchanges), and environmental friendly logistics flows, such as those related to product recovery activities and recycling.

A before-and-after comparison of these systems' indices allows the user to render quantitative judgments about the network development, and the impact of possible structure modifications can be evaluated using these tools, providing a simple estimate of possible scenarios. Thus, the proposed method takes a holistic point of view to tackle the problem of supply network optimization.

SNA aims to be a new quantitative model to achieve managerial insights over a supply network and eventually perform scenario analysis.

These parameters lead to a sound and meaningful analysis and optimization, a simple measurement of the level of complexity in the global Supply Network that rapidly evaluates the impact of modifications, which can then guide the choice of the best solution among all those available. The proposed method takes a global point of view, aiming to reach total optimization, thereby overcoming the problem of continuous research demanded by the constant need to find many possible local best solutions.

In conclusion, a user friendly tool to perform SNA has been developed in MATLAB environment, to provide speed and accuracy to the research, supplying an intuitive graphical mapping of a distribution network and the automatic and immediate computation of the main SNA indicators, such as the entropic indexes, the FCI and the LCIs.

”If you torture the data enough, it will confess"

Ronald Coase

4

Verification and validation of the model

In the previous section the SNA was introduced and discussed theoretically, in the present chapter, the model is applied to real world scenarios from different industrial sectors. Therefore, this part of the thesis aims to briefly discuss how the theoretical model was verified and validated and investigate practical effects of its application.

4.1 Introduction

In order to test the theoretical model described in the previous chapter, and to study its consistency, several verification and validation activities have been conducted.

In particular, an iterative verification of the SNA was carried on thanks to its application to thousands of samples, with the following approaches:

- “Sensitivity analysis”. In particular, fluxes and nodes were changed leading to the construction of several dummy networks to test its effects on the model effects. The purpose was to systematically investigate the reaction of the model output (i.e. Supply chain mapping and SNA indexes) to drastic changes in model inputs as well as to moderate any increase in network complexity in terms of number of nodes, number of flows and flow magnitude. Results of the sensitivity analysis were, of course, compared with expected trends, studying how the variation in output can be attributed to different effects on the model.

- "Extreme condition test". Sample situations were built due to represent different supply chains and to simulate supply chain extreme conditions, such as fully constrained networks or fully complex networks. Virtual forward and reverse logistics networks, characterized by drastically different elements were investigated to test the consistency of SNA indexes and to understand their behavior.

The validation process of the theoretical model was conducted, and SNA was applied to three different supply networks, belonging to different industrial sectors, and the results were shared and discussed with company managers, to be compared either with company expectation or company effective results. The validation process was then completed through the calibration of the model, iteratively comparing the model to the real networks behavior, and using the discrepancies between the two, and the insights gained, to improve the model.

Another accomplishment achieved through case study analysis was the deep and sharp understanding and interpretation of SNA indexes from an "industrial perspective", confirming the importance to understand the main purpose of the study, and the nature of the output required, in order to select the most critical flows, before mapping the supply chain and undertake its analysis.

In conclusion, several dummy networks were studied to verify the proposed methodology, and the model was tested and validated on real word applications. In the following pages, three case studies are presented. The first one is related to the implementation of SNA for supply network of a company manufacturing industrial catering equipment, in stainless steel, for both professional market and domestic use, whose outbound logistics is partially outsourced. The second case study deals with the automotive sector, focusing on an industrial reality manufacturing different kind of motorcycles (with respect to size and work content); here both inbound and outbound logistics are totally outsourced. Finally, the third case study copes with a 3PL, specialized in waste management and ecologic services, and presents a logistics network related to the collection, treatment and recovery of soils contaminated by hydrocarbons, typical of petrol filling stations, thus involving important reverse logistics flows. The three case studies are analyzed through SNA, in the attempt to achieve managerial insights about the supply networks on hand,

and eventually perform scenario analysis. Through the case studies, the diagnostic capability of the SNA is sound and effective. For privacy reasons, the identity of the companies involved in the testing will remain confidential.

4.2 Case study 1: Industrial catering equipment network

Computer simulation is widely used in manufacturing systems to validate the effectiveness of tentative decisions, such as a new plan or a new schedule, and to study supply chain behaviour and performance. Wu et al. (2001) applied simulation to study aspects of complexity in the supply chain and through a case study demonstrated and validated that the complexity index is a generic and stable measure of uncertainty (Frizelle and Woodcock, 1995). However, simulation is often difficult and time consuming when applied to very articulated supply chains, and so this study aims to demonstrate that even a set of entropic parameters like the one proposed can be easily computed to support an evaluation of the potential for structural changes.

This study investigates the supply network of an Italian company selected to test the research methodology. The supply network is here discussed showing a practical application of the procedure, via the application of ecological indicators to measure how much the fluxes are constrained inside the supply chain, and to provide general criteria for improving the network organization and control systems entropy. The company produces industrial catering equipment in stainless steel for both professional market and domestic use, and consists of three manufacturing units, with widespread sales coverage nationally and an international distribution network.

The study began with the identification of 9 classes of nodes/partners to be used to map the supply network of the company:

[1]. Raw Material supplier (“RM supplier”)

[2]. Semi-finished Components Supplier (“SFC supplier”)

[3]. Sub-contractor

[4]. Production Plant

[5]. Distributor (i.e. 3PL)

[6]. Direct Sales Agency (“DS Agency”)

[7]. Standard Customers (“SC”)

[8]. Directional Customers (“DC”, i.e. big supermarkets)

[9]. Hotel Chains Customers (“HC”).

Material Flows between partners could be measured in different units of value, such as tons of steel per year, Europallets per year, money value per year, etc. However, in order to ease an application of the ecological method, values of goods flows are measured in one unit of value only: tons of steel/year, since steel is the raw material used for the production of all the equipment produced by the company. An industrial network with a large number of nodes and edges produces uncertainty for the medium that flows through the network, as demonstrated for information by Shannon (1948), which is linked with the nature of the network structure (graph). In the industrial example reported, the supply chain is illustrated in its real configuration (as is) and in its future (i.e. foreseen, after improvement) configuration (to be). For this reason historical data have been collected to show the supply chain “as is”, while predictions of future data have been made to project the supply chain “to be”. The uncertainty is due to the complexity of the graph structure.

Figure 17 represents the whole complex network of the industrial group and shows the present situation of the supply network (“as is”). The company is planning five different management strategies to improve network organisation and increase global efficiency:

1. To reduce steel scraps and increase the productivity within the production plant by purchasing new pre-cut steel sheet in different sizes. This choice will reduce Dissipation values inside the production plant b) by approximately 50%, thus reducing the unorganised flows (Overhead Φ) and Total System Throughput (TST), which is simply the sum of all coefficients, that is to say, the “size” of the system or the total amount of medium flowing through the network.
2. To cut redundant connections and the cycling of goods via the Sub-contractor (second level components supplier), reducing consequently the 4th component of the Overhead, the Redundancy, which reflects parallelisms in trophic pathways, and Total System Throughput (TST) while increasing network organisation.
3. To reduce the number of Raw Materials suppliers from 5 to 3, which means simplifying the in-bound net, creating stronger relationships with suppliers that will push the network

to develop less redundant and more efficient configurations. The new network will have fewer nodes and the Overhead in Input (Φ_I) will consequently decrease.

4. To provide direct shipments of finished products from Production Plant c) to customers, eliminating Redundancy of flows, reducing TST, but increasing at the same time the Overhead in Export (Φ_E).

5. To manage and provide direct shipments from Production Plant b) to all foreign directional customers, decreasing Redundancy in out-bound and TST value.

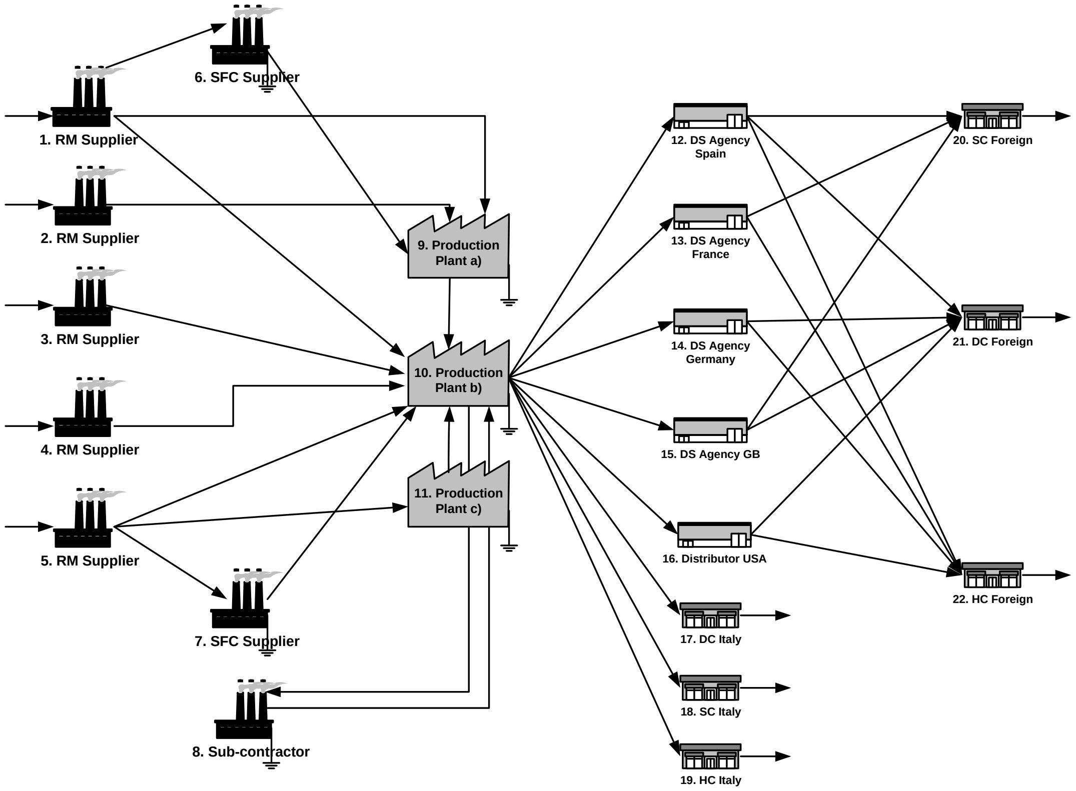


Figure 17. Goods exchanges in the industrial group analysed: the present "as is" configuration.

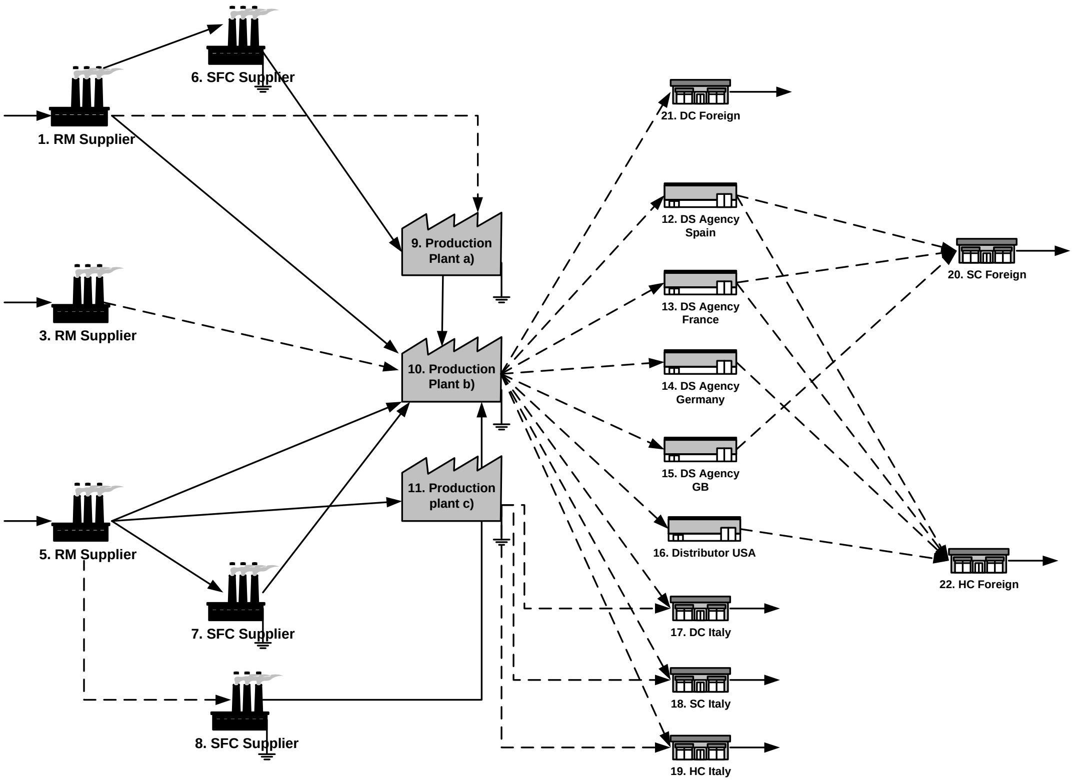


Figure 18. Goods exchanges in the industrial group analysed: the future "to be" configuration.

To increase network efficiency, possible management choices to improve the company were represented: the future configuration ("to be") of the potential network is shown in Figure 18, where the dashed lines, indicate the material flows subject to changes according to the strategies explained above.

The supply chain network has been translated in the Extended Transfer Matrix T^*, which reports all information about the network exchanges, and quantifies the Supply Chain organisation level and complexity level before and after the improvements.

Complexity makes it difficult to make decisions and understand the consequences and result of the modifications, hence, Bullinger et al. (2002) stress the idea that a structured analysis of the network-specific optimisation opportunities is fundamental to benefit from supply chain management. Furthermore, Shih and Efstathiou (2002) applied information entropy to indicate the effect of modification in the manufacturing network.

The case study in this section also aims to demonstrate whether or not network analysis is a useful tool, able to compare alternative supply chain configurations surging from different choices and strategies. Figure 18 and 19 report the two matrixes $\left[T^{*}\right]$ in which flows have been quantified tons/year of steel for both present and future configuration.

Table 6 reports the values of system network indexes and the percentage improvement made. Measuring TST quantifies the size of total supply chain, which depends on both magnitude of flows and number of compartments. In this table it is clear that the future configuration is reduced by approximately 9% due to the reduction in dissipations and redundant flows. At the same time, the total Capacity C, which represents the potential of the system to achieve further development, decreases by 12.8% as a result of the reduction in TST and Joint Entropy. As shown in the previous paragraph, higher values of AMI are obtained for flow structures where movement of goods and energy within the system are maximally constrained.

These systems are also highly organised: since only a small increase in AMI index is obtained in this industrial case, the other performance indexes must be computed in order to understand whether or not the supply network might develop a more organised structure of exchanges. In other words, identifying the degree of organisation only as any increase in the mutual information of the exchange configuration is not enough, so the other six system indexes need to be computed and expressed as a percentage of system Capacity. This will be useful when one network needs to be compared with another network (Figure 21).

The calculations in Table 7 show an increase of 5.9% in Ascendancy in the new network, with a decrease of 21.7 % in Overhead in Input (Φ_I), a decrease of 8.9% for Overhead in Dissipation (Φ_D), and a decrease of6.0%, in Redundancy (R). These were achieved by reducing dissipations, eliminating redundant connections, limiting partner duplication in the supply web, and depending on management strategies. Otherwise, the reduction in dissipation would provide an increase in productivity of finished products and consequently the Overhead in Export (Φ_E) would increase by 19.9%. An increase in Overhead in Export, is a direct result of both improved system productivity and a higher degree of complexity, which arises from new direct shipments from company to customers. On the one hand, this will provide an increase in sales, as desired by the company, with a consequent increase in management shipments and sales costs for the company.

	Imp.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**Exp.**	**Diss.**
Imp.		521	85	580	340	620																			
1							110			125	286														
2										85															
3											580														
4											340														
5								336			130	154													
6										94															16
7											280														56
8											278														62
9											243														61
10									340				191	85	65	110	120	480	400	150					323
11											127														27
12																					46	55	90		
13																					50		35		
14																						45	20		
15																					52	58			
16																						90	30		
17																								480	
18																								400	
19																								150	
20																								148	
21																								248	
22																								175	
Exp.																									
Diss.																									

Figure 19. Extended Transfer Matrix T* of network in Figure 17 ("as is")

	Imp.	**1**	**3**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**Exp.**	**Diss.**
Imp.		606	480	960																			
1					110			210	286														
3									480														
5						336	340		130	154													
6								94															16
7									280														56
8									278														62
9									243														61
10											145	85	38	52	64	447	345	110		248			163
11																33	54	40					27
12																			45		100		
13																			45		40		
14																					38		
15																			52				
16																					64		
17																						480	
18																						399	
19																						150	
20																						142	
21																						248	
22																						242	
Exp.																							
Diss.																							

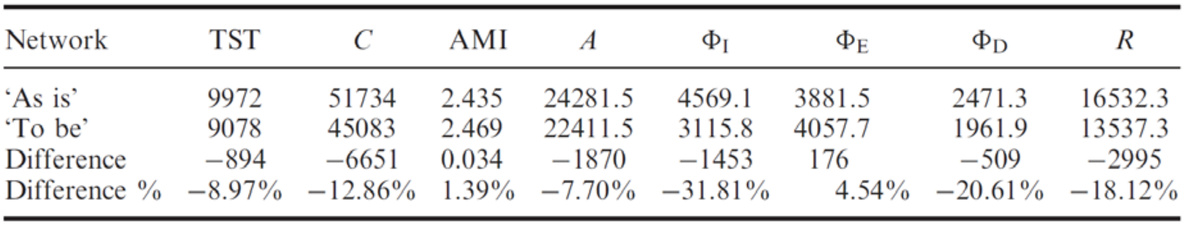
Figure 20. Extended Transfer Matrix T* of network in Figure 18 ("to be").

Figure 21 shows that the capacity configuration of the present "as is" network is divided into 46.9% of flows organisation (Ascendancy A) and 53% in redundant unorganised flows (Overhead Φ), while the capacity of the future configuration will be 49.7% Ascendancy and 50.2% Overhead.

Cutting redundant connections and cycling goods via Sub-contractors determines a considerable reduction in the level of Redundancy where the 3.21% of all logistics flows are related to part processing subcontracting (i.e. *Outsourcing LCI* = 0.0321). The company strategy of process internalization will result in complexity reduction, wiping out cycling thus leading Outsourcing LCI to zero.

To conclude, correct management choices will increase network Ascendancy from 46.9% to 49.7%, but will not determine what is the best trade-off between organisation and disorganisation of a web. This network retains 50.2% of the complexity due to logistic and economic constraints and the rigour of its environment. In fact, dissipation may never be equal zero, and eliminating redundant connections is only convenient when the risk of disrupting the remaining connections is low, that is, when the "external environment" is more benign" (Battini et al, 2007).

The aim of this research is to test a new application of the methodology developed and already successfully applied in other branches of science, such as ecology and information systems. The case study which is reported in this section demonstrates that a real application is feasible, in spite of the preliminary nature of the results, and that the research could very well spin off into useful applications.



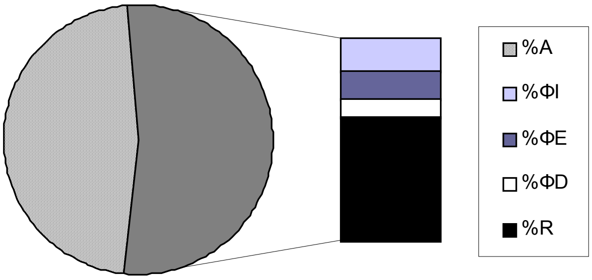
Network	TST	C	AMI	A	Φ_I	Φ_E	Φ_D	R
'As is'	9972	51734	2.435	24281.5	4569.1	3881.5	2471.3	16532.3
'To be'	9078	45083	2.469	22411.5	3115.8	4057.7	1961.9	13537.3
Difference	−894	−6651	0.034	−1870	−1453	176	−509	−2995
Difference %	−8.97%	−12.86%	1.39%	−7.70%	−31.81%	4.54%	−20.61%	−18.12%

Table 6. Results of network analysis: values of system indexes for the two networks in Figure 17 and Figure 18.

Network	%A	%Φ	%Φ_I	%Φ_E	%Φ_D	%R
'As is'	46.94	53.06	8.83	7.50	4.78	31.96
'To be'	49.71	50.29	6.91	9.00	4.35	30.03
Difference %	5.92	−5.23	−21.75	19.96	−8.90	−6.04

Table 7. Percentage values of Ascendancy and Overhead in the two supply network configurations.

a) "As is" configuration



b) "To Be" configuration

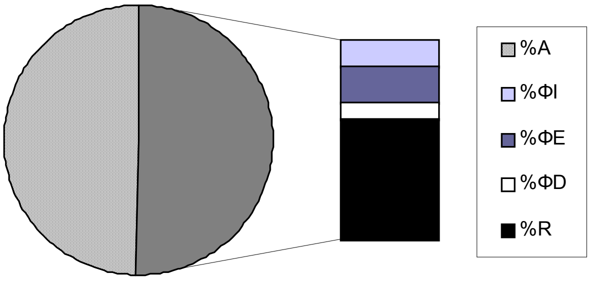


Figure 21. Graph representation of Performance System indexes of the supply network analysed.

4.3 Case study 2: Automotive network

To further prove the finding of this research and give a sharpened understanding of the methodology, we applied entropic measures to the network of an Italian company working in the automotive sector, with a production ofabout 250 motorcycles per day, with a wide range of sizes, functionality and design. The work force is organized into 3 different Production Units, one dedicated to mechanical and thermal treatments, one to the assembly process of naked motorcycles and the last one to the assembly process of not naked motorcycles. Human operators with high experience are involved in the assembly process of different product families on paced lines with several stations: at the end of each step, the product is handled over from one station to another using automatic conveyors with a constant speed.

The company has taken numerous initiatives aiming at strengthening production efficiency and reducing complexity, and has s spent the first decade of the second millennium in a large renovation project aiming to re-design inbound and outbound networks and to implement new outsourcing strategies. In facts, one of the most revolutionary attempts was to turn from a logistics self management policy to an outsourcing policy, recurring to global logistics providers for both inbound and outbound logistics, in three different areas: common pre-assembled groups inside products platforms (i.e. frame and tank), not-strategic technologies (i.e. motorcycle balance blocks production) and services (first of all logistic services).

The network before outsourcing is represented in Figure 22, while, after resorting to 3PLs , the network evolved into the configuration shown by Figure 23.

Again, without loss of significant information, the network was simplified due to the great amount of suppliers and clients of the firm, but the main structure of the supply chain was unchanged together with the magnitudes of flows. Input, output and dissipation flows of the networks were ignored. Flows were measured is units of load per year.

The methodology presented in section 4 was applied to the case company to evaluate its outsourcing strategy and to demonstrate how the process would have brought a considerable decrease of complexity.

We compared the results of the self management policy with those obtained with logistics outsourcing by comparing entropic indexes for the two networks as reported in Figures 22 and 23, and the results of SNA are reported in Figure 24.

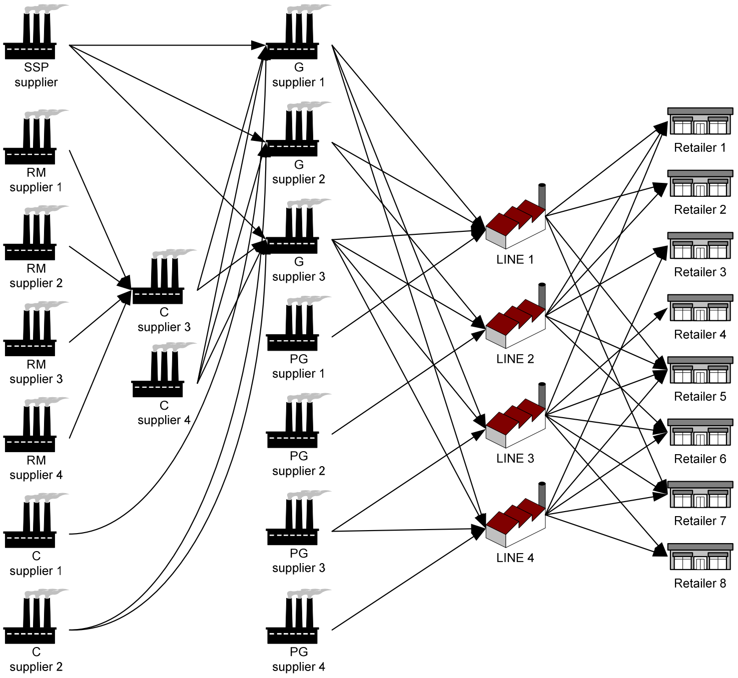


Figure 22. Goods exchanges in the industrial group analysed before logistics outsourcing.

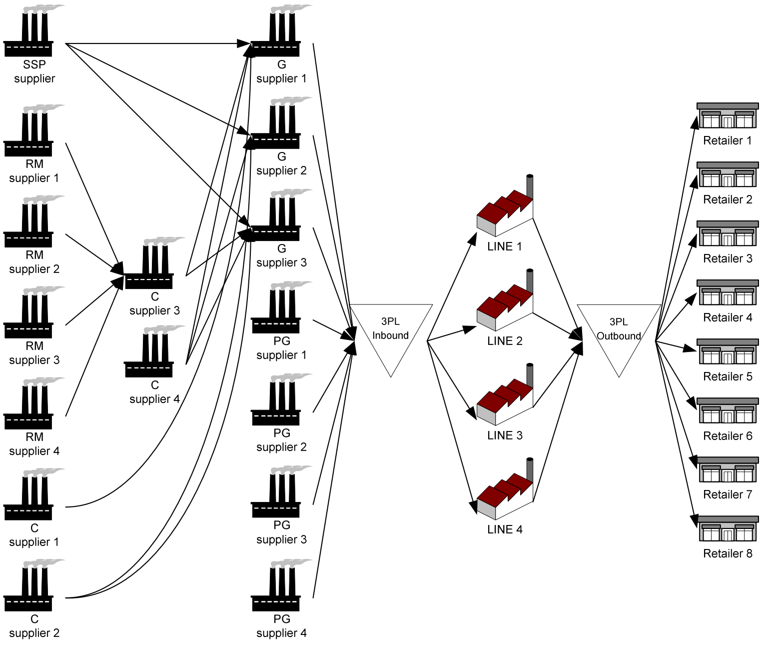


Figure 23. Goods exchanges in the industrial group analysed: inbound and outbound logistics are outsourced.

Figure 22 shows a network divided into 45.29% in flows organisation (Ascendancy %) and 54,71% in redundant unorganised flows (Overhead %), while figure 23 (with 3PLs) shows a 48.13% for Ascendancy (A%), and 51.87% for Overhead (**Φ** %), with a visible increment in A%, reflecting a reduction of network complexity. At the same way **Φ** % experiences a decrease; $\mathbf{\Phi}_I$% $\mathbf{\Phi}_E$% $\mathbf{\Phi}_D$% became worthless due to the choice of ignoring input, output and dissipation flows.

	H_I	H_O	$H_{I,O}$	AMI	TST	C	A	Φ	A%	Φ%
Network without 3PLs	3,43	3,76	4,95	2,24	145.871	721.427	326.727	394.700	**45,29%**	**54,71%**
Network with 3PLs	3,23	3,41	4,48	2,16	276.079	1.237.603	595.668	641.934	**48,13%**	**51,87%**
Difference	-0,20	-0,35	-0,46	-0,08	130.208,00	516.175,88	268.941,65	247.234,23	2,84%	-2,84%
Difference (%)	-5,71%	-9,30%	-9,36%	-3,67%	89,26%	71,55%	82,31%	62,64%	6,27%	-5,19%

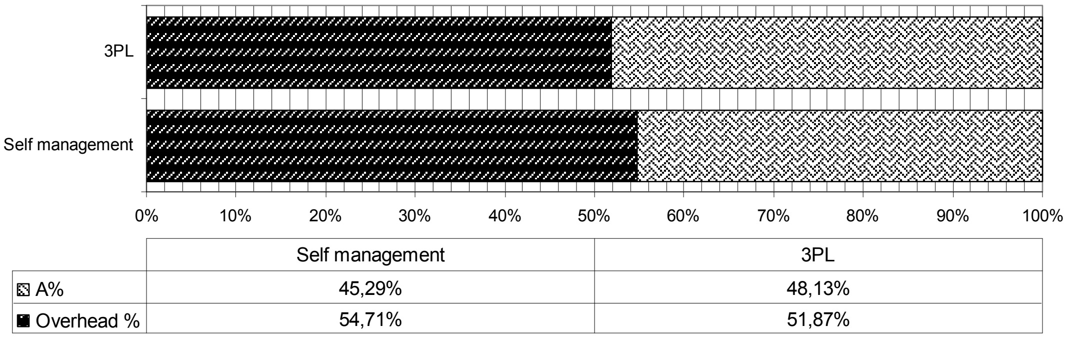


Figure 24. Results of network analysis and graph showing the comparison between values of Ascendancy and Overhead expressed as a percentage on the networks Capacity, for the two networks of figure 22 and 23.

Evidently, the growth of A% (from 45.29% to 48.13%) is noticeable, but not massive: actually, the complexity is retained in this network, fundamentally due to logistic and economic constraints and the rigour of its environment.

Finally, network cycling was not studied, since the magnitude of such flows were not significant to justify flow mapping and analysis.

SNA applied to the presented case study was useful to prove the robustness and correctness of managements' choices. Thus, the method can be considered an innovative and promising tool to be taken into account. Managerial implications can be summarized as follow:

- Managers can evaluate the performances of their choices through an objective and quantitative analysis.

- Managers have the possibility of comparing the various possible alternatives and coping with decision making and problem solving through a “what if” analysis supported by applying the method. In fact, the presented parameters can be easily computed for different options, enabling the managements to compare results before taking the final decision.

4.4 Case study 3: Soil washing network

The third case study involves a 3PL, specialized in waste management and ecologic services. The aim is to map and study the logistics network related to the treatment of soils contaminated by hydrocarbons, typical of petrol filling stations.

Every petrol filling station has the potential for releasing polluting agents into the soil. There are many possible causes for the discharge of these contaminants:

- leaking underground pipes;
- leaking or broken dispensers;
- broken underground tank walls;
- overfill when tanker is filling storage tanks;
- overfill when customer is refuelling the vehicle;
- no drainage and no oil separator at the fuel filling area or forecourt;
- inadequate pavement of fuel filling area or forecourt (i.e. not oil-proof);
- general damages to fuel equipment and facilities.

Thus, hydrocarbons escaped from containment at a petrol filling station may enter the soil directly beneath the site, or around its perimeter, and will have a detrimental or fatal effect on the flora and fauna within the contaminated area, due to its known toxicity, resulting in big environment hazards.. The extent and duration of the pollution will depend on the quantity and duration of fuel release and any subsequent action, while its dispersion will depend on migration ability of fuel, water movement, bio-degradation and soil absorption. To prevent these perils, periodic environmental audits are usually performed on existing tanks. Moreover, tanks are decommissioned and replaced with new ones, after about twenty years of operation.

The present case study deals with logistics activities related to this last job: after the decommissioning and removal of underground storage tanks, a logistics provider is in charge of collecting the contaminated soil at the filling station, transport it to a washing plant, providing reverse logistics activities as well. The logistics provider is related to the fuel companies from a global service contract, which provides not only the fulfilment of reverse logistics activities, but also other services related to product recovery, such as soil washing, and disposal. Network general characteristics are shown in figure 25.

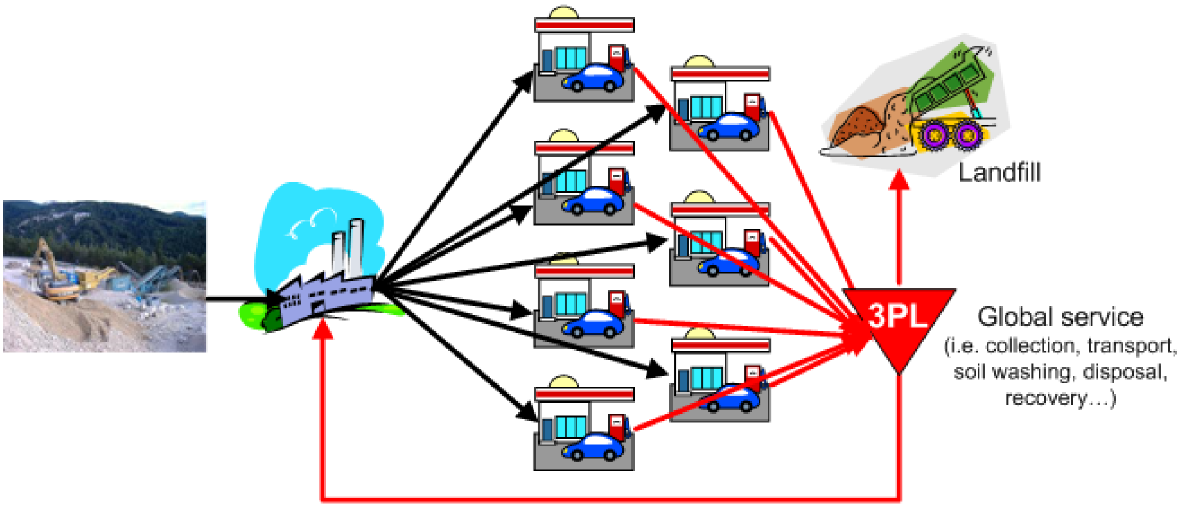


Figure 25. Network logistics flows.

The investigated network has very peculiar characteristics which distinguish it from the others previously discussed. In particular, the distribution network here is greatly dynamic, changing its structure rapidly since stations are in need of services once every few years (tanks are usually substituted on a twenty year basis, but they are not necessarily removed at the same time, thus the logistics provider may visit the same filling station more than once in a twenty years time range). Thus, quantifying flows in tons per year would lead to an incorrect supply network map , representing a not realistic level of complexity.

For these reason, we applied SNA with a dynamic approach, mapping and calculating indexes on a monthly basis and plotting the variability of the entropic indexes and LCIs over time. Results where then shared and discussed with the provider, prior to monitoring the performance as well as achieving a quantification of a average degree of the network sustainability. Data provided and analysed refer to an 11-months' time span. Results are shown through figure 26.

	MONTHS											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**AVARAGE**
Recycling_LCI (FCI)	43.08%	42.00%	30.71%	42.13%	28.80%	37.68%	33.56%	43.65%	33.14%	36.12%	24.53%	**35.95%**
TST	15281	9290	20435	16153	18093	11886	15156	11784	12054	16007	8460	**14054**
AMI	1.901	1.926	1.891	1.634	1.889	1.913	1.665	1.676	1.929	1.853	1.943	**1.838**
C	58546	32474	86603	59020	63558	42993	55155	40538	39685	63470	29012	**51914**
A %	49.61%	55.09%	44.61%	44.73%	53.76%	52.89%	45.75%	48.71%	58.60%	46.74%	56.65%	**50.65%**
ϕ %	50.39%	44.91%	55.39%	55.27%	46.24%	47.11%	54.25%	51.29%	41.40%	53.26%	43.35%	**49.35%**
ϕ_I %	4.13%	4.49%	3.51%	4.26%	3.91%	4.27%	3.92%	4.53%	4.37%	3.88%	3.65%	**4.08%**
ϕ_E %	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**0%**
ϕ_D %	6.19%	7.70%	6.65%	4.26%	6.55%	7.48%	3.92%	5.20%	8.26%	6.03%	7.92%	**6.38%**
R %	40.07%	32.72%	45.23%	46.74%	35.78%	35.37%	46.41%	41.55%	28.77%	43.35%	31.78%	**38.89%**
Num. of stations served	6	4	10	6	4	4	8	5	4	7	4	**5.64**
Num. of soil-washing facilities	2	2	2	1	2	2	1	2	2	2	2	**1.82**
Collected soil (tons)	4,566	2,749	5,902	4,756	5,123	3,482	4,329	3,472	3,449	4,682	2,356	**4,079**
Recovered soil (tons)	2,981	1,705	3,175	2,872	2,401	2,041	2,159	2,103	1,742	2,721	965	**2,261**
Recovered soil (%)	65.29%	62.02%	53.79%	60.39%	46.86%	58.62%	49.89%	60.58%	50.52%	58.11%	40.97%	**55.19%**

Figure 26. SNA results summarization.

As shown in figure 26, variability is related not only to the diversity of stations served, whose total number per months is reported, but also to the number of soil washing facilities utilized, which vary from one to two, depending on facility saturation.

First of all, due to FCI validation (which in this contest coincide with the Recycling LCI being soil recovery the only mean of logistics cycling), this index was analyzed according to recovered soil quantity, assuming a similar distribution between the two measures. This comparison is shown in figure 27. The great similarities in those two distributions validate the significance of LCIs. It is worth pointing out that the percentage of recycled soil per month typically varies according to the number of stations served, as well as station locations and characteristics, soil quality and contamination degree.

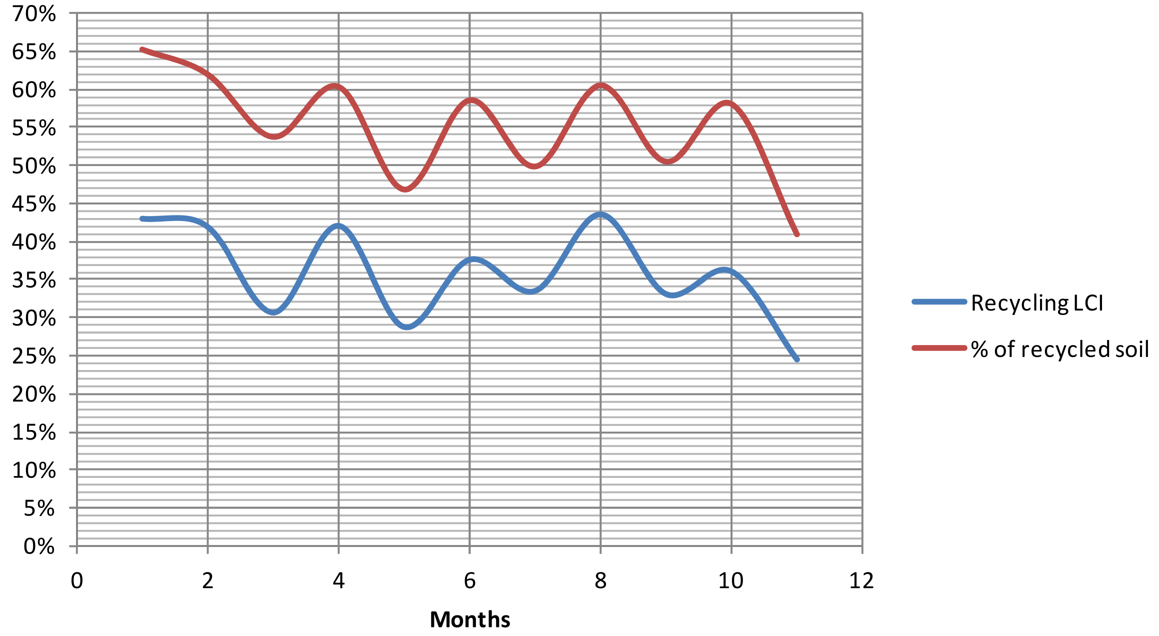


Figure 27. Comparison of Recycling LCI distribution and distribution of the percentage of recovered soil over the total amount of collected soil.

Entropic indexes are also reported, showing that the greater amount of complexity is ascribable to redundancy, due to the presence of significant reverse logistics flows in the network. Moreover, $\Phi_E\%$ is null since nothing is produced and sold. Figure 28 summarizes entropic indexes distributions over time.

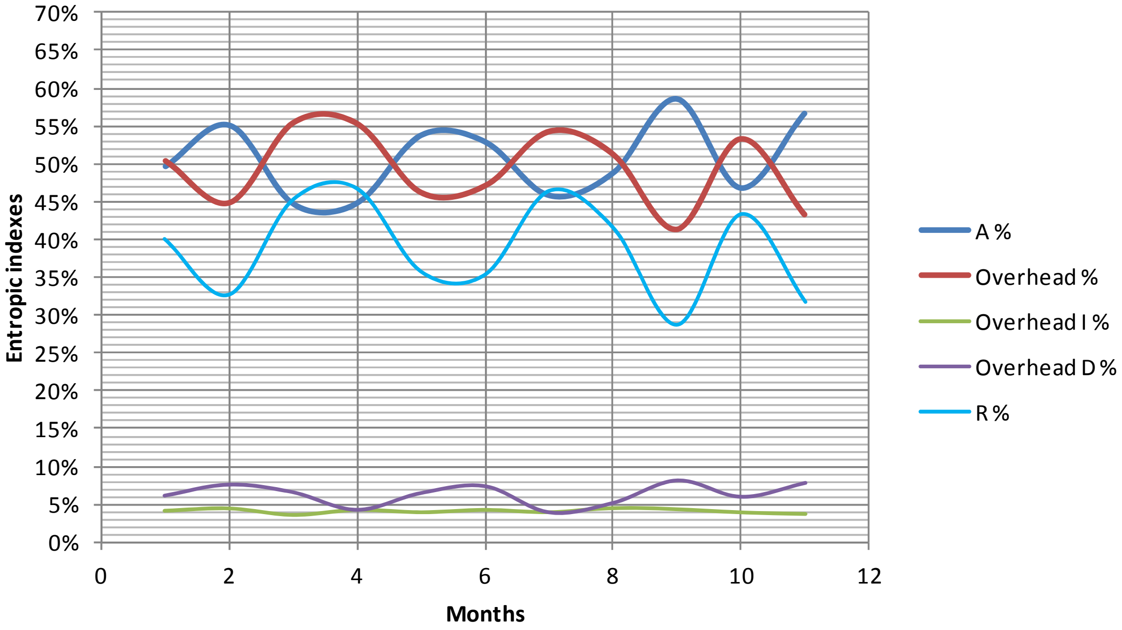


Figure 28. Entropic indexes distributions over time.

The average quantification of entropic indexed is also reporter through a pie chart (figure 29), which highlights how the dimensions of complexity and efficiency are somehow, once again, balanced.

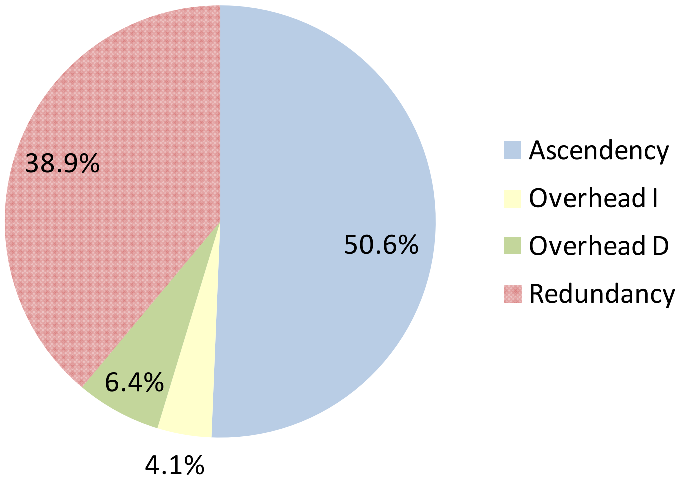


Figure 29. Entropic indexes distributions over time.

4.5 Complexity VS Efficiency or Resilience VS Vulnerability?

Supply chain disruptions are unplanned and unanticipated events that perturb or interrupt the ordinary flow of goods and materials within a supply chain (Svensson, 2000; Hendricks and Singhal, 2003; Kleindorfer and Saad, 2005) and, as a consequence, expose firms to operational and financial risks (Stauffer, 2003). Moreover, empirical evidence leads to affirm that our world is increasingly uncertain and vulnerable. Lately, we have witnessed many types of unpredictable disasters, including terrorist attacks, wars, earthquakes, economic and financial crises, nuclear crisis, devaluation of currencies, tsunamis, strikes, computer virus attacks, etc. (Tang, 2006; Tang and Tomlin, 2008). Historical data indicate that the total number of natural and manmade disasters has risen dramatically over the last 10 years (Tang, 2006). Thomas and Kopczac (2005) asserted that both natural and manmade disasters were expected to increase another five-fold over the next fifty years, as ascribable to many different factors like global warming, population growth rate, urbanization, residential densification, economical and financial global contingencies, natural resources immoderate use and depletion etc.

Because of the strong link between a supply chain's complexity and its efficiency, supply chain complexity management becomes a major challenge of today's business management. Craighead et al. (2007),in their work, assert that Supply chain complexity and the severity of a supply chain disruption appear to be positively related. In particular, their second postulate assert: "*An unplanned event that disrupts a complex supply chain would be more likely to be severe than the same supply chain disruption occurring within a relatively less complex supply chain. Consistent with this logic, a disruption that affects a more complex portion of a given supply chain would likely have more nodes and flows affected than the same disruption affecting a less complex part of a given supply chain*". Even if we agree with this perspective, case studies investigated by SNA also brings to evidence another perspective: a certain degree of complexity seem to be healthy.

In section 3.2 we introduced the concept of information entropy (H), Average Mutual Constrains (AMC) and Conditional Entropy (CE). As previously described, capacity for evolution or self-organization (H) can be decomposed into two components: 1) AMC, which quantifies all that is regular, orderly, coherent and efficient and 2) CE, which, by contrast, represents the lack of those same attributes, or the irregular, disorderly, incoherent and inefficient behaviors. The key point is that, if one is to address the issues of persistence and sustainability, Conditional Entropy becomes the indispensable focus of discussion, because it represents the reserve that allows the system to persist (Conrad, 1983). Scaling the argument on system dimension, one can say that Overhead is essential in guarantying the perseverance of the system.

Two very simple networks, which well illustrate what is intended for “complex network” and “constrained network” are reported on figure 30, proposed by Battini et al. (2007) to explain the significance of the AMI index.

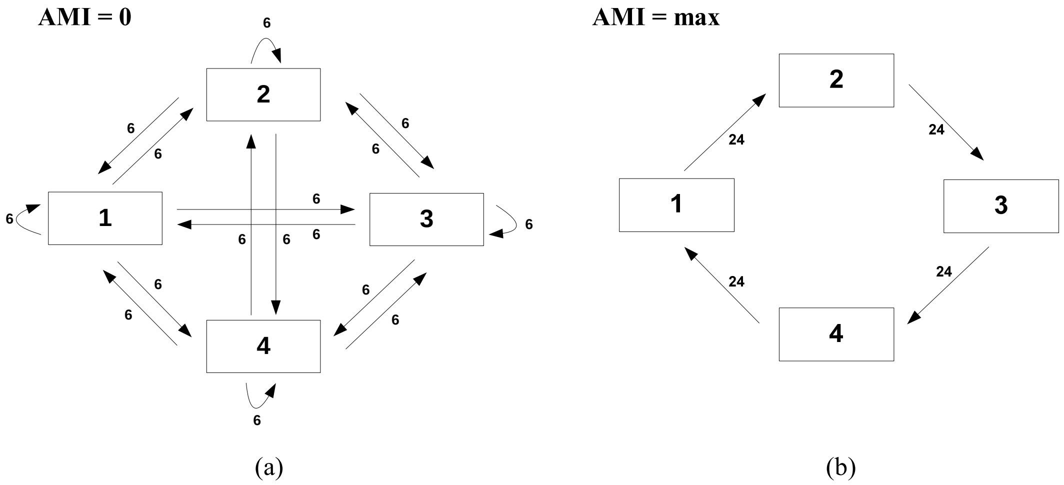


Figure 30. Two examples of network: (a) completely connected (maximal diversity of flows) and (b) completely determined (maximal organisation level); source: Battini et al. 2007.

The extreme values for AMI are sketched in Figure 30: two networks possess the same Activity level (TST = 96 arbitrary units of medium), but Figure 30(a) shows the most uncertain distribution, whose organization level is null, while Figure 30(b) shows a completely determined situation, where no uncertainty exists so that AMI reaches the maximum value. Intermediate configurations will lead to different values of AMI, that will be bounded by 0 (minimal AMI), and $H_{I,O}$ (maximal AMI).

Of course complex global supply chains are very vulnerable to business disruption, but what if a supply chain has a low degree of complexity? If some disruptive events happen to node 3 in the simple network configuration (b) (figure 30), the network is suddenly paralyzed, since node 4 is totally dependent from 3 as well as node 1 is totally dependent from 4 and so on. The great complexity of network (a), instead, would allow the supply chain to go on working, even if some turbulent events should perturb part of the system. Thus, only “robust” networks can return to equilibrium once they have been “disturbed”. Is it possible to identify a measure for this resilience?

The analysis conducted through the application of SNA to the presented case studies, seem to bring evidence to this trade-off. All the supply network, for instance, which belong to well consolidated and “healthy” industrial reality, seem to boast of a rather fair balance between their degree of complexity and their degree of organization, which are proximal to 50% of the development capacity in all analyzed cases. Results are summarized in figure 31.

Of course, this consideration cannot be taken as a result since more supply networks should be studied to assert such a precise and quantitative consideration. Thus, this topic can lead to further research: does vulnerability have a measure?

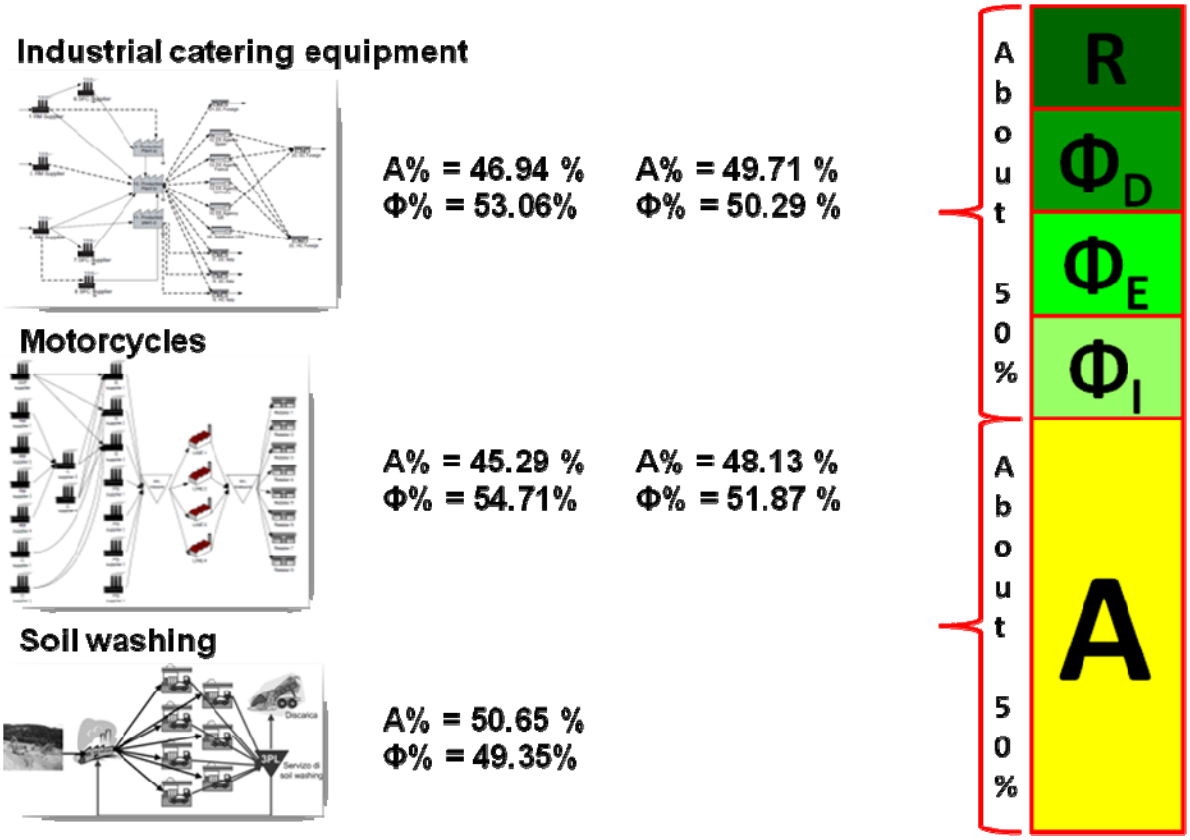


Figure 31. Supply chain complexity-organization trade-off: case study results.

4.6 Discussion

In this section, SNA was successfully applied to three different supply networks, varying in terms of industrial sector, structure and degree of logistics outsourcing. Through case studies the model was validated since it demonstrated to be consistent with real word result or managerial expectation. Real world applications also led to the following consideration:

- SNA is a real promising tool, which enables to map and understand the supply network structure, achieve managerial insights about the supply network on hand.
- SNA indexes facilitates the comparison of different supply networks performance as well as various possible alternatives of the same network, assisting scenario analysis and what if analysis.
- Picturing the supply chain, SNA helps in identifying areas in need of further analysis, since inefficiencies are not always easily visible by studying just a segment of the whole supply network.
- SNA enables managers to overcome the individualistic or dyadic approach when dealing with logistic outsourcing, moving to a more holistic perspective, defying the perception of a supply chain integration effort.
- SNA offers a basis for supply chain redesign or modification.
- SNA seems also promising in evaluating the progress of eventual supply chain redesign goals and assessing supply network evolution over time.
- Through SNA, managers can evaluate the performances of their choices through an objective and quantitative analysis.
- Opportunely investigated, SNA seems to be promising in representing a quantitative means of measuring supply chain resilience.

"Knowledge is argued through belief"

Plato

5

Decreasing network complexity with logistics outsourcing

The intention of this section is to show that a transition from a self managed structure to third-party logistics arrangements brings, if correctly managed, a decrease in information needs and consequently a reduction in supply network complexity.

5.1 Introduction

Over the years, third-party logistics (3PL) has been adopted by companies with the objective of helping organising their value chain activities and hence increase competitiveness, flexibility and responsiveness to dynamic market requirements. According to literature and practice, what is produced in outsourcing logistics has effects not only for the parties directly involved, but also for other relationships and organisations within the overall network. Up to now, 3PL outcomes perceived by the parties directly involved (shipper, manufacturer and logistics service provider) are often addressed in literature, while the 'external outcomes' experienced at the supply chain level need further analysis. This section investigates the implications of the outsourcing of logistics activities on the supply network structure, by using SNA entropic measures, useful to study the quantity of information required in a network. The intention of this work is to show that a transition from a self managed structure to third-party logistics arrangement brings, if correctly managed, a decrease in information needs and consequently a reduction in supply network complexity.

Existing studies of logistics triads and networks do not seem to add any intrinsically supra-dyadic insights (Aas et al., 2008; Selviaridis and Spring, 2007). As Karp and Ronen's (1992) purpose was to show that a transition from large to small-lot production brings a decrease in information needs, it is the intention of this chapter to show that resorting to a 3PL brings a decrease in information needs as well. Moreover, with the application of SNA, it is possible to highlight how networks where inbound and outbound logistics are outsourced , can be much more organised, since complexity level decreases.

5.2 Sensitivity analysis

This section aims to apply 'Supply Network Analysis' (SNA) to a supply chain characterized by logistics outsourcing. SNA (Battini et al., 2007; Allesina et al., 2010),an innovative approach borrowed by scientific ecological literature based on eight different entropic indexes to map the exchanges of goods between different actors in a complex supply chain, is a promising method to study Supply Chain as a complex web.

To demonstrate that logistics outsourcing does not require a vast amount of information, being characterized by a smaller degree of complexity, we are going to compare different supply networks, with and without 3PLs, evaluating values of Ascendancy, expressed as a percentage of the system Capacity.

In reality, it might very well happen that two systems with the same TST are characterized by totally different flow structures, or for networks characterized by the same AMI or the same Ascendency, to present totally different flow structures as well. Thus, to compare different systems it is necessary to evaluate Ascendancy, expressed as a percentage of the system Capacity; hence we will call it A%.

Showing that network configurations with 3PLs can boast a higher A%, can lead to the conclusion that supply networks benefit greatly from the logistics provider in terms of organization and decrease of complexity.

Due to the robustness of the analysis, we performed a sensitivity investigation exploring the distribution of A% according to the various number of partners in the networks both with 3PLs and without, using purely arbitrary unit measures of goods exchanges. They could reasonably be units of load, work pieces, trucks, tons of materials, money value etc., in a given period of time. Without loss of results' generality, we assumed the flows had unitary magnitude; the same outcome can be expected with flows of multiple or fractional magnitude.

As Figure 32 shows, the plot of the distribution of the sensitivities of A% to the numbers of suppliers and buyers was discovered from a basic supplier-company-buyer triad, with and without 3PLs providing inbound and outbound logistics. Partners upstream and downstream were then added reaching an amount of 100 suppliers upstream and 100 buyers downstream. According to the purpose of the study input flows, output flows and dissipations are not taken into account.

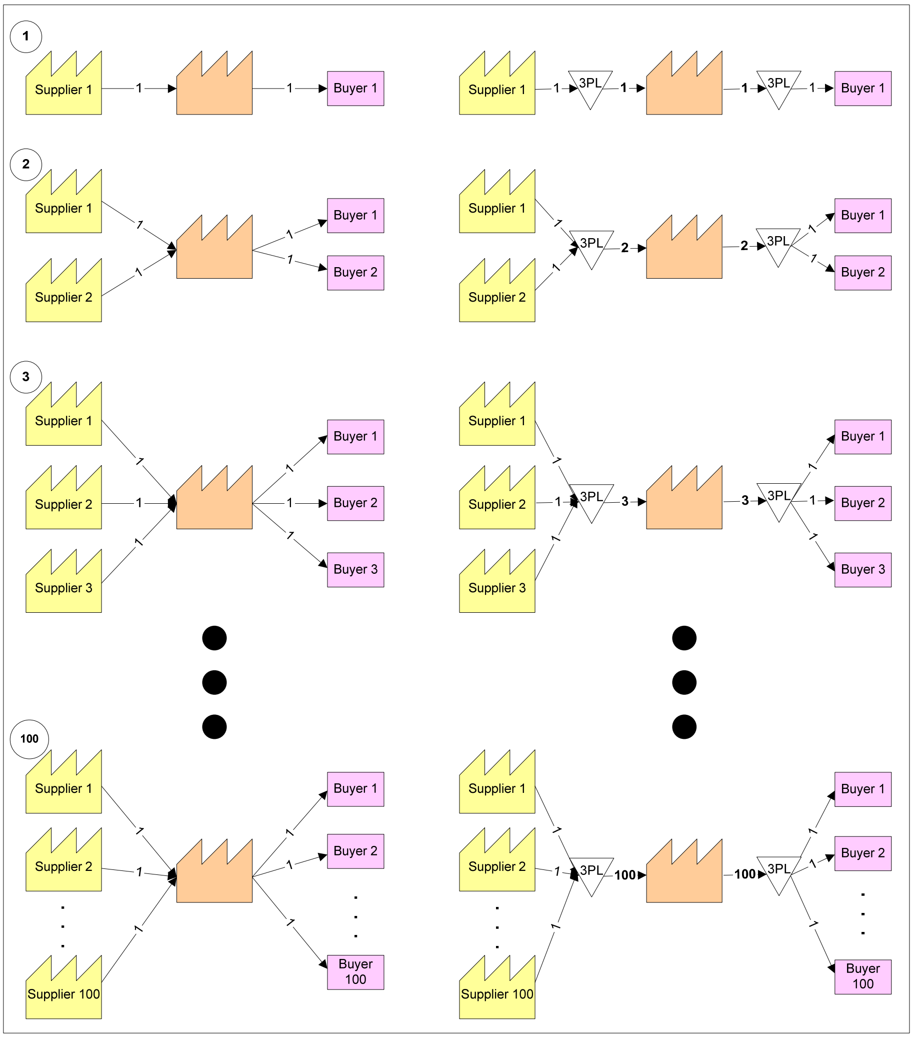


Figure 32. Plane network configurations used to evaluate A% in sensitivity analysis.

The graph of the percentage of Ascendency versus the number of partners upstream and downstream is given in Figure 33a, where A% varies from 100% to 37% where the inbound and outbound logistics are outsourced (solid curve) and from 100% to 13% where the network presents no 3PLs(dashed curve). Moving from a completely determined configuration (maximal organization level) with no uncertainty due to the constrictive nature of paths, to a more complex configuration with few additional flows and nodes, the plot experiences a great initial drop, while it seems to be less sensitive as long as the number of partners increases. If we compare the two curves representing networks with 3PL and without 3PL, we can see how, with the addition of more suppliers and buyers, A% continues to decrease in both cases, but the darkest curve remains higher. Similarly, Figure 33b shows how Overhead, also expressed as a percentage of the system Capacity, rapidly increases from an organized configuration, where flows are completely constrained, to a more complex network. Visibly the dashed line of the graph (representing a network configuration where logistics self management was chosen) shows a greater rise that the solid line.

As a consequence, we can assume that logistics outsourcing brings a decrease of supply chain complexity and a reduction in required information.

In Figure 34 the analysis takes a deeper insight to what happens if the number of partners is further increased, reaching the amount of 1600 suppliers upstream and 1600 buyers downstream, the solid line itself still higher, showing a difference of about 15%. Thus, it is evident how the network configuration with 3PLs remains highly more organized, which leads to the conclusion that having 3PLs in the network is always beneficial in term of complexity decrease.

Finally, like Karp and Ronen (1992), proposed entropy as a function of the number of lots, through Figure 35, we tried to illustrate the trend of joint entropy versus number of partners added upstream and downstream. After a break-even point very close to the origin, benefits derived by the presence of 3PL in a network became evident and, by the present study, mathematically demonstrated.

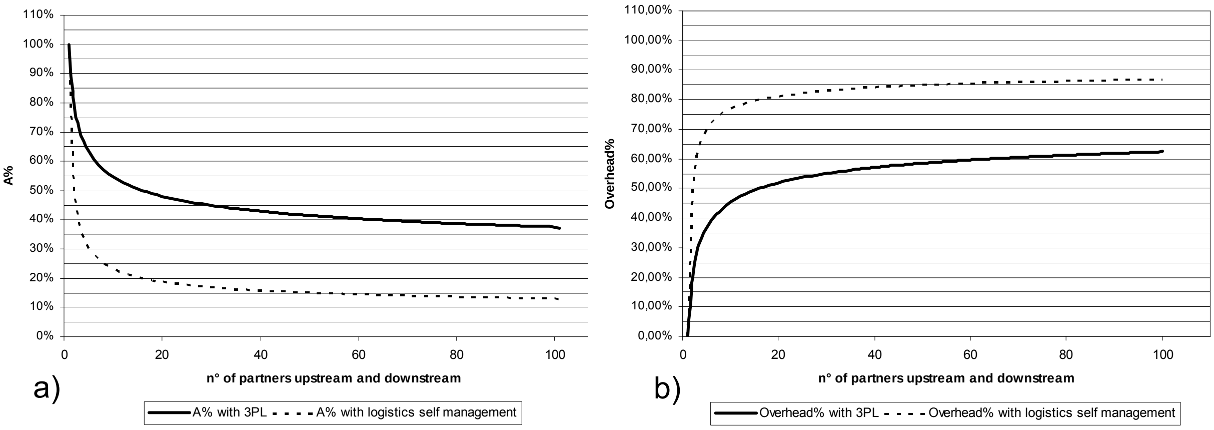


Figure 33. a) Sensitivity analysis of A% and b) Sensitivity analysis of Φ% when 3PLs are in the networks (solid curve) and when they are not (dashed curve), up to 100 suppliers upstream and 100 buyers downstream.

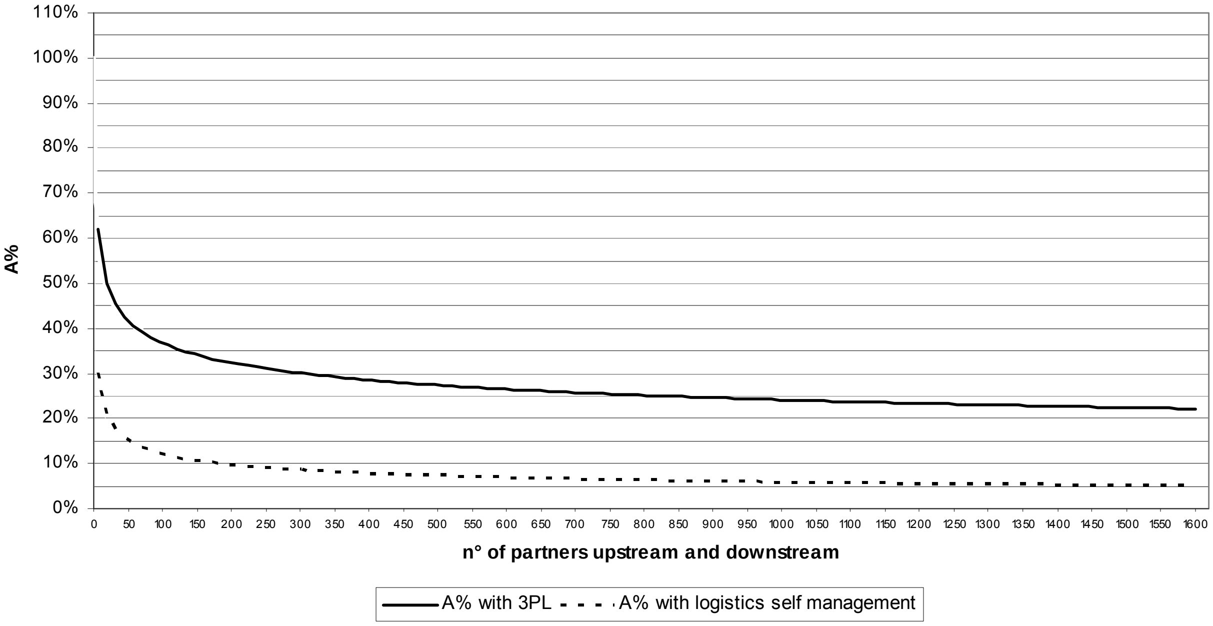


Figure 34. Sensitivity analysis of A% when 3PLs are in the networks (solid curve) and when they are not (dashed curve), up to 1600 suppliers upstream and 1600 buyers downstream.

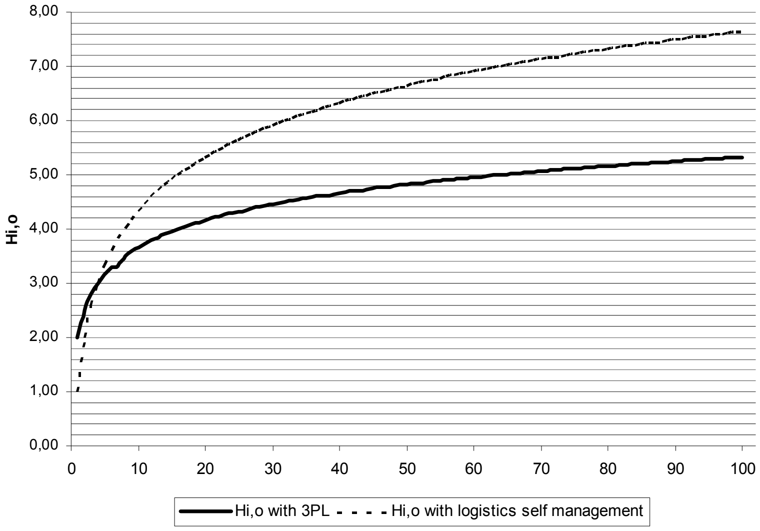


Figure 35. Joint entropy versus number of partners (upstream and downstream).

5.3 Discussion

Outsourcing is an increasingly popular solution pursued by many corporations seeking improved efficiency (Işıklar et al., 2007). 3PLs, with their professional and value-added services, are often selected to take charge of the logistics design, delivery, storage, and transportation in a supply chain (Yan et al, 2006). Several recent studies focus on 3PL's market penetration, highlighting the great success of logistics outsourcing as a way to improve cost efficiency and customer responsiveness (Gunasekaran and Sarkis, 2008; Yanxia et al., 2008). More than a few companies deal with benefits and risks associated to logistics outsourcing (please refer to section 2.2). The literature review also stresses a general lack of theoretical approaches on the topic of logistics outsourcing. Moreover, it shows a great interest to treat the issue from the company point of view or from the provider point of view, while only few observed the phenomenon considering the supply network as a whole.

The purpose of this work was to demonstrate the beneficial influence of 3PL on supply networks in terms of amount of information to deal with and in terms of system organization, and that was reached applying SNA. Allesina et al. (2010) suggested to apply SNA's set of performance measurements to quantify the potential of structural changes in supply networks, to understand the impact of strategic choices on the whole system, to compare the actual structure of the network with possible future structures, and to identify critical parts in the network structure.

To ensure the robustness of the study we went through a sensitivity analysis with the intent to explore the behavior of the SNA indexes in presence of a 3PL, adding suppliers and buyers to the network. The presented graphs give a clear understanding of the relationship between number of partners and Ascendency, expressed as a percentage of the system Capacity, as well as the distribution of joint entropy versus number of partners was plotted.

The investigation results visibly point out how logistics outsourcing positively influences the supply chain in term of network organization, complexity reduction and information. When no 3PL is in the network Ascendency (as fraction of development capacity) remains rather low because resources are used inefficiently.

To further demonstrate the effective impact of 3PLs, the reader can refer to section 4.3, where case study 2 is presented. Entropic measures were applied to the supply chain of an important industrial group, who experienced great benefits in terms of complexity reduction from logistics outsourcing. Comparing before-outsourcing A% with after-outsourcing A%, as offered by SNA, the improvement in organisation and reduction of information quantity is undisputable.

As previously discussed, the results of this study are largely in accord with our theoretical exceptions. However, like the earlier studies, the present one has its limitations that must be addressed in future researches.

If 3PLs reduces the need of information, the evaluation of logistics outsourcing risks can’t be underestimated: unsuccessful experiences that accrue undesirable consequences for clients have been reported (e.g. Harland et al., 2005; Bahli and Rivard, 2003). Another aspect that the research does not take into account is the different degree of commitment and integration between parties. Actually, we believe that benefits can be gained only through a long term relationship in which the parties are interdependent (Bowersox, 1990). At the same time different degrees of involvement may lead to different risk. As Gunasekaran et al. (2004) point out, evaluation of supply link performance is very important in managing the supply chain for peak efficiency and effectiveness: the parameters that need to be considered in the evaluation of partnerships are the ones that promote and strengthen these aspects. For example, the level of assistance in mutual problem solving is indicative of the strength of supplier partnerships. Partnership evaluation based on such criteria will result in win–win partnerships leading to more efficient and more thoroughly integrated supply chains.

Another important aspect to take into account is the trade-off between network complexity and network organization (Battini et al., 2007; Allesina et al., 2010). Deciding on the level of organization to achieve is almost like performing a balancing act: the higher the complexity the greater the chances of poor performance and poor quality, and the higher the costs; on the other hand, maximum efficiency (minimum complexity) often means maximum vulnerability and less flexibility in the management of sudden changes.

This particular study demonstrated mathematically the benefits derived from logistics outsourcing in term of organization and quantity of information, making the decision of turning to a logistics provider very appealing, but each company must take into account the risks associated with control costs and relationship management costs that come with this type of solution.

Future research in this field should develop guidelines to apply SNA in supporting managers to solve the problem of selecting providers. The results obtained, should then be compared with other data from different studies (e.g. Yan et al., 2003; Chen et al., 2006; Işıklar et al., 2007; Jharkharia & Shankar, 2007; Liu and Wang, 2009), along with the choice of the best set of measurement units to illustrate network flows and the consideration of the "time" factor with a comparison between "Dynamic Network Analysis" and "Static Network Analysis" as highlighted by Allesina et al. (2010) .

"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them".
Sir William Bragg

6

Conclusions

This thesis presented a collection of techniques and algorithms that can help theoretical logistics to draw conclusions on supply network design and structure. This last chapter aims to overview and summarize what has been presented, and anticipate the need for further research.

6.1 Conclusions and recommendations

Envisioning, tracking and managing supply chains becomes more complicated as firms pursue outsourcing strategies; .despite the fact that logistics providers are often required to offer skills and services linked to supply chain management. Approaches belonging to existing literature are merely dyadic, and the very few studies of logistics triads and networks do not seem to add any supra-dyadic insights .

This work had a simple aim: to study the phenomenon of logistics outsourcing, with the application of innovative advanced models and tools to support this widespread phenomenon, in an industrial context characterized by high complexity. The presented methodology, called Supply Network Analysis (SNA) aims to overcome the traditional dyadic approach, taking into account the whole system, thus measuring the complexity of the industrial network as a whole.

The study opened with Chapter 2 and the description of the state of the art related to logistics outsourcing: according to literature and practice what is produced in outsourcing logistics has effects not only for the parties directly involved, but also for other relationships and organizations within the overall network, emphasising the need for a new integrated and holistic approach for supply chain mapping and engineering. Such approach and methodology is the subject of Chapter 3, which consists in the description of the new proposed SNA methodology, inspired by Ecological Network Analysis and based on the concept of *information entropy*. This new interdisciplinary approach is based on eight different entropic indexes and ten Logistics Cycle Indexes (LCIs), which are meant to accomplish several tasks: 1) map the exchanges of goods between different actors in a complex supply chain and measure complexity and organization level; 2) identify complexity drivers (i.e. relate complexity with import, export, redundancy, dissipation and cycling flows); 3) provide an innovative quantification of supply chain sustainability, based on its autonomy from external resources. The methodology and the quantitative indexes are extensively discussed and lead to the development of custom-made software application to sustain further research. In Chapter 4, the model is applied to real world cases belonging to different industrial sectors, creating the opportunity not only to discuss how the theoretical model was verified and validated, but also to investigates practical effects of its application. One of the results achieved is to shows how the design of efficient and durable Supply Network from a logistical point of view should be supported by appropriate mathematical models. Then it emphasizes how SNA supports the mapping and rating activities of a logistics network, thereby assisting decision-making, scenario analysis and supply chain mapping and reengineering. The intention of Chapter 5 is to show that a transition from a self managed structure to third-party logistics arrangement brings a decrease in information needs and consequently a reduction in supply network complexity level.

This dissertation allowed me to address, at least partially, a number of unanswered questions, which should clearly be the topic for further research, from the validation process to creating sector-specific applications. The first one, for instance, should be strengthen with the application of SNA to several other supply networks, testing consistency of all quantitative indexes in a broader industrial case history. Further investigation will eventually lead to the determination of sector-specific guide indexes for various industrial realities, as well as to further investigate the intriguing and fascinating issue of vulnerability of a supply network, discussed in section 4.5. Future tests of the procedure on new industrial supply networks might also guide a comparison between ‘dynamic network analysis’ and ‘static network analysis’, developing guidelines to support the choice of the best set of measurement units used to depict network flows. The employment of these sets of such measurements in practice needs to be investigated as well to overcome the existing limitations mainly due to the analytical model comprehension difficulty for industrial practitioners. Furthermore, another intriguing interrogative is related to supply chain granularity: which is the best level of abstraction that can be possibly used to map a supply chain and identify its members?

Attempting to answer to any one of these questions could very well entail another dissertation each.

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LIST OF PAPERS ENCLOSED

Paper [I]

Allesina S, Azzi A., Battini D, Regattieri A (2010). **Performance Measurement in Supply Chain: New Network Analysis and Entropic Indexes**. *International Journal Of Production Research*, vol. 48 (8); p. 2297-2321.

Paper [II]

Azzi A., Battini D, Persona A, Sgarbossa F (2010). **Decreasing Network Complexity with Logistics Outsourcing: An Entropic Approach**. *International Journal Of Procurement Management*, vol. 3 (4); p. 339-360.