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DYNAMIC MODELING OF NETWORKS AND LOGISTIC COMPLEX SYSTEMS

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DYNAMIC MODELING OF NETWORKS AND LOGISTIC COMPLEX SYSTEMS

BY

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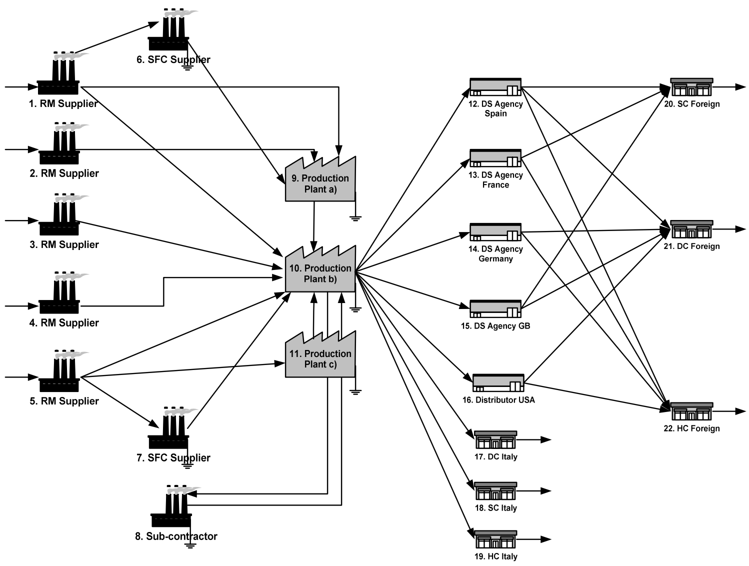

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INTRODUZIONE

Le moderne reti logistiche sono caratterizzate da legami e interconnessioni molto complesse fra i partners coinvolti: fornitori, produttori, distributori, clienti, etc. Questi legami non sono solo basati sullo scambio di materiali e prodotti finiti ma anche su flussi di informazioni e scambi finanziari.

Le crescenti richieste di un mercato sempre più esigente enfatizzano lo studio della rete logistica da parte di fornitori e produttori e accelerano la ricerca di nuove alternative logistiche ai tradizionali sistemi di distribuzione di prodotti e servizi. Questa esigenza è sempre più avvertita in conseguenza al fatto che la complessità dei sistemi industriali e i costi ad essa legati, evidenti e sommersi, aumentano di giorno in giorno.

I termini “Supply Network” e “Business Web” sono ormai parole interscambiabili quando vengono utilizzati con riferimento agli innumerevoli flussi e ai legami presenti in una catena logistica (Tapscott, 2000).

Le reti distributive e i network logistici richiedono urgentemente nuove 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.

Questo elaborato analizza le teorie fondamentali riguardanti l’ottimizzazione dei network distributivi (Distribution Network Optimization) e affronta l’analisi della complessità di un Supply Network (Supply Network Complexity Analysis), proponendo nuove tecniche per studiare aspetti peculiari di una rete logistica complessa e sottolineando l’importanza e la necessità di nuovi approcci sistemici (supportati da adeguati strumenti software) per favorire lo sviluppo futuro di queste discipline.

Questo lavoro si pone quattro obiettivi principali:

1. Mostrare come l’ottimizzazione della rete distributiva di prodotti e servizi sia possibile e al tempo stesso critica al fine di creare network efficienti.
2. Investigare come la progettazione di un network di distribuzione (Distribution Network Design) sia cruciale al fine di aumentare efficienza e competitività nel mercato globale;
3. Misurare la performance di nuovi algoritmi di controllo e calcolo della complessità di un network industriale;
4. Sviluppare nuove misure quantitative della complessità dei network logistici basate sulla “Network Analysis”, disciplina utilizzata con successo per studiare gli ecosistemi naturali, focalizzandosi soprattutto sul concetto di “entropia dell’informazione” (derivata da Shannon, 1948).

Tutte queste attività sono associate all’utilizzo di opportune applicazioni software.

La tesi è divisa in tre parti: 1. Framework teorico 2. Sviluppo di nuove metodologie di Network Analysis 3. Raccolta di tre articoli pubblicati sull’argomento.

Questo lavoro di ricerca è stato sviluppato grazie ad un’efficiente collaborazione interdisciplinare con il Department of Ecology and Evolutionary Biology della Michigan University (Ann Arbour) e, fin dall’inizio, si è posto l’obiettivo di apportare un’innovazione sia nella base teorica riguardante la progettazione dei network logistici, sia nella conseguente applicazione pratica in contesti industriali a noi contemporanei.

ABSTRACT

Modern supply chains usually provide very complex inter-correlations between various actors: suppliers, manufacturers, distributors, customers, etc. Such inter-correlations are not only based on material flows but also on data and financial flows.

Discussions about alternatives for traditional goods and services distribution in the company are becoming more frequent, as the constantly increasing demands and requirements of the market put pressure on suppliers and manufacturers logistics. Therefore, this need is emphasized by the growing of industrial systems complexity and its indirect and drown costs, increasing day by day.

The terms “Supply Network” and “Business Web” are now interchangeable in the way they are used to summarise flow in supply chains (Tapscott, 2000).

Distribution Webs and Supply Networks are urgently demanding new effective management strategies to preserve competitiveness, increase organization and control the complexity level increment.

This dissertation touches upon the fundamental theories of Distribution Network Optimization and Supply Network Complexity Analysis, it proposes new techniques to characterize peculiar Supply Network aspects and underline the importance of adequate systemic approaches and software support in the development of this particular discipline.

This work has four main goals:

1. Show how Goods Delivery Distribution Optimization is feasible and critical to creates efficient networks
2. Investigate how the issue of Distribution Network Design is crucial in order to increase efficiency and competitiveness
3. Assess the performance of new algorithms for industrial network complexity control and computation;
4. Develop new quantitative measurements of complexity for supply networks based on Network Analysis, which is often used to study natural ecosystems, focusing in particular on the concept of entropy of information (derived by Shannon, 1948).

All these accomplishment are associated with appropriate software applications.

The dissertation is divided in three Parts (1. Theoretical framework, 2. New network analysis methodologies development, 3. Three published papers collection).

This work, conducted with a profitable interdisciplinary collaboration with the Department of Ecology and Evolutionary Biology at Michigan University (Ann Arbour), is devoted to investigate alternatives for goods distribution in Supply Networks and develop advances in both theories on Supply Network Design problem and on its application to industrial contexts.

The new interdisciplinary approaches developed exploit new performances indexes to map the exchange of goods and information between different actors in a complex supply chain and show how Network Analysis and systemic approaches are relevant tools in providing a new perspective in defining supply network organization and complexity.

ACKNOWLEDGEMENTS

First of all I would like to express sincere gratitude to the PhD program supervisor, Prof. Alessandro Persona for the shining and constant example of expertise and humanity, for the kind assistance and guidance throughout the research process.

Thanks to the Department Coordinator Prof. Roberto Caracciolo (DTG, Vicenza), the first person I met at Padova University, during the PhD selection exam.

All my appreciation goes to my colleagues at the Department of Management and Engineering (DTG, Vicenza): Fabio Sgarbossa, Maurizio Faccio, Pietro Vecchiato and the “applied mechanic” Dario Richiedei. Thank you for your collaboration.

I can’t forget Stefano Allesina, a brilliant researcher of the Michigan University (working now at the University of Santa Barbara), who encouraged me to discover Ecosystem Network Analysis and who helped me with a successful interdisciplinary collaboration: we discovered together that natural ecosystems and ecology are not so far from industrial networks.

Many thanks to the representatives of the companies who provided industrial data and granted me fruitful meetings, interviews and support, I will not mention their name only due to privacy reasons. They allowed me to get inspiring ideas for the work and I’m very grateful for the useful information received.

A special thanks to my friend Eng. Anna Azzi and to Prof. Alberto Regattieri, for their profitable collaboration: they helped me a lot with comments and reviews during the papers writing and revision, but first of all they believed since the beginning in the importance of these new research themes.

Thank you to Prof. Bianca Rimini who told me (about three years a go) 'Why don't you consider a PhD at Padova University?' and believed in my capacities.

Finally, and most important, I emphasize my gratitude to my family and my friends, especially to my husband Alberto for encourage me all the way.

Vicenza (Italy),

January 2008,

Daria Battini

Dedicated to Alberto and Caterina

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"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

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Introduction

1.1 The Purpose

In today's business environment, where the pressure is put on providing accuracy and flexibility to partners, while reducing costs, the only way of achieving goals is by improving processes both internally and externally. At the same time, 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. Nowadays companies live in a fast moving and rapidly changing business environment. Customer requirements become more rigorous not only on the product's quality, but on quality of the services and value-adding activities as well. The notion that products have to be delivered at the right time, to the right place, in the right quantity and damage free is relevant more than ever to stay competitive in today's market.

Customers’ requirements put pressure on the whole system, increasing the complexity of the production processes: marketing requires constant development of new products and at the same time logistic costs advocate for the reduction of inventories in warehouses, and distribution network nodes which are widespread and dependent on each other.

A supply chain is not a simple linear sequence of connections, though. We are therefore operating with a complex network of relations and connections between different partners rather than with a simple chain: the key idea id that supply chain network creates an ecosystem edge.

On the one hand, modern enterprises need to overcome the barriers that prevent them from connecting with partners to maintain competitiveness, and, at the same time, they need more sophisticated methods to study and control connections in their global network: if the number of partners increases production might increase, with consequent increase in system entropy and its indirect and drown costs. Managers’ decisions, and external resources and business can amplify or attenuate effects of complexity on Supply Chain. These are only few of the considerations that should warn us of the urgency for effective management strategies to preserve competitiveness, increase organization and control complexity of industrial supply chain. Understanding and improving this integrated network ecosystem is complicated. System analysis can contribute to overcoming this short -sightedness allowing the global examination of elements and links in an interacting group. Now, "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" (Barabasi, 2002).

Barabasi (2002) in his publication titled “Linked” underlines that Reductionism was the driving force behind much of the twentieth century’s scientific research. The theory springs from the assumption is that once we understand the parts, it will be easy to grasp the whole. Therefore, for decades we have been forced to see the world through its constituents. Reductionism leads directly into the hard wall of complexity. In complex systems the components can fit in many different ways and nothing happened in isolation, most events and phenomena are connected and everything is linked to everything else. Network and network science will dominate the new century to a much greater degree than people are yet ready to acknowledge.

This work has a simple aim: to investigate industrial complex networks, what they look like, how they evolve and how they can be optimized and controlled. Industrial Engineers understand the importance of functioning networks in every day working experiences and in order to control or at least manage all the logistics processes efficiently, many different systems and models were approached by a systemic point of view.

The goal is mainly to review Industrial and Distribution Network optimization procedures and consequently implement new tools, and then create a new theory based on extensive observation of the systems and investigate the possibilities and to reach a more efficient distribution of goods/services and information within a complex supply network.

The main objectives of this study are:

1. to provide new criteria for assessing organization and measure performances and complexity level of industrial supply networks
2. to apply such criteria to real industrial systems to suggest strategies to reduce complexity and increase efficiency and competitiveness in companies and industrial supply networks
3. to show the potential of Network Analysis and systemic approaches not only to deal with complex systems, but as tools that provide a new perspective in which supply chain organization and complexity can be framed.

The different analytical models developed, already material for publications in two different international journals, will be described extensively in this work.

1.2 Thesis outline

This thesis falls naturally into three parts, as follows.
Part I) Analysis of the state of the art: this part (Ch.2 and Ch.3) will provide the theoretical framework of the whole research. These chapters focus on Distribution Networks Analysis and Design and in particular on published theory regarding the optimization problem of such networks and their growing process. In order to complete the project, we decided to present and analyse in depth the following alternatives for physical distribution network improvement:

- Distribution network design (or re-design) and goods delivery distribution optimization
- New facility location and allocation problem

We reviewed and classified existing theories and used them to conduct the analytical part.

Part II) New network analysis and empirical applications: Ch. 4 investigates a new approach to Supply Network performances measurement and complexity control and computation. This part will provide a quantitative description which includes entropic indexes and measures derived by ecology theory (Ulanowicz et al., 2000) and information theory (Shannon, 1948), that take into account both the structure/topology of the network and the different weights of interaction between partners (i.e. species in ecology). The key idea is that natural ecosystem networks and industrial supply networks are intimately linked. The methodology developed in this chapter is the result of the interdisciplinary collaboration between the research group of Industrial Plants of the University of Padova and the Department of Ecology and Evolutionary Biology at the University of Michigan.

Part III) Published papers collection: This part consists of three papers studying the distribution network optimization problem and the supply network complexity evaluation. Three published researches developed during this doctorate program are enclosed at the end of this thesis.
These papers have already been published in three different works developed in collaboration with other researchers and industrial companies, in order to provide a new contribution to Complex Supply Network Analysis.

Finally, to conclude this dissertation, **Conclusions and Recommendations** in Ch.5 explains and analyses guidelines, criticises models and illustrates future research opportunities.

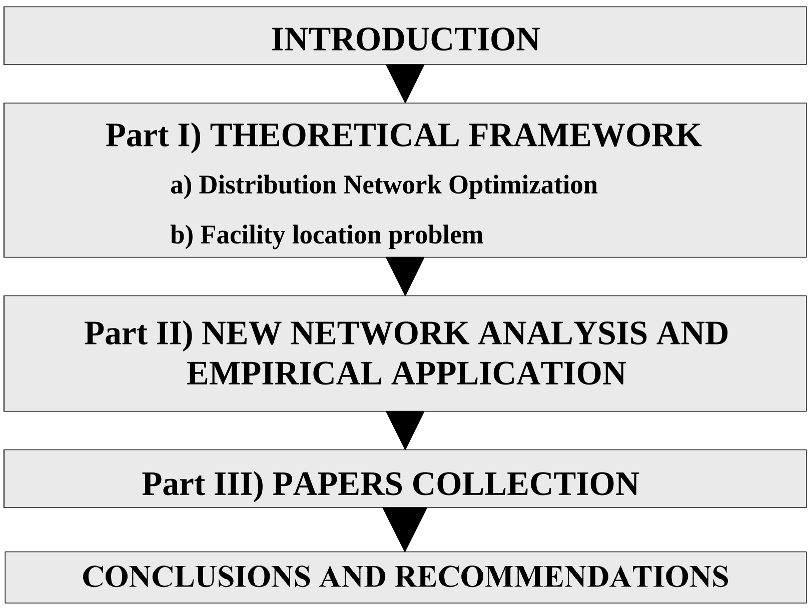


Fig.1 Thesis outline

1.3 Summary of the papers

The third and last part of this thesis consists of three papers, the first of them basically concerning Supply Network Complexity Analysis, while the second paper addresses the issue of optimizing flows of goods and deliveries inside a Distribution Network and finally, the third provides an innovative conceptual framework on network organization structure in case of Remote Maintenance applications.

I have had the privilege of co-authoring all the included papers. One of them with doctor Stefano Allesina of the Michigan University (Ann Arbor), one with Prof. Alberto Regattieri (University of Bologna) and Prof. Hoang Pham (Rutgers University). The second paper has been co-authored with two PhD students Maurizio Faccio and Pietro Vecchiato and, finally, all the papers have been co-authored with my PhD supervisor Prof. Alessandro Persona.

Paper [I]: Daria Battini, Alessandro Persona, Stefano Allesina, "Towards a use of network analysis: quantifying the complexity of Supply Chain Networks", *The International Journal of Electronic Customer Relationship Management*, 2007, Vol. 1, No.1, pp. 75-90.

This paper develops a new quantitative measurement of complexity for industrial supply network based on Network Analysis (NA), which is often used to study natural ecosystems, focussing in particular on the concept of entropy of information. This new interdisciplinary approach exploits new entropic indexes to map the exchanges of goods between different actors in a complex supply chain (the suppliers, manufacturers, distributors, customers, etc.). Using these parameters results in robust and meaningful analysis and optimisation, 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 obtain total optimisation, thereby overcoming the problem of the continuous research demanded by the need to find a great many local best solutions.

By measuring flows of goods and interaction costs between different sectors of activity within the supply chain borders, a network of flows is built and successively investigated by network analysis, a tool widely applied in ecosystem ecology. The result of this study supports the idea that an ecosystem approach can provide an interesting conceptual perspective in which modern supply network can be framed, and that network analysis can handle these issues in practice.

The supply network of an important Northern Italy industrial group is discussed showing a practical application of the procedure. Ecological indicators are then applied to measure how much the fluxes inside the supply network are constrained, and to provide general criteria for improving the network organization and control systems entropy.

Paper [II]: Daria Battini, Maurizio Faccio, Pietro Vecchiato, Alessandro Persona, "Goods delivery optimisation in distribution networks with batch production", *The International Journal of Electronic Customer Relationship Management*, 2007, Vol. 1, No.2, pp. 200-230.

Distribution network optimization and warehouse decentralization are two of the most significant and competitive management topics in modern Supply Chains. To achieve operational benefits and costs reduction in a specific multi-level distribution network, goods delivery policies must be carefully planned. Managers must define which products should be delivered directly to customers, and which products need to be forwarded to an intermediate "hub", such as a local/regional warehouse and then sent to the customers.

The aim of this paper is to present a new iterative procedure, based on a linear programming model, in order to plan goods distribution inside the supply chain under critical constraints. The model, applied to batch production, defines the best delivery policies for each product's family. It provides possibilities to reach a more efficient distribution within the network and, at the same time, to optimize the warehouse use. A real application to test the model is presented as a result of this paper.

Paper [III]: Alessandro Persona, Alberto Regattieri, Hoang Pham and Daria Battini "Remote control and maintenance outsourcing networks and its applications in supply chain management", *Journal of Operations Management*, 2007, Vol. 25, No. 6, pp. 1275-1291.

The paper analyzes, by a theoretical point of view, the design structure of supply networks regarding the Remote Maintenance Service field. The aim of this work is to investigate the network organization level of supply chains in case of remote maintenance application and to understand how maintenance policies are coupled with information technology (IT) solutions. To this purpose two literature reviews are presented: firstly, on the supply chain and network integration, and then on the evolution of maintenance using information technology. Following this, the paper present four specific industrial case-studies of eMRO network organisation. They have been chosen as reference models from a set of practical applications and pilot tests performed by the authors in different production sectors in the last 5 years. Technology complexity environments, maintenance outsourcing level, and supply chain integration context are discussed for each case-study with particular regards to the profitable forms of collaboration provided by the introduction of IT and the Web. This analysis work toward the development of a framework useful to: (1) classify different e-maintenance complex systems and understand the relationships between the different partners of the network, and (2) identify the variables which can influence the introduction and development of these networks.

“Nothing is more practical than theory"
Richard Levins

2

State of the art

As mentioned in the introduction, the theories illustrated in this part present the issues topic of this research and explain what is meant by network logistics efficiency, physical distribution and strategies for improvement.

2.1 Distribution Network Design

Logistics is a holistic science: it does not look at the individual parts of the system in isolation, but at the ways in which the parts are linked and suggests measures for a better connection between the parts. Thus, the logistician must fully understand the cost structure of complex supply networks and all kind of exchanges between different partners involved, in order to manage complexity and increase system competitiveness. In fact, all companies that aim to be competitive on the market have to pay attention to the whole organization starting with the supply chain. In particular, they have to analyze the supply chain in order to improve customer service quality without an uncontrolled cost increase. Christopher (1992) argues that the real competition does not see company against company, but rather supply chain against supply chain. Vertical as well as horizontal integrations are required for the flow optimization in the supply chain, and for the optimization of all related activities. That implies agreements among subjects that operate at different levels of the supply chain (vertical integration), and among actors of the same level (horizontal integration).

In this dissertation, we focus on complex supply network analysis and optimization, in network design problems, complexity-level measures and control. The aim is to optimize the flows (of goods, unit of load, information, money,..) through the nodes of the network, from the production plants to the supply points for an extensive assessment of the published literature on network analysis we will start with the analysis of Distribution Network Design Problems, which consist traditionally of determining the best way to transfer goods from the supply to the demand point, by choosing a network structure (number of layers, different kinds of facilities, their number and their location), while minimizing the overall costs (Ambrosino and Scutella, 2004).

We can generally distinguish two kinds of Distribution Network Analysis:

1) <u>Network flows optimization</u>: in this case we consider a pre-designed or existing distribution network, and we want to optimize the flows of goods-information-money through the network.

2) <u>Network design or re-design:</u> in this case we choose the best configuration of the facilities within the network in order to satisfy the goals of the company.

Distribution network design problems involve strategic decisions which influence tactical and operational decisions (Crainic and Laporte, 1997), such as facility location, transportation and inventory decision, which affect the cost of the distribution system, and the quality of the service level (Ambrosino and Scutella, 2004). The design or re-design of large-scale distribution networks entails taking decisions on a different scale, including the location and size of distribution centres, the capacities required to fulfil these activities, their allocation to specific product groups, and the control system to manage all activities.

To the purpose of this dissertation, we now define and investigate the Distribution Network Design Problem, in its general form, as the problem of determining 6 major points:

A. *<u>Facility location and demand allocation problems</u>:* where to locate a new facility or more facilities (i.e. distribution centre, regional warehouse, transit point, etc.), the number of each type of facilities and how to allocate the products demand (i.e. clients) to the open facilities.
B. *<u>Vehicle Routing Problems:</u>* the Vehicle Routing Problem (VRP) is one of the most challenging combinatorial optimization task. Defined more than 40 years ago, this problem consists in designing the optimal set of routes for fleet of vehicles in order to

serve a given set of customers. The interest in VRP is motivated by its practical relevance as well as by its considerable difficulty.

C. *Inventory management decisions:* determine the inventory level stored at each warehouse to satisfy facilities capacity constraints and customer demand, which include stocks centralization and decentralization decisions, safety buffers dimensioning and replenishment policies.
D. Goods delivery strategies and optimization: delivery quantity optimization and transportation modalities between facilities of the distribution network, including transportation cost rate computation and transportation outsourcing decisions.
E. Network complexity analysis: industrial networks grow, both in size and complexity and flexibility enables quick adaptation to their changing needs while ensuring the security of the entire enterprise, but new complexity measures are necessary to study networks growth and development and to understand their real level of competitiveness and performance.
F. Network performances measurement: identify and measure key dimensions and indexes along which to evaluate the performance of a distribution network.

As emerged from the above classification, distribution network design problems involve a lot of integrated decisions, which are difficult to consider all together. Decisions on the issues are all closely interrelated, making it difficult to develop a sound distribution strategy, which requires a complex trade-off analysis between various cost elements, together with an evaluation of a broad range of non-quantifiable factors. Generally, some simplifying assumptions have been adopted in the literature, and only some aspects related to the complex network decisions have been modelled. For instance, in the past some authors dealt with distribution network design problems as pure location problems, without trying to address and integrate the different types of strategic decisions. Since then, some papers focused on the relationship between facilities and transportation costs, stressing that location of distribution facilities and routing problems are interdependent decisions, investigating the location-routing problems (LRP). Other researches, recently, considered the relationship between inventory management, the facilities location and the definition of transportation policy simultaneously. Tables 1 and 2 show some of the most important contributes we will refer to, the problems addressed (according to our previous classification) and the methodology applied.

The area of mathematical optimization is well developed and a widely diversified range of models are available from literature, as underlined in the matrix. Several distribution models have been developed such as multi-objective facility location decisions, location-allocation problems, and vehicle routing problems.

The most studied problems in literature concern both facility location and demand al location problem and both VRP problems. Many heuristics methods have been proposed recently to solve these problems and reduce the computational complexity. Most of the existing literature on physical distribution network comprises articles connected with specific goods delivery optimization problems. Most of them aim to reduce and minimize the Total Distribution Costs function and first of all delivery lead times in presence of time windows constraints.

The relationship between management of inventories and goods distribution policy and location of facilities has been analysed by a number of published papers in recent literature. The attention of researchers is focused in the last decade on the interdependence among these three areas and most of them propose integrated mathematical programming mixed-integer models or multi-objective theoretical frameworks, able to take into account also inventory carrying costs and warehouse capacities constraints.

A good performance measurement system is a necessity for a supply network to grow and sustain industry leadership. Applied researches focused only in this area are not numerous. Normally to conduct a performance evaluation of a distribution network many data need to be collected and analysed and many case studies to be compared. For this and other reasons we think that is necessary to increase study on these area and first of all regarding network complexity analysis, control and evaluation. A few papers have been published during the last ten years about complexity computation for supply network optimization. Most famous name in this area are Frizelle and Woodcock (1995) and Sivadasan and Efstathiou (2002), they apply Shannon (1948) entropy formula to compute network complexity in a production system.

A complete literature review in this area is provided in chapter 4 of this thesis and we cross-refer to Table 7 for a complete comprehension of the literature background.

Finally, in Tables 1 and 2 we added two yellow rows to specify how our publications in these filed are positioned. These two publications are enclosed at the end of this thesis and have been derived directly by the research activities conducted during this PhD program.

	DISTRIBUTION NETWORK DESIGN PROBLEMS					
AUTHORS	**A.Facility location and demand allocation problem**	**B.Vehicle Routing Problem**	**C.Inventory management decisions**	**D.Goods delivery strategy and optimization**	**E.Network complexity analysis**	**F.Network performance measurement**
Vaidyanathan Jayaraman, 1998	X		X	X		
Marcel Mourits and Joseph J.M. Evers, 1995	X		X	X		
Ambrosino and Scutellà, 2004	X	X	X			
L.M. Berry et al., 1998				X		
Neil Hooper, 1996			X	X		
Tien-Fu Liang, 2006				X		
Lawrence Christensen, 1996			X	X		
B.A. Murtagh and J.W. Sims, 1995			X			
Mats Abrahamsson, 1993	X			X		
Jukka Korpela and Antti Lehmusvaara, 1999	X					
Ismail Erol, William G. Ferrell Jr., 2003	X					
Chun-Ho Kuo et al., 1999						X
Karel van Donselaar et al., 1998				X		X
Antti Lehmusvaara, 1997				X		
Manuel Cardòs and Josè P. Garcìa-Sabater, 2004		X	X			
David Mester et al., 2005		X				
Tzong-Ru Lee and Ji-Hwa Ueng, 1999		X				
Ramin Djamschidi et al, 2000	X					
A. Gunasekaran and E.W.T. Ngai, 2003				X		X
Iwo V. Riha and Bernd Radermacher, 2006						X
Vlasios Sarantinos, 2006	X					
Linda K. Nozick and Mark A. Turnquist, 2000	X		X	X		
Chandrasekhar Das and Rajesh Tyagi, 1997	X		X			
B.Abdul-Jalbar, J.Gutièrrez, J.Puerto, J.Sicilia, 2003	X		X	X		
Mehmet Gumus and James H.Bookbinder, 2004	X		X	X		
Ali Amiri, 2004	X			X		
Sunil Chopra, 2003			X	X		
Bilge Bilgen and Irem Ozkarahan, 2004						
Comley W.J., 1995	X					
Hsieh K.-H. and Tien F.-C., 2004	X					
Infante-Macias R., Munoz-Perez J., 1995	X					
D.Battini, M.Faccio, A.Persona, P.Vecchiato, 2007				X		
S. Allesina, D. Battini, A. Persona, 2007					X	X

Table 1. A literature classification on Distribution Network Design Problems

AUTHORS	NOTES ON THE METHODOLOGY
Vaidyanathan Jayaraman, 1998	FLITNET: A MIXED INTEGER PROGRAMMING MODEL
Marcel Mourits and Joseph J.M. Evers, 1995	INTEGRATED PLANNING SUPPORT FRAMEWORK AND SOFTWARE TOOL DEVELOPMENT
Ambrosino and Scutellà, 2004	INTEGER LINEAR PROGRAMMING MODELS
L.M. Berry et al., 1998	GENETIC ALGORITHMS AND NON LINEAR PROGRAMMING MODELS
Neil Hooper, 1996	DYNAMIC AND NOT TRADITIONAL DISTRIBUTION REQUIREMENTS PLANNING
Tien-Fu Liang, 2006	INTERACTIVE FUZZY MULTI-OBJECTIVE LINEAR PROGRAMMING
Lawrence Christensen, 1996	CASE STUDY: Safeway stores and The Ford Motor Company
B.A. Murtagh and J.W. Sims, 1995	NON-LINEAR PROGRAMMING MODEL + CASE STUDY: New Zeland and Australia
Mats Abrahamsson, 1993	INVENTORY CENTRALIZATION PROBLEM AND 3 CASE STUDIES
Jukka Korpela and Antti Lehmusvaara, 1999	MIXED INTEGER LINEAR PROGRAMMING + ANALYTIC HIERARCHY PROCESS
Ismail Erol, William G. Ferrell Jr., 2003	MULTI-OBJECTIVE MODEL
Chun-Ho Kuo et al., 1999	CASE STUDY: 5 DISTRIBUTION CENTERS (Pacific Northwest)
Karel van Donselaar et al., 1998	BRAVO RESEARCH PROJECT
Antti Lehmusvaara, 1997	MIXED INTEGER LINEAR PROGRAMMING + CASE STUDY
Manuel Cardòs and Josè P. Garcìa-Sabater, 2004	Retail chain inventory management problem linked with VRP
David Mester et al., 2005	MULTI-PARAMETRIC MUTUATION PROCEDURE
Tzong-Ru Lee and Ji-Hwa Ueng, 1999	MIXED INTEGER LINEAR PROGRAMMING + HEURISTIC ALGORITHM WITH WORK LOAD BALANCING
Ramin Djamschidi et al, 2000	HEURISTIC ALGORITHMS + "ZONE ORIENTED MODEL" with delivery time and time windows
A. Gunasekaran and E.W.T. Ngai, 2003	THEORETICAL FRAMEWORK FOR THIRD PARTY LOGISTICS AND CASE STUDY: a small third-party logistics company in Hong Kong
Iwo V. Riha and Bernd Radermacher, 2006	CASE STUDY: Automotive Logistics-Network
Vlasios Sarantinos, 2006	THEORETICAL
Linda K. Nozick and Mark A. Turnquist, 2000	MULTI-OBJECTIVE MODEL + CASE STUDY: Automotive manufacturer in USA
Chandrasekhar Das and Rajesh Tyagi, 1997	WAREHOUSE CENTRALIZATION RATE
B.Abdul-Jalbar, J.Gutièrrez, J.Puerto, J.Sicilia, 2003	WAREHOUSE CENTRALIZATION Vs DECENTRALIZATION
Mehmet Gumus and James H.Bookbinder, 2004	MIXED INTEGER PROGRAMMING MODEL FOR CROSS-DOCKING
Ali Amiri, 2004	MIXED INTEGER PROGRAMMING + HEURISTIC SOLUTION BASED ON LAGRANGEAN RELAXATION OF THE PROBLEM
Sunil Chopra, 2003	DISTRIBUTION NETWORK STRUCTURES CLASSIFICATION AND FRAMEWORK
Bilge Bilgen and Irem Ozkarahan, 2004	LITERATURE REVIEW
Comley W.J., 1995	NONLINEAR PROGRAMMING MODEL
Hsieh K.-H. and Tien F.-C., 2004	HEURISTIC METHOD WITH NEURAL NETWORKS AND RECTILINEAR DISTANCES
Infante-Macias R., Munoz-Perez J., 1995	COMPETITIVE LOCATION MODEL WITH RECTILINEAR DISTANCES
D.Battini, M.Faccio, A.Persona, P.Vecchiato, 2007	HEURISTIC METHOD TO OPTIMIZE DELIVERIES WITH BATCH PRODUCTION AND INTERMEDIATE WAREHOUSES
S. Allesina, D. Battini, A. Persona, 2007	NETWORK COMPLEXITY LEVEL EVALUATION

Table 2. Methodologies applied by the authors analysed

2.2 The impact of logistics on distribution network

Logistics encompasses all the information and material flows throughout an organization (Gunasekaran and Ngai, 2003). It includes everything from the movement of a product or a service that needs to be rendered, to the management of incoming raw materials, production, storing of finished goods, delivery to the customer and after-sales service (Pollitt, 1998). According to Bowersox et al. (1986), from the viewpoint of logistical operations, physical distribution is the critical interface between customers and manufacturing. By a logistic point of view, “Network Optimization” addresses strategic studies to determine the least costly and most logistically efficient configuration of factories, depots, and sub-depots required to satisfy a given set of demand points (Sussams, 1994). Moreover, according to K. Lumsden (2002), “logistical efficiency can be described in terms of service, costs and tied up capital”, directly influencing profitability of the whole distribution network. There is a strong connection among these efficiency components, because one cannot be overseen without the other. For example, reduction of transportation costs is obtained through decreasing the number of shipments. This reduces costs, but at the same time requires that the company keeps larger volumes in stock while awaiting to accumulate enough products for a shipment . This solution requires increased tied up capital, and deteriorates the customer service with lower shipment frequency. This dilemma is sometimes called the “logistical goal mix”, i.e. the intention is to try to make the three components concur in a way that will optimise the total result (Lumsden, 2002). Following this logic it is important to find the optimum balance between different components of logistics efficiency, so that the profitability of the company is maximised. Such actions to improve one part of the business can entail negative effects for other parts. A measure intended to reduce the costs might at the same time deteriorate the service and thereby the revenues in the long run (Lumsden, 2002).

Conflicts might arise in a company when drawing a strict line between the various phases of the production/distribution process. That’s why authors such as Stock/Lambert (2001) do not draw any line at all and consider all logistics activities equally important.

Customer service can be considered the measure of how well the logistics system is performing in creating time and place utilities, such as delivering the correct product to the right place, time, cost, quantity, and quality. The figure below shows five activities categories of logistics, which are inseparable with customer service.

In the following paragraphs we will discuss two important logistic questions: logistic costs distribution and the outsourcing of logistic services.

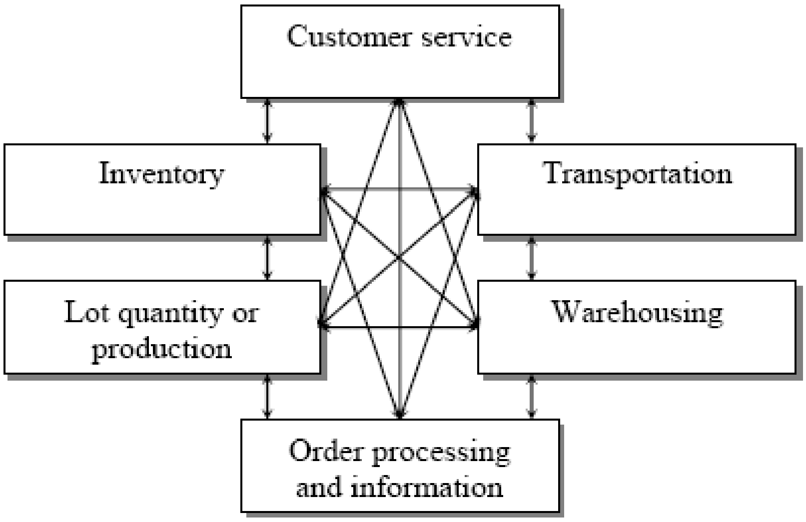


Fig.2 Logistics activities. Source: Stock/Lambert, 2001.

2.3 Distribution costs and total logistics costs

According to S. Chopra (2003), the performance of a distribution network should be evaluated along two different dimensions:

1. Customer needs that are met.

2. Cost of meeting customer needs.

The customer needs that are met influence the company's revenues, which along with costs decide the profitability of the delivery network. While customer service consists of many components, we will focus on those measures that are influenced by the structure of the distribution network. These include:

-Response time, is the time between when a customer places an order and receives delivery.

-Product variety, is the number of different products/configurations that a customer desires from the distribution network.

-Product availability, is the probability of having a product in stock when a customer order arrives.

-Customer experience, the ease with which the customer can place and receive their order.

-Order visibility, is the ability of the customer to track their order from placement to delivery.

-Returnability, is the ease with which a customer can return unsatisfactory merchandise and the ability of the network to handle such returns.

At first it may seem that a customer always wants the highest level of performance along all these dimensions. In practice, however, this is not always the case. Companies who target customers who can tolerate a large response time require few locations that may be far from the customer and can focus on increasing the capacity of each location. On the other hand, companies that target customers who value short response times need to locate close to them. These companies must have several low capacity facilities, spread throughout the network in order to decrease in the response time.

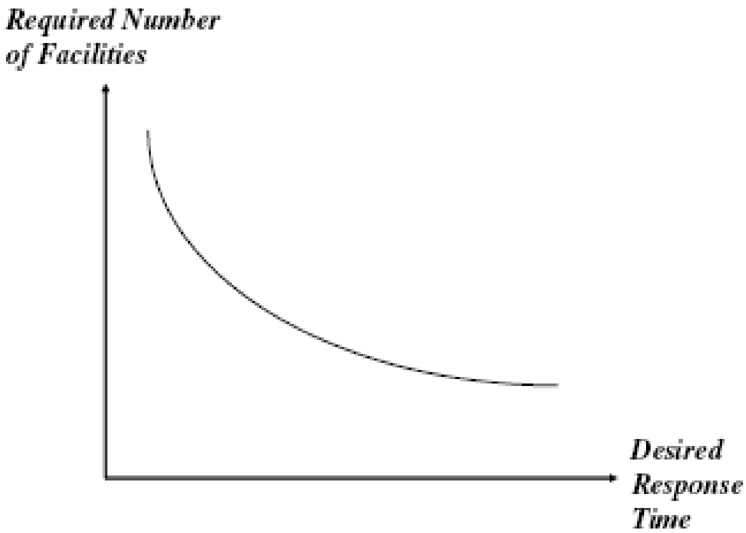


Fig.3 Relationship between desired response time and number of facilities.
Source: Sunil Chopra, 2003.

Distribution costs are defined as the sum of order processing, information costs, warehousing costs and transportation costs. As the distribution costs are only a part of the total logistics costs, the total logistics costs concepts are to be mentioned in this chapter as well. An analysis of the total distribution cost shows that several single cost elements influence each other in a complex way. To minimise one cost element can, for example, lead to an increased total cost (sub-optimisation), e.g. a decreased delivery frequency can lead to a loss of customers.

We would like to pay attention to two concepts, which are widely used in recent logistics theories before going into distribution costs: 1) cost trade-off and 2) total cost concepts. As "the central to the scope and design of the logistics system is trade off- analysis, which, in turn, leads to the total cost concept" (Ballou et al., 2002).

According to Ballou (1978) the concept of the cost trade-off is fundamental to physical distribution management. The cost trade-off is the recognition that the cost patterns of the various activities of the company sometimes display characteristics that put them in conflict with one another. For instance, the decision to increase number of warehouses in a system may reduce transport costs (shorter distances for small volume shipments), but on the other hand, will increase inventory costs by creating the need to increase stock volume, to guarantee availability.

The total cost concept goes hand in hand with cost trade-off. The total cost concept is the recognition that conflicting cost patterns should be examined collectively and balanced at optimum (Ballou et al., 2002). It was recognized that managing transportation, inventories and order processing activities could collectively lead to substantial cost reduction when compared with the cost of managing them separately. The total cost idea is instrumental in deciding what company's activities can be considered physical distribution activities. Thus, the essence of the total cost concept is to consider all the relevant cost factors in a particular decision, add them to obtain the total cost, and search for the minimum total cost alternative (Ballou, 1978).

As it was discussed earlier the major goal of organization is to reduce total costs of logistics activities rather than focusing on each activity in isolation. Attempts to reduce cost of individual activities may lead to increased total costs.

Changing the distribution network design affects the following supply chain costs (Chopra, 2003):

1) Transportation costs,
2) Facilities and handling costs,
3) Inventory costs,
4) Information costs.

Transportation costs include all costs involved in the movement or transport of a shipment, and can be categorized by customer, by product line, by type of channel, by carrier, etc. The costs vary considerably with volume, weight of shipment, distances, transport mode, etc.
Four correlated factors make up the transportation costs:

1) goods delivery quantities
2) physical characteristics of goods delivered
3) transportation policy used (direct delivery/groupage and inter-company shipment/company-to-customer shipment)
4) distance

Facilities costs include fixed cost for opening a new facility, the materials handling and management costs of the facility. When products are moved from plant to trucks, from truck to customers, from truck to intermediate warehouse and from warehouse to trucks again, handling costs are inevitable. Handling costs due to the transit of products through the facility is often a direct function of the volume moved and depends on the characteristics of the product's family. As a consequence, these costs may vary according to changes in production lot size, order size or frequency; specific handling costs are normally expressed in Euro per cube meter of goods handled in the intermediate warehouses.

Inventory costs are created by goods inventory carrying costs (as tied up capital costs), and by warehousing and storage activities costs.

Four major categories of inventory carrying costs are:

- Capital costs, or opportunity costs, which is the return a company could make on the money tied up in inventory
- Inventory service costs, which includes insurance and taxes on inventory
- Storage space costs, which include those warehousing space-related costs relative to level of inventory
- Inventory risk costs, including obsolescence, pilferage, movement within the inventory system and damage.

Inventory costs also include various levels of sophistication in terms of warehouse accounting and control. Four levels of sophistication have been identified (Ernst and Whinney, 1985):

- Warehouse costs are allocated in total, using a single allocation
- Warehouse costs are aggregated by major warehouse functions (e.g., handling, storage, administration, etc.) and are allocated using separate allocation bases for each function.
- Warehouse costs are aggregated by major activity within each function (e.g., receiving, put-away, order pick, etc.) and are allocated using a separate allocation base for each activity.

- Costs are categorized in matrix form reflecting each major activity, natural expense and cost behaviour type. Separate allocations are developed for each cost category using allocation bases that reflect the key differences in warehousing characteristics among cost objectives.

Information costs are generated from the management of information flow between the various partners involved in the network and from data collection, updating activities and software tools implementation.

As the number of facilities in a supply chain increases, the inventory costs also increase as shown in Fig. 4. As long as inbound transportation economies of scale are maintained, increasing the number of facilities decreases total transportation cost, as shown in Fig. 4, if the number of facilities is increased to a point where there is a significant loss of economy of scale in inbound transportation, increasing the number of facilities increases total transportation cost. Facility costs decrease as the number of facilities is reduced, because a consolidation of facilities allows a company to exploit economies of scale.

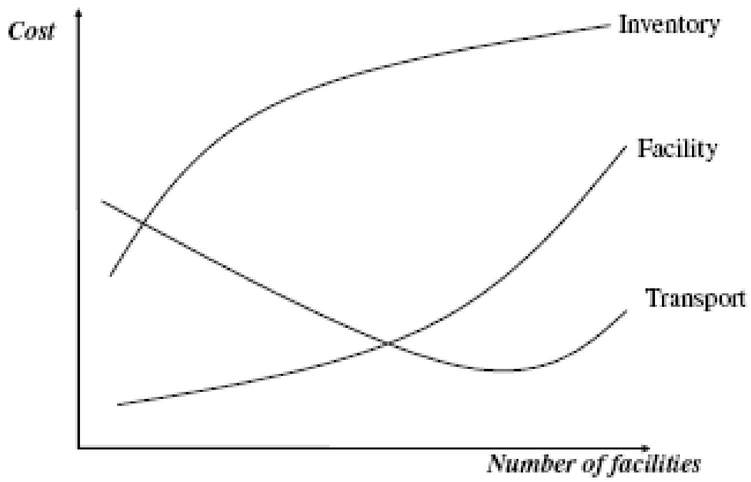


Fig.4 Relationship between number of facilities and logistics cost. Source: Chopra, 2003.

Total logistics costs are the sum of inventory, transportation, and facility costs for a supply chain network (Chopra, 2003). As the number of facilities is increased, total logistics costs first decrease and then increase as shown in Fig. 5. Each company should have at least the number of facilities that minimize total logistics costs. As a company wants to further reduce the response time to its customers, it may have to increase the number of facilities beyond the point that minimizes logistics costs. A company should add facilities beyond the cost-minimizing point only if managers are confident that the increase in revenues due to of better responsiveness is greater than the increase in costs because of the additional facilities.

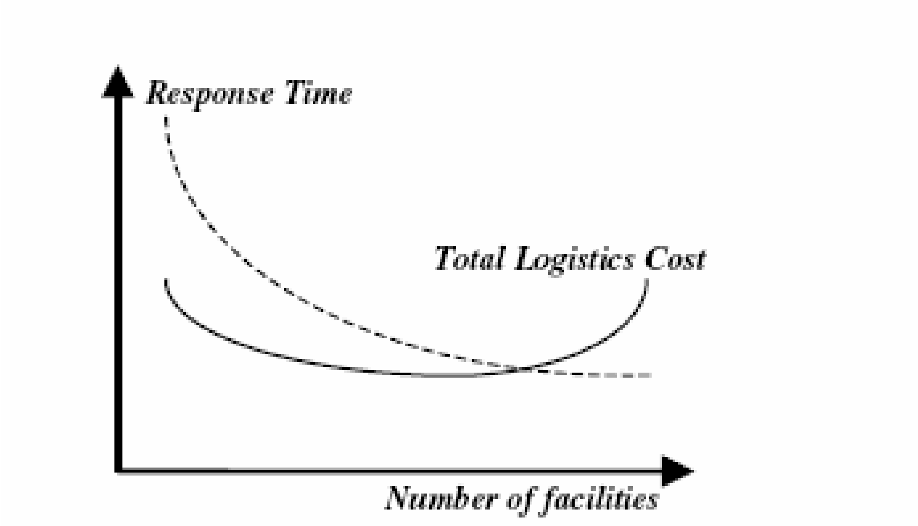


Fig.5 Variation in logistics cost and response time with number of facilities.
Source: Chopra, 2003.

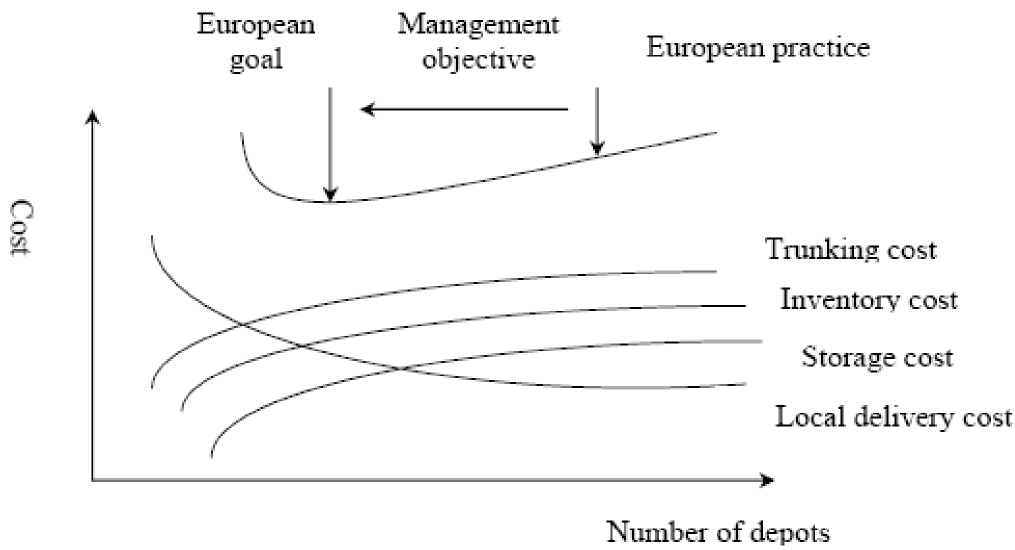


Fig.6 Total logistics costs reduction by reducing the depot network.
Source: Adapted from Cooper et al., 1994.

In a similar way, Cooper et al. (1994) represent logistic costs behaviour according to variation in the number of depots existing in the distribution network using the figure above. They stress the idea that the goal that a company should have is to open the number of facilities that minimize total logistics costs (Fig.6).

2.4 Outsourcing of logistic services

Over the years, logistics has developed from single-party logistics (self-managed) to multi-party logistic (5PL), using e-logistics networks focusing on global operations. Third-Party Logistics (3PL) is contractual logistics focusing on regional operations (Gunasekaran and Ngai, 2003).

The main objectives behind the outsourcing of logistics services are to:

1. Reduce operating costs;
2. Meet demand fluctuations;
3. Reduce capital investment.

The general problems that arise in corporate logistics include delayed and inaccurate information, incomplete services, slow and inefficient operations, and a high product damage rate. The possible consequences are: inability to provide inter-linked services, high operating costs, high inaccuracy rate, and lack of flexibility in responding to changing demand requirements. The integration of logistics with other functional areas will help bring a company to realize the full potential of its value-added activities and, hence, to gain a significant competitive advantage. It will also lead to a reduction in operational costs and an improvement in customer services (Christopher, 1989; Richardson, 1995). E-logistics and the outsourcing of logistics business processes are subsets of a larger external logistics market. E-logistics can be defined as the transfer of goods and services using Internet communication technologies such as electronic data interchange (EDI), e-mail and World Wide Web.

Quinn and Hilmer (1994) discuss how core competencies should be identified in evaluating items to be outsourced. Welch and Nayak (1992), Babbar and Prasad (1998) and Fawcett et al. (1993) explain how companies could become world-class competitors through global sourcing, which places a tremendous amount of pressure on companies to develop their logistics systems in order to manage complex global outsourcing and markets in a competitive manner. As indicated earlier, competitiveness has forced many manufacturing companies to outsource their logistics service, leading to the growth of 3PL.

Aldin and Stahre (2003) present a conceptual model for logistics supply chain management, with a special focus on 3PL, (Figure 7). This model consists of three major components:
1) Logistics structure;
2) Logistics processes and related activities; and
3) Information and reporting systems.

All three components are essential for a successful 3PL operation. Logistics structure includes the participants in the logistics processes, inventory storage points, multi-echelon distribution centres and warehouses.

Logistics processes and related activities comprise order fulfilment processes, customer relationship management, and customer service, and procurement and demand management. Information and reporting systems are essential for any management system, as they drive the decisions based on the data collected. These include the designing and planning of information systems, control and coordination, and cross-organizational coordination. Rao et al. (1993) discuss the role of 3PL in the logistics processes of global firms. Lieb et al. (1993) present the results of a comparative study of 3PL services in American and European manufacturing companies. Some of the logistics activities include transport, trans-shipment, maintenance of the inventory, and the assembling or reconditioning of products. In the new economy, the focus has been on core strengths; and on providing real-time information, globalizing service demands, visibility in key performance indicators, collaboration in supply chain operations, and e-commerce development (Deborah, 1997). An overview of the functions that logistics service providers (LSP) typically perform, based on a survey among buyers of logistics services, is provided by Sink et al. (1996). Each company should have at least the number of facilities that minimize total logistics costs. The role of 3PL has become increasingly important and, hence, has the role of small and medium sized logistics companies (SML). Gunasekaran and Ngai (2003) propose a framework with the objective of developing a comprehensive 3PL for a small to medium sized company. The framework was based on a survey of the existing literature and on case studies analysis. This framework is presented in Table 3 and consists of five major dimensions:

1) strategic planning;
2) inventory management;
3) transportation;
4) capacity planning;
5) Information technology.

Function	Activities	Strategies/techniques	Technologies
Strategic planning	Corporate/business strategy development, resource management, budgeting, product/service selection, market segment analysis	Forming strategic alliances, outsourcing, forecasting demand, aggregate planning, selecting partners, selecting criteria for partnership, gaining the support of top management, improving continuously, getting government support	Groupware, shared information systems such as WWW, the Internet and EDI, ERP
Inventory management	Forecasting, location analysis, network consulting, slotting/layout design, order management	Demand-pull system, just-in-time, Kanban, material requirements planning, supply chain management, demand management	MRPII, EDI, ERP, WWW, online purchasing
Transportation planning	Shipping, forwarding, de(consolidation), contract delivery, freight bill payment, load tendering and brokering	Outsourcing, forming strategic alliances, optimizing routing and scheduling, managing capacity, total productive maintenance	Groupware, Internet, e-mail, WWW, Intranet, extranet, linear programming
Capacity planning	Capacity of transportation vehicles, warehouse capacity, human resources, material handling equipment	Make or buy decisions, planning aggregate capacity, minimizing costs, maximizing capacity	Linear programming, waiting line models, scheduling optimization, MRPII, CRP, ERP
Information management	Performance measures and metrics, data collection, processing, reporting	Groupware, IT/IS, shareware, data mining, data warehousing, intranet, extranet	EDI, e-commerce, Internet, WWW, AI and expert systems, ERP

Table 3. A framework for transforming a SML company into a comprehensive 3PL company.
Source: Gunasekaran and Ngai, 2003.

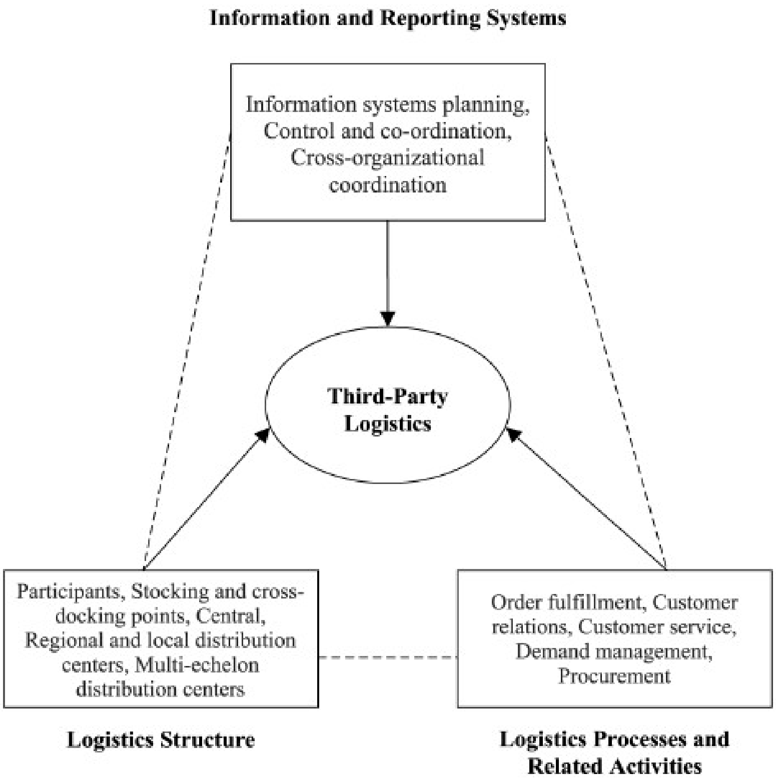


Fig.7 A conceptual model for supply chain management. Source: Aldin and Stahre (2003).

2.5 Distribution network structures: framework and classification

In this paragraph we will discuss distribution network design options in the context of distribution from the manufacturer to the end customer. There are two key decisions when designing a distribution network according to Chopra (2003):

1. Will product be delivered to the customer location or picked up from a preordained site?
2. Will product flow through an intermediate location (i.e. warehouse)?

Based on these two decisions and according to literature, we will analyse five distinct distribution network structures as follows:

a. Direct delivery distribution
b. Direct delivery with stock-less platform and in-transit merge
c. Stockholding intermediate warehouses with packaged carrier delivery

d. Stockholding intermediate warehouses with last mile delivery

e. Distribution structure with customer pickup

2.5.1 Direct delivery distribution

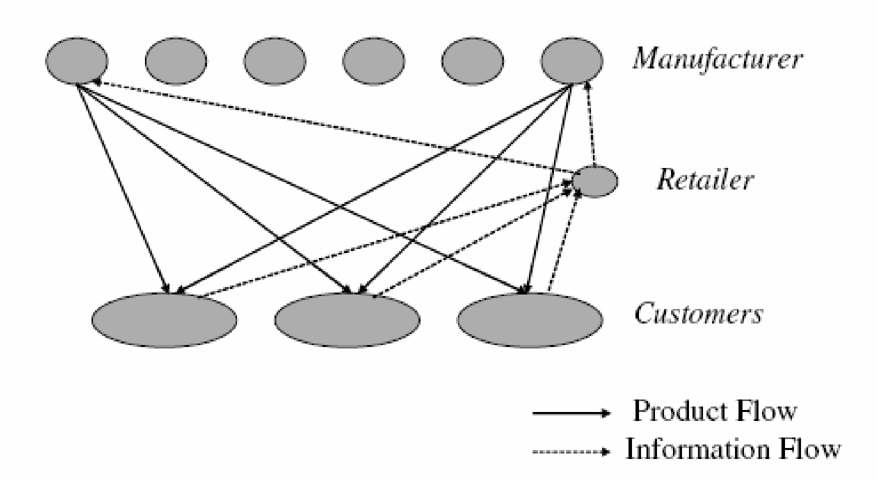


Fig.8 Manufacturer storage with direct shipping. Source: Chopra, 2003.

One of the widely utilized structures in physical distribution networks is defined as Direct Distribution Structure, which implies that products are shipped directly to customers from one or a limited number of centrally located inventories. Direct distribution typically uses premium transport combined with information technology to rapidly process customer orders and achieve delivery performance. This combination of capabilities, designed into the order delivery cycle, reduces time and geographical separation from customers. Examples of direct shipments are plant-to-customer truckload shipments, and various forms of direct to consumer fulfilment required to support catalogue and e-commerce shopping. Direct logistical structures are also commonly used for inbound components and materials to manufacturing plants because the average shipment size is typically large.

Usually logisticians choose direct delivery alternative to reduce anticipatory inventories and intermediate product handling. On the other hand, the deployment of direct logistics is limited by high transportation cost and potential loss of control (Bowersox et al., 2002).

Lumsden K. (2002) defines Direct Delivery Distribution (further referred to as DDD) system as very resource-demanding for transport. Let's assume there are a number of manufacturing units and a number of customers, each manufacturing unit produces different products, and therefore each customer might need goods from all producing units. Consequently, all units must be connected with all customers, which create a practical distribution problem with demand for a large number of transport relations. At the same time in a system built on direct relation, there are no item restrictions, i.e. all existing transport in the system is totally disconnected from each other. This leads to a large freedom to adapt the transport need to the buyer's time demand (Lumsden, 2002, p. 348).

According to Lumsden (2002), in an extensive distribution system where there are many sources, each node must meet the demand of every customer, i.e. there must be a large number of relations (m x c), which clearly creates several problems low frequencies in each link, low recourse utilization, large demand of vehicles etc.

Fleischman et al. (1998) describe DDD structures where order size limit exceeds, say 1 or 2 tonnes, and they are shipped directly from the origin (or central warehouse) to the destination. But if the order size is small, several orders can be consolidated in one truck in order obtain a full truck load (FTL). And according to Fleischman et al. (1998), this trip can contain 2, 3 or at most 4 deliveries. The composition of the trips is mainly restricted by the vehicle capacity. In a carrier distribution network, transport to transhipments points are often combined with direct delivery trips.

According to Chopra (2003), this option is also referred to as drop shipping. All inventories are stored at the manufacturer's, information flows from the customer, via the retailer, to the manufacturer, while product is shipped directly from the manufacturer to customers as shown in Fig. 8. In some instances, the manufacturer sells directly to the customer.
The biggest advantage of drop shipping is the ability to centralize inventories. A manufacturer can aggregate demand and provide a high level of product availability with lower levels of inventory than individual retailers. The benefits from centralization are highest for high-value-low-demand items with unpredictable demand (Chopra, 2003). Drop shipping also offers the manufacturer the opportunity to further lower stored inventories by postponing customization until after the customer order has been placed. Transportation costs are high with drop shipping because the average outbound distance to the end consumer is large and often package carriers must be used to ship the product. Package carriers have high shipping costs per unit compared to truckload (TL) or less-than-truckload (LTL) carriers. With drop shipping, a customer order with items from several manufacturers will involve multiple

shipments to the customer, and such loss in aggregation in outbound transportation further increases cost.

On the other hand, Drop Shipping saves on the fixed cost of storage facilities, because all inventories are centralized at the manufacturer. There can be some savings in handling costs as well because the transfer from manufacturer to retailer no longer occurs. Handling costs can be further reduced if the manufacturer has the capability to ship orders directly from the production line.

The handling of returns is more expensive under drop shipping because each order may involve shipments from more than one manufacturer. A manufacturer storage network is likely to have difficulty handling returns, which will hurt customer satisfaction. There are two ways that returns can be handled. One is for the customer to return the product directly to the manufacturer. The second is for the retailer to set up a separate facility (across all manufacturers) to handle returns.

Given its performance characteristics, manufacturer storage with direct shipping is best suited for a large variety of low-demand,-high-value items where customers are willing to wait for delivery and accept several partial shipments. Manufacturer storage is also suitable if it allows the manufacturer to postpone customization, thus reducing inventories. Drop shipping is hard to implement if there are more than 20–30 sourcing locations that have to ship directly to customers on a regular basis. For products with very low demand, however, drop shipping may be the only option.

2.5.2 Direct delivery with stock-less hub and in-transit merge

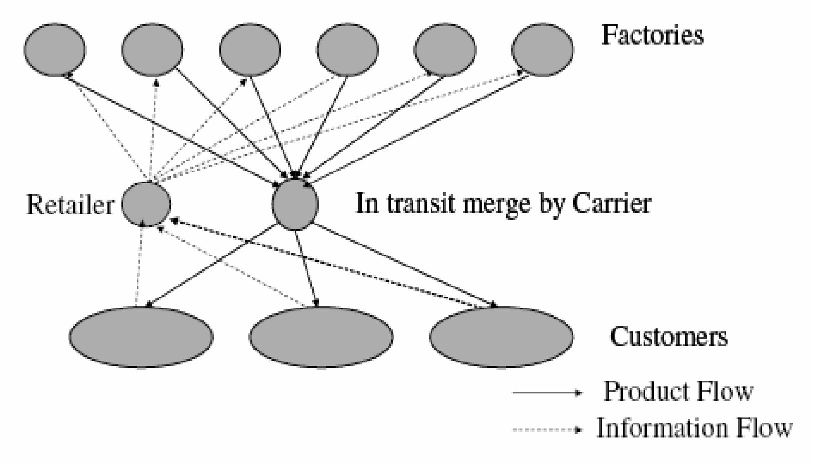


Fig.9 Direct delivery with in-transit merges. Source: Chopra, 2003.

Unlike pure drop shipping where each product ordered is sent directly from each manufacturer to the end customer, in-transit merge combines parts of the order coming from different locations so that the customer gets a single delivery.

As with drop shipping, the ability to aggregate inventories and postpone product customization is a significant advantage of in-transit merge. This approach will have the greatest benefits for high-value products whose demand is hard to forecast, in particular if product customization can be postponed.

In most cases, transportation costs are lower than drop shipping because of the merge that takes place at the carrier hub prior to delivery to the customer. An order with products from three manufacturers thus requires only one delivery to the customer compared to three that would be required with drop shipping. Fewer deliveries save transportation cost and simplify receiving. Facility and processing costs for the manufacturer and the retailer are the same as in drop shipping. While the party performing the in-transit merge has higher facility costs because of the merge capability required. Receiving costs at the customer are lower because a single delivery is received. Overall supply chain facility and handling costs are somewhat higher than drop shipping.

The main advantage of in-transit merges over drop shipping is the somewhat lower transportation cost and improved customer experience. The major disadvantage is the additional effort during the merge itself. Given its performance characteristics, manufacturer storage with in-transit merge is best suited for low/medium-demand-high-value items where the retailer is sourcing from a limited number of manufacturers. Compared to drop shipping, in-transit merge requires a higher volume from each manufacturer to be effective. If there are too many sources, in-transit merge can be very difficult to coordinate and implement. In-transit merge is best implemented if there are no more than four or five sourcing locations and each customer order has products from multiple locations.

Stockless platform using cross-docking strategy

A Cross-docking strategy could be defined as*: "a warehousing strategy that involves movement of material directly from the receiving dock to the shipping dock with a minimum dwell time in between"* (M.Apte & S.Viswanathan), or *"an operational technique for receiving, allocating, sorting and dispatching product, whilst it remains on the dock of a Distribution Center (DC) and therefore does not rely upon withdrawing stock from storage"* (M.Johnson, TNT Logistics).

Fig.10 shows the structure of cross-docking. Stock directly delivered from suppliers/manufacturers A, B and C is transported to the DC, through the inbound docks. Once received and checked it is sorted into the required order profile and through the outbound dock is transported to the pre-determined retailer. Consequently, inbound volume should be equal to outbound volume. At the end of the working shift no stock should remain in the DC.

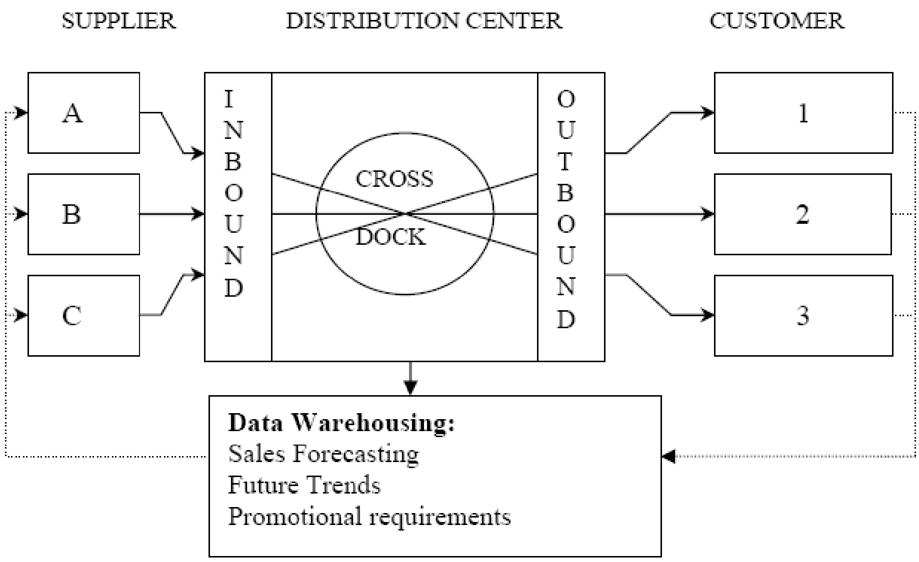


Fig.10 Cross-docking structure. Adapted from: Apte and Viswanathan, 2000.

Stockholding intermediate warehouses and DCs are coming under greater pressure to meet the requirements of a more demanding consumer market, while reducing operational and overhead costs to maintain profit growth. In other words, general resources have to be reduced yet overall performance increased. Cross-docking is not going to solve all issues, it does offer significant opportunities to reduce costs in the DC by reducing inventory and hence physical size, whilst accepting and managing a larger range of product lines at greater throughputs (TNT). Cross-docking may offer significant benefits, such as:

a. Reduced inventory lead times
b. Rapid replenishment cycles from suppliers to stores
c. Increased assets productivity, since large holding spaces and supporting equipment are no longer required

d. Reduced operating costs for handling, storage, damage, obsolescence, etc.

e. Cuts shipping and receiving errors

f. Lets retailer obtain larger orders at better prices

However, all these improvements are achieved at a cost. One of the main disadvantages of a cross-dock system is the reduced contingency for failure throughout the supply-chain. Highlighted next are some of the pressures, which could reduce the efficiency of a system and must, therefore, be viewed as challenges to be either overcome or managed, although an aim is to reduce inventory there may be a requirement to hold some stock in storage.

- Slow moving product: Should daily demand fall below an economic order quantity, as agreed with the supplier, it may be necessary to hold a level of stock within a warehouse to retain order demand satisfaction and to maintain a market profile.

- Imported stock containerised goods arriving from overseas create a large stockholding, only reduced by order depletion until the next delivery, in effect, managing the inventory to a saw-tooth profile. Due to the inherent nature of the transportation channels, stock could not be relied upon to fulfil the criteria for a cross-dock operation.

- Start-up: An initial stock, specifically of best selling lines, should be held and only reduced once confidence in the system has been achieved.

- Supplier freedom: As previously explained, cross-docking enables the retailer to increase the product lines, yet on the reverse side this limits the freedom to deal with just any supplier. It increases the reliability for success on suppliers who are willing to enter into a "Trust in Partnership" agreement. While in optimal conditions, these can be controlled successfully, however, if not managed and organized well, they can potentially cause the retailer to lose significant control of the operation. This further emphasises the absolute need for a "Secure Partnership" agreement.

- Transportation: One cause of failure in cross-docking, which is worth highlighting is the increase in road traffic congestion. Precision timing is of critical importance. Failure to meet with the operational time slots could delay other connected activities within the supply-chain. Should sales floor stockholding be reduced to a single day with no supplementary stockroom storage then a delay in delivery could mean a complete stock out.

For these and other reasons, it could often be preferable to maintain a certain level of contingency whilst retaining the benefit of cross-docking, by diversifying the cross-dock operation into regional stockless centres creating multi-purpose consolidation depots. These could receive stock from a centralised warehouse - slow moving, imported and promotional stock - and product lines direct from suppliers for immediate sortation and consolidation. If required, value added work can be undertaken to ensure that the stock will arrive in a "floor ready" condition.

Exploring a regional supply base could lead to reduced transportation costs and give greater flexibility and response in transportation scheduling. Stock not supplied regionally could be despatched through the DC - primary sort - into batch lots consolidating with the slower moving stock to be transported to the depots.

Another important factor that influences the decision to use cross-docking is the level of unit stock-out cost or the cost of lost sale on a single unit of product. Cross-docking inherently leads to a minimal level of inventory at the warehouse, and thereby strips the system of safety stocks consequently; cross-docking raises the probability of stock-out situations. However, if the unit stock-out cost is low, cross-docking can still be the preferred strategy, since the benefits of reduced transportation cost under cross-docking can outweigh the increased stock-out cost. Cross-docking is therefore preferred for products with stable and constant demand rate and low unit stock-out cost. On the other hand, for products with unstable or fluctuating demand and high unit stock-out cost, the traditional warehousing and distribution strategies are still preferable (Fig. 11).

Other factors that can influence the suitability of cross-docking include the distance of the warehouse from other points in the distribution channel, the service requirements for the product and the density of business in the region. Since the technology and systems used in cross-docking can be quite expensive, therefore, apart from stable demand, the total volume handled by the warehouse for the region should result in scale economies and should also be stable across time. When the warehouse is located close to several demand points or retailers, then scale economies and stability of demand are easier to achieve, and the service requirement for the product essentially impacts the stock-out cost or lost sale. Generally, high service requirements imply greater fluctuations in demand, and therefore a greater difficulty to operate the cross-docking facility.

In order to establish a successful cross-dock system, accurate and up-to-date integrated information is needed about every stage in the supply chain. In order to obtain the correct information, two integrated information systems for cross-docking implementation have been developed: Electronic Point of Sales (EPOS) system for capturing and compiling accurate online information and Electronic Data Interchange (EDI) for ensuring that the data is quickly and efficiently transferred throughout the operating structure.

Unit stock-out costs	Stable and constant	Unstable and fluctuating
High	Cross-docking can be implemented with proper systems and planning	Traditional warehousing/distribution preferred
Low	Cross-docking preferred	Cross-docking can be implemented with proper systems and planning

Product demand rate

Fig.11 Cross-docking implementation matrix.

The information acts as the main driver to the supplier dictating the next batch delivery from inventory and synchronizes it with the production in maintaining minimum levels of inventory. It is of great importance that the cross-docking system fulfils operational requirements as well such as material handling equipment, which can be automated or manual and the quality of equipment and after sales service is paramount and must be treated on an equal basis along with performance and cost.

2.5.3 Stockholding intermediate warehouses with packaged carrier delivery

According to Chopra’s framework (2003), inventory is not held by manufacturers at the factories, but is held by distributors/retailers in intermediate warehouses and products are transported from the intermediate location to the final customer with package carriers. Amazon.com as well as industrial distributors like Grainger use this approach combined with drop shipping from a manufacturer.

Relative to manufacturer storage, distributor storage requires a higher level of inventory, because the distributor/retailer warehouse aggregates demand uncertainty to a lower level than the manufacturer.

From an inventory perspective, distributor storage makes sense for products with higher demand.

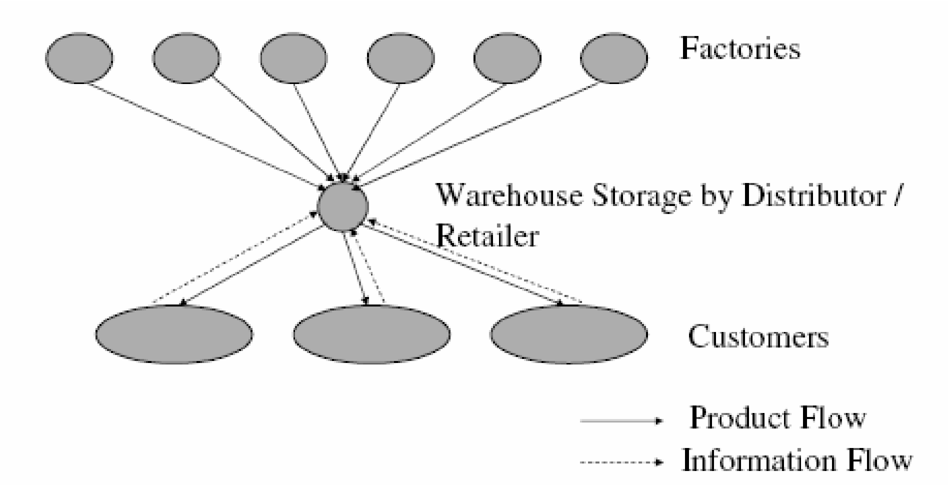


Fig.12 Distributor storage with carrier delivery. Source: Chopra, 2003.

Both Amazon and Grainger only stock the medium to fast moving items at their warehouse with slower moving items stocked further upstream. In some instances, postponement can be implemented with distributor storage, but it does require that the warehouse develops some level of assembly capability. Distributor storage, however, requires much less inventory than a retail network.

Transportation costs are somewhat lower for distributor storage compared to manufacturer storage because a more cost efficient mode of transportation (e.g. Truck Load) can be employed for inbound shipments to the warehouse, which is closer to the customer. Unlike manufacturer storage where multiple shipments may need to go out for a single customer order with multiple items, distributor storage allows outbound orders to the customer to be bundled into a single shipment further reducing transportation cost. Transportation savings from distributor storage relative to manufacturer storage increase for faster moving items.

Compared to manufacturer storage, facility costs are somewhat higher with distributor storage because of a loss of aggregation. Processing and handling costs are comparable to manufacturer storage unless the factory is able to ship to the end customer directly from the production line. In that case, distributor storage will have higher processing costs. From a facility cost perspective, distributor storage is not appropriate for extremely slow moving items.

The information infrastructure needed with distributor storage is significantly less complex than that needed with manufacturer storage. The distributor warehouse serves as a buffer between the customer and the manufacturer, decreasing the need to completely coordinate the two. Real time visibility between customers and the warehouse is needed, whereas real time visibility between the customer and the manufacturer is not. Visibility between the distributor warehouse and manufacturer can be achieved at a much lower cost than real time visibility between the customer and manufacturer.

In addition, the response time with distributor storage is better than response time with manufacturer storage because distributor warehouses are, on average, closer to customers than manufacturer warehouses and the entire order is aggregated at the warehouse when shipped. Returnability is better than that with manufacturer storage because all returns can be processed at the warehouse itself. The customer also has to return only one package even if the items are from several manufacturers. Distributor storage also makes sense when customers want delivery faster than offered by manufacturer storage but do not need the order immediately.

2.5.4 Stockholding intermediate warehouses with last mile delivery

According to Chopra (2003), "Last mile delivery" refers to the distributor/retailer delivering of the product to the customer's home instead of using a package carrier. Unlike package carrier delivery, last mile delivery requires the distributor warehouse to be much closer to the customer, increasing the number of warehouses required. The warehouse storage with last mile delivery network is as shown in Fig. 13.

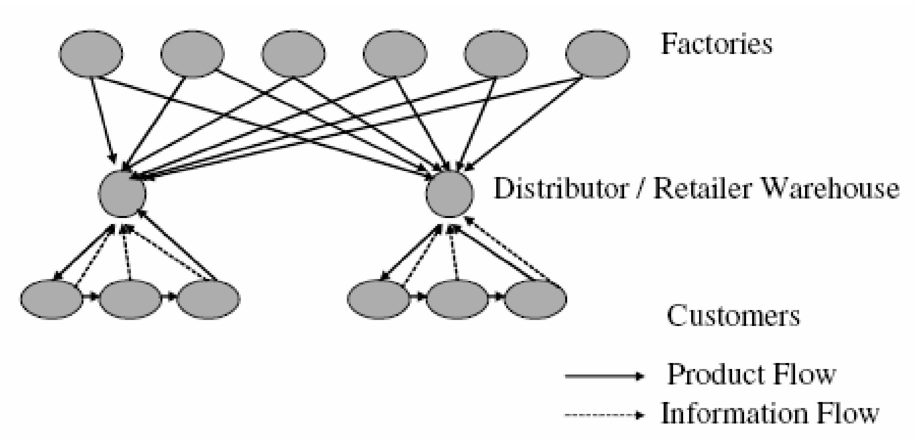


Fig.13 Distributor storage with last mile delivery. Source: Chopra, 2003.

In a last mile delivery scenario, distributor storage requires higher levels of inventory than all other distribution options except for retail stores, because it has a lower level of aggregation. From an inventory perspective, warehouse storage with last mile delivery is suitable for relatively fast moving items where desegregation does not lead to a significant increase of inventory. Transportation costs are highest using last mile delivery, because package carriers aggregate delivery across many retailers and are able to obtain better economies of scale than that available to a distributor/retailer attempting last mile delivery. Delivery costs (including picking and transportation) can be as high as $30–40 per home delivery in the grocery industry. Last mile delivery may be somewhat cheaper in dense cities.

Facility and processing costs in last mile delivery systems are very high due to the large number of facilities required. Facility costs are somewhat lower than a network with retail stores, but much higher than either manufacturer storage or distributor storage with package carrier delivery.

The information infrastructure with last mile delivery is similar to distributor storage with package carrier delivery, with, additional capability of scheduling deliveries. Response times are faster than those with package carriers, and product variety is generally lower than distributor storage with carrier delivery. While the cost of providing product availability is higher than every option other than retail stores, returnability is best because trucks making deliveries can also pick up returns from customers.

2.5.5 Distribution structure with customer pickup

In the scenario of a distribution structure with customer pick-up, inventory is stored at the manufacturer or distributor warehouse, customers place their orders online or on the phone and then come to designated pickup points to collect their orders.

Orders are shipped from the storage site to the pickup points as-needed; or network structures with several distribution centres (DCs) where products from manufacturers are cross-docked and sent to retail outlets on a daily basis. Inventory costs using this approach can be kept low with either manufacturer or distributor storage to exploit aggregation. Grainger keeps its inventory of fast moving items at pickup locations, while slow moving items are stocked at a central location or warehouse, or in some cases at the manufacturer.

Transportation cost is lower than any solution using package carriers because significant aggregation is possible when delivering orders to a pickup site.

This allows the use of TL or LTL carriers to transport orders to the pickup site.

Facility costs are high if new pickup sites have to be built, but costs can be contained using existing sites. Processing costs at the manufacturer or the warehouse are comparable to other solutions, while processing costs at the pick up site are high because each order must be matched with a specific customer upon arrival.

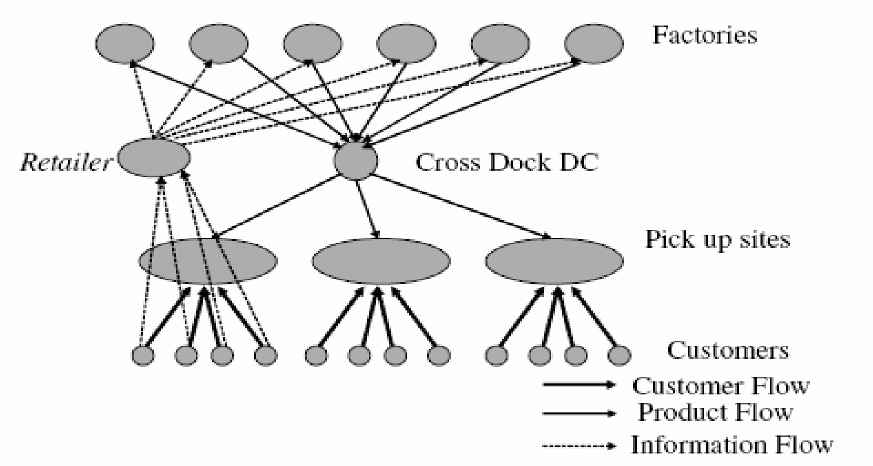


Fig.14 Manufacturer or distributor warehouse storage with consumer pickup.
Source: Chopra, 2003.

Creating this capability can increase processing costs significantly if appropriate storage and information systems are not provided. A significant information infrastructure is needed to provide visibility of the order until the customer picks it up. Very good coordination is needed between the retailer, the storage location, and the pickup location to guarantee smooth transitions.

The main advantage of a network with consumer pickup sites is that it can lower delivery costs, thus expanding the set of products sold as well as the number of customers served online, while the major hurdle is the increased handling cost at the pickup site. A consumer pick-up network is likely to be most effective if existing locations such as convenience or grocery stores are used as pickup sites because such a network improves the economies from existing infrastructure. Unfortunately, such sites are typically designed to allow the customer to do the picking and will need to develop the capability of picking a customer specific order.

Retail storage with customer pickup

In this option, inventory is stored locally at retail stores, customers either walk into the retail store or place an order online or on the phone, and pick it up at the retail store.

A B2B example is Grainger where customers can order online, by phone, or in person and pick up their order at one of the Grainger retail outlets.

Transportation costs are much lower than those in other solutions because inexpensive modes of transport can be used to replenish product at the retail store, but, facility costs are high because many local facilities are required. A minimal information infrastructure is needed if customers walk into the store and place their order in person, while, to provide visibility until the customer picks up online orders, a significant information infrastructure is needed. This methods grants a very good response time, since it relies on local storage, but it is considerably more expensive than all other options, because it provides a high level of product availability. Order visibility is extremely important for customer pickups where orders are placed online or on the phone. Overall returnability is fairly good using this option, since returns can be handled at the pickup site.

The main advantage of a network with local storage is that it can lower the delivery cost and provide a faster response than other networks. The major disadvantage is the increased inventory and facility costs. This type of network is best suited for fast moving items or items where customers value the rapid response.

2.6 Distribution network design selection

Transport time is defined as the time between the beginning and ending of the delivery. Basically, there are five means to improve transport time (Lehmusvaara, 1998):

1. Change the source (plant or distributing warehouse) of the products,
2. Locate the distribution warehouses closer to customers,
3. Locate the plants closer to customers,
4. Find new customers from better locations,
5. Use faster transport methods.

The first, fourth and fifth means cannot be improved boundlessly; moreover, the fourth is in principle outside the possibilities of logistics. Improving the third means is often impossible, because it normally causes heavy investments. Therefore, the second means is mostly under consideration when transport time is improved. Building more own warehouses means at least more fixed warehouse costs, which can be avoided by using subcontractors. Sometimes it means also more transportation and variable warehouse costs, especially if transportations take place from plants via warehouses to customers instead of direct full-loaded transportations from plants to customers.

Chopra (2003) pointed out that network designer needs to consider product characteristics as well as network requirements when deciding on the appropriate delivery network.

The various networks considered earlier have different strengths and weaknesses.

Only niche companies will end up using a single distribution network. Most companies are best served by a combination of delivery networks.

The combination used will depend upon product characteristics as well as the strategic position that the firm is targeting.

The suitability of different delivery designs (from a supply chain perspective) and of different warehouses location inside the supply chain is shown in Figure 15: warehouses can be built at manufacturer's site, as distribution centres or closed to customers, at a local site.

More we are closer to customer more we can improve and reduce the response time and transportation costs. A hybrid network combines all the above options into its distribution network.

The network, however, is tailored to match the characteristics of the product or the needs of the customer. Fast moving and emergency items are stocked locally and customers can either pick them up directly or have they shipped depending upon the urgency.

Slower moving items are stocked at a national DC from where they are shipped to the custode within a day or two. Very slow moving items are typically drop shipped from the manufacturer and involve a longer lead time.

A famous hybrid network is Amazon where some items are stocked at their warehouse while other slow moving items may be drop shipped from distributors or publishers.

Finally, intermediaries such as distributors add value to a supply chain between a supply stage and a customer stage if there are many small players at the customer stage, each requiring a small amount of the product at a time.

The value added increases if distributors carry products from many manufacturers. Improvement in supply chain performance occurs for the following reasons:

• Reduction in inbound transportation cost because of Truck Load shipments from manufacturers to distributor.

• Reduction in outbound transportation cost because the distributor combines products from many manufacturers into a single outbound shipment.

• Reduction in inventory costs because distributor aggregates safety inventory rather than disaggregating at each retailer.

• By carrying inventory closer to the point of sale, distributors are able to provide a better response time than manufacturers can.

• Distributors are able to offer one stop shopping with products from several manufacturers.

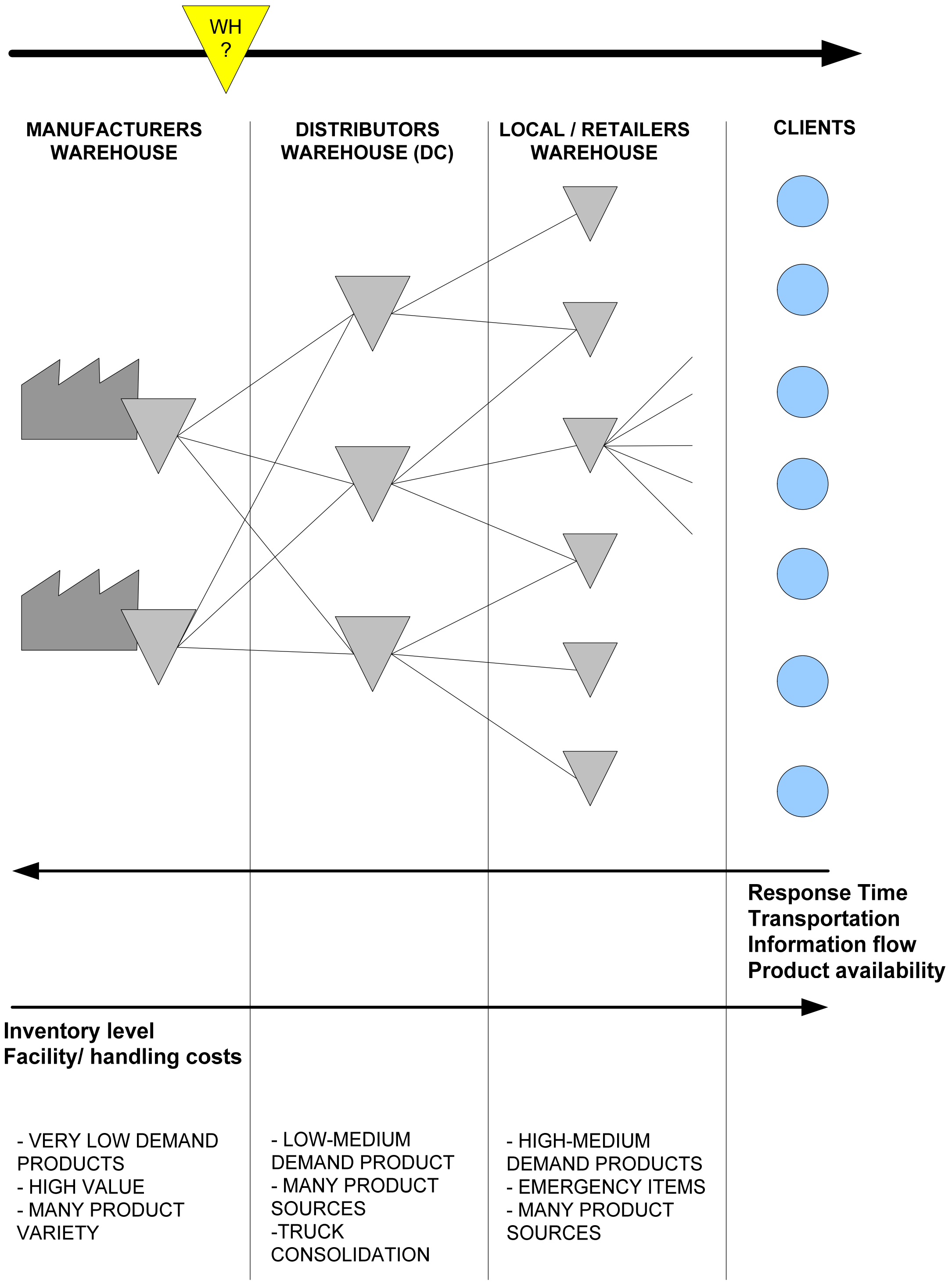


Fig.15 Comparative performance of delivery network design according to different warehouses location.

2.7 Centralization and Decentralization: network structure

Most industrial companies have a distribution system with many local warehouses geographically close to the customers. One or more warehouses in each country in Europe are not unusual (Abrahanmsson, 1993).

Production oriented companies usually have a long distribution channel to break down large production batches, step by step, warehouse by warehouse, to a product-mix demanded by the customers. A sales-oriented company uses a wide distribution channel, with many sales offices and warehouses, to be geographically close to the customers.

In such decentralized, and traditional, distribution structures, each link in the distribution chain usually manages both sales and warehousing with a great increase of the network complexity level. In Abrahamsson's analysis of Distribution Network structures (1993), the author stresses that by using modern information systems and by implementing a more effective distribution strategy, the goods can be delivered directly to the customer from a central warehouse or a production site, where the main focus is on centralisation of the distribution structure. His article presents the effects of a change from traditional distribution system to a system with distribution from a central warehouse directly to customers (Figure 16), and the results are based on a study of three Swedish companies and their successful distribution network re-design.

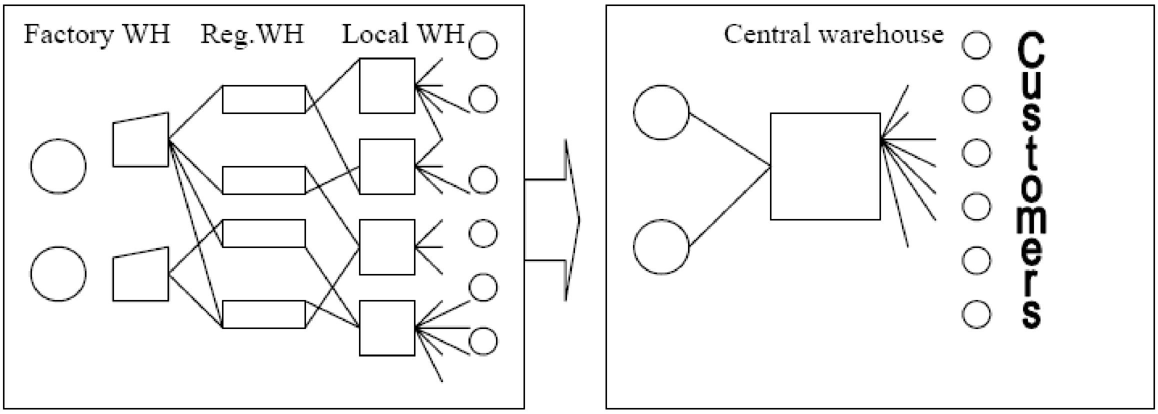


Fig.16 The change from a Decentralized to a Centralized Distribution Structure.
Source: Adapted from Abrahamsson and Brege, 1995.

Previous studies of the companies who implemented Direct Distribution showed that the companies changed focus from production and sales orientation to effective material flow orientation (Abrahamsson and Brege, 1995). These new centralized distribution systems are Time Based: in a time-based distribution system it is more important to deliver the goods to the customers within a specified time, i.e. 48 hours, than it is to have warehouses geographically close to the customers (Abrahansson, 1993). The main difference between those concepts is that in time-based distribution system the distribution measurements are made in time, while in DDD they are based on costs or customer service level. The distance between shipping point and the customer is defined in lead time, i.e. the time from the order receipt till order delivery to the customer. Thus, the distance is measured in time instead of kilometres and geographical measurements.

The border between sales activities and logistics activities gets eliminated and allows the creation of a unique service for customers in terms of high delivery service and decreased total logistics costs.

Based on his studies, Abrahamsson (1995) defines the impacts of the centralized structure on the manufacturer and retailer in terms of logistics costs and value added services:

1. Lower fixed distribution costs: decreased costs for staff, warehousing space and administration.
2. Lower variable distribution costs: reduced inventory costs and transport costs can be kept at a defined constant level (according to the traditional logistics theories the transportation costs were expected to increase considerably, but they didn't increase in any of the Swedish industrial cases. The reason was a complete assortment in the central warehouse stock in combination with a smooth flow of small deliveries out from the warehouse with a reduction in shortage and in express freights and an increment in turnover).
3. Integration feedback: centralised control of the material flow (economies of scale) leads to the recourse decrease in sales department.
4. Quicker integration of the new products and distribution system is not so sensitive to volume variation
5. Shorter lead-time for all the markets and the entire assortment.
6. Increased on-time deliveries
7. Differentiation: opportunity to provide different services to different customer groups

8. Better information provided to customers: reliable “first hand” information about inventory level or product availability.

Fig.17 shows that the total distribution costs will decrease with the network centralization, because the transportation costs curve and the sales curve will change according to a reduction in the number of warehouses in the network.

From an organisational point of view, the centralized distribution structure with direct deliveries is more flexible than a traditional decentralized structure, but in order to successfully implement the Direct Distribution Structure some requirements should be met. First, large capital investments need to be made in order to cover high operating costs. Second, efficient information systems and reliable transport provider with flexible fleets are crucial. Third, the information technologies in the company should help to minimise order administration lead-time and integrate information flows in the whole organisation.

As for the first task, the total lead-time consists of operative (or physical) part and administrative part, including order receiving, registering, drop size planning, issue of the transport documents, which could take up to 90% of the whole lead time. The goal here should be to decrease administrative time to zero. Nowadays, the information systems can reduce total lead time to less than 20 hours.

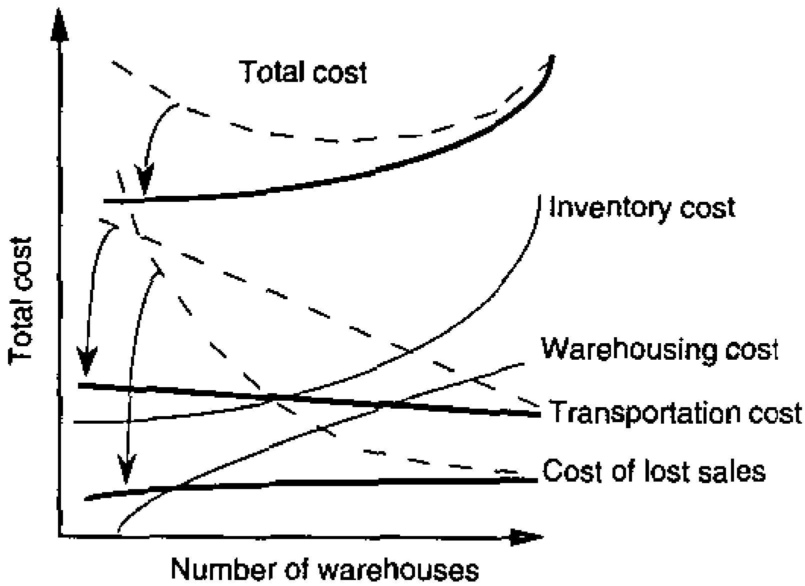


Fig.17 Total distribution costs: changes from a decentralized structure to a centralized structure. Source: Abrahamsson, 1993.

Organisational integration should unite sales departments and departments dealing with physical distribution to achieve full control over inventory level, information about deliveries and the whole process in common. Thus, it is more beneficial to have the production site closer to the market, because it allows a quicker reaction to the changes on the market itself.

As mentioned above, the Direct Distribution Structure is highly demanding and logistics managers must be creative in applying innovative ideas and technologies as well as proven approaches that will make sense for each specific case. A Direct Distribution Structure requires a concentration of a volume in a given transportation lane in order to be cost effective. This is why even if transportation costs usually increase, the benefits can be easily offset.

It’s very important to take into consideration freight consolidation techniques in order to achieve transportation efficiency, especially since Direct Distribution increases the instances of small shipments and Less Than Truck Loads (LTL), with a consequent cost increase.

“If you torture the data enough, it will confess"
Ronald Coase

3

Facility location problem

In chapter 2 we introduced the integrated distribution network design problems under investigation. This chapter presents the theoretical framework followed to asses the Facility Location and the Location-Routing Problem introduced before.

3.1 Location-allocation problem categories

According to Brockmann (1995) and Djamschidi (1998) few problem categories exist:

- **Location Problem:** consists of a set of customers with their geographical location, the quantities of their demands and exactly one storage which supplies all the customers. In order to minimize the linear transportation costs the location of the storage needs to be determined.
- **Multifacility Location Problem:** consists of a set of customers with their geographical location and the quantities of their demands. This time, several warehouses supply the customers. The allocation of the customers to the storages is default. In order to minimize the linear transportation costs, which depend on the distances and the transportation quantities, the locations of all the warehouses are to be determined simultaneously. Additionally transportation between the different storages needs to be considered.

- **Location Allocation Problem:** the Location Allocation Problem (LAP) is a generalization of the Multifacility Location Problem, where the allocation of the customers to the storages is not given and two distribution echelons exist with exactly one main storage on the first echelon. The storage location in the second echelon needs to be determined in order to minimize transportation costs, which depend on the transportations between the main storage and the storages of the second echelon and between the storages of the second echelon and the customers. The methods developed so far for LA can be classified into three categories: branch and bound algorithms (BBA), combinatorial optimization techniques, and specially designed algorithms (i.e. Neural Network).
- **Warehouse Location Problem:** the Warehouse Location Problem is a generalization of the Location Allocation Problem, but the number of storages of the second echelon is not given. The number of the storages is to be additionally optimized to the location and allocation of the storages, considering transportation costs and storage costs.

Researchers normally subdivide location problems into two different classes: location problem in a real space d-dimension *(planar problem)* and location problem inside a network *(network problem).* The distances considered in the first class are in most cases derived from the distances of Minkowski, a distance family with a single parameter p. In particular the distance between a point (ai ,bi) and a point (aj ,bj), with i≠j, defined as:

$$d_{ij}^{p} = [\,|a_i - a_j|^{p} + |b_i - b_j|^{p}\,]^{1/p} .$$

Most of the authors use the following three cases:

1) with p=1, we will have Rectilinear distance (or Manhattan, they are usually applied in urban areas and they can overestimate the distance travelled by as much as 44% then the Euclidean distances) :

$$d_{ij} = |a_i - a_j| + |b_i - b_j| ;$$

2) with p=2, we will have square Euclidean distances

$$d_{ij}^{2} = [\,|a_i - a_j|^{2} + |b_i - b_j|^{2}\,]^{1/2} ;$$

3) with p=∞, we will have the Chebyshev distances

$d_{ij}^{\infty} = max \{ | a_i - a_j | ; | b_i - b_j | \}$.

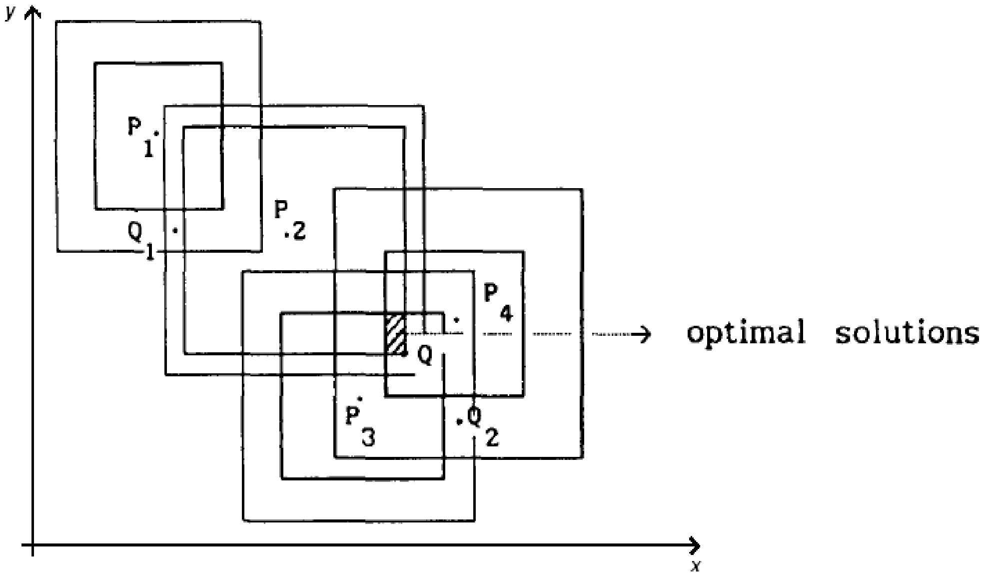


Fig.18 Competitive location with rectilinear distances.
Source: Infante-Macias, Munoz-Perez, 1995.

The first single facility location problem was cited by Weber (1909), while the first algorithm was developed by Weiszfeld (1937). The so-called Single facility Weber Problem (SWP) and the Multi-source Weber Problem (MWP), are characterized by the following objective functions:

Single facility Weber Problem (SWP)

$min\ z = f(x,y) = \sum_i d_i(x,y)\, w_i = \sum_i w_i\, [(x - a_i)^2 + (y - b_i)^2\,]^{1/2}$;

where the clients are located in (ai, bi), the facility is in (x, y), and wi is the demand or weight of client i є I .

Multi-source Weber Problem (MWP)

$min\ z = \sum_i \sum_j d_{ij}(x_j,y_j)\, w_i\, u_{ij}$

where J are the set of facilities to locate, (xj, yj) are the coordinates of facility j, and uij is the portion of the whole demand of client i, with i є I, satisfied by facility j.

More recent literature investigates location problems subdividing them into three big families:

a) *Simple Plant Location Problem (SPLP)* also called *Uncapacitated Facility Location Problem (UFLP),* without any assumption regarding the capacity of each plant and facility. Balinski (1965), Morris (1978) and ReVelle and Swain (1970) demonstrate that the SPLP are Integer-friendly. The already cited Weber, father of the multi-facility-location problem, while trying to solve continuous planar problems, came across impossible solutions in which facility couldn't be positioned (as on the top of a mountain or in the centre of a lake). For this reason his fellow researchers underlined the necessity of admitting only a finite number of solutions for the problem and the continuous problem was changed into a discrete problem. As a consequence, literature focuses mostly on the network problem instead of to planar problem. The objective functions of this set of problems usually aim to minimize the total costs of the whole system or maximize the total profit, considering not only transportation costs, but also inventory costs, facility fixed costs, and handling costs.

Table 4 illustrates the SPLP problem sub-families:

1. Simple Plant Location Problem (SPLP)
2. Simple Plant Location Problem with Order (SPLPO)
3. Simple Plant Location Problem with Convex transportation costs (SPLPC)
4. Simple Plant Location Problem with Spatial interaction (SPLPS)
5. Simple Plant Location Problem with General cost functions (SPLPG)
6. Dynamic Simple Plant Location Problem (DSPLP)

b) *Capacitated Plant Location Problem (CPLP).* This scenario is similar to the SPLP, but it considers restrictions in the production capacity of each facility. For example we can limit the capacities of supply centres to a value that can't be exceeded.

Table 5 shows the CPLP problem sub-families:

1. Capacitated Plant Location Problem with Single Source constrains (CPLPSS)
2. Capacitated Plant Location Problem with General setup cost (CPLPG)
3. Capacitated Plant Location Problem in global Environment (CPLPE)
4. Capacitated Facility Location Problem PLANWAR
5. Two-Stage Capacitated Facility Location Problem with Single Source constraints (TSCFLPSS)
6. Dynamic Capacitated Facility Location Problem (DCFLP)

c) <u>*Competitive flow capturing location allocation problem FCLAP (by Hodgson, 1990) and the Gravity Model:*</u> in many situation, a company may wish to locate a new facility which will compete with the existing ones. The Gravity Model developed by Drezner et al. (2002) deals with the location of facilities in a competitive environment. Lumsden (2003) developed a method based mainly on the localisation of the facility in the point of gravity of the customer demands and a determined distribution area. The method requires that all involved units be positioned in a coordinate system (Xi, Yi) and that only terminal (X,Y) is used in the total goods distribution system. The number of consumers (n-customers) and producing units (m-suppliers) to the terminal can be unlimited (Lumsden, 2003). In our case, a number of producers *(Xsj, Ysj)* will deliver to several customers *(Xki, Yki)* via terminal. The total volume of goods from all suppliers *(ΣVsj)* is equal to the total volume demanded by the customers *(ΣVki)*. The existing transportation cost for every single relation *(Tsj)* influences the relative significance of every supplier *(Vsj*Tsj)*. (Lumsden, 2003).

Where, i = 1, …..n (number of customers) and j = 1, ……n (number of suppliers)

$$X = \frac{\Sigma(Xlj*Tlj*Vjl) + \Sigma(Xki*Tki*Vki)}{\Sigma(Tlj*Vjl) + \Sigma(Tki*Vki)}$$

$$Y = \frac{\Sigma(Ylj*Tlj*Vjl) + \Sigma(Yki*Tki*Vki)}{\Sigma(Tlj*Vjl) + \Sigma(Tki*Vki)}$$

In the following three tables (4, 5 and 6) we will sum-up the wide range of location problems investigated in literature, and the three families described above. In particular we will distinguish between models derived from the SPLP scenario and models derived from the CPLP scenario, putting in evidence for each problem category the hypothesis, the resolutive methodology and the referring author.

Model	Hypothesis	Other assumptions	Relevant authors	Methodology
SPLP	Facilities' capcities are not fixed	Linear cost function	D.C. Cho et al. (1983)	Integer programming model
			P. Greistorfer,, C.Rego (2006)	Filter & Fun algorithm (Tabu search)
			B. Goldengorin et al. (2004)	Branch & Peg, algorithm with pre-processing
SPLPO	Facilities' capcities are not fixed	Customers express preferences for new facility locations	P. Hanjoul,, D. Peeters (1987)	*Type greedy algorithm based on heuristic interchange*
			L. Canovas et al. (2006)	Preprocessing
SPLPS	Facilities' capcities are not fixed	Customers sensibility to distribution costs: customers are free to chose the facility	K. Holmberg (1999)	Branch & bound algorithm
SPLPC	Facilities' capcities are not fixed	No linear distribution costs	K. Holmberg (1999)	Branch & bound algorithm
SPLPG	Facilities' capcities are not fixed	Installation cost function can be linear, convex or concave	L.-Y. Wu et al. (2006)	Heuristic alghoritm and Lagragian relaxation
DSPLP	Facilities' capcities are not fixed	Dinamic model considers different time period	T.J. Van Roy, D.Erlenkotter (1982)	Dual-based algorithm

Table 4. SPLP location problem family classification

Model	Hypothesis	Other assumptions	Relevant authors	Methodology
CPLP	Facilities' capacities are fixed		R. Sridharan (1995)	Local search algorithm
CPLPSS	Facilities' capacities are fixed	Each customer demand is satisfied by only one facility	R.K. Ahuja et al. (2002)	Local search algorithm
CPLPG	Facilities' capacities are fixed	Installation cost function can be linear, convex or concave	L.-Y. Wu et al. (2006)	Heuristic alghoritm and Lagragian relaxation
CPLPGE	Facilities' capacities are fixed	The number of facilities is limited per each region /zone	S.S. Syam (1997)	Heuristic alghoritm and Lagragian relaxation
CFLP PLANWAR	Facilities' capacities are fixed	Location of plants and distribution centers in a two levels distribution network with multi products	H. Pirkul, V. Jayaraman (1997)	Heuristic alghoritm and Lagragean relaxation
TSCFLPSS	Facilities' capacities are fixed	Location of plants and supply center with single source constraints	S.Tragantalerngsak et al. (1999)	Branch & bound and Lagragian relaxation with preprocessing
DCFLP	Facilities' capacities are fixed	Multi products, multi-period, with two levels for the location of distribution centers	C. Canel et al. (1999)	Branch & bound and dynamic programming model

Table 5. CPLP location problem family classification

Model	Aim	Hypothesis	Relevant authors	Methodology
GRAVITY MODEL	Maximization of the market captured by the new facilities	Cuncurrent sales points presence	Drezner et al, 2002	Heuristic alghoritm
GRAVITY MODEL (BUDGET)	Maximization of the market captured by the new facilities	Limited budget for new facilities installatiion	Drezner, 1998	Heuristic alghoritm
FCLAP	Maximization of the market captured by the new facilities	Considers the flow of clients inside the network	Hodgson, 1990 Wu and Lin, 2003	Heuristic alghoritm
COMPETITIVE FCLAP	Maximization of the market captured by the new facilities	Cuncurrent sales points presence	Wu and Lin, 2003	Heuristic alghoritm

Table 6. Competitive location problem family classification.

3.2 Facility location problem: methods and models

A distribution network is characterized by its elements (stores, transport and order processing), as well as by the relations between them, i.e.

• Structure of the distribution network and

• Strategy behind the distribution of goods (warehousing and delivery strategies).

This structure describes the physical arrangement of the distribution network regarding the regional locations of the stores and their scopes of responsibility, i.e. delivery regions. While re-structuring a distribution network and locating new facilities the following questions, need to be answered:

• How many distribution echelons (i.e. hierarchic storing levels) are to be designated?

• How many stores are to be established per distribution level?

• At which locations are these to be located?

• Which customers are to be supplied by which stores?

By warehousing strategy the necessary basic and safety stock amounts are determined for each warehouse as well as for each item, while delivery strategy determines type and range of goods streams between stores and customers, and in particular which distribution level supplies, which warehouse or end customer.

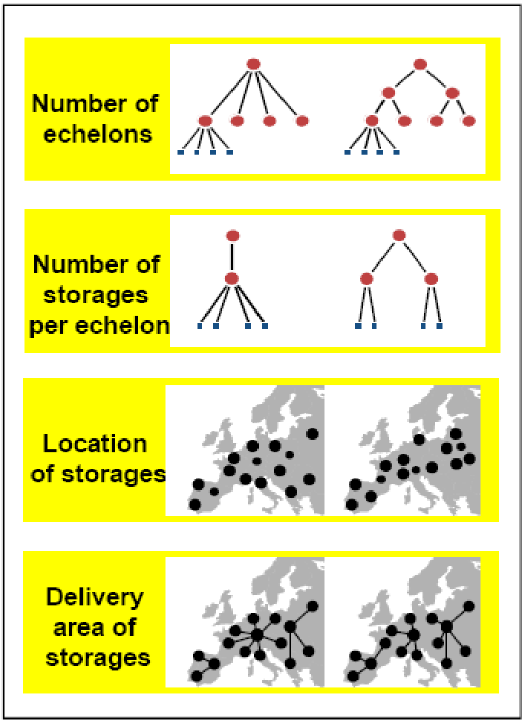


Fig.19 Questions which have to be answered.
Source: Djamschidi, Dohmen and Ruttgers, 2000.

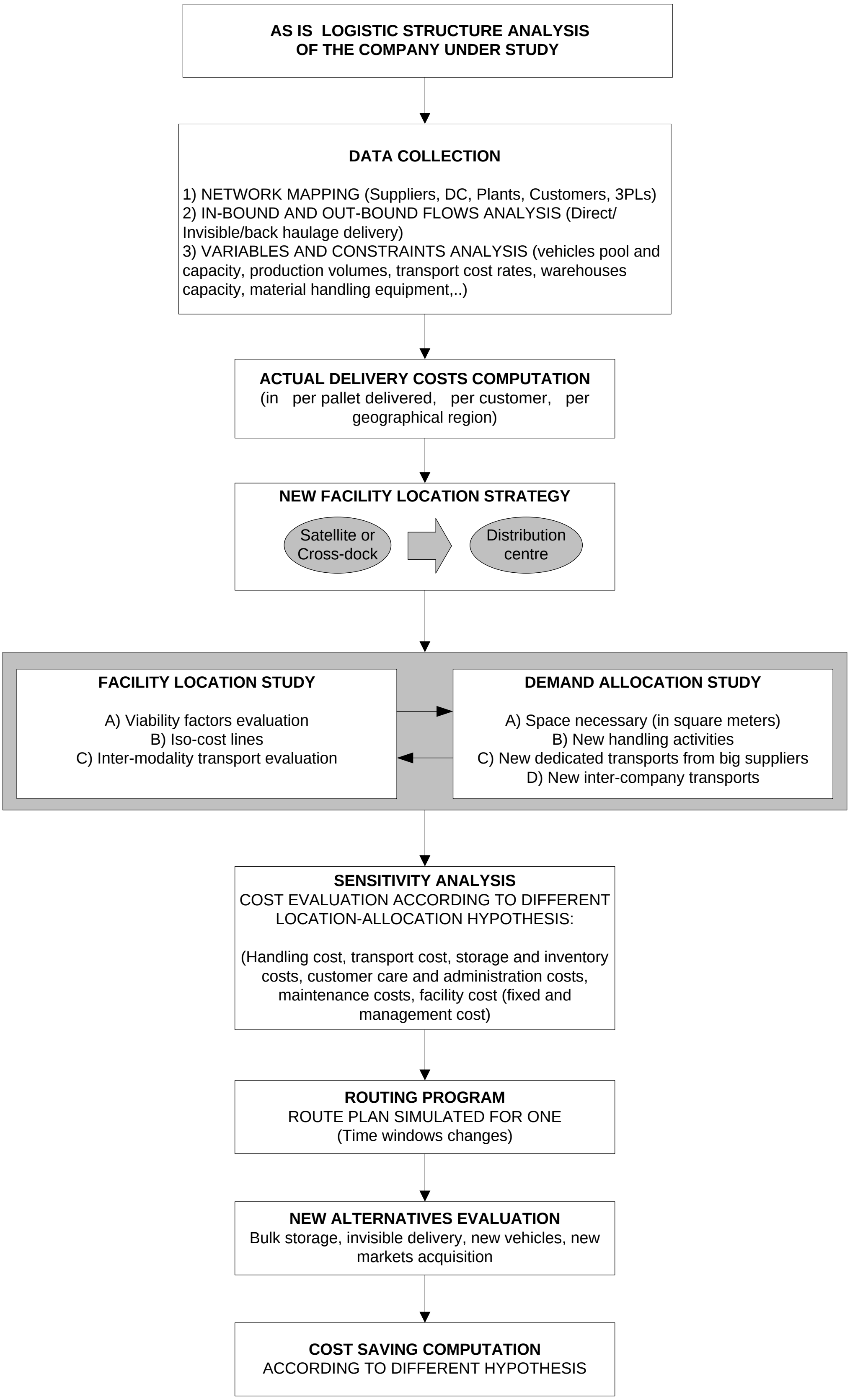


Fig.20 A framework for the feasibility study of a new facility location.

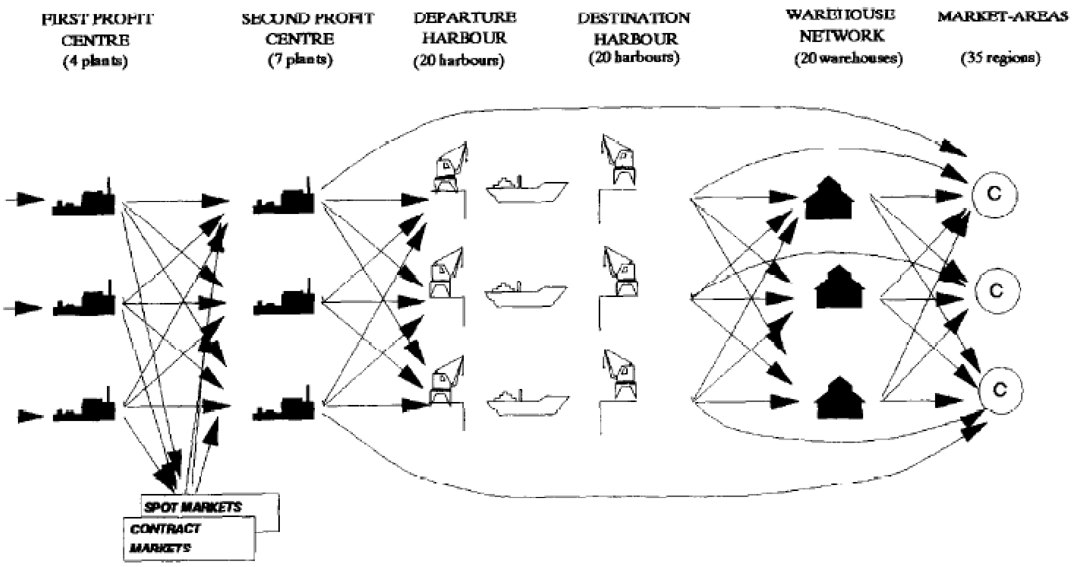


Fig.21 Example of the logistics structure of a case company. Source: Lehmusvaara, 1998.

Almost every supply network that we can think of has been faced with the task of locating facilities. Daskin (1995) and Drezner (1995) provide a complete survey on facility location. An important strategic issue related to the design and operation of a physical distribution network in a supply chain system is the determination of the best sites for intermediate stocking points, or warehouses. Many published works consider the problem of determining the best sites of both plants and warehouses (facilities) and a few consider simultaneously the problem of distributing the product from the new facility location to the customers (Amiri, 2006). Here we use the term facility in its broadest sense, to include entities such as factories, warehouses, retail outlets, cross-docks and other. A common objective is to determine the least costly system design so that the demands of all customers are satisfied without exceeding the capacities of warehouses and plants (Amiri, 2006). This usually involves making trade-offs among the cost components of the system that include:

a. costs of opening and operating the new facilities
b. inbound and outbound transportation costs
c. new handling costs arising at each new facility

Mathematical location models are designed to address a number of questions including:

How many facilities should be sited?

Where should each facility be located?

How should customer demand be allocated to facilities?

Proximity is a fundamental metric and many siting models seek to optimize it. The distribution/location family of problems covers formulations which range in complexity from a simple single commodity linear deterministic models, to multi-commodity non-linear stochastic versions.

Another important characteristic for a facility is its capacity: capacity constraints limit the total workload for which a facility will be responsible. Most of the existing mathematical models have focused on individual components of the network design like warehouse location. They fail to include inventory cost as a component of their objective function and have assumed pre-specified transportation choices. Sirisoponsilp (1989) proposed the only existing work on the interdependence between facility location, transportation and inventory decisions.

Strategic decisions on distribution centre locations can include determination and location of various warehouses and plants, warehouse and plant capacity load ratio, assignment of customer demands to open warehouses and assignment of open warehouses to open plants.

Following we propose two recent mathematical programming mixed-integer models developed by Jayaraman (1998) and Amiri (2006) to asses the facility location problem considering the relationship between the management of inventory, the transportation policy and the fixed cost of opening a new facility.

The FLITNET model (V. Jayaraman, 1998)

The FLITNET model (Facility Location, Inventory, Transportation Network) relates the transportation mode attributes, the location of distribution centres and plants, and the inventory policy parameters subject to constraints imposed by the distribution network design.

The FLITNET model's total costs can be expressed as follows:

<u>*Annual Cost*</u> *= Fixed cost to open and operate a warehouse + Transportation cost + Delivery cost + In-transit inventory cost + Plant cycle stock cost + Warehouse cycle stock cost + Fixed cost to open and operate a plant.*

The following notation is used for the FLITNET model:

I – Set of potential plants

J – Set of potential warehouses

K – Set of customer demand outlets

L – Set of products

R – Set of different transportation modes

T_{ijlr} – Unit transportation cost for shipping product l between plant i and warehouse j by transportation mode r

F_{ijlr} – Shipment frequency using transportation mode r for product l from plant i to warehouse j

d_{jklr} – Unit delivery cost for shipping product l between warehouse j and demand point k using transportation mode r

L_{ijlr} – Average lead time for shipments of product l from plant i to warehouse j by transportation mode r

CS_{ijlr} – Cycle stock cost at plant i associated with shipment of product l to warehouse j by transportation mode r

CC_{il} – Unit carrying cost for product l at plant i

CW_{jl} – Unit inventory cost for product l at warehouse j

Clr – Unit carrying cost for in-transit inventory of product l per unit transit time on transportation mode r

a_{kl} – Demand placed by customer k for product l

W_j – Capacity of warehouse

G_i – Capacity of plant

F_j – Fixed cost to open and operate a warehouse

O_i – Fixed cost to open and operate a plant

S_l – Space occupied by product l

W – Number of warehouses to open

P – Number of plants to open

The decision variables for this model are:

X_{ijlr} – Total quantity of product l shipped from plant i to warehouse j by transportation mode r

Y_{jklr} – Total quantity of product l shipped from warehouse j to demand point k by transportation mode r

Z_j = 1 if warehouse j is open, 0 otherwise

P_i = 1 if plant i is open, 0 otherwise

The objective function is:

$$MIN$$

$$Z = \sum_j F_j Z_j + \sum_i \sum_j \sum_l \sum_r T_{ijlr} X_{ijlr} + \sum_j \sum_k \sum_l \sum_r d_{jklr} Y_{jklr} + \sum_i \sum_j \sum_l \sum_r C_{lr} L_{ijlr} X_{ijlr} +$$
$$+ \sum_i \sum_j \sum_l \sum_r 0.5 \cdot \left(CC_{il} X_{ijlr} lF_{ijlr} \right) + \sum_i \sum_j \sum_l \sum_r 0.5 \cdot \left(CW_{jl} X_{ijlr} lF_{ijlr} \right) + \sum_i O_i P_i$$

The formulation involves minimizing the cost due to locating warehouses and plants, inventory related costs and transportation costs to transport products from open plants to open warehouses and cost to deliver the products from warehouses to customer outlets. Eight different kinds of constraints are considered in the model as following: Constraint (1) ensures that the demand of every customer is satisfied.

Constraint (2) represents the capacity restrictions of open warehouse j in terms of handling the demand of customers. Constraint (3) ensures that we locate at most W warehouses. Constraint (4) ensures that all the demand of customer k for product l is balanced by the total units of product l available at warehouse j which has been transported from open plants. Constraint (5) represents the capacity restriction of plant k in terms of the amount of demand it can handle. Constraint (6) restricts the number of open plants to not exceed P plants. Constraint (7) enforce the non-negativity restriction to be placed on two sets of decision variables ($Xijlr$, $Yjklr$) and constraint (8) imposes the binary nature on two other sets of decision variables (Zj, Pi).

GAMS provides a consistent modelling environment to obtain optimal solutions to the problem.

The model could be used to vary the number of open manufacturing plants and warehouses and to evaluate its effects on the transportation modes and the amount of inventory (in-transit and cycle stock) to be carried by these plants and warehouses, based on their location in the distribution network.

However, the results of the integrated model indicate that companies have to reconsider their transportation, inventory, and location strategies in the light of changing market conditions. The FLITNET model could be useful in studying the effect of switching from one strategy (e.g., open two plants and warehouses) to another (e.g., loading the open warehouses to 95 per cent of their capacity) during a given planning horizon.

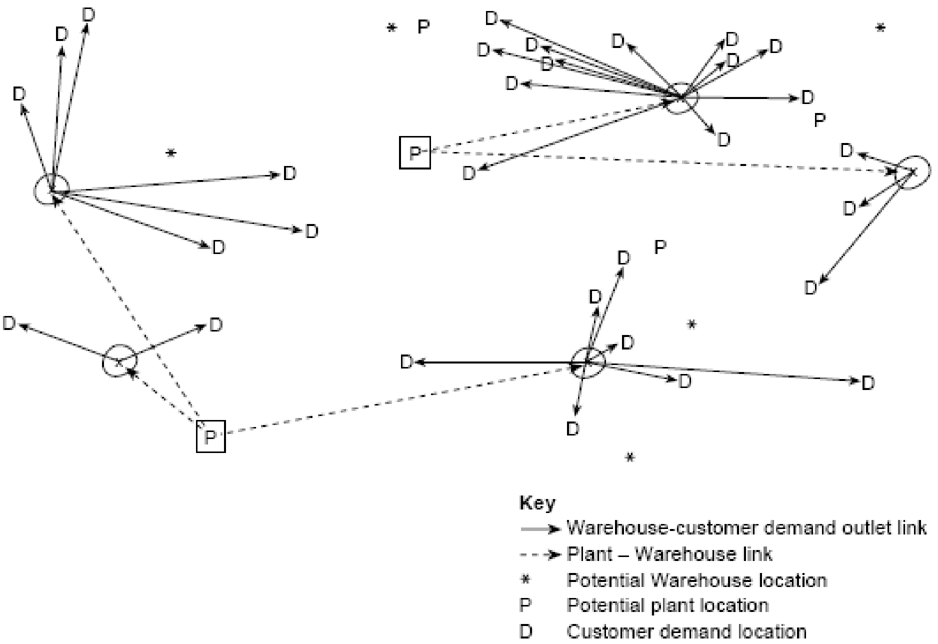


Fig.22 Geographical display of FLITNET results. Source: Jayaraman, 1998.

The DISTRINET problem (A. Amiri, 2006)

The model minimizes the following total costs.

<u>Total costs</u> *= the costs to serve customers' demands from the warehouses + the costs of shipments from the plants to the warehouses + the costs associated with opening and operating the warehouses and the plants.*

The following notation is used in the formulation of the model.

N – Index set of customers/customer zones

M – Index set of potential warehouse sites

L – Index set of potential plant sites

R – Index set of capacity levels available to the potential warehouses

H – Index set of capacity levels available to the potential plants

C_{ij} – Cost of supplying one unit of demand to customer zone i from warehouse at site j

C_{jk} – Cost of supplying one unit of demand to warehouse at site j from plant at site k

F_{rj} – Fixed cost per unit of time for opening and operating warehouse with capacity level r at site j

G_{hk} – Fixed cost per unit of time for opening and operating plant with capacity level h at site k

a_i – Demand per unit of time of customer zone i

b_{rj} – Capacity with level r for the potential warehouse at site j

e_{hk} – Capacity with level h for the potential plant at site k

The decision variables are:

X_{ij} – Fraction (regarding a_i) of demand of customer zone i delivered from warehouse at site j

Y_{rjk} – Fraction (regarding b_{rj}) of shipment from plant at site k to warehouse at site j with capacity level r

U_{rj} – 1 if a warehouse with capacity level r is located at site j, 0 otherwise

V_{hk} – 1 if a plant with capacity level h is located at site k, 0 otherwise

In terms of the above notation, the problem can be formulated as follows.

$$MIN$$
$$Z = \sum_i \sum_j C_{ij} a_i X_{ij} + \sum_r \sum_j \sum_k \underline{C}_{jk} b_{rj} Y_{rjk} + \sum_j \sum_r F_{rj} U_{rj} + \sum_k \sum_h G_{hk} V_{hk}$$

The model minimizes total costs, which consist of: the costs to serve the demands of customers from the warehouses, the costs of shipments from the plants to the warehouses, and the costs associated with opening and operating the warehouses and the plants.

Ten kinds of constraints are considered in the model: Constraint (1) ensures that the demands of all customers are satisfied by open warehouses. Constraints (2) and (4) guarantee that the total customer demands satisfied by an open warehouse do not exceed both the capacity of the warehouse and the total shipments to the warehouse from all open plants, respectively. Constraints (3) and (6) ensures that a warehouse and a plant, can be assigned at most one capacity level. Constraint (5) represents the capacity restrictions of the plants in terms of the total shipments to the warehouses. Finally, constraints (7) and (9) enforce the non-negativity restrictions on the corresponding decision variables and constraints (8) and (10) enforce the integrality restrictions on the binary variables.

Problem DistriNet is a mixed-integer programming problem, which includes, as a special case the classical uncapacitated NP-hard facility location problem. Commercial general purpose optimization software can solve small instances of problem P; however, with such software, computational times become prohibitive for reasonably sized instances.

For this reason, the author adopts a heuristic method to solve problem DistriNet based on the well-established Lagrangean relaxation technique.

The results of the experiments show that the heuristic procedure proposed by the author produces very good feasible solutions compared to the optimal/best available ones generated by CPLEX in significantly less CPU time.

3.3 Vehicle Routing Problem

The VRP is one of the most studied among the combination optimization problems, due both to its practical relevance and to its considerable difficulty. The VRP is concerned with the determination of the optimal routes used by a fleet of vehicles, based at one or more depots, to serve a set of customers.

Many additional requirements and operational constraints are imposed on the route construction in practical applications. For example, the load along each route must not exceed the given capacity of the vehicles, the total duration of each route must not take longer than a prescribed time, customers service must occur within given time windows, precedence relations may exist between customers, customer demands may not be completely known in advance, one customer service may be split among different vehicles, and some other problems, such as dynamic variations of demands or travel times.

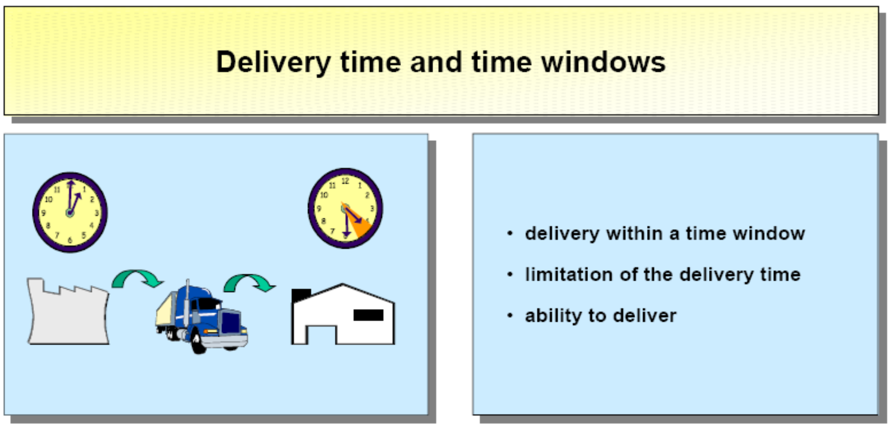


Fig.23 VRP: Delivery time and time windows.
Source: Djamschidi, Dohmen and Ruttgers, 2000.

First, it is interesting to consider the static and deterministic basic version of the problem, known as the capacitated VRP (CVRP). All the customers in the CVRP correspond to deliveries, the demands are deterministic, known in advance and may not be split, the vehicles are identical and are based at a single central depot, only the capacity restrictions for the vehicles are imposed, and the objective is to minimize the total cost (i.e., the number of routes and/or their length or travel time) needed to serve all the customers. Generally speaking, the travel cost between each pair of customer locations is the same in both directions, i.e., the resulting cost matrix is symmetric, whereas in some applications the cost matrix is asymmetric, such as the distribution in urban areas with one way directions imposed on the roads.

The CVRP has been extensively studied since the early sixties, and many new heuristic and exact approaches have been presented over the recent years. The greatest problems that can be consistently solved by the most effective exact algorithms proposed so far, contain about 50 customers, whereas larger instances may be solved only in particular cases. Thus, most of the problems arising in practical applications may only be tackled with heuristic methods.

A great deal of work has been devoted to the development of heuristics for the CVRP; see, for example, Christofides (1985), Fisher (1995), Federgruen and Simchi-Levi (1995) or Bertsimas and Simchi-Levi (1996).

In case of the time period VRP (PVRP), the classical VRP is generalised by extending the planning period to M days. The problem might be defined as follows: the objective is to minimize the vehicle fleet (or the sum of travel times or distances) to deliver to a given number of customers. A solution will be considered as feasible if all constraints of VRP are satisfied. Furthermore, a vehicle may not return to the depot the same day it departs. Over the M-day period, each customer must be visited as many times as required, but only once a day. For example, a customer may require two visits during a 5-day period, imposing that these visits take place on Monday–Thursday or Tuesday–Friday.

The PVRP problem consists of simultaneously selecting a day combination for each customer, and designing the VRP vehicle routes, solving a VRP for each day of the planning period, so that each customer is visited the required number of times, therefore all constraints are satisfied and the route costs are minimized. All papers on the PVRP reported in the literature present heuristic methods. To the best of our knowledge, the heuristic proposed by Cordeau et al. (1997) is the best currently published, since the computational results and test problems from the literature show that this method outperforms all other heuristics, and no exact method has been proposed.

Webb (1968) and, more recently, Salhi and Rand (1989) recognized the error introduced into location problems by ignoring the interdependence between routing and location decisions. Since then, some papers focused on the relationships between facilities and transportation costs, stressing that location of distribution facilities and routing of vehicles from facilities are interdependent decisions. In particular, in recent years, some location–routing problems (LRP) arising in the context of distribution network design problems have been investigated. In these cases, the facility location and the vehicle routing aspects are solved simultaneously (Laporte, 1988). Given a set of candidate depot sites and customer requirements, the simplest form LRP consists of determining the location of the depots and the vehicles routes to serve the customers, in such a way that some constraints, (generally related to depot and vehicle capacity, route lengths and durations), and all the customer requirements are satisfied, while minimizing an objective function involving routing costs, vehicle fixed costs, depot fixed costs and depot operating costs.

In this work (Laporte, 1988), the distribution network design problems have been classified according to the number of layers in the distribution network, and to the type of routes between layers. In particular, Laporte introduced the terminology ‘route of type R’ (for replenishment), if the route connects a pair of nodes of two different layers (for instance, a depot is connected to a customer), and ‘route of type T’ (for tour), if it is a tour connecting a node in a layer with more nodes belonging to other layers (for instance, a depot is connected via a tour to a certain number of customers served by the same vehicle). Laporte observed that a distribution network design problem can be formulated as a location–routing problem if and only if routes of type T are allowed, and location decisions arise at least at one layer. In the last two decades, many LRP models have been proposed in the literature to formulate and solve distribution network design problems. Most of them are related to a simple network with two layers (depots and customers), where routes of type T are allowed. Each model is characterized by the number of depots to locate (single depot or multi-depot), by the presence of capacity constraints (depot capacity and vehicle capacity) and other route constraints, and by the form of the objective function. In his work, some mathematical models have been proposed by distinguishing between three-index and two-index formulations. Two-index formulations were used for the single depot LRP, solved in (Laport and Nobert, 1981) via an exact approach, as well as for the multi-depot LRP, which is an extension of the single depot LRP (Laporte at al, 1983), for the multi depot capacitated LRP (Laporte at al, 1986), solved in an exact way, and for some asymmetric versions (Laporte et al, 1988).

As far as the solution methods are concerned, due to the complexity of LRP exact methods have been limited to small sized instances, and to two-index formulations. Three-index formulations, more versatile but more complex, have not been solved exactly until now.

To solve larger problems and real instances, the only helpful methods have been heuristics (see, for example, Jacobsen and Madsen, 1980 and Madsen, 1983, where the practical use of LRP for designing a newspaper distribution system is illustrated).

The majority of the heuristic approaches are based on the decomposition of the problem into sub-problems, which are then solved sequentially, in order to address interdependencies. Sub-problems are usually solved in an approximate way (Hansen et al., 1994). Another popular approach, also used within the decomposition methods, is the saving method (Hansen et al., 1994 and Srivastava, 1993).

A new approach has been presented in (Tuzun and Burke, 1999). The authors proposed a two-phase tabu search approach which integrates facility location and routing decisions. They also compared the performance of alternative LRP heuristics, by comparing their approach with one of the algorithms proposed, and by furnishing a set of test problems. Finally, we want to mention an interesting set-partitioning formulation of some LRP problems proposed Berger, 1997.

Generally, no LRP studied in the literature includes inventories, except for two cases. Perl et al., (1988) presented a mathematical model to explicitly represent the trade-off among facility, transportation and inventory costs; this integrated model differs from existing models only in the form of the objective function. Noziek et al.. (1998), the authors tried to estimate the inventory costs and include them in the fixed costs related to facilities. Ambrosino and Scutella (2005) recently addressed more complex distribution network design problems, which have so far received limited attention, and which involve facility location, transportation and inventory decisions. They referred to these problems as the integrated distribution network design problems. More precisely, they considered distribution networks made up of four layers (plants, central depots, regional depots and customers/demand points), with the aim of defining the number and the location of the different types of facilities for designing a new distribution network or for improving an existing network. The analysis takes into account facility, warehousing, transportation and inventory costs, where realistic scenarios will be investigated. In conclusion, heuristics for the Vehicle Routing Problem may be divided into two parts: classical heuristics and modern heuristics.

Classical VRP heuristics: 1. the savings method; 2. the sweep algorithm; 3. various two-phase approaches.

Modern VRP heuristics: 1. tabu heuristics search

Because servicing points can be represented as a node or as an arc of a network, vehicle routing problems can be classified as follows:

- Node covering problem. The objective of this type of problem is to serve all the assigned nodes of a network and to meet the stated goal of optimization.
- Arc covering problem. The objective of this type of problem is to travel through all the assigned arcs in a network and to meet the goal of optimization. Sul and Chang (1993) divided arc covering problems into three parts: partitioning problems, augmenting problems and sequencing problems. In fact, arc covering problems can be solved by considering more than one part of a problem at a time.

However, as more parts of a problem are added, the complexity and difficulty of problem solving increases.

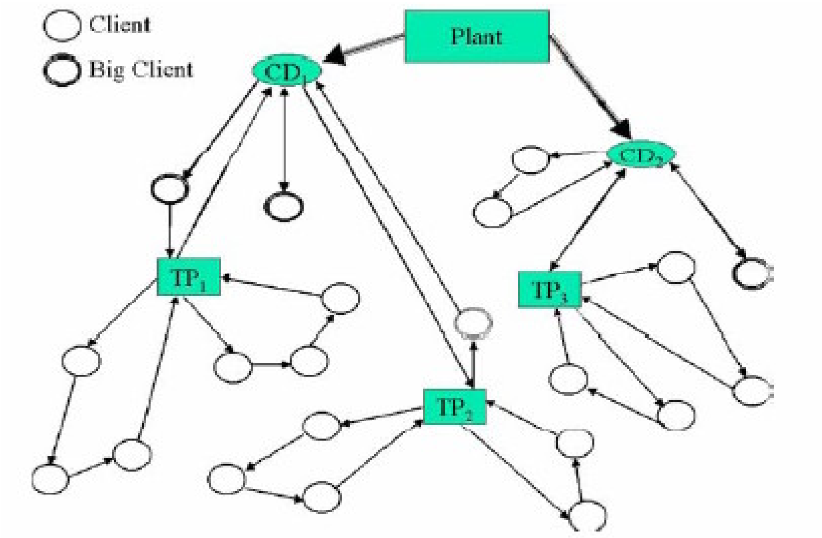


Fig.24 A feasible solution to the static scenario: location routing problem.
Source: D. Ambrosino, M.G.Scutella, 2005.

Bodin et al. (1983) classified vehicle routing problems into seven categories:

1. Single travelling salesman problems.
2. Multi-travel salesmen problems.
3. Single service station with multi-vehicles routing problems.
4. Multi-service stations with multi-vehicles routing problems.
5. Single service station with random demand multi-vehicles routing problems.
6. Chinese postman problems.
7. Chinese postman problem with load constraints.

Besides the aforementioned seven categories, in practice, other variations of vehicle routing problems emerge because of differences in problem characteristics and goals. Chyu and Chen (1996) designed a heuristic algorithm to solve material handling/vehicle routing problems among manufacturing workstations. Lin (1995) considered distribution priority in solving large vehicle problems. Chen and Kuo (1994) developed a two-layer facility location mathematical model to determine locations of distribution centres for delivering food. Viswanathan and Mathur (1997) considered stock warehousing and vehicle routing problems when designing a logistic system. Lee et al. (1998) and Lee and Ueng (1998) applied SPT (shortest path theory) in vehicle routing problems. Furthermore, Lee (1997) used the integer programming model to determine optimal vehicle size and the best distribution allocation for a hog transportation company. All of the above are studies of vehicle routing problems, each of them only takes one objective into account, and none of them has taken employees' welfare into consideration. Chen (1992) applied multi-objective conditions in solving vehicle routing problems. However, the objectives were expressed as vehicle management cost, waiting time cost and delay cost. For industrial problems, scalable methods that are able to produce high quality results in limited time, even for several hundreds of customers, are particularly important. Mester et al. (2007) developed a solution algorithm based on the ideas of (1 + 1)-evolution strategies and a new multi-parametric mutation procedure, based on the ruin and recreate principle. The extensive computational experiments on six real-life problems and 199 standard benchmark problems demonstrate that the suggested algorithm is efficient and competitive with the state-of-art solution methods from the literature.

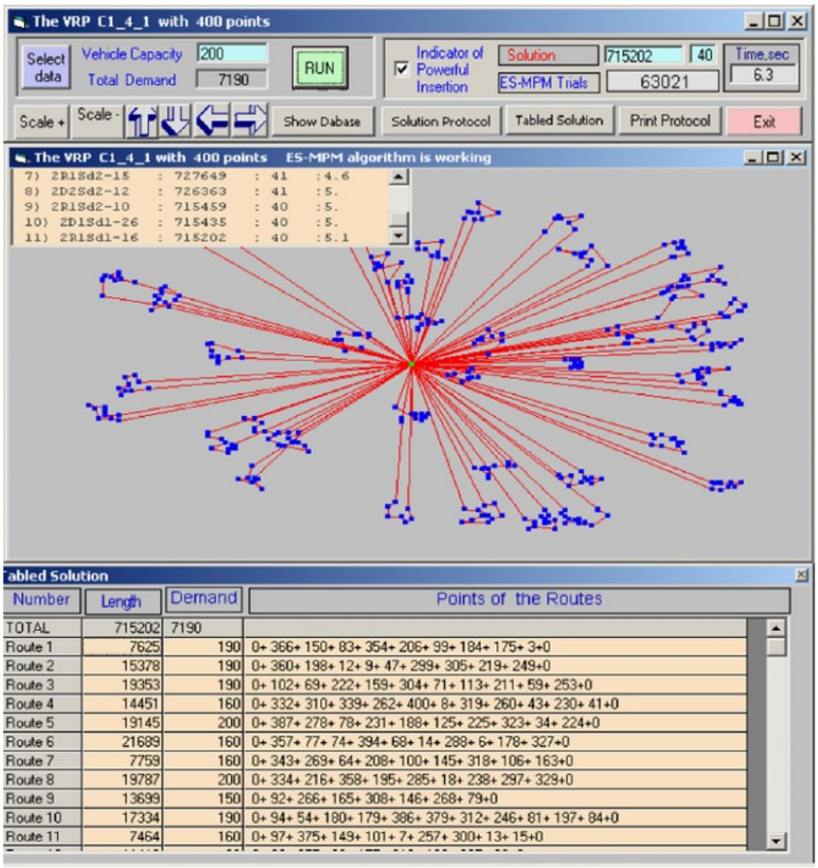


Fig.25 Graphical user-interface of a multi-parametric evolution strategies algorithm for vehicle routing problems. Source: David Mester, Olli Braysy,Wout Dullaert, 2007.

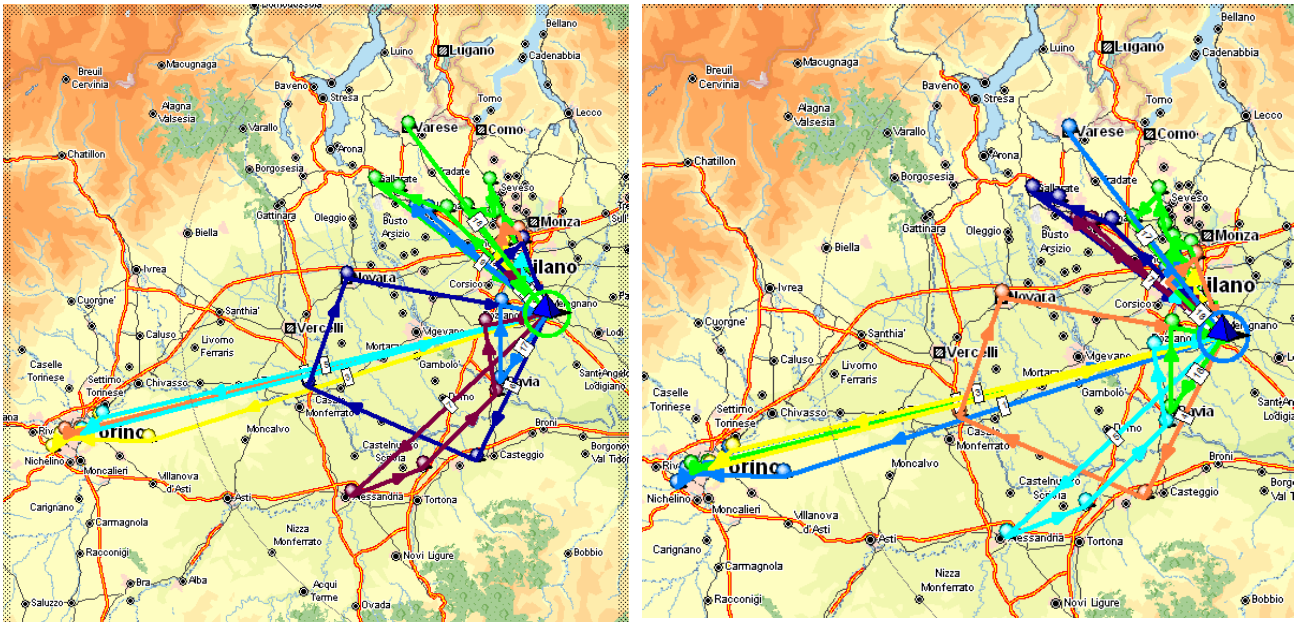


Fig.26 Example of two different daily route plans performed by the use of the software PTV Intertour. Source: Persona et al., 2007.

3.4 Goods delivery optimization: a new procedure

The following model has been developed during this thesis project in order to design an innovative goods delivery system for a supply chain. A three level distribution network is analyzed: first, the manufacturers, second, the intermediate warehouses that can be used or not in order to deliver goods and third, the customers. In comparison to the actual state of the art this approach focuses on the importance of the physical characteristics of the products, the product's demand, and the production rate as key factors to decide the optimum choice in a distribution network. The existing literature on distribution problem offers information about facility location, type of warehouse and transportation channels to use, and inventory decisions, but in reality many companies also need to manage goods distribution, considering the limited capacity of the manufacturers' warehouses and the presence of a batch production. In this way the model copes with a real problem for industrial environment not deeply studied. The linear programming model developed is formulated as follows.

Assumption:

1) Inventory costs at each manufacturer's plant depend only on the quantity of product's families delivered directly from manufacturer to customer, assuming that all other quantities are immediately shipped to the correspondent intermediate warehouses.

2) An intermediate warehouse receives goods from the manufacturer's plant and quickly processes them for reshipment to customers with handling costs (depending on product's families) and inventory costs (depending on product's quantity).

3) Product's families with an indirect delivery policy are immediately delivered from manufacturer's plant to the warehouse with a delocalization of inventory. As a consequence, the Inventory Rotation Index of the product's family in manufacturer's warehouse will be equal to the Inventory Rotation Index of the product's family in the intermediate warehouse.

4) If two different manufacturer's plants produce the same product's family, they will be considered as two different entities. For this reason, in the model, the same product's family manufactured in two different plants will be indexed as two different entries.

Indices:

i: manufacturer (M); i=1,...,I

j: intermediate warehouse (W); j=1,…,J

k: customer (C); k=1,…,K

l: product's family (PF); l=1,…, L

Decision Variables:

$X1_{i,j,l}$: quantity of product's families delivered PF_l from manufacturer M_i to intermediate warehouse W_j

$X2_{j,k,l}$: quantity of product's families delivered PF_l from intermediate warehouse W_j to customer C_k

$X3_{i,k,l}$: quantity of product's families delivered PF_l from manufacturer M_i to customer C_k

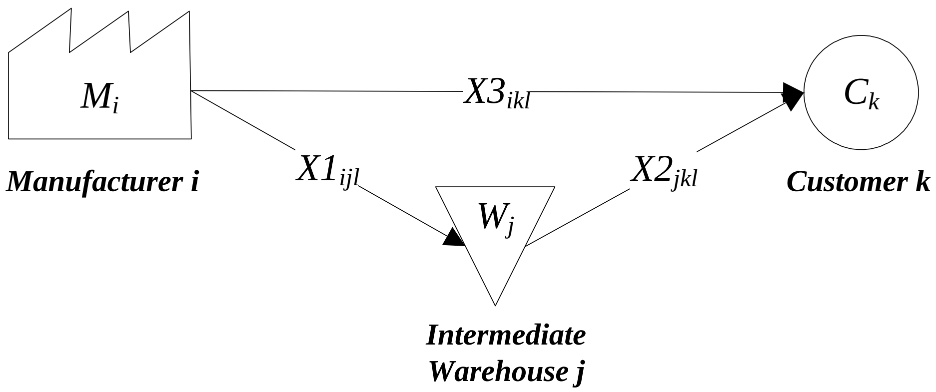


Fig.27 Network model considered.

Input data:

H_l , handling cost per cube meter of product's families PF_l , [€/m^3]

C_l , cost per cube meter of product's families PF_l , [€/m^3]

s_i , inventory cost rate at manufacturer M_i

s_j , inventory cost rate at warehouse W_j

$CT1_{i,j,l}$: transport cost of a cube meter of product's families PF_l from manufacturer M_i to intermediate warehouse W_j , [€/Kmm^3]

$CT2_{j,k,l}$: transport cost of a cube meter of product's families PF_l from intermediate warehouse W_j to customer C_k , [€/Kmm^3]

$CT3_{i,k,l}$: transport cost of a cube meter of product's families PF_l from manufacturer M_i to customer C_k , [€/Kmm^3]

$MC_{i,k,l}$: total demand matrix of product's families PF_l by customer C_k to manufacturer M_i [m^3 /year]

$MD1_{i,j}$: distance matrix from manufacturer M_i to intermediate warehouse W_j ,[Km]

$MD2_{j,k}$: distance matrix from intermediate warehouse W_j to customer C_k , [Km]

$MD3_{i,k}$: distance matrix from manufacturer M_i to customer , [Km]

$q_{i,k,l}$: average order quantity of product's families PF_l by customer C_k to manufacturer M_i [m^3 /order]

$p_{i,k,l}$: number of production cycles of product's families PF_l in manufacturer M_i for customer C_k [number of time/year]. Note: in this model the manufacturer can choose different production lot size for the same product's family to satisfy a specific customer C_k .

$d_{i,k,l}$: number of supplies to customer C_k product's families PF_l by manufacturer M_i [number of time/year], equal to: $d_{i,k,l} = \dfrac{MC_{i,l,k}}{q_{i,l,k}}$

g_l : average inventory level of product's families PF_l .

$$g_l = \frac{1}{2}\sum_{k=1}^{K}\frac{MC_{i,k,l}}{p_{i,k,l}}$$

$r_{i,l}$: inventory rotation index related to product's family PF_l produced by manufacturer M_i (number of rotation/year), equal to:

$$r_{i,l} = \frac{\sum_{k=1}^{K} MC_{i,k,l}}{g_l}$$

$r_{j,l}$: inventory rotation index related to product's families PF_l shipped to intermediate warehouse W_j (number of rotation/year) equal to $r_{i,l}$ for the same product family PF_l, (Assumption 3).

$K_{i:}$: manufacturer's warehouse capacity $M_i\,[m^3]$

Average inventory cost for product's families PF_l at Manufacturer's plant $[€ / year]$

$$\sum_{k=1}^{K}\sum_{i=1}^{I} \frac{X3_{i,k,l}}{r_{i,l}} \cdot C_l \cdot s_i + \sum_{i=1}^{I} SS_{i,l} \cdot C_l \cdot s_i = IC_{i,l}$$

Average inventory cost for product's families PF_l at intermediate warehouses , $[€ / year]$

$$\sum_{j=1}^{J}\sum_{i=1}^{I} \frac{X1_{i,j,l}}{r_{j,l}} \cdot C_l \cdot s_j + \sum_{j=1}^{J} SS_{j,l} \cdot C_l \cdot s_j = IC_{j,l}$$

$SS_{i,l}$: safety stock in manufacturer's M_i warehouse of product's family PF_l calculated with the following formula (Persona et al., 2005).

$$SS_{i,l} = k \cdot \sigma_{\%}^{l} \cdot F_{i,l} \cdot \sqrt{LT_l}$$

$SS_{j,l}$: safety stock in intermediate warehouse W_j for product's family PF_l calculated with the following formula (Persona et al.,2005).

$$SS_{j,l} = k \cdot \sigma_{\%}^{l} \cdot F_{j,l} \cdot \sqrt{LT_l}$$

Where:

k adjusting parameter for customer service level

$\sigma_{\%}^{l}$ standard percentage demand deviation of the product's family PF_l

$F_{i,l}$ forecasted annual demand of the product's family PF_l directly delivered from manufacturer's M_i warehouse. The model assumes that $F_{i,l}$ is equal to $\sum_{k} X3_{i,k,l}$ during a year time.

$F_{j,l}$ forecasted annual demand of the product's family PF_l delivered from manufacturers' warehouses to intermediate warehouse W_j. The model assumes that $F_{j,l}$ is equal to $\sum_k X2_{j,k,l}$ during a year time.

LT_l average production Lead Time of the product's family PF_l.

The linear programming model developed introduces a new decision parameter, the Distribution Index, linked to the delivery policy used for each product's family:

∂_l: Distribution Index, is the percentage of the annual quantity of product's family PF_l produced by manufacturer M_i and then delivered to customers through the intermediate warehouse, with values from 0 to 1. If the distribution index is equal to 0 the total annual amount of goods of a specific product's family will be delivered directly from manufacturer to customers, indeed if it assumes value equal to 1, the deliveries will be completed through the intermediate warehouse. In the model the Distribution Index value is in 0.1 increments from 0 to 1.

Methodology:

Calculate delivery quantities (i.e. measured in cube meters per year) that minimize the Total Distribution Cost function for each product's family PF_l produced by each manufacturer M_i changing the ∂_l distribution index from 0 to 1, with 0.1 increments, according to the following formulas:

Minimize the total distribution cost function:

$$\sum_{j=1}^{J}\sum_{i=1}^{I} X1_{i,j,l}\cdot CT1_{i,j,l}\cdot MD1_{i,j} + \sum_{j=1}^{J}\sum_{k=1}^{K} X2_{j,k,l}\cdot CT2_{j,k,l}\cdot MD2_{j,k} + \sum_{k=1}^{K}\sum_{i=1}^{I} X3_{i,k,l}\cdot CT3_{i,k,l}\cdot MD3_{i,k} +$$
$$+ \sum_{j=1}^{J}\sum_{i=1}^{I} X1_{i,j,l}\cdot H_l + \sum_{k=1}^{K}\sum_{i=1}^{I} \frac{X3_{i,k,l}}{r_{i,l}}\cdot C_l\cdot s_i + \sum_{i=1}^{I} SS_{i,l}\cdot C_l\cdot s_i +$$
$$\sum_{j=1}^{J}\sum_{i=1}^{I}\frac{X1_{i,j,l}}{r_{j,l}}\cdot C_l\cdot s_j + \sum_{j=1}^{J} SS_{j,l}\cdot C_l\cdot s_j$$

Subject to:

$$\sum_{j=1}^{J} X1_{i,j,l} + \sum_{k=1}^{K} X3_{i,k,l} = \sum_{k=1}^{K} MC_{i,k,l}$$

$$\sum_{j=1}^{J} X2_{j,k,l} + \sum_{i=1}^{I} X3_{i,k,l} = \sum_{i=1}^{I} MC_{i,k,l}$$

$$\sum_{i=1}^{I} X1_{i,j,l} = \sum_{k=1}^{K} X2_{j,k,l}$$

$$\sum_{j=1}^{J} X1_{i,j,l} = \partial_{i,l} \cdot MP_{i,l}$$

The costs found for each manufacturer M_i are function of ∂_l and of the product's families PF_l. The 8 addenda present in the Total Distribution Cost Function formula are computed as follows:

$C1_{l,\partial} = \sum_{j=1}^{J} \sum_{i=1}^{I} X1_{i,j,l} \cdot CT1_{i,j,l} \cdot MD1_{i,j}$: global transport costs for product's families PF_l from manufacturer M_i to intermediate warehouse W_j, [€ / year].

$C2_{l,\partial} = \sum_{j=1}^{J} \sum_{k=1}^{K} X2_{j,k,l} \cdot CT2_{j,k,l} \cdot MD2_{j,k}$: global transport costs for product's families PF_l from intermediate warehouse W_j to customer C_k, [€ / year].

$C3_{l,\partial} = \sum_{k=1}^{K} \sum_{i=1}^{I} X3_{i,k,l} \cdot CT3_{i,k,l} \cdot MD3_{i,k}$: global transport costs for product's families PF_l from manufacturer M_i to customer C_k, [€ / year].

$C4_{l,\partial} = \sum_{j=1}^{J} \sum_{i=1}^{I} X1_{i,j,l} \cdot H_l$: global handling costs for product's families PF_l produced by manufacturer M_i [€ / year].

$C5_{l,\partial} = \sum_{k=1}^{K} \sum_{i=1}^{I} \frac{X3_{i,k,l}}{r_{i,l}} \cdot C_l \cdot s_i$: average inventory costs for manufacturer M_i for product's families PF_l , [€ / year].

$C6_{l,\partial} = \sum_{j=1}^{J} \sum_{i=1}^{I} \frac{X1_{i,j,l}}{r_{j,l}} \cdot C_l \cdot s_j$: average inventory costs for intermediate warehouse W_j for product's families PF_l, delivered by manufacturer M_i [€ / year].

$C7_{l,\partial} = \sum_{i=1}^{I} SS_{i,l} \cdot C_l \cdot s_i$,: safety stock of product's family PF_l in manufacturer's warehouse [€ / year].

$C8_{l,\partial} = \sum_{j=1}^{J} SS_{j,l} \cdot C_l \cdot s_j = IC_{j,l}$, : safety stock of product's family PF_l in intermediate warehouse, [€ / year].

$CTOT_{l,\partial}$: total distribution costs given by the sum of $C1_{l,\partial}$, $C2_{l,\partial}$, $C3_{l,\partial}$, $C4_{l,\partial}$, $C5_{l,\partial}$, $C6_{l,\partial}$, $C7_{l,\partial}$ and $C8_{l,\partial}$ [€ / year].

The output of this programming model is the Total Distribution Cost values for each product's family PF_l and for each distribution index ∂_l produced by a manufacturer M_i.

For a given distribution network, with I manufacturer, J intermediate warehouses, L product's families, K final customers, a heuristic procedure has following been developed, which consists of 4 steps and an input-output process as illustrated in Figure 28.

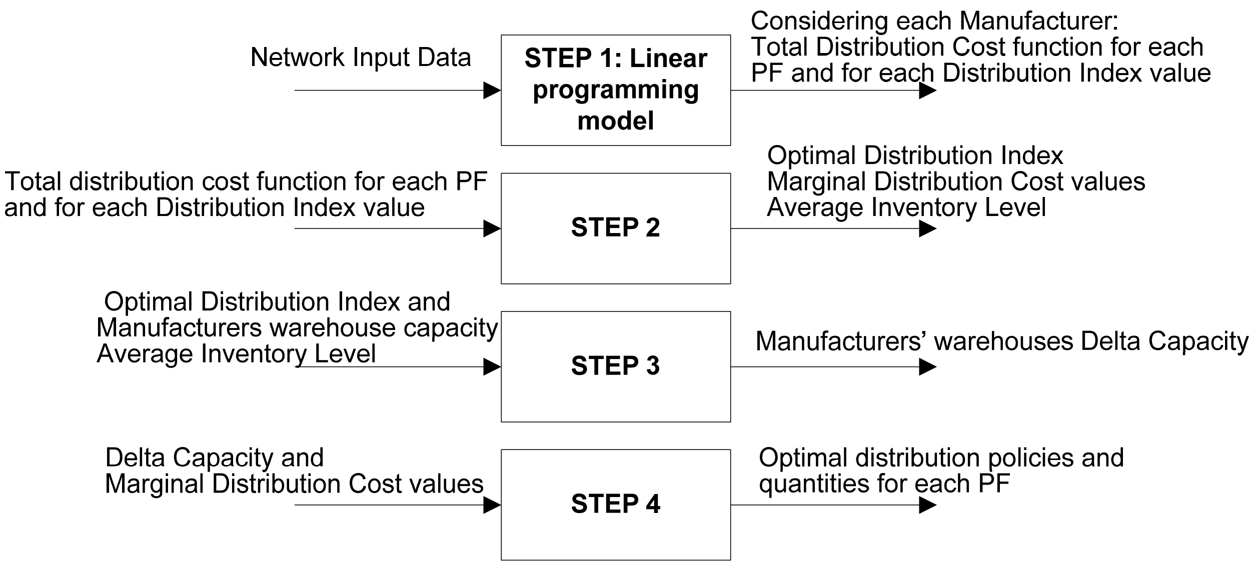


Fig.28 Steps of the iterative procedure developed.

For the complete comprehension of the heuristic procedure we cross refer to the Battini et al., 2007, which is enclosed at the end of this thesis.

At the beginning the procedure calculates the delivery quantities directly or indirectly delivered to customers, for each product's family and from each manufacturer, that minimize the value of Total Distribution Cost for every of ∂_l, the Distribution Index (Step 1). Then the optimal value of ∂_l index, the Marginal Distribution Cost value and the Average Inventory

Level are calculated for each combination manufacturer-products' family (Step 2). The Marginal Distribution Cost quantifies the incremental cost due to change in distribution policy, the Average Inventory Level quantifies the manufacturer's storage capacity needed for each product's family. After that, a feasibility analysis is done for each manufacturer to establish storage capacity considering all the product's families produced and their single optimal distribution policy previously defined.

If the result of this analysis (Step 3) is positive it means that the independent optimization of the distribution policy for each product's family produced by that manufacturer complies with the constrain of the storage capacity of the manufacturer plant. If not, the procedure will continue (Step 4) to find the best sub-optimization distribution policy increasing the indirect delivery quantity for the product's family with the minimum Marginal Distribution Cost.

The procedure will be repeated in iterative way until the manufacturer's warehouse capacity constrain is respected.

The model's output is a feasible solution of both direct delivery and delivery using intermediate warehouses that minimize global distribution costs according to the storage restrictions of the manufacturer's warehouses.

The heuristic creates a sub-optimization for the product's families with minor impact on the distribution cost.

“Measure what is measurable, and make measurable what is not so"
Galileo Galilei

4

Network Analysis and Entropic Indexes

As mentioned in the introduction, the theories illustrated in this part develops a new quantitative measurement of complexity for supply network based on Network Analysis, which is often used to study natural ecosystems, focussing 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 contexts. This new interdisciplinary approach exploits eight different entropic indexes to map the exchanges of goods between different actors in a complex supply chain and measure complexity and organization level.

4.1 Introduction

A generic supply chain usually provides very complex inter-correlations between its various actors, that is, the suppliers, manufacturers, distributors, customers, etc., and this is 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. Moreover, the best approach is to obtain optimal performance throughout the entire system network: this is the fundamental challenge for Supply Chain Management (SCM).

This idea even is stressed even more forcefully 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.

Mills et al. (2004) present an interesting survey of the literature on SCM. They emphasise that several aspects of SCM have yet to be investigated fully (i.e. material and data queuing problems, data integration, and especially SCM complexity).

This chapter deals with the question of Supply Chain Complexity arising out of these previous studies, and proposes a new methodology for complexity evaluation based on an entropic model structured by using eight performance parameters.

Monitoring supply chain complexity is very important for two reasons. Firstly, the information obtained results in good knowledge of the global system, and so a clear definition of the causes and effects of problems. Secondly, it supports the research into the best solutions for a network very effectively by comparing the various possible alternatives to provide objective and quantitative analysis.

A new methodology inspired by the analysis of natural ecosystems is presented, the main idea is based on the great morphological analogy between ecosystem networks and industrial supply networks.

Network analysis is a technique that allows one to quantify the structure and function of ecosystems by evaluating biomasses and energy flow in a food web. Efficiency with which energy and material is transferred, assimilated, and dissipated conveys significant information about the structure and function of food webs (Ulanowicz and Platt, 1985; Baird and Ulanowicz 1989 and 1993; Baird et al., 1991; Ulanowicz and Wulff, 1991). Network analysis evaluates these components within a food web context using input/output analysis, trophic and cycle analysis, and information theory to calculate ecosystem properties (see NOAA-National Oceanic and Atmospheric Administration- web site for details). Thus, changes in fish communities can be linked directly to changes occurring within an ecosystem. Network analysis has been used to compare ecosystems of different size, geographical location, hydrological characteristics, and trophic status.

Most recently, arguments have been made for the use of network analysis for quantifying the health and integrity of ecosystems (Ulanowicz, 2000) and evaluating the magnitude of stress imposed on an ecosystem.

The following two figures make a comparison between ecosystem network structure and supply network structure: the analogy existing between them permit 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 optimising manufacturing systems with interesting results.

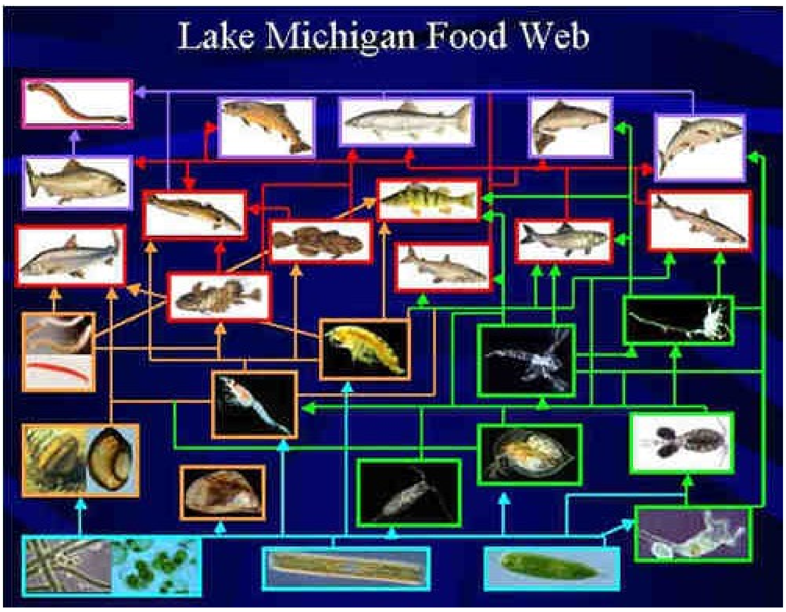


Fig.29 Ecosystem network example. Source: www.glerl.noaa.gov.

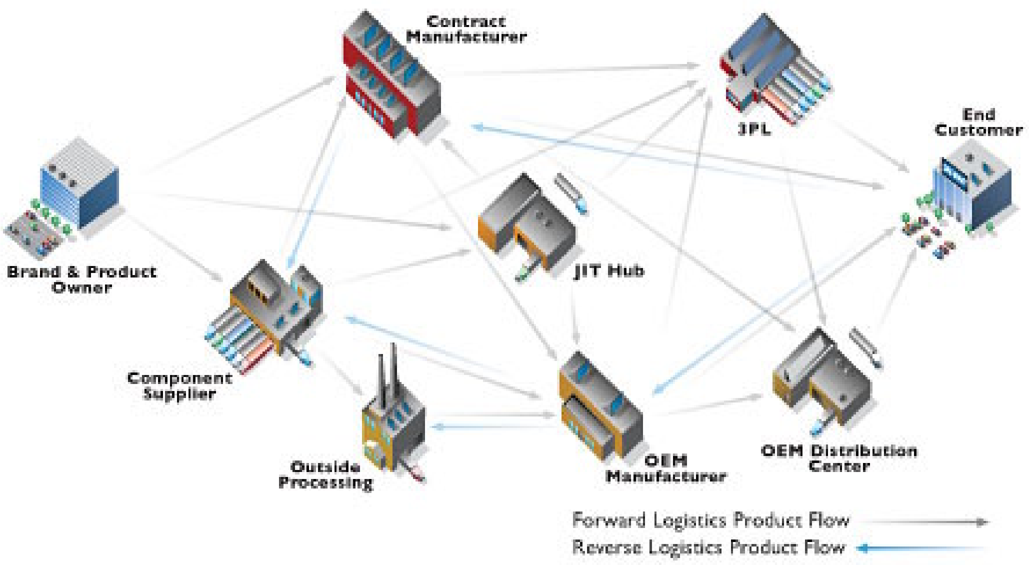


Fig.30 Supply Network example. Source: www.clearorbit.com.

The fundamental development is a new set of quantitative entropic parameters that can be used to analyse supply chains.

These are introduced, discussed theoretically, and then applied to real world applications.

In conclusion, this part of the thesis introduces a new method of analysing and measuring a supply network based on eight entropic indexes, in addition to investigating theoretical aspects and practical effects of its application.

4.2 Review of the literature on network complexity computation

In recent years several authors have proposed different approaches to Supply Chain Management techniques and to Supply Network Complexity Computation.

The matrix shown in Table 7 summarises the most useful studies according to aim: analysis of Supply Chain management and complexity of production systems in which both internal (i.e. manufacturing) and external (i.e. distribution) aspects are considered.

The literature divides complexity into three types – firstly, static complexity i.e. linked to system structure, secondly dynamic complexity i.e. related to the material and data flows between different actors, and thirdly decisional complexity created by the managerial choices required.

It is typically possible to find studies devoted to definition of performance indexes and methodologies to support scheduling as well as tactical and strategic choices.

There are four types of methodology:

- Introductions and/or general studies. The whole problem of Supply Chain Performance Management and Control is presented, and the complex features of 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, Sheoran and Wang, 2004; Tan et al., 2004).
- Statistical approaches. Analysis of the correlation between qualitative measurements of complexity and general supply chain performance indexes (i.e. Perona and Miragliotta, 2004; Milgate, 2001).
- Entropic models used to quantify complexity of supply chains and manufacturing systems (i.e. Frizelle 1995, Calinescu 1998, and Sividasan 2002).
- Surveys: Mills J., Schmitz J., and Frizelle (2004) propose and discuss several methods that provide support to companies in a complex supply chain, populated by a great many actors. However, the same authors do not discuss the problem of complexity in the

supply chain but emphasise the need for studies into this important topic, justifying and validating the aims and objectives of the present research.

The study of supply chain complexity is fundamentally based on the definition of performance indexes. As defined by the important study of Shannon (1948), entropy of information (hereafter referred to only as entropy) and derivative indexes can provide effective efficient support.

The first application of Shannon theory to the analysis of production systems was developed by Karp and Ronen (1992), who focused on the individual production system. A great many authors have examined the relationship between performance/flexibility and complexity (Calinescu et al., 1998; Milgate 2001; Perona et al., 2002; Arteta et al., 2004).

However, the results are 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) even assert 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.

Several authors (Huan et al., 2004; Bulliger et al., 2002) trust to the SCOR model (Supply Chain Operation Reference model) developed by the Supply Chain Council (SCC) (http://www.supply-chain.org/cs/root/home).

In conclusion, the recent literature shows that companies are taking a growing interest in the global network, from raw materials through to final products.

It is now time to consider company performance by correlating it strictly to its global supply chain performance by considering suppliers, the production system, and the distribution network.

From this global point of view, system management is confronted by great complexity, and so optimal measurement and management of complexity is a strategic advantage. Consequently, in depth study of the literature on this argument is beneficial.

		Targets										
		Complexity analysis internal Supply Chain			Complexity analysis external Supply Chain			Supply Chain Management				
Year	Authors	static complexity	dynamic complexity	decisional complexity	static complexity	dynamic complexity	decisional complexity	performance indexes	operative planning	tactical planning	strategical planning	Methodologies
1992	Karp et al.		×									entropic model development
1995	Frizelle et al.	#	#									entropic model development
1998	Deshmukh et al.	V										entropic model development
1998	Calinescu et al.	#	#									entropic model development
2001	Seese et al.				V							graph theory
2001	Shih et al.	×										entropic model development
2001	Milgate				×	×		×				entropic model development
2001	Beamon et al.							×				sattistical model and simulation
2002	Sivadasan et al.		×			×			×			entropic model development
2002	Meijer	V		V								teorical model
2002	Wu et al.				#	#						simulation and entropic parameters
2002	Efstathiou et al.	V	V	V								software development and entropic parameters
2002	Makui et al.	V										entropic model development
2002	Bulliger et al.						V	V			V	decision making model
2003	Sivadasan et al.								V			teorical model
2003	Albino et al.				#	#			#	#		linear progamming model
2004	Huan et al.						V	V			V	decision making model
2004	Arteta et al.				#			#				Petri net model
2004	Mills et al.				–	–						survey
2004	Perona et al.	#	#		#	#						complexity index development
2004	Tan et al.			#								software development and entropic parameters
2004	Blackhurst et al.				#	#			#	#		statistical model and Petri net model
2004	Blecker et al.				V	V					V	teorical model
2006	Manzoni et al.							×				perfomance index model
2006	Helo et al.				×			×	×	×		software development
2006	Laumanns et al.				×	×			×			numerical model
2006	Battini et al.				#	#		#	#	#	#	entropic model development

LEGEND

V teorical approach

– survey

× numerical application

case study

Table 7. Literature review matrix.

4.2.1 Methodologies for Supply Chain complexity study and management

Sivadasan et al. (2002) define complexity as the amount of information required to manage a system. The main idea is that the data set for complex system design and management must be particularly rich.

In addition to numerousness, other characteristics of information generate complexity. For example, its consistency, and its ability to be updated when the system is changed. Bulliger et al. (2002) and Seese et al. (2001) have effectively demonstrated these concepts.

Perona et al. (2004) define the skill of managing supply chain complexity as strategically fundamental to modern organisations.

Complexity is always transferred between actors in a Supply chain (Sivadasan et al., 2002). The empirical evidence shows that companies usually manage complexity in four ways (Sivadasan et al., 2003):

- by exporting operational complexity to other actors in their own supply chain;
- by charging for the service 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 confronting 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 (Arteta et al., 2004).

Bullinger et al. (2002) assert that only something that can or has been measured improves and only a holistic view prevents the taking of sub-optimal decisions.

The literature contains several methodologies to measure and reduce complexity. There are either models based on graph theory (Seese et al., 2001), statistical models (Milgate, 2001; Beamon et al., 2001; Blackhurst et al., 2004), or models that exploit entropic measurements (information entropy).

Entropy (of information) was introduced by Shannon (1948) and measures the level of uncertainty (or the information level) found in an aleatory signal.

Since complexity produces uncertainty in flows (materials and information), increases lead times, and results in aleatory 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 et al., 1995).

4.2.2 Entropic models

As defined above, complexity is expressed in three ways: static (linked to system structure), dynamic (linked to the operation of systems), and decisional.

Karp and Ronen (1992) propose entropic indexes to demonstrate that decreasing batch dimensions and 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) define a measurement of the first type of complexity (static), while Deshmukh et al. (1998) enlarge this approach by considering the relationship between resources. This concept is further developed by Shih et al. (2001), who propose an algorithm to analyse the effects of different manufacturing network configurations.

Frizelle and Woodcock (1995) also introduced a definition for the second type of complexity (dynamic). This complexity deals with the uncertainty found in material and data flows, which mainly evidences itself in supply chains in queue formation in input from and/or output to different participants (Sivadasan et al., 2002).

Calinescu et al. (1998) put forward two complementary methodologies to estimate the complexity of a production system: the entropic procedure introduced by Frizelle, and a similar method named MFC proposed by Foley and Mayer Curley (1995).

To reach the same goal Efstathiou et al. (2002) propose a web-based expert system that mainly focuses on the third kind of complexity (organisational), and is based on measurement of the entropy generated by information transfers. They define “decision making entropy” as the level of entropy (organisational entropy) required for decisions to be taken correctly.

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.

Arteta and Giachetti (2004) develop a new measurement of complexity at the business process level of an organisation by creating a Petri net model of the system in order to obtain a probabilistic analysis of the system. They argue 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) try 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 robustness, while Wu et al. (2001) used simulation to carry out a similar validation.

The extensive effort found in the literature indicates the importance of measuring complexity in Supply Chain Networks, and in studying their complexity, entropic measurements have been applied successfully to production process analysis. Moreover, Supply Chain complexity and organisation have never been extensively measured, so this paper introduces a new set of entropic indices, different but correlated in nature, which have never been tested.

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

4.3 New proposed method

As stressed by Calinescu et al. (1998), opinions on what complexity is, why it should be measured, and how this can be done vary widely. The literature proposing entropic methods to analyse complexity have focused their attention on the information entropy of Shannon, aiming to measure the uncertainty characteristics associated with the material and information flows of a manufacturing network (i.e. Frizelle and Woodcock ,1995; Karp and Ronen ,1992). Sivadasan et al. (2002) extended this concept to a single-vendor and single-buyer system for the first time. What we propose is a quantitative method to consider an entire supply network in which many different partners, positioned in different levels of the chain, are involved. The procedure proposed below is derived from ecological theory, and quantifies not a single, but a set of parameters so that an idea of the organisation of the web is obtained.

Food Webs and Ecological Networks use graph-theory to describe ecosystems by examining nodes-species and edges-trophic relationships. Ecological Network Analysis (ENA) is composed of a set of tools for examining ecosystems. Researchers use ENA procedures to test the degree of organisation in the ecosystem, analyse the pathways occurring in the system, evaluate the number of trophic levels, estimate indirect effects, and much more besides. Ecologists have worked to identify which Ecosystem-level indexes quantify global attributes of a natural ecosystem (Ulanowicz and Kay, 1991). The analysis of ecosystem network trophic transfers (Ulanowicz, 2003) and ecological network indicators (Ulanowicz, 2004) are also useful tools with which to study the performance of industrial supply chain networks. They help understand and quantify the complexity of process interactions, measure the organisation level and identify dynamic bottlenecks in the system. Ecosystems are collections of plant and animal species organised in complicated web-like structures by which energy and matter are transferred and transformed. Similarly, the supply chain of a company is composed of different departments ranging from material procurement to customer services. A number of socio-economic activities take place along the supply chain that transfer and transform energy, information, and goods or services. These processes create functional connections that link the activities to one another in a web-like structure. In both supply chains and ecological systems this web-like structure is described by a network.

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 furthermore, it is important to understand the trade-off between network complexity and network organisation of the structure. In fact, maximum efficiency (minimum complexity) for the network often means maximum vulnerability and less flexibility in the management of sudden changes. On the other hand, high redundancy and complexity of node and edge links increases total costs and reduces system performance.

The method is applied in two main steps:

1.Network mapping and quantification of flows

2.Network analysis and computation of indexes.

Ecological network analysis provides a set of tools that can be used to picture the structure of the supply network under investigation.

These tools are divided into:

1. Input/Output analysis;
2. Trophic level analysis;
3. Analysis of cycles;
4. Performance indexes computation.

The forth of these tools forms the focus of this paper, which presents how to compute performance network indexes and how they can help to understand and analyse a supply network.

4.3.1 Phase 1: Network mapping and quantification of flows

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, the simple industrial example in Figure 31 is used involving a small supply network composed of 7 compartments: 3 suppliers, 1 manufacturer, and 3 customers .

First of all, a unit of measurement needs to be selected, for example goods exchanged in tons/year. Then the inputs from outside the system into each compartment in the given period need to be measured.

This will form the Import vector, called “I”. The flows exiting the system can be divided into reusable material, Exports, called “E”, and Dissipations, called “D”.

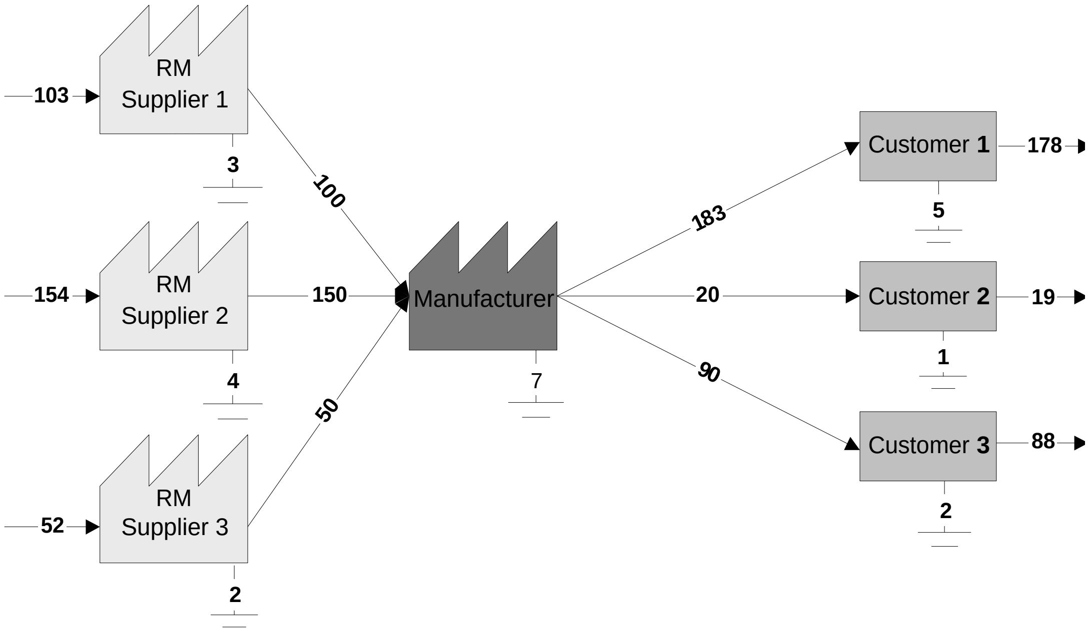


Fig.31 Example of a typical industrial supply chain.

$$I = \begin{bmatrix} 103 \\ 154 \\ 52 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad E = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 178 \\ 19 \\ 88 \end{bmatrix} \qquad D = \begin{bmatrix} 3 \\ 4 \\ 2 \\ 7 \\ 5 \\ 1 \\ 2 \end{bmatrix}$$

Then, taking goods supplied between partners into account, a matrix representing transfers that occur inside the system, called the Transfers Matrix T, can be set up.

Consequently, an Extended Transfers Matrix T* can be associated with the oriented graph. This matrix reports all information about exchanges occurring in the network (Figure 32).

The Extended Transfer Matrix T* of the network in Figure 31, which includes all the flows occurring inside the system and all the exchanges with the external environment, is shown in Figure 33.

<table>
<tr><th></th><th>0</th><th>1</th><th>2</th><th>…</th><th>N</th><th>N+1</th><th>N+2</th></tr>
<tr><td>0</td><td>0</td><td colspan="4">Input [I]</td><td>0</td><td>0</td></tr>
<tr><td>1</td><td>0</td><td colspan="4" rowspan="4">Transfers between compartments [T]</td><td rowspan="4">Export [E]</td><td rowspan="4">Dissipation [D]</td></tr>
<tr><td>2</td><td>0</td></tr>
<tr><td>…</td><td>0</td></tr>
<tr><td>N</td><td>0</td></tr>
<tr><td>N+1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>N+2</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
</table>

Fig.32 Extended transfer matrix T*.

	Imp	S1	S2	S3	M	C1	C2	C3	Exp	Diss
Imp		103	154	52						
S1					100					3
S2					150					4
S3					50					2
M						183	20	90		7
C1									178	5
C2									19	1
C3									88	2
Exp										
Diss										

Fig.33 Extended transfer matrix T* of network in Figure 31.

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:

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

where the 'dot' stands for summation 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 indices (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.

4.3.2 Phase 2: Network analysis and calculation of entropic indexes

Ulanowicz assembled the primary methods used in Network Analysis into a single software package, NETWRK (Ulanowicz and Kay, 1991), and it is this software that was used in the present study. Among the various types of analysis performed by the software, this paper focuses on the calculation of entropic indexes that characterise the entire system: Total System Throughput (TST), Average Mutual Information (AMI), Ascendancy (ASC), Development Capacity (DC), and Overhead and its four components, the first of which is Redundancy (RED). Having identified the indexes requiring calculation, the problem becomes one of how to compute them, and how to use them in understanding and analysing a supply network.

Total System Throughput – TST

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, ti. is the sum of the ith row, and t.j the sum of the jth column.

Consequently, the TST for the network in Figure 31 can be computed as the sum of all flows:

TST = 1211 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, this quantity does not provide information about the distribution of the flows inside the system.

Average Mutual Information - AMI

The Extended Transfer Matrix T* includes all flows inside the system and all exchanges with the external environment.

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:

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

Shannon (1948) introduced a measurement of the entropy associated with a process, and his published theory (1948) explains the computation of the analytical entropy measurement. 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 depicted 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 box 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, in this paper 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 a given time, a product that is 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 $H_{O,I}$:

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

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:

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

These quantities will be positive or null, and will possess all the properties of entropies. In the example 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 34): $H_{I,O}$= 3.463 bits.

	Imp	S1	S2	S3	M	C1	C2	C3	Exp	Diss
Imp	0	0,302	0,378	0,195	0	0	0	0	0	0
S1	0	0	0	0	0,297	0	0	0	0	0,021
S2	0	0	0	0	0,373	0	0	0	0	0,027
S3	0	0	0	0	0,190	0	0	0	0	0,015
M	0	0	0	0	0	0,412	0,098	0,279	0	0,043
C1	0	0	0	0	0	0	0	0	0,407	0,033
C2	0	0	0	0	0	0	0	0	0,094	0,009
C3	0	0	0	0	0	0	0	0	0,275	0,015
Exp	0	0	0	0	0	0	0	0	0	0
Diss	0	0	0	0	0	0	0	0	0	0

Fig.34 Matrix of joint entropy contributions.

In the same way, the contribution of each compartment to the entropy associated with inputs H_I can be found by computing the column sum t.j for each compartment: the contribution of compartment j will be $-\frac{t_{\cdot j}}{t_{\cdot\cdot}}\log\left(\frac{t_{\cdot j}}{t_{\cdot\cdot}}\right)$ and the entropy associated with output H_O will be: $-\frac{t_{i\cdot}}{t_{\cdot\cdot}}\log\left(\frac{t_{i\cdot}}{t_{\cdot\cdot}}\right)$.

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:

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

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

The following important 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 31 is:

$$AMI = H_O + H_I - H_{I,O} = 2.666 + 2.766 - 3.463 = 1.969$$

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.

The AMI index measures this degree of specialisation or the amount of constraints on the medium.

The two entropies are represented as areas (Figure 35): 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. AMI is a 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.

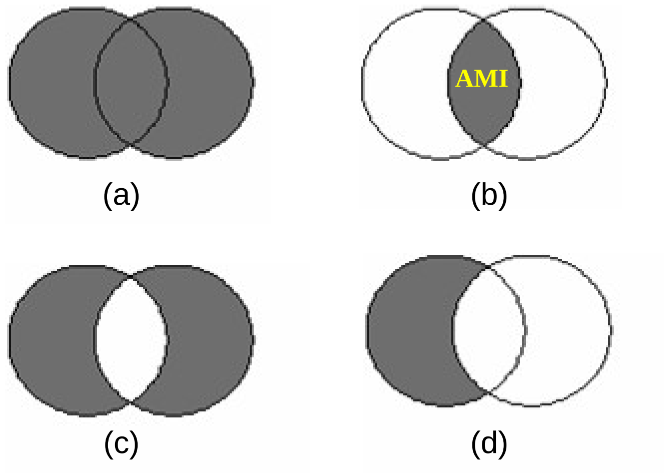


Fig.35 Venn diagrams expressing the relations between entropies and information: HI and HO are sketched as circles that intersect. (a) The joint entropy expressed as the union of the two circles; (b) Average Mutual Information expressed as the intersection between the two circles; (c) the sum of the conditional entropies expressed as the union minus the intersection of the two entropies; (d) the conditional entropy HI/O expressed as the union minus the output entropy.

Ascendancy, Capacity, and Overhead

Because AMI is a-dimensional, Ulanowicz (1991) proposed to scale it for the sum of all TST flows. This would combine the size of the system (TST) with its degree of organisation/development (AMI). This combined measurement is called Ascendancy. Ascendancy is defined as the product of the AMI and the 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 summation 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 detail 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 a few efficient routes and consequently the cost of managing the whole system decreases. From this 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. In 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 dominates the first two stages and declines 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 at the disposal of a system and as this is what can be used to achieve further development, 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 4 different contributions: Overhead on Imports, Exports, Dissipations, and Redundancy. 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. High values of Redundancy reflect a high proportion of parallel 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. They were computed for the example system shown in Figure 31. 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.

Indexes	Value	Percentage
$TST = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} = t_{..}$	1211.0	
$C = TST \times H_{I,O} = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} \log\left(\frac{t_{ij}}{t_{..}}\right)$	4194.0	100.00%
$A = TST \times AMI = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} \log\left(\frac{t_{ij} t_{..}}{t_{i.} t_{.j}}\right)$	2384.2	56.85%
$\Phi_I = -\sum_{j=1}^{N} t_{0,j} \log\left(\frac{t_{0,j}^2}{\sum_{i=1}^{N} t_{ij} \sum_{j=1}^{N} t_{0,j}}\right)$	451.7	10.77%
$\Phi_E = -\sum_{j=1}^{N} t_{i,N+1} \log\left(\frac{t_{i,N+1}^2}{\sum_{j=1}^{N} t_{ij} \sum_{i=1}^{N} t_{i,N+1}}\right)$	355.7	8.48%
$\Phi_D = -\sum_{j=1}^{N} t_{i,N+2} \log\left(\frac{t_{i,N+2}^2}{\sum_{j=1}^{N} t_{ij} \sum_{i=1}^{N} t_{i,N+2}}\right)$	187.0	4.46%
$R = -\sum_{i=1}^{N}\sum_{j=1}^{N} t_{ij} \log\left(\frac{t_{ij}^2}{\sum_{j=1}^{N} t_{ij} \sum_{i=1}^{N} t_{ij}}\right)$	815.5	19.44%

Table 8. Entropic Indexes (Ascendancy, Capacity, and Overhead) for the supply chain analysed.

Table 8 reports all principal system entropic indices introduced in this paragraph and numerical value for the example network in Figure 31.

As Bullinger et al. (2002) say 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.

4.4 Methodology application

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 as a measure of uncertainty (Frizelle et al., 1995) is generic and stable. However, simulation is often difficult and time consuming when applied to very articulated supply chain and so this study aims to demonstrate that even a set of entropic parameters like the one proposed is easy to compute and can support evaluation of the potential for structural changes.

This study investigates the supply network of an Italian company selected to test the research methodology. The company produces industrial catering equipment in sheet stainless steel for both the professional market and domestic use. It comprises three manufacturing units, with widespread Italian sales coverage and an international distribution network.

Initially 9 classes of nodes/partners by which we can map the supply network of the company need to be identified:

1.Raw Material supplier (“RM supplier”)

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

3.Sub-contractor

4.Production Plant

5.Distributor

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/year of steel, which is the raw material of all equipment produced by the company. An industrial network with a large number of nodes and edges produces uncertainty in the medium that flows through the network, as demonstrated for information by Shannon (1948). The uncertainty is linked with the nature of the network structure (graph). In the industrial example reported, the supply chain is depicted in its real configuration (as is) and in its future (foreseen, after improvement) configuration (to be). For this reason historical data have been collected to depict the supply chain "as is" and they are certain and deterministic (tons of goods per last year) and predictions of future data have been made to depict the supply chain "to be". The uncertainty is due to the complexity of the graph structure.

Figure 36 represents the whole complex network of the industrial group and depicts 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 of the production plant by purchasing new pre-cut sheet steel in different sizes. This choice will reduce Dissipation values inside the production plant b) by approximately 50%, reducing 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 recycling of goods via the Sub-contractor (second level components supplier). Consequently, the 4th component of the Overhead, the Redundancy, which reflects parallelisms in trophic pathways, is reduced and network organisation will consequently increase. Total System Throughput (TST) will decrease, cutting redundant connections in the web.
3) To reduce the number of Raw Materials suppliers from 5 to 3, which means simplifying the in-bound net. The presence of positive feedback partnership with Raw Material Suppliers forces the supply network to develop towards less redundant and more efficient configurations. The new network will have two nodes less and the Overhead in Input (Φ_I) will consequently decrease.

4) To provide direct shipments of finished products from Production Plant c) and its direct customers. By performing direct shipments the Redundancy of flows and TST will be reduced, but at the same time the Overhead in Export (Φ_E) will increase.
5) To manage and provide direct shipments from Production Plant b) and all foreign directional customers. This will decrease the Redundancy in out-bound and TST value.

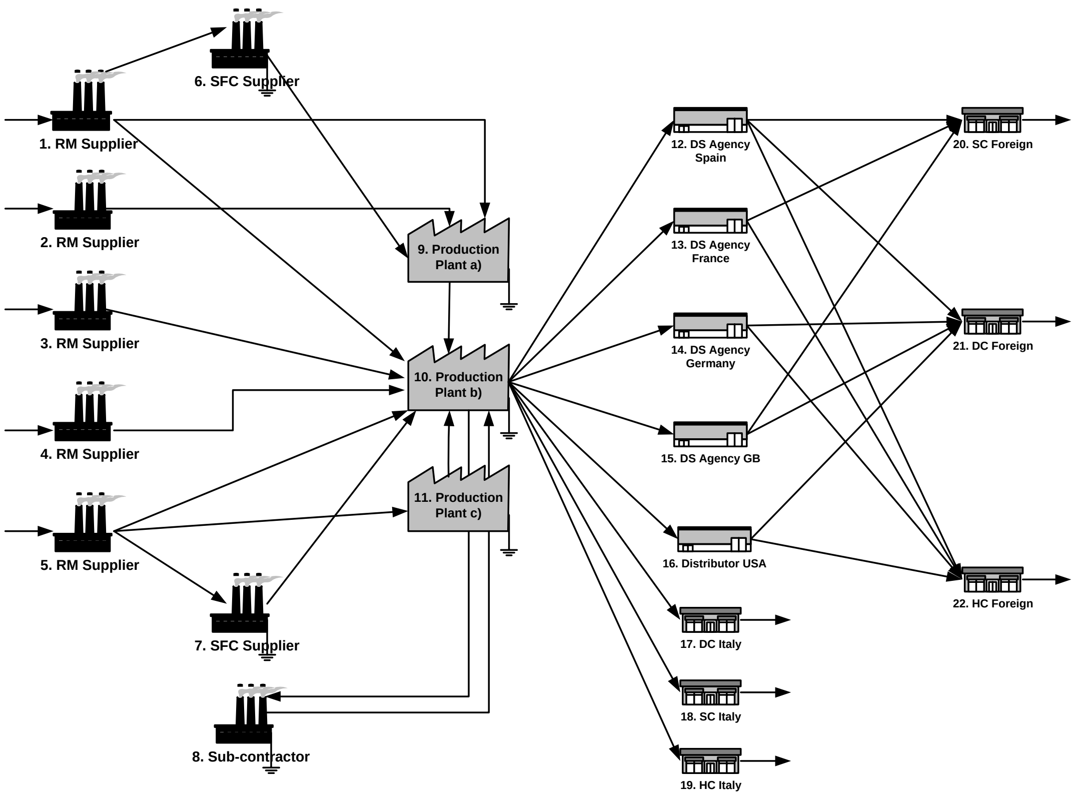


Fig.36 Goods exchanges in the industrial group analysed: the present “as is” configuration.

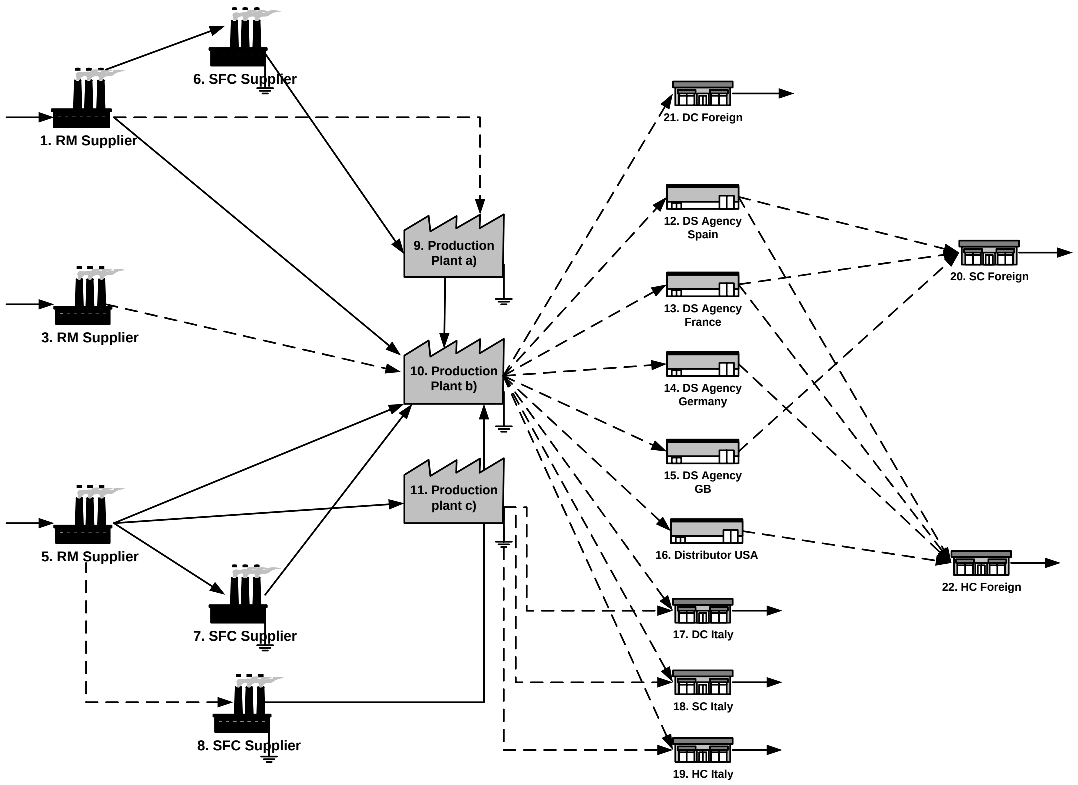


Fig.37 Goods exchanges in the industrial group analysed: the future “to be” configuration.

To increase network efficiency, possible management choices to improve the company were represented: the future configuration (“to be”) of the resulting network is shown in Figure 37. The dashed lines in Figure 37 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 as discussed above, reports all information about the network exchanges, and the computations explained above have been applied to quantify 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. From this point of view, Bullinger et al. (2002) stress the idea that to benefit from supply chain management an essential precondition is a structured analysis of the network-specific optimisation opportunities. Furthermore, Shih and Efstathiou (2001) applied information entropy to indicate the effect of modification in the manufacturing network. Consequently, 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 arising out of different choices and strategies.

Figure 38 reports the two matrixes [T*] in which flows have been quantified in steel tons/year for both present and future configuration.

Table 9 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.

As shown in Table 10 the TST of 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 maximum potential that a system has at its disposal to achieve further development, decreases by 12.8% as a result of the reduction in TST and Joint Entropy. As shown in previous paragraph, higher values of AMI are obtained for flow structures in which movement of goods and energy within the system are maximally constrained.

These systems are also highly organised. Only a small increase in AMI index is obtained in this industrial case, so 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 this organisation degree 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 (Figure 39).

The calculations in Table 10 show an increase in Ascendancy of 5.9% in the new network while Overhead in Input (Φ_I) decreased by 21.7%, Overhead in Dissipation (Φ_D) by 8.9%, and Redundancy (R) by 6%. These were achieved by reducing dissipations, pruning away redundant connections, limiting partner duplication in the supply web, depending on management strategies of the company. Otherwise, the reduction in dissipation would provide an increase in the productivity of finished products and consequently the Overhead in Export (Φ_E) would increase by 19.9%. An increase in Overhead in Export is often a direct result of both improved system productivity and of a higher degree of complexity, which arises from new direct shipments between company and the customers. On the one hand, this will provide an increase in sales, as desired by the company, while on the other hand, it will result in an increase in management shipments and sales costs for the company.

Figure 39 shows that the capacity of the present "as is" network configuration is divided into 46.9% in flows organisation (Ascendancy A) and 53% in redundant unorganised flows (Overhead Φ).

The capacity in the future configuration is then divided into 49.7% Ascendancy and 50.2% Overhead.

i)

	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.																									

ii)

	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.																							

Fig.38- Extended Transfer Matrix T* of network in Figure 36 (“as is” – i)) and network in Figure 37 (“to be” – ii)).

To conclude, the management choices of the company will increase the Ascendancy of the network from 46.9% to 49.7%, but there is still the question of what is the best trade-off between organisation and disorganisation of a web. In other words, what is the best trade off between simplification and complexity in a supply network? 50.2% of the complexity is retained in this network, fundamentally due to logistic and economic constraints and the rigour of the environment. In fact, “dissipation may never equal zero, and pruning away 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, 2006).

	TST	C	AMI	A	Φ_I	Φ_E	Φ_D	R
Network								
"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 9. Results of network analysis: values of system indexes for the two networks in Figure 36 and Figure 37.

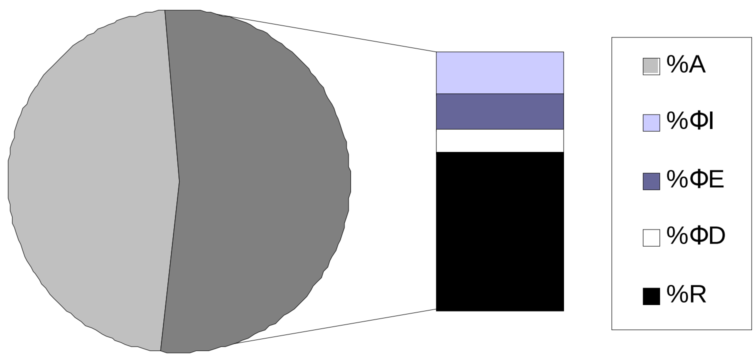
	%A	%Φ	%ΦI	%ΦE	%ΦD	%R
Network						
"AS IS"	46,94%	53,06%	8,83%	7,50%	4,78%	31,96%
"TO BE"	49,71%	50,29%	6,91%	9,00%	4,35%	30,03%
Difference %	5,92%	-5,23%	-21,75%	19,96%	-8,90%	-6,04%

Table 10. Percentage values of Ascendancy and Overhead in the two supply network configurations.

The aim of this research is to test a new application of the methodology developed and successfully used in other branches of science, such as ecology and information systems. The case study reported in this section demonstrates that a real application is feasible, even if the authors are well aware of the preliminary nature of the results.

Moreover, the research could very well spin off into useful applications.

a) "As is" configuration



b) "To Be" configuration

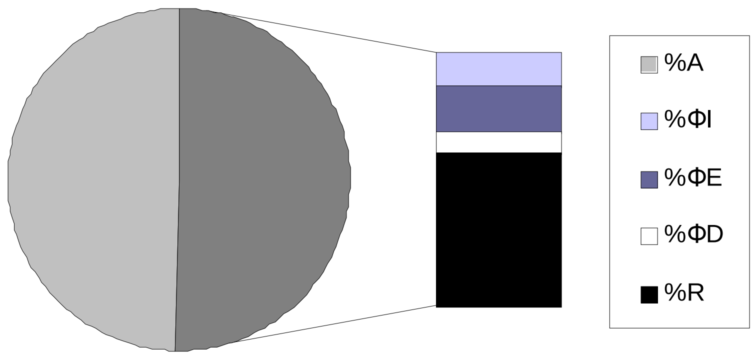


Fig.39 Graph representation of Performance System indexes of the supply network analysed.

"As far as the laws of mathematics refer to reality, they are not certain, and as far as they are certain, they do not refer to reality"

Albert Einstein

5

Conclusions

5.1 Conclusions and recommendations

This thesis presents a collection of techniques and algorithms that can help theoretical logistics to draw conclusions on supply network design and structure. In this last paragraph we summarize the possible development of the work presented in the various chapters.

In Chapter 2 we analyzed the state of the art paradigms and we provided guidelines on distribution network design and optimization.

In Chapter 3 we presented a theoretical framework on facility location inside a distribution network structure and a new model for goods delivery optimization in case of batch production and capacity constraints is presented in the last paragraph of the paper and it has been largely applied by the authors in the last year to different industrial cases. The model has been published on 2007 by the International Journal of Electronic Customers Relationship Management and it is enclosed at the end of this dissertation.

Chapter 4 emphasises the new idea that Network Analysis is a promising method with which to study Supply Chain as a complex web, and which can be understood from a systemic point of view. It provides a simple and fast method providing an idea of the complexity level of a

Supply Network. The methodology proposed is in direct agreement with both Shannon's model and the entropic measurements introduced by ecologists (especially Ulanowicz and colleagues) to study ecosystem network structure and organisation. The research aims to apply these measures to a new environment: the supply chain network. As far as the authors are aware, this is the first time these indices have been applied to the Supply Network measurements. Chapter 4.3 introduces eight entropic performance indexes: 1.Total System Throughput, 2.Average Mutual Information, 3.Ascendancy, 4.Development Capacity, 5.Overhead in Input, 6.Overhead in Export, 7.Overhead in Dissipation, and 8.Redundancy. The ecological entropic indexes introduced in this thesis provide the analyst with an immediate comparison of various alternative complex industrial webs in terms of network organisation and network complexity. The most representative index seems to be Ascendancy, expressed as a percentage on the system Capacity. Nevertheless, it is important to evaluate all performance indexes because each one of them communicates different information about the graphic structure of the supply network.

The results of the applications carried out are coherent with modern Supply Chain management paradigms. The reduction in goods rejection (dissipations), elimination of redundant connections, limitation of partner duplication, re-cycle in the supply web, and simplification of in-bound and out-bound partnerships work to reduce the network disorder and increase the Ascendancy value. Furthermore, ascendancy is a measure of how developed a system is. It considers both the size of the flows (Total System Throughput, TST) and their organisation (the Average Mutual Information Index, AMI).

A new paper derived by Chapter 4 of this thesis is actually under review on the International Journal of Production Research.

In conclusions, some recommendations must be done: the analysis of a Supply Network in which goods flows are measured in different units of value (kg, m^3, units of load, containers, trucks, pallets, money value, etc.) examines the system by different points of view and consequently can find different entropic performance index values. By itself using only one unit of measurement may not be enough to explain a complex supply network structure.

Future research in this field should develop guidelines to support the choice of the best set of measurement units with which to depict network flows inside a logistic web.

Moreover, the usability of these sets of measurements in practice needs to be investigated. In fact, further studies into the practical application of this multi-unit scenario are required.

A company could apply this set of performance measurements to quantifying the potential of structural changes in the supply network, to understanding the impact that strategic choices

will have on the whole system, to comparing the actual structure of the network with the future structure, and identifying critical parts of the network structure.
Finally, just as Efstathiou et al. (2002) developed a computer program to calculate manufacturing complexity under different system layouts and operating characteristics, one future direction of this research should be to program a software tool capable of analysing the network structure and of quickly computing the proposed new entropic performance indexes.

In July 2006 I participated to the International Conference of Supply Chain Management and Information Systems in Taiwan (SCMIS, 2006, Taichung). In this occasion, I was able to compare my ideas on the state of the discipline with the leading scientist in the field. Quite surprisingly I discovered that many of them were concerned with the same problems I exposed in the chapters of this dissertation, and they were actually working along the same pathway I followed while starting my PhD. Moreover many of them expressed interest in questions such as the effects of resolution and network construction on the measured properties (Chapter 4), and the possibility to develop new software tools able to help practitioners in study and control the whole distribution network.
This is the reason why, for example, a number of recent call for papers for special issues on the most important International Journals of our sector, (i.e. The International Journal of Production Economics, The Journal of Operations Management and The International Journal of Production Research) focus on the topic of supply network complexity modelling and measuring and of Distribution Network Optimization linked to business outsourcing.
The boost for the increasing interest of scientists of all branches in network theory is due to recent advances in Network Mechanics. Concepts such as Small World, six degrees of separation, error and attack sensitivity, hubs and so forth escaped the academic (small) world and ended up making the headlines. Recently, the book “Linked” (Barabasi, 2003) tried to present these issues to the general public in a readable but rigorous fashion.
The context of network analysis can be extended to a broader range of applications, both in ecology and in other fields. For example, Antonio Bodini and Cristina Bondavalli (University of Parma) applied network analysis to assess the sustainability of water utilization, John Rueter made a network analysis of the academic life in university, Ann Krause and Ken Frank at Michigan state University are connecting social and ecological networks for effective management of natural resources or Bob Ulanowicz, Mike Zickel and Stefano Allesina tried to grasp information on fluid mechanics using Network Analysis indexes. The idea is that once we have a network, we can try to apply Network Analysis techniques, exactly as we can apply other mathematical treatments to a variety of different problems from all branches of science.

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LIST OF PAPERS ENCLOSED

Paper [I]

Daria Battini, Alessandro Persona, Stefano Allesina, "Towards a use of network analysis: quantifying the complexity of Supply Chain Networks", *The International Journal of Electronic Customer Relationship Management*, 2007, Vol. 1, No.1, pp. 75-90.

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Paper [III]

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