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Advanced Models & Tools for Inbound & Outbound Logistics in Supply Chain

"Logistica Inbound ed Outbound nei sistemi produttivi"

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Advanced Models & Tool for Inbound & Outbound Logistics in Supply Chain

BY

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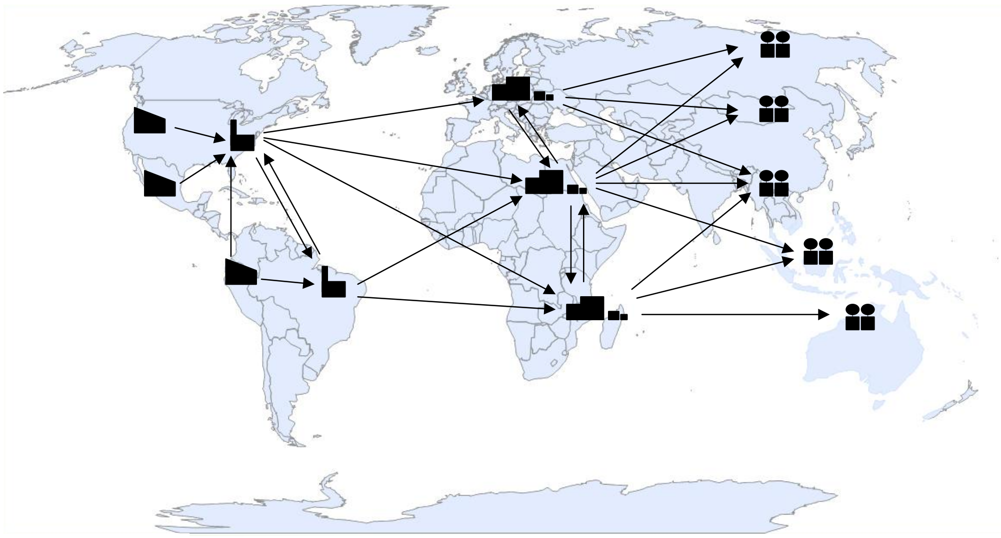

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Abstract

The present Ph.D. Thesis is focused on Inbound & Outbound Logistics in Supply Chain, specifically on issues regarding the configuration of a generic multi stage distribution network, determination of fulfilment policies and material flows, the optimal daily allocation of customer demand, and the following design, management and optimization of storage systems, especially for the storage allocation of order picking systems.

The set of methodological hierarchical approaches and methods introduced in the present research aim to became a ***modelling system to integrate the main supply chain management decisions***. In particular this modelling system groups concepts about *integrated planning* proposed by operations research practitioners, logistics experts, and strategists over the past 40 years. Indeed it refers to *functional coordination* within the firm, between the firm and its suppliers, and between the firm and its customers. It also refers to *inter-temporal coordination* of supply chain decisions as they relate to the firm's operational, tactical and strategic plans.

The modelling system following a top down approach starts with limited detail of the big picture, that is the physical design of a supply network, and then, after a rough first design is outlined, looking inside storage systems, where the design is refined. This is essentially as breaking down a distribution network to gain insight into its compositional sub-systems (i.e. distribution centers).

Various frameworks, models, heuristics, and software tools are introduced and discussed in the following chapters. Significant case studies are given to demonstrate the effectiveness of the proposed tools.

Finally the goal of this thesis is to present a set of advanced models and tools for the design and control of an integrated supply chain. This set of methods and tools have the ambition to replace the basic rules-of-thumb too often in use in supply chain management practice.

Sommario

La presente tesi di dottorato è basata sulla logistica inbound ed outbound nei sistemi di imprese, relativamente alle tematiche riguardanti la configurazione di reti distributive multi livello, la determinazione dei relativi flussi logistici, l'allocazione ottimale della domanda, e la successiva progettazione, gestione ed ottimizzazione dei sistemi di stoccaggio (centri distributivi), specialmente per quel che riguarda l'allocazione della merce nei sistemi di order picking.

La serie di approcci metodologici di tipo gerarchico presentati in questa ricerca mirano a diventare un ***sistema di modellazione che integra le principali decisioni del supply chain management***. Nello specifico il sistema di modellazione raggruppa i concetti tipici della *pianificazione integrata* così come è stata sviluppata nel corso degli ultimi 40 anni dai professionisti di ricerca operativa, dagli specialisti della logistica e dagli esperti di strategia aziendale. Infatti, tale sistema di modellazione si basa sia sul concetto di *coordinamento funzionale* tra imprese, tra l'impresa ed i suoi fornitori e tra l'impresa ed i suoi clienti, sia sul concetto di *coordinamento intertemporale* delle decisioni di supply chain, poiché considera la pianificazione operativa, tattica e strategica dell'azienda.

Il sistema di modellazione presentato nella tesi, seguendo un approccio top down, inizia con il delineare la struttura fisica e la configurazione del network distributivo attraverso un numero limitato di elementi, conseguentemente la progettazione è raffinata aumentando il grado di dettaglio, spingendosi fino alla progettazione dei centri di distribuzione, anello essenziale di ogni rete distributiva.

Nei seguenti capitoli sono presentati e discussi vari modelli, euristiche originali, framework e strumenti software. Alcuni significativi casi studio sono illustrati per dimostrare l'efficacia del sistema di modellazione proposto.

In definitiva lo scopo ultimo di questa tesi è quello di presentare un insieme di modelli e strumenti avanzati per la progettazione integrata ed il controllo della supply chain che possano essere di riferimento ed in sostituzione alle approssimative regole empiriche troppo spesso utilizzate nella pratica del supply chain management.

Acknowledgements

One time someone said that doing a Ph.D. is as hard as crossing an ocean by a vessel. I firmly think that is more difficult than that. Absolutely I can affirm that is as hard as crossing an ocean by a windsurf board! Anyway after about three years of hard maneuvering, I have been now almost approaching the destination. It is the right moment for me to think about the people who have contributed to this venture.

At the first place, I would like to express my sincerely thanks to Prof. Riccardo Manzini, the coach of my journey. He was the person who told me about the chance to take the challenge, welcomed me on board. He was the first who taught me how to firmly "hold the boom and close the gap" to sail off the coast. During the journey he has been always side by side exchanging with me useful advices, amazing tricks, and showing how to improve my technique. He spurred me to glide faster over the ocean whenever the weather turned bad.

Certainly, such a venture couldn't be undertaken without a supporting crew. I am grateful to all the members of the Industrial Mechanical Plants Section of the DIEM-Department (University of Bologna – Italy), who have kept an eye on me from the supporting boats. I would like to thank Prof. Arrigo Pareschi and Prof. Emilio Ferrari, the 'clever pilots of the boats', Prof. Alberto Regattieri with his pragmatic expertise that was a magnificent compass, Prof. Mauro Gamberi and Prof. Cristina Mora, two essential members of the crew always ready to grab me off the water when in need and dispense impressive advices.

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How can I forget the group of adventurers encountered along my path? First of all, the viking sailor Johan Lundin, a friend indeed. He taught me how to improve my steering and how to get a new confidence. It is my great gratitude to Johan for welcomed me in the foreign deep water and sharing with me many interesting days. I would like to thank Alejandro ‘big daddy’ Mac Cawley, for the pleasant chats also with his family, the coffee breaks provided and to be the family man who is, a source of inspiration for me. I would like also to thank anyone who helped me in somehow: “Singaporean guys” at ISyE, Fabio Sgarbossa, Altair Campos, Ale & Sonia, Fede & Giulia, Wally & Sama, Riccardo Accorsi, Barbara & Cristian, Lore & Sabry with Tommasino, Maria Pia & Armando, Andrea Giuliodori, Massimiliano Ceccarini, Ruth Showalter, Alfredo & Silvia, Andrea & Alessandra with Lapo, Massi & Lassi with Beatrice, Vasco Rossi, Sean Ordonez, Francisco Goya, and my dog Tommy.

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Finally, I would like to express my grateful to my beloved mum Naila and daddy Leo for their unconditional and constant loves, supports, encouragements, and sacrifice. Without them behind I would not be able neither to finish nor to start this venture.

Thank you all!

Bologna, Monday, January 25th, 2010
Filippo Bindi

'The sea. The sea enchants, the sea kills, it moves, it frightens, it also makes you laugh sometimes, it disappears every now and then, it disguises itself as a lake, or it constructs tempests, devours ships, gives away riches, it gives no answers, it is wise, it is gentle, it is powerful, it is unpredictable. But, above all, the sea calls. You will discover this. All it does, basically, is this: it calls. It never stops, it gets under your skin, it is upon you, it is you it wants. You can even pretend to ignore it, but it's no use. It will still call you. The sea you are looking at and all the others that you will not see, but will always be there, lying patiently in wait for you, one step beyond your life. You will hear them calling, tirelessly. It happens in this purgatory of sand. It will happen in any paradise, and in any inferno. Without explaining anything, without telling you where, there will always be a sea, which will call you.'

Alessandro Baricco (Ocean Sea)

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1. Introduction

Inbound and outbound logistics is a vital part of the supply chain process. To keep supply chains running smoothly, companies need to efficiently move, store and physically transport products (raw material, goods-in-process, finished goods) from one location to another. As a matter of fact once a good is produced, it must be shipped to its final destination going through each rings of the supply chain generating a stream of flows from supplier to supplier until the good reaches an end user. In other words that is a network of a variety of actors made up of retailers, distributors, transporters, storage facilities, and suppliers that participate in the production, delivery, and sale of a product to the consumer. Oftentimes, a manufacturing facility acts as a supplier to a downstream manufacturing facility. For example, a company could have their manufacturing plant in India and their assembly plant in China. The Indian plant would be considered an internal supplier, since it's part of the same company. It follows that sometimes the actors across the entire network are mutually interdependent and could develop changing connections.

Even though the modelling of a common logistics chain network is a complex configuration of various companies, storage facilities and branches, usually a supply chain (*SC*) could be fairly described with four main parts:

- **Supply** - focuses on the raw materials supplied to manufacturing, including how, when, and from what location
- **Manufacturing** - focuses on converting these raw materials into finished products
- **Distribution** - focuses on ensuring these products reach the consumers through an organized network of distributors, warehouses, and retailers
- **Customers** - also called clients, buyers, or purchasers are current or potential final users of the product

At the same time a supply chain can be divided into three main flows:

- The **Product flow** includes moving goods from supplier to consumer, as well as dealing with customer service needs
- The **Information flow** includes order information and delivery status
- The **Financial flow** includes payment schedules, credit terms, and additional arrangements.

In past years several authors have proposed different approaches to *Supply Chain Management Techniques* and to *Supply Chain Planning* trying to improve single parts of the logistics network according to bottom-up strategies. The latest challenge for supply chain planning is to find a global approach in order to obtain optimal performance throughout the whole logistics network. This idea overcomes the traditional approach according to which each actor aims at obtaining best performance for his own local system. Demonstrating that trend Shen (2005) affirms that, in order to achieve important costs savings, many companies have realized that the generic supply chain should be optimized as a whole, i.e., the major cost factors and levels of decision that impact on the performance of the chain should be considered jointly in the model for decision making process.

Abundant research has been done in this field from modeling by considering different scenarios to methods such as different heuristic methods. Almost all of them discriminate and focus alternately between the strategic level on one side, and the tactical and operational levels on the other (Bowersox et al., 2003). The strategic level refers to a long-term planning horizon (e.g. 3–5 years) and to the strategic problem of designing and configuring a generic multi-stage SC. Management decisions deal with the determination of the number of facilities, their geographical locations, the capacity of facilities, and the allocation of customer demand (Manzini et al., 2006). Tactical level refers to both short and long-term planning horizons and deals with the determination of the best fulfillment policies and material flows in an SC, modeled as a multi-echelon inventory distribution system (Manzini et al., 2008). In the operational level the variable of time is introduced, correlating the determination of the number of logistic facilities, geographical locations, and capacity of facilities to the optimal daily allocation of customer demand to retailers, distribution centers, and/or production plants.

Once an integrated approach for the design and planning of SC has been developed and applied to the logistics network, so an effective physical configuration of the chain has been assessed, then it is compelling to focus on the next level of decisions regarding how to design, plan and optimize the distribution centers/storage systems.

Warehousing is a central supply chain function. Goods must be unpacked, sorted, stored, repacked, and sent out to their correct destinations. Sometimes warehousing involves more than these basic functions. It can demand value added processes, such as simple assembly, checking for errors and correcting them, and making the goods store-ready. Warehouses and distribution centers (DCs) serve as nodes in the SC where the state of the inventory is assessed and from which replenishment orders are placed. They are vital to the entire process of moving goods.

The logistics revolution has changed the character of warehousing. In the past when *push* production was the general standard, warehouses served primarily as storage facilities. Goods were manufactured in large batches and stored in warehouses until they were ordered. The modern warehouse and DC, based on a *pull* production, aims to minimize the amount of inventory and maximize the flow of good so that they sit in storage for as little as possible. On the other hand today distribution centers often need to process a far higher volume of smaller orders of multiple products which considerably increases logistics costs. They generally use the so-called order picking (OP) where products have to be picked from a set of specific storage locations by an OP process usually driven by production batches or customer orders. As a united part of the logistics network, order picking operations have a significant impact on the chain performance. Any inefficiency in order picking can lead to unsatisfactory customers service level (long processing and delivery times, incorrect shipments) and high operational cost (i.e. labor cost, cost of additional and emergency shipments, etc.) for its warehouse, and consequently for the whole supply chain. Moreover the OP is often very labor-intensive and its efficiency largely depends on the distance the order pickers have to travel, which therefore needs to be minimized. It may consume as much as 60% of all labor activities in the warehouse (Drury, 1988). And for a typical warehouse, the cost of order picking is estimated to be as much as 55% of the total warehouse operating expense (Tompkins et al., 2003). Minimizing this distance is affected by several factors e.g. facility layout, shape of storage area, and especially the storage assignment rules. In order to operate efficiently, the order process needs to be robustly designed and optimally controlled.

Therefore, the overall aim of the thesis is firstly to provide analytical models, integrated approaches, and present some original tools to support the ***design and control of whole distribution logistics network*** according to three different planning levels (i.e. strategic, tactical and operational), secondly to investigate and explore ways and means for the efficient ***design of general storage systems and order picking processes***, as they are united part of the logistics network and directly connected with the chain performance. Following a top-down strategy, the thesis begins formulating a modeling overview for the entire supply chain network using limited detail, so a rough first design is outlined while at subsequent stages this design is successively refined. The hierarchical frameworks, approaches and tools presented in the thesis allow the logistics planner and managers to design inbound and outbound logistics simultaneously optimizing the various problems at different levels of decision in order to reach a global optimum. Significant case studies demonstrates the effectiveness of the proposed rules in minimizing logistic costs.

1.1. Thesis Outline

This chapter presented the general introduction to the supply chain inbound and outbound logistics and highlighted the main motivations for undertaking the research presented in this dissertation. The rest of the dissertation is organized as follows:

- **Chapter 2** presents an innovative hierarchical framework for the development of new modeling approaches to the strategic, tactical, and operational decision problem. Some original methods, heuristics, tools, and linear programming models are introduced to integrate supply chain planning decisions. Finally a significant case study is illustrated to demonstrate the effectiveness of the approach. This Chapter is based on Manzini and Bindi (2009).
- **Chapter 3** presents a tool for the design, planning, managing and control of a multi-level multi-period supply chain distribution network. It also outlines an original approach for a complete experimental analysis. This Chapter is based on Manzini, Bindi, and Bortolini (2010 IN PRESS).
- **Chapter 4** outlines warehousing issues: the role of storage systems in the supply chain, the main operations and functions, the general equipment, and the order picking process.
- **Chapter 5** presents an original approach for the design, management and control of order picking systems. Focusing on the *storage allocation problem*, a set of different storage allocation rules based on the application of original similarity coefficients and clustering techniques are introduced. The potential benefits offered by the product correlation are explored. Lastly, a case study demonstrates the effectiveness of the proposed rules in minimizing logistic costs. This Chapter is based on both Bindi et al. (2009) and Bindi et al. (2010).
- **Chapter 6** introduces a tool supporting the proposed approach for order picking systems. It could be taken as framework to integrate the interrelated decisions

situated at a strategic, tactical and operational level for the generic design and control of order picking systems.

- **Chapter 7** gives concluding remarks and suggests potential future research directions.

Figure 1 illustrates the thesis outline. It can be seen from the figure where the different chapters of the thesis are placed. Furthermore, each chapter presents indication regarding the impact level of the related argued issues. The top-down approach used as base for this research is underlined by the scheme in the figure. It can be clearly seen that the research begins with limited detail of the big picture, and then, after a rough first design is outlined, looking inside storage systems, where the design is refined.

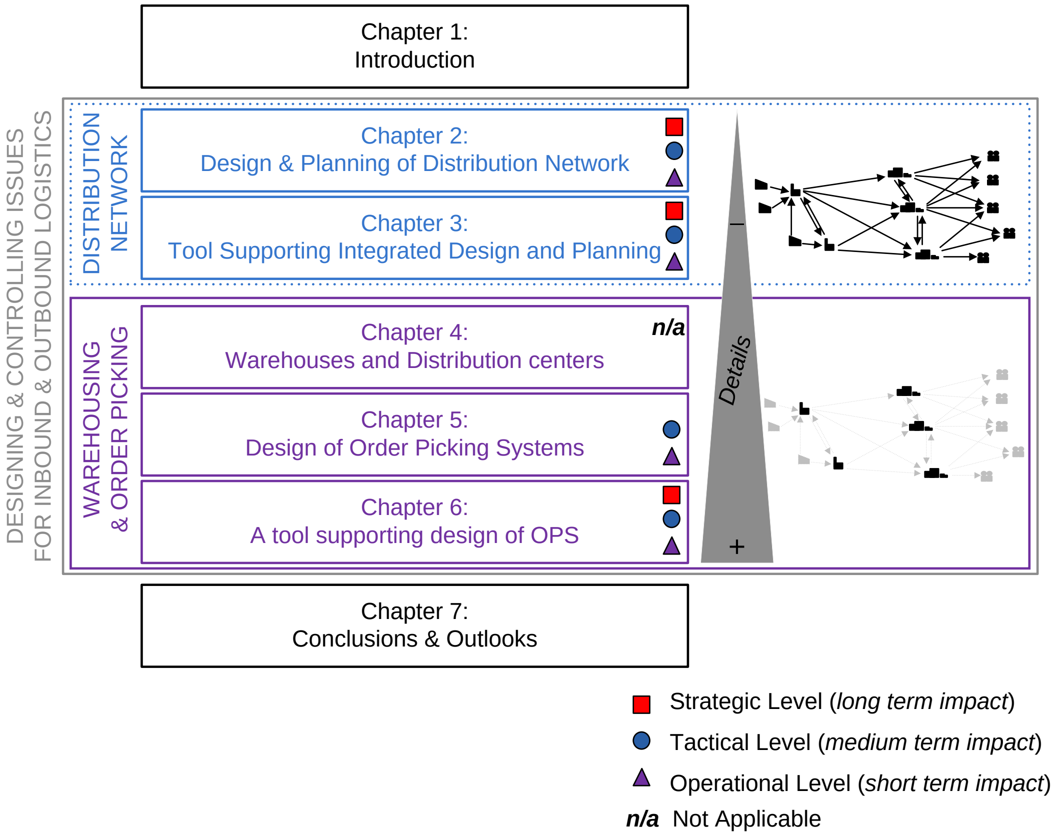


Figure 1: Thesis Outline

2. Design & Planning of Distribution Network

Design and management of logistic networks is one of the most critical issues in Logistics and Supply Chain Management. Literature studies does not present effective models, methods and applications to support management decisions from the strategic design of the distribution system to the operational planning and organization of vehicles and containers trips adopting different transportation modes.

Aim of this chapter is the illustration and application of an original framework for the design and optimization of a multi echelon and multi level production/distribution system. In particular some models and methods for both the strategic design and tactical/operational design and optimization of a logistic network are presented. They are based on the use of mixed integer linear programming modelling and linear programming solvers combined to the application of Cluster Analysis, heuristic clustering algorithms and optimal transportation rules. A significant case study is illustrated demonstrating the effectiveness of the this approach and proposed tools.

2.1. Introduction and literature review

FL and SCM are two important and interrelated disciplines in logistics and management science. In particular, the generic FL problem in logistic systems can be defined as the taking of simultaneous decisions regarding design, management, and control of a generic distribution network:

1. Location of new supply facilities given a set of demand points, which correspond to existing customer

locations.

2. Demand flows to be allocated to available or new suppliers.

3. Configuration of a transportation network i.e. design of paths from suppliers to customers, management of routes and vehicles in order to supply demand needs simultaneously (in case of the adoption of the so called "groupage strategy").

Recent literature reviews on SCM and FL are presented by van der Vaart and van Donk (2008), Gebennini et al. (2009) and Melo et al. (2009). Literature presents also a very large number of studies on models and methods for the design and control of complex distribution systems, but the largest part of them deals with one specific problem such as the facility location, the location and allocation problem (LAP), the vehicle routing, etc., renouncing to find a global optimum for the whole systems by the application of an integrated approach for production, distribution and transportation issues (Manzini et al. 2008). Researchers have focused relatively early on the design of distribution systems considering the SC as a whole (Melo et al. 2009). Recent contributions to the management and optimization of inventory/distribution systems are presented by Abdul-Jalbar et al. (2009), Amiri (2006), Manzini and Gebennini (2008), Monthatipkul and Yenradee (2008).

They are based on mixed integer linear programming and deal with one-warehouse/multi-retailer SC. Recent publications on the design and management of a logistic distribution network are presented by Kengpol (2008), who proposes an analytical hierarchy process (AHP) combined to the use of mixed integer linear programming (MILP). All these contributions refer to simplified operating contexts where the variable time is not modelled, a single commodity hypothesis is adopted and one stage made of two levels (the sources level or the DCs level, and the customers' level) is considered.

A recent production-distribution model based on MILP is presented and applied by Tsiakis and Papageorgiou (2008). Thanh et al. (2008) present a MILP-based dynamic model focusing on strategic and tactical decisions.

Classifications and reviews of the existing models and tools for the logistic networks design and optimization are presented by Klose and Drexl (2005), ReVelle et al. (2008), Thanh et al. (2008), Gebennini et al. (2009), Melo et al. (2009)

A few studies combining production, inventory, distribution and transportation issues are presented in the literature (Manzini and Bindi 2009). Significant contributions on integrated approaches, models and methods for the design, management and control of such systems are presented by Manzini and Bindi (2009), and Manzini et al. (2008).

This paper presents an integrated approach and an automatic tool for the execution of the strategic planning, the tactical planning and the operational planning in a multi-echelon multi-stage multi-commodity and multi-period production, distribution and transportation system. The proposed software platform can be applied to the design, management and control of real instances and can efficiently support the decision making process of logistic managers, planners and practitioners from industry and large enterprises as multi-facilities companies and supply chain networks.

2.2. Strategic design & operational management in a distribution network

Figure 2 classifies main key planning issues and decisions regarding the activities of design and scheduling of a logistic production & distribution system made of multi level entities, e.g. sources, production plants, DCs, distributors, customers, etc. These decisions are grouped in terms of time horizon, long, medium and short, and in accordance to the portion of the logistic chain they deals with, i.e. purchase & production, distribution and supply. This figure can be considered also a reference framework for the development of the original integrated approach as illustrated below. In particular the following models and methods proposed can support the decision maker to face all these issues simultaneously, even if with an interactive and sequential process. The process is sequential especially in presence of very large problem instances because made of thousands of entities, e.g. facilities, distributors, and customers, all located in different and numerous geographic locations.

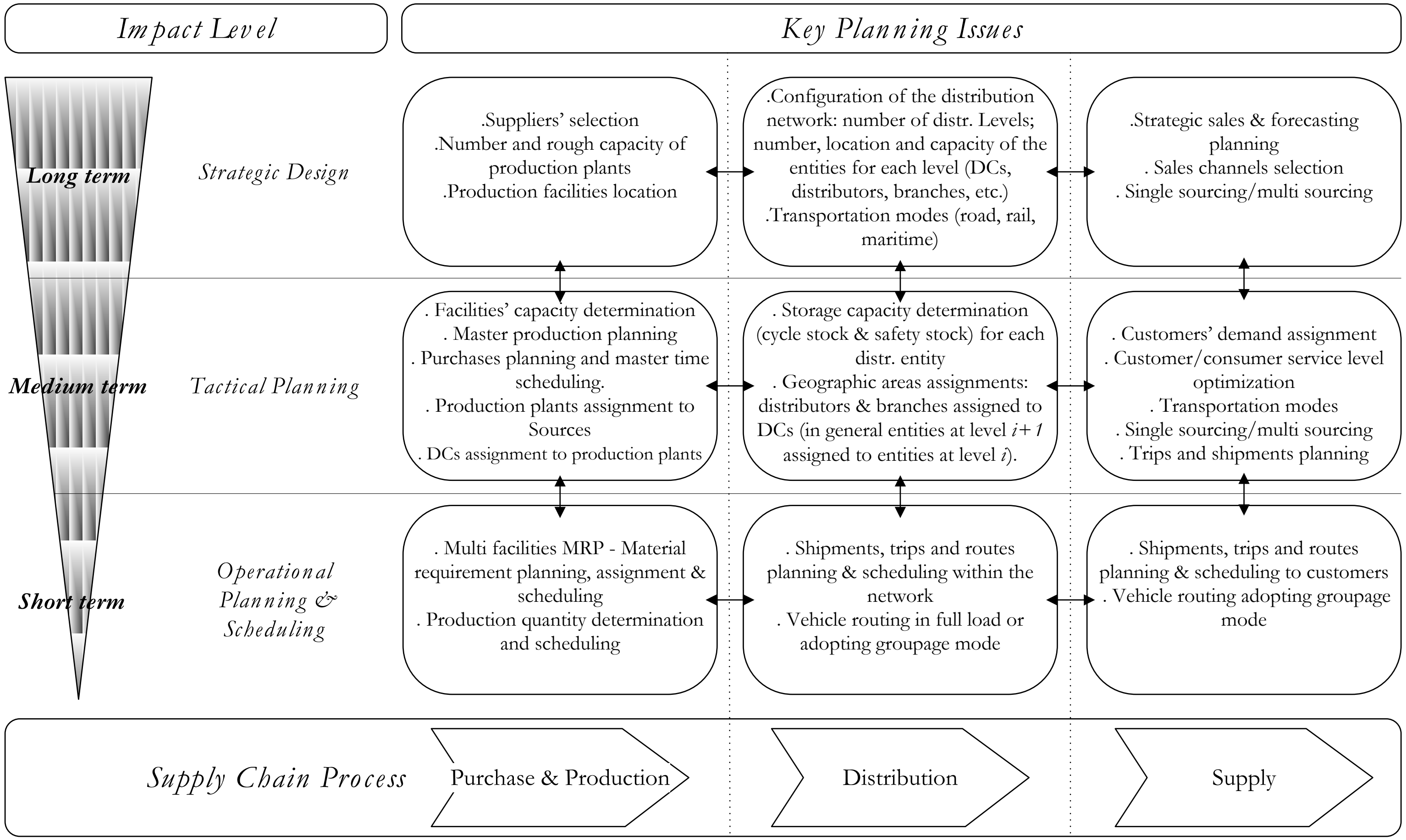


Figure 2: Process, Key planning issues and impact levels

2.2.1. Strategic model I

Figure 3 presents a logic scheme which illustrates the first mixed-integer linear programming model developed by the authors to support the strategic planning of the logistic network. This is single product, single period, 4 levels (sources, DCs, distributors and customers), single sourcing (a customer cannot be supplied by two different distributors) and single channel. In particular the last hypothesis means that there is only a transportation mode from a supplier, e.g. a distributor center DC, to a demand point, e.g. a distributor. It is possible to define more than one sources (level 1), distribution centers – DCs (level 2) and distributors (level 3), and the solver decides which ones use and take open and which ones do not use and do not open. The location of these potential entities is given, while the choice of using them is the aim of the model and solver.

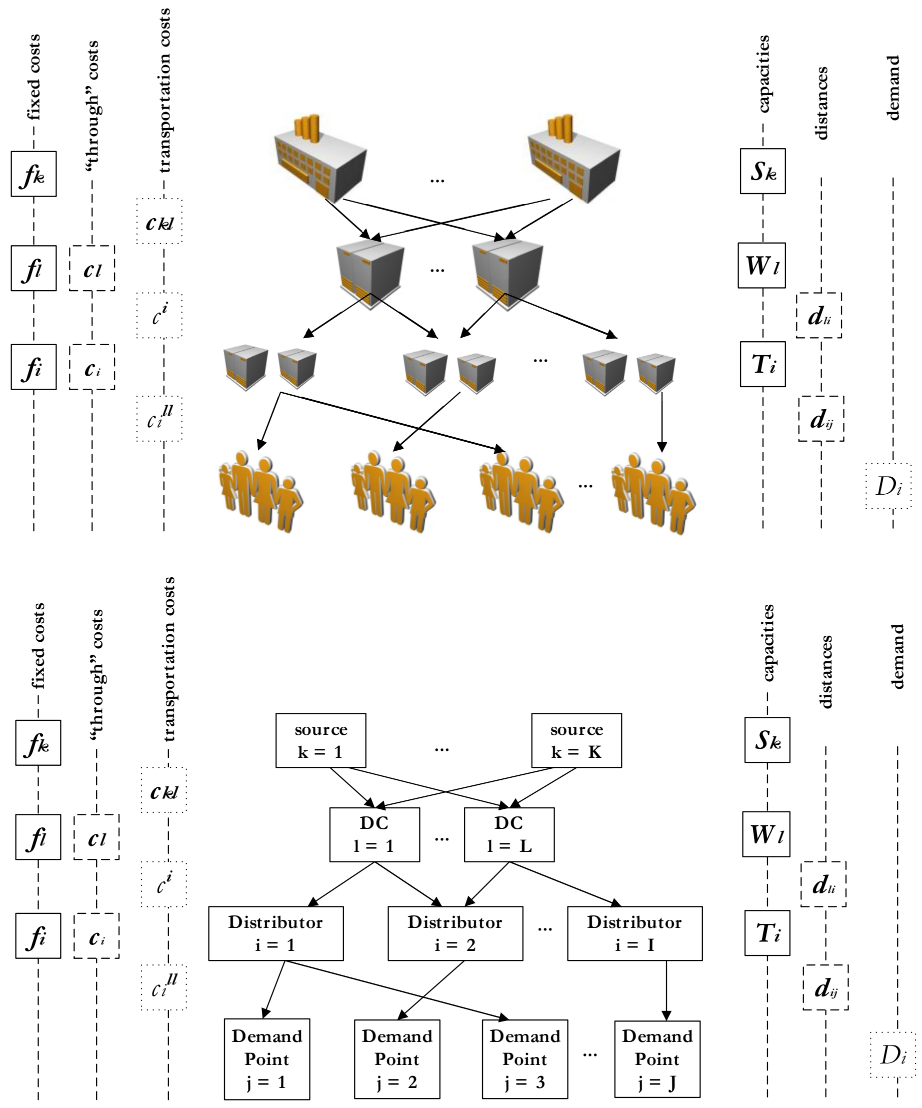


Figure 3: Strategic Model I

The objective function is defined as follows:

$$\varphi_I = \sum_{k=1}^{K}\sum_{l=1}^{L} c_{kl}x_{kl} + \sum_{k=1}^{K} f_k y_k + \sum_{l=1}^{L}\sum_{i=1}^{I} c_l x_{li} + \sum_{l=1}^{L} f_l y_l + \sum_{l=1}^{L}\sum_{i=1}^{I} c^i d_{li} x_{li} + \sum_{i=1}^{I} f_i y_i + \sum_{i=1}^{I}\sum_{j=1}^{J} c_i D_j x_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} c_i^{II} d_{ij} D_j x_{ij} \qquad \text{Eq. 1}$$

The linear model is:

$$min\{\varphi_I\} \quad \text{Eq. 2}$$

$$\sum_{l=1}^{L} x_{kl} \leq y_k S_k \quad \text{Eq. 3}$$

$$\sum_{k=1}^{K} x_{kl} - \sum_{i=1}^{I} x_{li} \geq 0 \quad \text{Eq. 4}$$

$$\sum_{i=1}^{I} x_{li} \leq y_l W_l \quad \text{Eq. 5}$$

$$\sum_{l=1}^{L} x_{li} - \sum_{j=1}^{J} D_j x_{ij} \geq 0 \quad \text{Eq. 6}$$

$$\sum_{j=1}^{J} D_j x_{ij} \leq y_i T_i \quad \text{Eq. 7}$$

$$\sum_{i=1}^{I} x_{ij} = 1 \quad \text{Eq. 8}$$

$$x_{kl}, x_{li} \geq 0 \quad \text{Eq. 9}$$

$$y_k, y_i, y_l, x_{ij} \in \{0,1\} \quad \text{Eq. 10}$$

where:

$k \in \{1, \dots, K\}$	source point. It is generally a production plant or a products/services supplier	
$l \in \{1, \dots, L\}$	distribution center (DC). *l* can be considered as the location of a DC	
$i \in \{1, \dots, I\}$	distributor. *i* can be considered as the location of a distributor	
$j \in \{1, \dots, J\}$	demand point	
S_k	production/supply capacity of the source point *k*	*[ft²/year]*
c_{kl}	production and transportation unit cost from the source *k* to the DC *l* including production unit cost in *k*	*[$/ft²]*
f_k	fixed cost to operate using source *k*	*[$/year]*
W_l	maximum handling capacity for the DC *l*	*[ft²/year]*
f_l	fixed cost to operate using the DC *l*	*[$/year]*

c_l	unit cost of product passing through the DC l. This is the cost of processing a unit of product by the DC l	*[$/ft²]*
c^i	transportation unit cost from the distribution center to the distributor i	*[$/(ft²mile)]*
d_{li}	distance from the DC l to the distributor i	*[miles]*
T_i	maximum handling capacity of the distributor i	*[ft²/year]*
f_i	fixed cost of using the distributor i	*[$/year]*
c_i	unit cost of product passing through the distributor i. This is the cost of processing a unit of product by the distributor i	*[$/ft²]*
c_i^{II}	transportation unit cost from the distributor i to the generic demand location	*[$/(ft²mile)]*
d_{ij}	distance from the distributor I to the demand point location j	*[miles]*
D_j	demand from demand point j	*[ft²/year]*

The variables are:

y_k	1 if source k is used, 0 otherwise	*[boolean]*
y_l	1 if DC l is used, 0 otherwise	*[boolean]*
y_i	1 if distributor i is used, 0 otherwise	*[boolean]*
x_{kl}	product quantity from the source k to the DC l	*[ft²/year]*
x_{li}	product quantity from the DC l to the distributor i	*[ft²/year]*
x_{ij}	1 if demand point j is supplied by the distributor i, 0 otherwise	*[boolean]*

The units of measure explicitly reported in the legenda which describes the strategic model I, refer to the case study illustrated in the second part of the manuscript. For example the unit of measure of a fixed cost is *[$/year]* and of a transportation, travelling, unit cost is *[$/(ft²mile)]*.

Equations Eq. 3, Eq. 5, and Eq. 7 guarantee the respect of the capacity constraints respectively for the generic source k, the generic DC l, and the generic distributor i. Eq. 4 and Eq. 6 guarantee the equilibrium of product flows at nodes (respectively DCs and distributors). Equations Eq. 8 represent the single source constraints for demand points: a customer cannot be supplied by two different distributors. By the relaxation of this set of constraints the generic customer can be supplied by more than one distributor ("multi sourcing" hypothesis).

2.2.2. Strategic model II

This model differs from the strategic model I for the introduction of multi type DCs, at the second level, and multi type distributors, at the third level. In particular the typologies of DC can be distinguished by the variable $p=1,..,P$, similarly the typologies of distributors can be distinguished by the variable $q=1,..,Q$. In a generic location it is not possible to locate two different kinds of entities, e.g. two DCs of different types *p* or two distributors of different types *q*.

The choice to discriminate different kinds of distributors reflect the need of managing entities able to operate with different maximum distances and unit costs to supply their assigned points of demand. For this purpose the distance parameter $d_q^{\max}$, associated to the type of distributor *q*, has been introduced. The model changes as illustrated below. Similarly to Figure 3, Figure 3 presents the logic scheme illustrating this mixed-integer linear programming model.

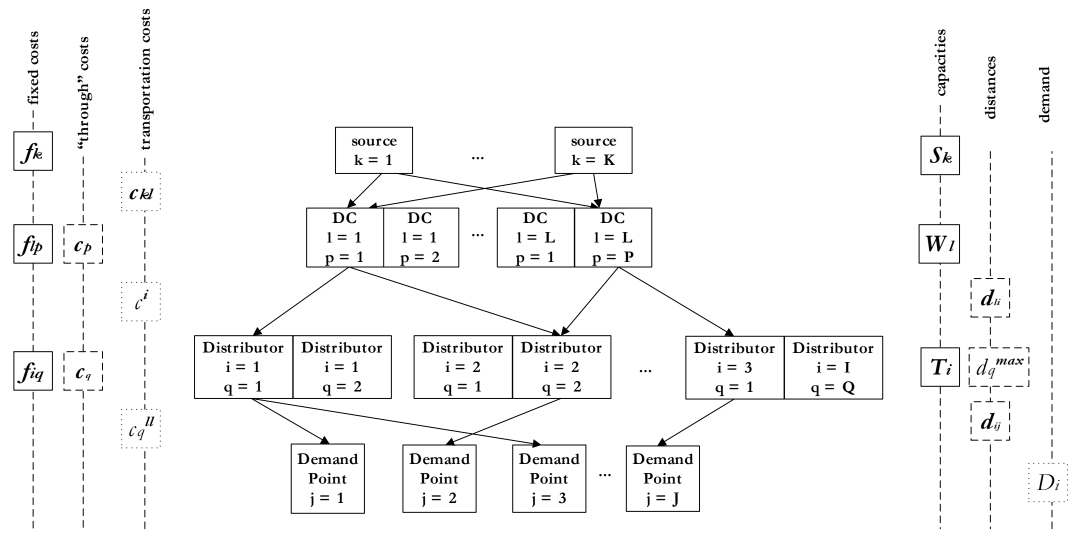


Figure 4: Strategic Model II

The objective function is:

$$\varphi_{II} = Min \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P} c_{kl}x_{klp} + \sum_{k=1}^{K} f_k y_k + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q} c_p x_{lpiq} + \sum_{l=1}^{L}\sum_{p=1}^{P} f_{lp}y_{lp} + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q} c^i d_{li}x_{lpiq} + \sum_{i=1}^{I}\sum_{q=1}^{Q} f_{iq}y_{iq} + \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{j=1}^{J} c_q D_j x_{iqj} + \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{j=1}^{J} c_q^{II} d_{ij} D_j x_{iqj} \quad \text{Eq. 11}$$

The linear model is:

$$min\{\varphi_{II}\} \quad \text{Eq. 12}$$

$$\sum_{l=1}^{L}\sum_{p=1}^{P} x_{klp} \leq y_k S_k \quad \text{Eq. 13}$$

$$\sum_{k=1}^{K} x_{klp} - \sum_{i=1}^{I}\sum_{q=1}^{Q} x_{lpiq} \geq 0 \quad \text{Eq. 14}$$

$$\sum_{i=1}^{I}\sum_{q=1}^{Q} x_{lpiq} \leq y_{lp} W_p \quad \text{Eq. 15}$$

$$\sum_{p=1}^{P} y_{lp} \leq 1 \quad \text{Eq. 16}$$

$$\sum_{l=1}^{L}\sum_{p=1}^{P} x_{lpiq} - \sum_{j=1}^{J} D_j x_{iqj} \geq 0 \quad \text{Eq. 17}$$

$$\sum_{j=1}^{J} D_j x_{iqj} \leq y_{iq} T_q \quad \text{Eq. 18}$$

$$\sum_{q=1}^{Q} y_{iq} \leq 1 \quad \text{Eq. 19}$$

$$x_{iqj} d_{ij} \leq d_q^{max} \quad \text{Eq. 20}$$

$$\sum_{i=1}^{I}\sum_{q=1}^{Q} x_{iqj} = 1 \quad \text{Eq. 21}$$

$x_{klp}, x_{lpiq} \geq 0$ Eq. 22

$y_k, y_{lp}, y_{iq}, x_{iqj} \in \{0,1\}$ Eq. 23

where (only new introduced terms and parameters are defined):

$p \in \{1, \dots, P\}$	type of DC	
$q \in \{1, \dots, Q\}$	type of distributor	
W_p	maximum handling capacity for the DC of type *p*	*[ft²/year]*
f_{lp}	fixed cost to operate using the DC *l* (as a DC in the location *l*) of type *p*	*[$/year]*
c_p	unit cost of product passing through the DC of type *p*	*[$/ft²]*
T_q	maximum handling capacity for the distributor of type *p*	*[ft²/year]*
f_{iq}	fixed cost of using the distributor *i* (as a distributor in the location *i*) of type *q*	*[$/year]*
c_q	unit cost of product passing through the distributor of type *q*	*[$/ft²]*
c_q^{II}	transportation unit cost from the distributor of type *q* to the generic demand location	*[$/(ft²mile)]*
d_q^{max}	maximum distance from the distributor of type *q* and the generic demand point location assigned to it	*[miles]*

The variables, which differ from those defined for model I, are:

y_{lp}	1 if DC of type *p* in the location *l* is used, 0 otherwise	*[boolean]*
y_{iq}	1 if distributor of type *q* in the location *i* is used, 0 otherwise	*[boolean]*
x_{klp}	product quantity from the source *k* to the DC of type *p* located in *l*	*[ft²/year]*
x_{lpiq}	product quantity from the DC of type *p* located in *l* to the distributor of type *q* located in *i*	*[ft²/year]*
x_{iqj}	1 if demand point *j* is supplied by the distributor of type *q* located in *i*, 0 otherwise	*[boolean]*

Constraints Eq. 16 guarantee no more than one DC is kept open in a generic location *l*. Similarly equation Eq. 19 controls the number, at maximum equal to 1, of distributor in a generic location *i*. Constraints Eq. 20 assurance the generic distributor of type *q* does not supply demand point locations located too far away.

2.2.3. Strategic model III

By this model it is possible to design a logistic network based on different transportation modes from the DCs to the distributors. The number of DCs is generally limited to a few, e.g. 3 or 4 warehousing systems located in strategic areas, while the number of distributors can be several tens because they supply the demand of customers located everywhere and in number of thousands. Consequently in general it is possible to travel from a DC to a distributor by several available transportation modes, e.g. rail, road, maritime, air. The model parameterization is also based on the introduction of terms as $Kcont_m$, $cont_m^{\min}$ and $cont_m^{\max}$ for the determination of the type and number of containers moving from the DCs to the distributors in accordance to minimum and maximum threshold values. In other words this model also consider the minimum and maximum number of containers for the generic trip from the DC to the distributors. In particular by train it is possible to simultaneously transport several containers, while by road the number is generally one or two.

The proposed model also quantifies the storage costs in accordance to the inventory management and capacity of warehousing systems both in DCs and distributors. For this purpose the terms SS_p, h_p, R_p^I, defined for the generic DC of type *p,* have been introduced and similarly SS_q, h_q, R_q^I for the generic distributor of type *q*. Figure 4 presents the logic scheme illustrating this mixed-integer linear programming model.

R_p^I is defined as the time between two consecutive shipments from the DC of type *p* to a distributor. Consequently if R_p^I decreases the customer service level increases at the generic point of demand and the logistic cost increases too, because the level of saturation of vehicles and containers reduces and the transportation cost for the unit of product increases.

In particular the cost generated by the use of containers between a DC and a distributor $\hat{i}$ is quantified by the following equation:

$$\frac{C_{container} \cdot Z}{R}$$

$$Z = \max \begin{cases} \left\lceil \dfrac{R \cdot D(T)}{Kcont} \right\rceil \\ cont^{\min} \end{cases} \qquad \text{Eq. 24}$$

where

Z	number of container from the DC to the distributor $\hat{i}$
$C_{container}$	unit cost of transportation of a container, *e.g. [$/container]*
R	time between two consecutive shipments to a distributor, e.g. *[year/shipments]*
Kcont	capacity of the container, e.g. *[(units_of_product)/container]*
D	distributor's demand in a period of time *T*, e.g. annual demand *[(units_of_product)/year]*

Similar terms are properly introduced in the analytical model which follows and are properly defined by its legenda of terms and symbols.

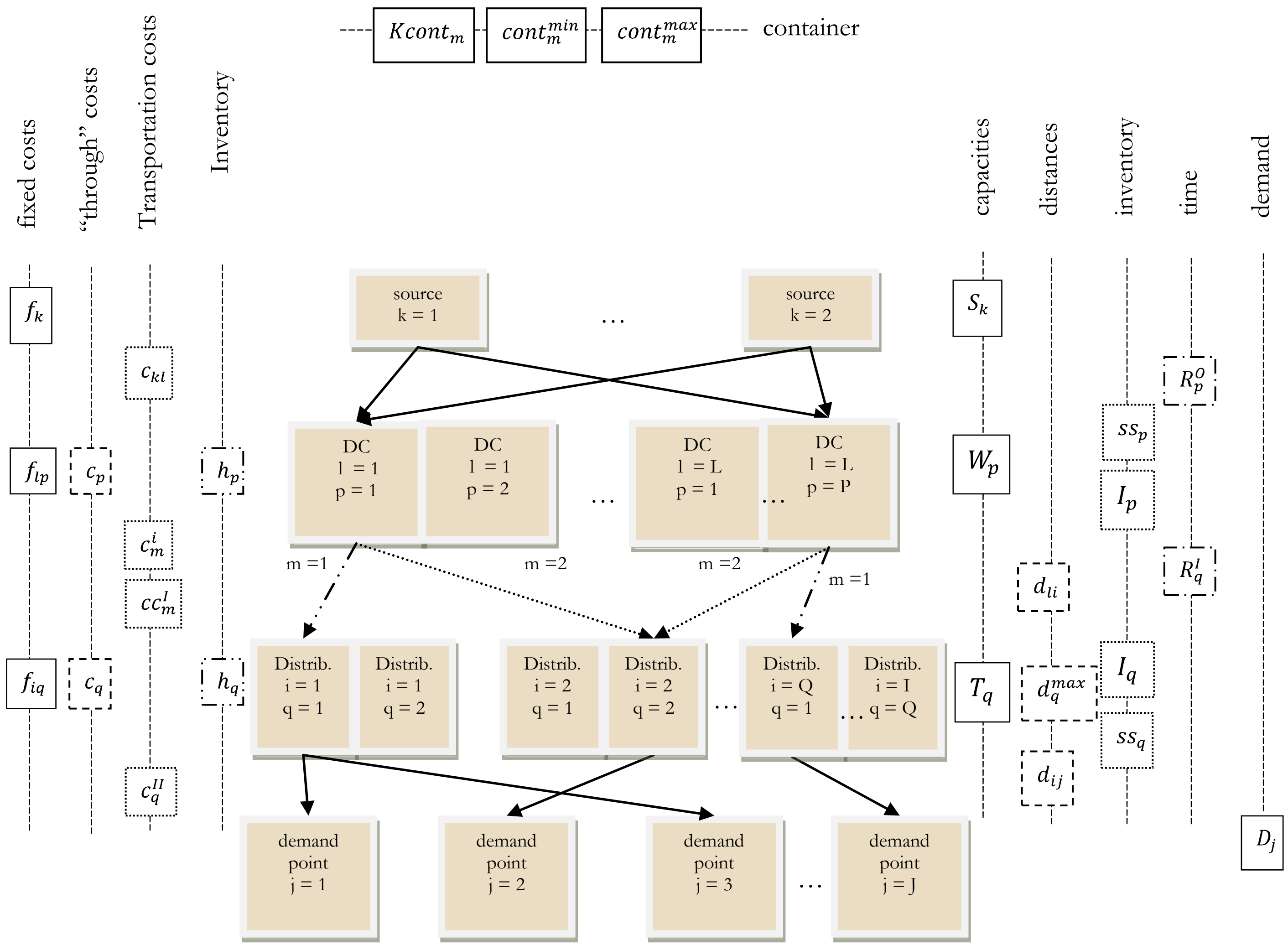


Figure 5: Strategic Model III

The objective function is:

$$\begin{aligned}
\varphi_{III} = Min \; & \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P} c_{kl}x_{klp} + \sum_{k=1}^{K} f_k y_k + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} c_p x_{lpiqm} \\
& + \sum_{l=1}^{L}\sum_{p=1}^{P} f_{lp} y_{lp} \\
& + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P} h_p \, Val\left(ss_p R_p^O x_{klp} + \frac{1}{2} R_p^O x_{klp}\right) \\
& + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} c_m^i d_{li} x_{lpiqm} \\
& + \sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} \frac{cc_m^I}{R_q^I} z_{liqm} + \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{j=1}^{J} c_q D_j x_{iqj} \\
& + \sum_{i=1}^{I}\sum_{q=1}^{Q} f_{iq} y_{iq} \\
& + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} h_q \, Val\Bigg(ss_q R_q^I x_{lpiqm} \\
& + \frac{1}{2} R_q^I x_{lpiqm}\Bigg) + \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{j=1}^{J} c_q^{II} d_{ij} D_j x_{iqj}
\end{aligned}$$

Eq. 25

The linear model is:

$min\{\varphi_{III}\}$ Eq. 26

$\sum_{l=1}^{L}\sum_{p=1}^{P} x_{klp} \leq y_k S_k$ Eq. 27

$\sum_{k=1}^{K} x_{klp} - \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} x_{lpiqm} \geq 0$ Eq. 28

$\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} x_{lpiqm} \leq y_{lp} W_p$ Eq. 29

$\sum_{k=1}^{K}\left(ss_p R_p^O x_{klp} + R_p^O x_{klp}\right) \leq y_{lp} I_p^{max}$ Eq. 30

$\sum_{p=1}^{P} y_{lp} \leq 1$ Eq. 31

$z_{liqm} \geq cont_m^{min} y_{liqm}$ Eq. 32

$z_{liqm} \leq cont_m^{max} y_{liqm}$ Eq. 33

$\sum_{p=1}^{P} R_q^I x_{lpiqm} \leq Kcont_m z_{liqm}$ Eq. 34

$y_{liqm} \leq \sum_{p=1}^{P} y_{lp}$ Eq. 35

$y_{liqm} \leq y_{iq}$ Eq. 36

$\sum_{l=1}^{L} \sum_{p=1}^{P} \sum_{m=1}^{M} x_{lpiqm} - \sum_{j=1}^{J} D_j x_{iqj} \geq 0$ Eq. 37

$\sum_{j=1}^{J} D_j x_{iqj} \leq y_{iq} T_q$ Eq. 38

$\sum_{l=1}^{L} \sum_{p=1}^{P} \sum_{m=1}^{M} \left(ss_q R_q^I x_{lpiqm} + R_q^I x_{lpiqm} \right) \leq y_{iq} I_q^{max}$ Eq. 39

$\sum_{q=1}^{Q} y_{iq} \leq 1$ Eq. 40

$x_{iqj} d_{ij} \leq d_q^{max}$ Eq. 41

$\sum_{i=1}^{I} \sum_{q=1}^{Q} x_{iqj} = 1$ Eq. 42

$x_{klp}, x_{lpiqm}, z_{liqm} \geq 0$ Eq. 43

z_{liqm} *integer* Eq. 44

$y_k, y_{lp}, y_{iq}, y_{liqm}, x_{iqj} \in \{0,1\}$ Eq. 45

where (only new introduced terms and parameters are defined):

$m \in \{1, \dots, M\}$	transportation modes from a DC to the distributors	
R_p^O	time between two consecutive fulfilments for the DC of type *p*	*[year/fulfil.]*
I_p^{max}	storage capacity for the DC of type *p*	*[ft²]*
ss_p	safety stock (SS) factor for the DC of type *p*	*[fulfil.]*
h_p	holding unit cost factor for the DC of type *p*	*[year⁻¹]*
c_m^i	transportation unit cost from the distribution center to the distributor *i* by the transportation mode *m*. This unit cost is used to quantify the transportation cost proportional to the travelling quantity.	*[\$/(ft²mile)]*
cc_m^I	cost for one container using the transportation mode *m*. This unit cost is used to quantify the transportation cost proportional to the number of travelling containers.	*[\$/container]*
$Kcont_m$	capacity of the container by the transportation mode *m*	*[ft²/ container]*

$cont_m^{min}$	minimum number of containers in a trip/shipment using the transportation mode *m*	*[container / shipment]*
$cont_m^{max}$	minimum number of containers in a trip/shipment using the transportation mode *m*	*[container / shipment]*
R_q^I	time between two consecutive shipments for the distributor of type *q*	*[year/ shipments]*
I_q^{max}	storage capacity for the distributor of type *q*	*[ft²]*
ss_q	SS factor for the distributor of type *q*	*[fulfil.]*
h_q	holding unit cost factor for the distributor of type *q*	*[year⁻¹]*
Val	average product unit cost	*[$/ ft²]*

The variables, which differ from the previously defined, are:

y_{liqm}	1 if the transportation mode *m* between the DC locate in *l* and the distributor of type *q* located in *i* is adopted, 1 otherwise	*[boolean]*
x_{lpiqm}	product quantity from the DC of type *p* located in *l* to the distributor of typology *q* located in *i* by the adoption of the transportation mode *m*	*[ft²/year]*
z_{liqm}	number of containers in a shipment adopting the transportation mode *m* from the DC located in *l* and the distributor located in *i*	*[container/shipment]*

$$\frac{C_{container} \cdot Z}{R}$$

By equation
$$Z = \max \begin{cases} \left\lceil \dfrac{R \cdot D(T)}{Kcont} \right\rceil \\ cont^{\min} \end{cases}$$

Eq. 24 there are two different kinds of cost contributions between the DCs level and the distributors:

Transportation costs I DCs – distributors. They depends upon the product quantity travelling from DCs to the distributors.

$$\sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} c_m^I d_{li} x_{lpiqm} \qquad \text{Eq. 46}$$

Transportation cost II DCs – distributors. They are "transportation modes costs" due to the number of containers travelling from DCs level to the distributors level.

$$\sum_{l=1}^{L}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{m=1}^{M} \frac{cc_m^I}{R_q^I} z_{liqm} \qquad \text{Eq. 47}$$

Constraints Eq. 29 guarantee the storage quantities respect the capacities of the DCs. Similarly equation Eq. 38 control the storage quantity at the generic distributor of type *q*. Eq. 31 and Eq. 32 control the number of containers in a trip from the DC located in *l* to the distributor of type *q* located in *i,* by the use of the transportation mode *m*.

2.3. Models and methods for the operational planning and organization

This section present an original approach to the tactical & operational planning and to the organization and execution of logistic trips within the system to satisfy daily customers' demand.

2.3.1. A multi-period mixed integer programming model

This model differs from those presented in Section 2.2 because it is a multi-period location-allocation model. For this reason it is called also dynamic. It can support the design of a distribution system by the identification of the best locations of entities, e.g. DCs, distributors, plants/production systems, sources, etc., and the allocation of products demand to each supplier in different periods of time. The choice of the length of the unit of time, the authors call "granulation problem", decides the dimension of the instance and the ability of a solver to find the optimal solution minimizing the objective and cost function. To efficiently solve the problem is generally useful to adopt the best solution generated by a previous executed strategic design step, as exemplified in Section 2.2. The results from a strategic model can support a presetting process conducted to reduce the complexity of the operational model. This activity consists on the pre-definition of a very large number of variables.

In particular in case the generic allocation of demand and needs is planned adopting a period of time equal to the day, the model can effectively support the daily planning of shipments within the network to supply customers' demand in t_1, t_2, etc. points in time.

The frequent complexity of a multi-period, i.e. dynamic, and mixed integer programming model can be bypassed by the adoption of an alternative approach illustrated below and based on Cluster Analysis. Nevertheless the clustering approach can be applied also after the application of a multi-period LAP model in order to effectively plan and organize the trips of vehicles and containers.

The authors choice to present the following multi period model, whose objective function is:

$$\varphi = \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{t=1}^{T} c_{kl}x_{klpt} + \sum_{k=1}^{K} f_k y_k + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{t=1}^{T} c_p x_{lpiqt} + \sum_{l=1}^{L}\sum_{p=1}^{P} f_{lp}y_{lp} + \frac{h_p}{T}Val\left[\sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{t=1}^{T} ss_p x_{lpiqt} + \sum_{l=1}^{L}\sum_{p=1}^{P}\frac{(I_{lp,1}+I_{lp,T+1})}{2} + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{t=2}^{T} I_{lpt}\right] + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{t=1}^{T} c^i d_{li}x_{lpiqt} + \sum_{i=1}^{I}\sum_{q=1}^{Q} f_{iq}y_{iq} + \frac{h_q Val}{T}\left[\sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{j=1}^{J}\sum_{t=1}^{T} ss_q D_{jt}x_{iqjt} + \sum_{i=1}^{I}\sum_{q=1}^{Q}\frac{(I_{iq,1}+I_{iq,T+1})}{2} + \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{t=2}^{T} I_{iqt}\right] + \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{j=1}^{J}\sum_{t=1}^{T} -c_q D_{jt}x_{iqjt} + \sum_{i=1}^{I}\sum_{q=1}^{Q}\sum_{j=1}^{J}\sum_{t=1}^{T} c_q^{II} d_{ij}D_{jt}x_{iqjt} \quad \text{Eq. 48}$$

The linear model is:

$$min\{\varphi\} \quad \text{Eq. 49}$$

$$\sum_{l=1}^{L}\sum_{p=1}^{P} x_{klpt} \leq y_k S_{kt} \quad \text{Eq. 50}$$

$$I_{lp,t} + \sum_{k=1}^{K} x_{klpt} = I_{lp,t+1} + \sum_{i=1}^{I}\sum_{q=1}^{Q} x_{lpiqt} \quad \text{Eq. 51}$$

$$I_{lp,1} = I_{lp}^{start} y_{lp} \quad \text{Eq. 52}$$

$$I_{lp,T+1} = I_{lp}^{fin} y_{lp} \quad \text{Eq. 53}$$

$$I_{lpt} + ss_p \sum_{i=1}^{I}\sum_{q=1}^{Q}\left(x_{lpiq,t-1} + x_{lpiq,t} + x_{lpiq,t+1}\right)/3 \leq I_p^{max} y_{lp} \quad \text{Eq. 54}$$

$$I_{lp,T} + ss_p \sum_{i=1}^{I}\sum_{q=1}^{Q}\left(x_{lpiq,T-1} + x_{lpiq,T}\right)/2 \leq I_p^{max} y_{lp} \quad \text{Eq. 55}$$

$$\sum_{i=1}^{I}\sum_{q=1}^{Q} x_{lpiqt} \leq y_{lp} W_{pt} \quad \text{Eq. 56}$$

$$\sum_{p=1}^{P} y_{lp} \leq 1 \quad \text{Eq. 57}$$

$$I_{iq,t} + \sum_{l=1}^{L}\sum_{p=1}^{P} x_{lpiqt} = I_{iq,t+1} + \sum_{j=1}^{J} D_{jt} x_{iqjt} \quad \text{Eq. 58}$$

$$\sum_{j=1}^{J} D_{jt} x_{iqjt} \leq y_{iq} T_q \quad \text{Eq. 59}$$

$$I_{iq,1} = I_{iq}^{start} y_{iq} \quad \text{Eq. 60}$$

$$I_{iq,T+1} = I_{iq}^{fin} y_{iq} \quad \text{Eq. 61}$$

$$I_{iqt} + ss_q \sum_{j=1}^{J}\left(D_{j,t-1} x_{iqj,t-1} + D_{j,t} x_{iqj,t} + D_{j,t+1} x_{iqj,t+1}\right)/3 \leq I_q^{max} y_{iq} \quad \text{Eq. 62}$$

$$I_{iq,T} + ss_q \sum_{j=1}^{J}\left(D_{j,t-1} x_{iqj,T-1} + D_{j,t} x_{iqj,T}\right)/2 \leq I_q^{max} y_{iq} \quad \text{Eq. 63}$$

$$\sum_{q=1}^{Q} y_{iq} \leq 1 \quad \text{Eq. 64}$$

$$x_{iqjt} d_{ij} \leq d_q^{max} \quad \text{Eq. 65}$$

$$D_{jt} \leq m_{jt} D^{max} \quad \text{Eq. 66}$$

$$D_{jt} \geq D^{max} (m_{jt} - 1) \quad \text{Eq. 67}$$

$$\sum_{i=1}^{I}\sum_{q=1}^{Q} x_{iqjt} = m_{jt} \quad \text{Eq. 68}$$

$$x_{klpt}, x_{lpiqt} \geq 0; \quad \text{Eq. 69}$$

$$y_k, y_{lp}, y_{iq}, x_{iqjt}, m_{jt} \in \{0,1\} \quad \text{Eq. 70}$$

$$I_{lpt}, I_{iqt} \geq 0 \quad \text{Eq. 71}$$

where (only new introduced terms and parameters are defined[1]):

$t \in \{1,,T\}$	units/periods of time	*[u.t]*
I_{lp}^{start}	storage quantity, inventory level, at the beginning of period 1 in the DC of type *p* and located in *l*. It does not include SS.	*[ft²]*
I_{lp}^{fin}	storage quantity, inventory level, at the end of period *T* in the DC of type *p* and located in *l*.	*[ft²]*
I_p^{max}	maximum storage quantity in the DC of type *p*	*[ft²]*

[1] Several parameters and variables are now time dependent. For example S_{kt} is similar to S_k defined in Model I, but it depends on the unit of time *t*.

T_q	maximum handling capacity of the distributor of type q in the period T	*[ft²/year]*
I_{iq}^{start}	storage quantity, inventory level, at the beginning of period 1 in the distributor of type q and located in i. It does not include SS.	*[ft²]*
I_{iq}^{fin}	storage quantity, inventory level, at the end of period T in the DC of type q and located in i.	*[ft²]*
I_q^{max}	maximum storage quantity in the distributor of type q	*[ft²]*
h_q	holding unit cost factor in the period of time T for the distributor of type q	*[year⁻¹]*
Val	average unit product value	*[$/ft²]*
D^{max}	maximum admissible demand D_{jt}	*[ft²/u.t]*

The variables, which differ from the previously defined, are:

x_{klpt}	product quantity from the source k to the DC of type p located in l, in the period of time t	*[ft²/period]*
x_{lpiqt}	product quantity from the DC of type p in location l to the distributor of type q located in i, in the period of time t	*[ft²/period]*
x_{iqjt}	1 if the demand from customer j in the period of time t is supplied by the distributor of type q located in i; 0 otherwise	*[boolean]*
I_{lpt}	storage quantity in the DC of type p, located in l, at the beginning of the generic period t	*[ft²/period]*
I_{iqt}	storage quantity in the distributor of type q, located in i, at the beginning of the generic period t	*[ft²/period]*
m_{jt}	1 in case it is necessary to assign a demand point j to a distributor in the period of time t; 0 otherwise	*[boolean]*

Equations Eq. 50 and Eq. 57 control the equilibrium of flows through a generic nodes, as an inventory system able of receiving products, storage and ship them to its customers. In particular Eq. 50 refer to DCs equilibrium and Eq. 57 to the distributors' one. Constraints Eq. 58 limits the handling capacity of the generic distributor in the period of time T.

Equations Eq. 53 and Eq. 61 represent the storage capacity constraints respectively in DCs and distributors in accordance to the maximum admissible storage levels. Equations Eq. 54 and Eq. 62 refer to the last period T because the demand in $T+1$ is not known.

Equations Eq. 51 and Eq. 52 define the starting and final inventory levels for the DCs. Equations Eq. 67 guarantee the single sourcing hypothesis. Nevertheless the model can be update to admit multi sourcing suppliers in a generic period of time t.

The generic instance of this model can be made of thousands of variables, a large part of them boolean or integer. Consequently the problem can be unfeasible adopting a solver for optimal solution. A heuristic approach can be applied to obtain good and feasible solutions.

2.3.2. Short time planning and trips organization

This subsection illustrates a new approach to the planning activity of daily trips of containers/vehicles within the logistic network. It is based on Cluster Analysis and similarity based heuristic clustering algorithms as proposed by Statistics and properly modified by the authors to support the decisions of logistic managers. The generic strategic model or the operational model illustrated above can be considered as automatic and optimizing cost-based tools for the simultaneous location of plants/sources, distributors centers DCs and distributors in general, and the assignment of customers to the distributors, distributors to the DCs and so on.

This assignment activity can be consider *time based* when the strategic decision step is followed by the tactical/operational one supported by a model similar to that illustrated in subsection 2.3.1. For example in a generic period of time t_1, e.g. the month of February, the customer C can be assigned to the distributor d_1, while in the following period t_2, March, his/her demand can be supplied by the distributor d_2. Similar consideration can be drawn for the assignment of distributors to the DCs. In case only the strategic design is executed, as discussed in Section 2.2, the generic assignment is unique, i.e. no time dependent.

In general given a period of time t a set of customers is assigned to a distributor in accordance to the partition process of all customers with no zero demand in t. By this assignment it is possible to plan and organize the trips of vehicles within the logistic network in accordance to the daily demand and promised shipments dates to each customer. In particular this activity can be supported by the construction of the *dendrogram* as a result of the clustering activity of customers. The clustering can be executed by the adoption of heuristics inspired to the well known CLINK, SLINK, etc., and similarity indices, e.g.

Pearson or ad hoc measures of similarity between the items to group. The aim of this approach is to organize the shipments minimizing logistic costs, which are usually strongly related to the travelled distances and to the number of trips and containers travelling within system. For this reason the Pearson index reveals suitable because two customers located nearby can reasonably belong to the same cluster, i.e. the same trip (mission) of vehicles. By the use of the Person index in a clustering rule it is possible to generate disjunctive clusters respecting capacity constraints of vehicles and the maximum admissible distance in a single trip.

Consequently the clustering process defines new capacity constraint and time dependent assignments of customers to distributors. These groups of customers correspond to trips to be scheduled and sequenced.

Similar considerations refer to the organization of trips of vehicles and containers from the DCs to the distributors, by adopting one of the available transportation modes (train, road, etc.). The use of Cluster Analysis is particularly effectiveness in case the adoption of the *groupage transportation mode* typical of national transports, which differs from the *full-load transportation mode* generated/commissioned by a single customer.

In case the groupage mode is adopted entities to supply, e.g. the customers or distributors, are grouped in disjunctive clusters and each cluster is assigned univocally to a supplier, e.g. a distributor or a DC. Then a Travelling Salesman Problem (TSP) solver can be applied to construct the minimum Hamiltonian circuit which starts from the supplier, visits all demand points, and minimizes travelled distance.

The proposed approach to the strategic and tactical design, the operational planning and trips organization can be considered a reference and effective framework for developing a *capacity constraint scheduling tool for logistic distribution*.

2.4. Case study from tile industry

This section presents a significant case study which deals with a company producing and distributing tiles all over the world. The enterprise is made of several companies operating in different part of the world by the simultaneous use of production plants, distribution centers - DCs, warehousing systems, different transportation modes, distributors and branches, shops for the final customers, etc. The authors chose to concentrate the analysis to the US logistic distribution network. It results to be very complex by the activity of managing and controlling logistic flows of materials. The approach proposed in Section 2.2 has been applied to the optimization of the strategic configuration of the whole system as illustrated in Section 2.5.

Section 2.6 presents the results obtained by the application of the operational planning optimization, illustrated and proposed in Section 2.3, to this case study adopting the configuration of the network defined in the strategic decision step.

Figure 6 shows the supply chain structure of the US distribution system object of the case study to which the proposed strategic models and mixed integer programming solver have been applied (Section 2.4). We call this configuration AS-IS in order to distinguish it from different optimizing configurations. In particular the following levels and entities can be identified:

- raw materials suppliers;
- a US production plant located in Lawrenceburg, Kentucky;
- production plants of property in Europe. These plants are also warehousing systems for the storage quantities waiting to come to the USA network;
- other companies' production plants, e.g. located in Canada, Turkey, Spain, Italy, etc.;
- a DC, called also national distribution center – NDC. In AS-IS configuration there is only one central distribution center – DC which is located in Lawrenceburg;
- a set of independent distributors, called "independent";
- a set of property distributors, called "branches";
- a large number of customers.

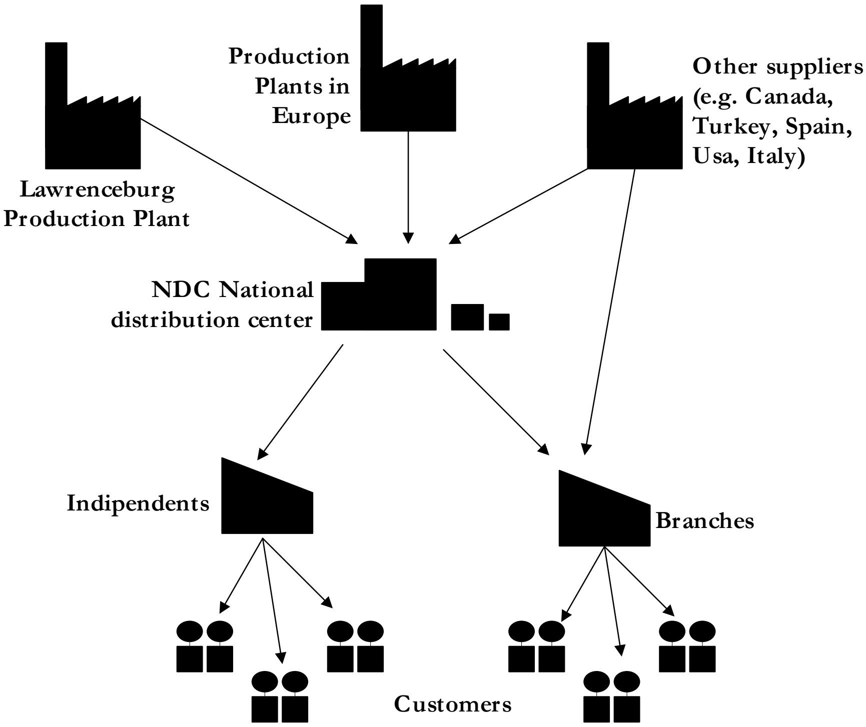


Figure 6: As is configuration - Supply Chain

Figure 7 presents the statistical distribution of annual customer demand of products as *[ft²/year]* of tiles. Figure 8 presents the trend of the week sales for independents and branches, Figure 9 the statistical distribution of demand for each US county.

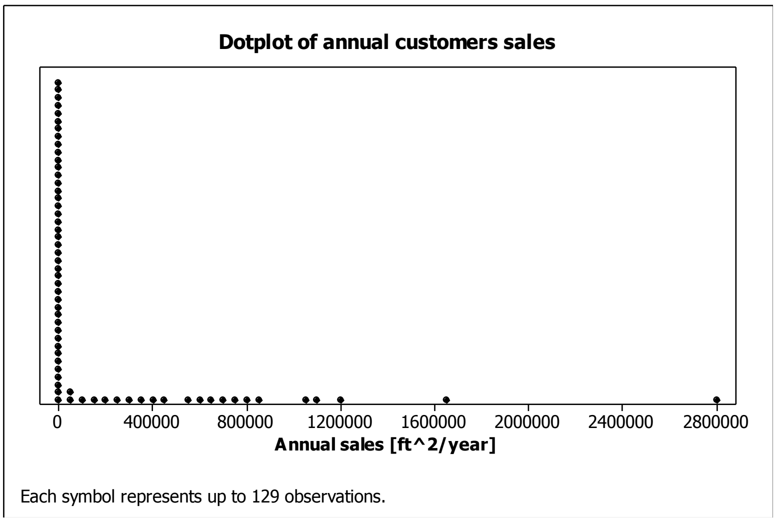


Figure 7: Annual customer demand distribution

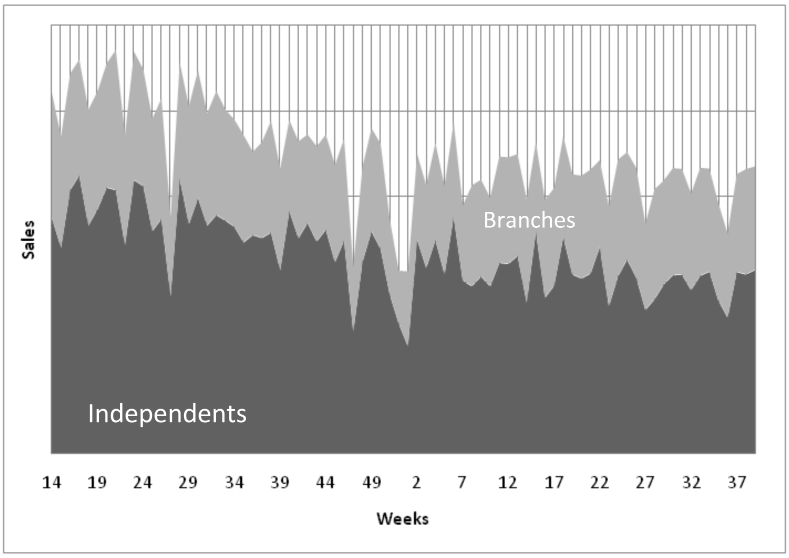


Figure 8: Week sales for independent distributors and "branches"

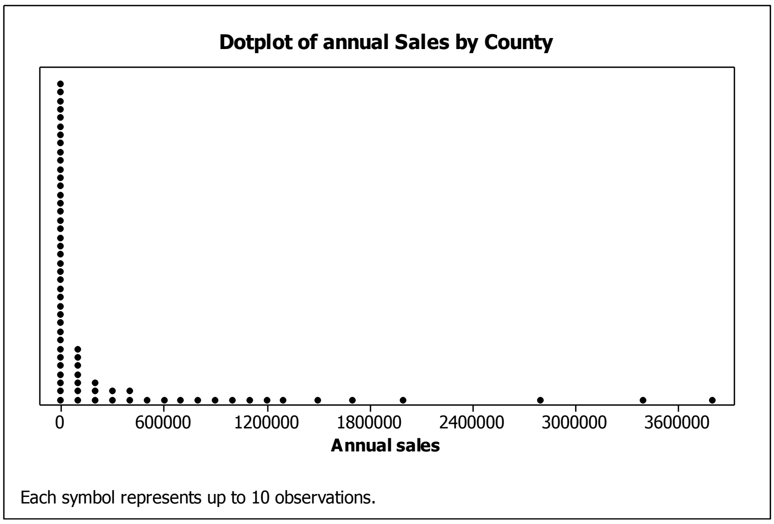


Figure 9: Annual sales by county

2.5. Strategic design, case study

A brief presentation and discussion of main results obtained by the application of the strategic models to the case study object of this manuscript is reported in this section.

2.5.1. Model I

The first strategic model, Model I, for the design of the logistic network is:

- *Single period.* The planning time period is one year;
- *Single product.* The number of different items of product is about 2000. Nevertheless the common unit of measure is the square foot, i.e. ft^2. Consequently the authors adopted this measure of product without distinguishing the specific items produced and/or distributed during the year;
- *Multi-level.* 4 different kinds of levels have been modelled: suppliers/sources, national distribution centers (DCs), distributors and points of demand. In AS/IS configuration the whole production passes through the unique DC. The point of demand corresponds to a county and not the single customer/consumer because the number of active, i.e. interested by a non null annual demand, customers is more than 5700. The number of active counties is about *2400*[2], each univocally identified by a ZIP (Zoning Improvement Plan) code. But the number of significant, in term of significant annual demand, counties is *464* if only those counties with annual demand over *1000* ft^2 are considered. The number of distributors as branches is about *25*, while the number of independents is about *160*.
- *Single sourcing.* The demand from a point of demand can be supplied by only one distributor.
- *Single channel.* The transportation mode from two entities of different levels (e.g. from a DC to a distributor) is unique, that is the travelling unit cost is unique.

The instance representing the case study is made of 2 sources, 168 distributors, 464 points of demand, 78291 variables and 803 constraints. In this model the typology of distributor is consider, consequently the annual fixed cost of using an independent differs from a more expensive branch.

The first system configuration which results by the application of the mixed-integer linear Model I is called AS–IS_I. In AS–IS_I all 25 branches are supposed to be available and are forced to be open: no independent distributors are available because Model I does not support different kinds of distributors.

A second configuration is the result of the optimization of the system when all 168 distributors, branches and independents, are available: this is the TO–BE_I configuration.

[2] The U.S. Census Bureau counts 3141 counties in the U.S.A.

However branches cannot be distinguished by independents: it is necessary to apply the strategic Model II.

Both AS–IS_I and TO–BE_I configurations serve the whole number of "significant counties" equal to 464.

The solutions proposed by the solver are illustrated in detail in Table 1. All costs are reported in a generic unit of measurement named [u.c.], which stands for unit of cost, because permission to reveal the real values in dollars and to publish the results obtained by the optimization process was withheld by the tile company.

	AS-IS_I	**TO-BE_I**
VARIABLE PRODUCTION COSTS	67,729	67,729
FIXED PRODUCTION COSTS 16,010 16,010	16,010	16,010
VARIABLE HANDLING COSTS IN DCs 2575 2575	2575	2575
FIXED COSTS IN DCs 10,056 10,056	10,056	10,056
TRANSPORTATION COSTS DCs – distributors 11,538 11,736	11,538	11,736
FIXED COSTS distributors 42,384 16,283	42,384	16,283
VARIABLE COSTS distributors 139 370	139	370
TRANSPORTATION COSTS distributors – demand points 23,283 29,188	23,283	29,188
TOTAL COST 173,714 153,947	173,714	153,947
Number of demand points 464 464	464	464
Number of DC kept open 1 1	1	1
Number of distributors kept open 25 10	25	10
Number of distributors available 25 168	25	168

Table 1: Case study: strategic Model I, costs in [u.c.].

Figure 9 illustrates the geographic location of the DC in Kentucky and the locations of the distributors kept open in AS-IS_I (all dots black and light colour) and TO-BE_I configurations (light colour dots): black dots correspond to distributors kept closed by the new logistic network. The number of DCs remains one and in particular its location is still in Lawrenceburg.

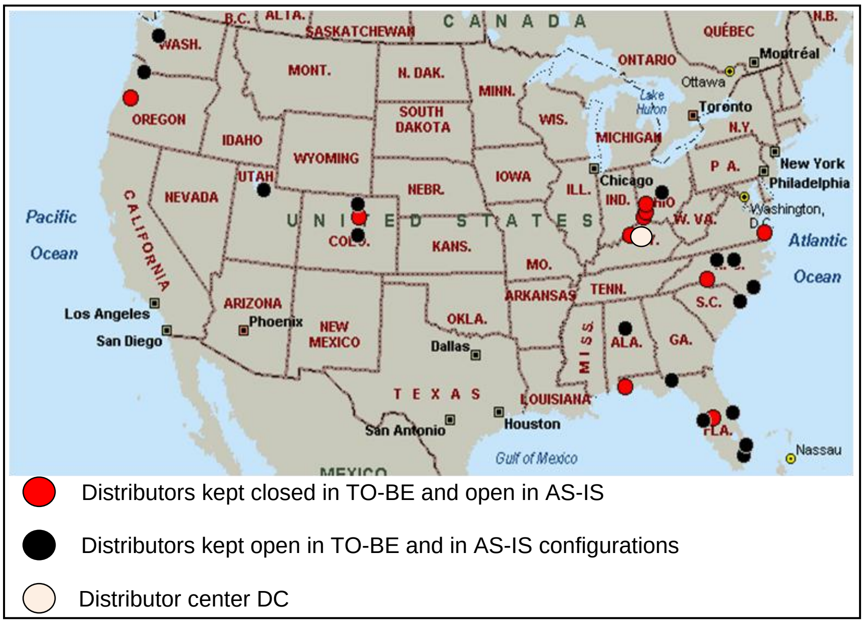


Figure 10: Strategic Model I, distributors in AS-IS and TO-BE configurations

2.5.2. Model II

The second strategic model, Model II, can distinguish different kinds of distributors, e.g. independents and branches, little and big ones, each one with a capacity expressed in millions of square feet of products and with a specific transportation unit cost. By the introduction of these new hypotheses and assumptions it was necessary to recalculate the performance and costs associated to the AS-IS configuration of the network which differs from AS-IS$_I$. The obtained values can be compared with those obtained by the application of the solver to the mixed integer programming model introduced in section 2.3: for this purpose different operating scenarios have been evaluated. The solver, given the model and the parameterization representing the operating scenario, finds the best values of all free variables and quantifies the minimum logistic costs as reported in Table 2

By the evaluation of the AS-IS configuration, called also "actual", the following main results have been obtained: the number of really used branches is 21 on 25 available and open, while the number of independents distributors kept open and used is only 11 on 143 available and open.

The first optimized configuration, called TO-BE$_{II,1}$, is the result of the availability of "actual" DCs, branches and independents distributors. The distributors are 168 (i.e. 143+25), but only 11 branches and 11 independents are kept open demonstrating that the AS-IS capacity of the distribution network is actually greater than the real need. The second solution, called TO-$BE_{II,2}$, is based on the actual availability of DCs but the number, location and type of distributors is free. A third solution, called TO-$BE_{II,3}$, refers to the actual configuration of the distributors' network, but the location (3 available) and type (2 available) of DCs are subject to the solver's best choices. Finally a fourth solution, TO-$BE_{II,4}$, is the result of the choice of the best type and location of both DCs and distributors. This solution reduce the global costs of about 22% if it is compared with AS-IS_{I}.

	AS-IS_{II}	TO-$BE_{II,1}$	TO-$BE_{II,2}$	TO-$BE_{II,3}$	TO-$BE_{II,4}$
VARIABLE PRODUCTION COSTS	67652	67652	67652	66510	66510
FIXED PRODUCTION COSTS	16009	16009	16009	16009	16009
VARIABLE HANDLING COSTS IN DCs	2573	2573	2573	2966	2966
FIXED COSTS IN DCs	10055	10055	10055	11173	11173
TRANSPORTATION COSTS DCs - distributors	12760	13005	12308	10722	10530
FIXED COSTS distributors	39037	18369	16008	18369	16775
VARIABLE COSTS distributors	8873	10503	1651	10320	1769
TRANSPORTATION COSTS distributors - demand points	22889	23363	16388	23545	15286
TOTAL COST	179853	161533	142649	159618	141022
number of demand points	464	464	464	464	464
number of DC kept open	1	1	1	2	2
number of available DC	1	1	1	3	3
number of used distributors	33	22	15	22	16
number of distributors kept open	168	22	15	22	16
number of available distributors	168	168	168	168	168

Table 2: Strategic Model II, case study

Figure 10 presents the network configuration TO-$BE_{II,4}$ based on two DCs which are represented by the dots in figure, one in Kentucky and the second in Georgia. Light colour squares represent the independent distributors, mainly located on the west of USA, coloured/grey big squares represent the "big branches" and finally coloured/grey little squares represent "little branches".

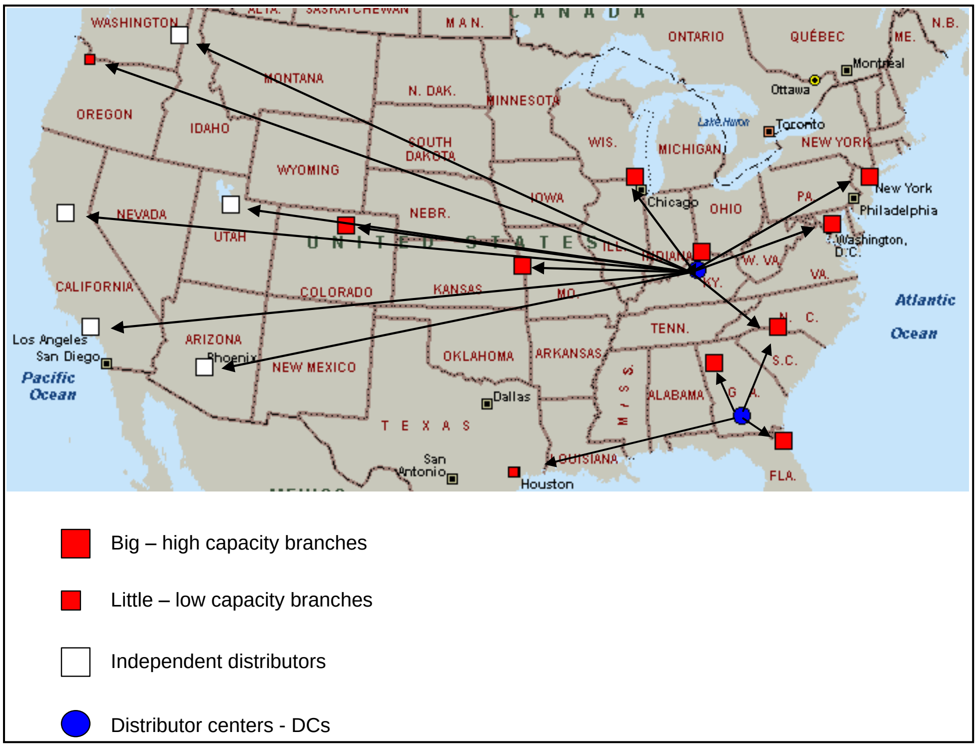


Figure 11: Strategic Model II, TO-BEII,4 configuration

2.5.3. Model III

This model is able to quantify the storage cost of warehousing systems and also the cost of transportation due to the use of containers with different capacity through different transportation modes. Before the illustration of exemplifying results obtained by different parameterizations of the model and similarly to those discussed in Sections 4.1 and 4.2, Figure 12 presents the trend of the average cost of transportation due to containers for different values of shipments in a week. This cost depends on the customer service level by the introduction of the term “number of shipments in a week”. In particular this dependency is explicit till this term generates a good saturation of the adopted minimum number of containers travelling from the DC to one or more distributors in a trip.

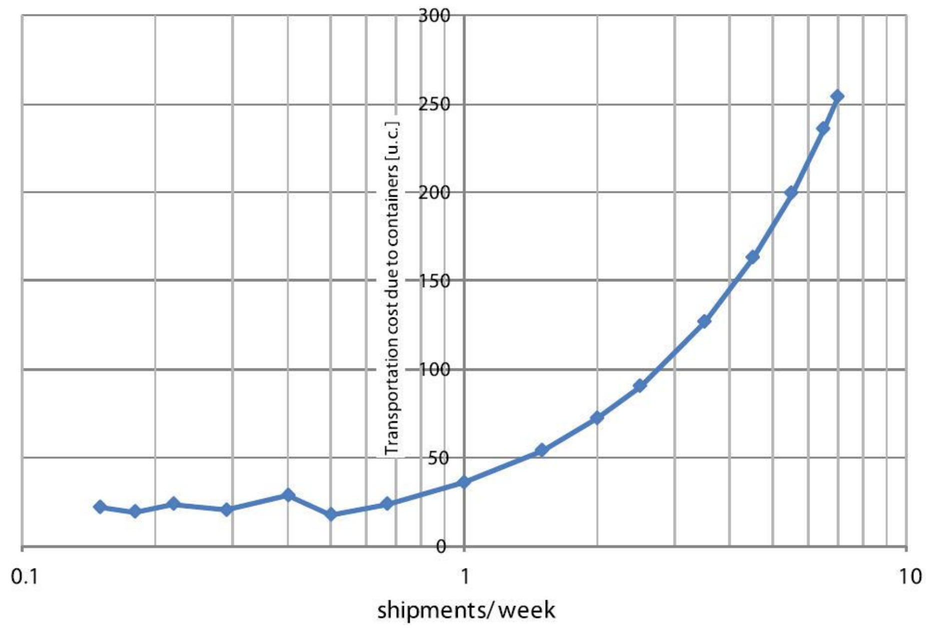


Figure 12: Container costs in [u.c.] from DC to distributors for different service levels (shipments/week).

The introduction of new hypotheses and assumptions need to re-simulate the AS-IS configuration whose main performance are reported in Table 3: the authors call this scenario AS-IS_{III}. This table presents also the result obtained by simulating a new system parameterization, called TO-$BE_{III,1}$, in presence of 22 distributors (11 branches and 11 independents) and 462 points of demand. The solver can open or close the available distributors as it prefers but the DC is located in the same location of the "actual" scenario. The number of used distributors proposed by the optimal solution is 20. Then a set of alternative scenarios based on different hypotheses on service level have been evaluated: the location of the DC is supposed to be the "actual". The customer service level can be controlled by the time between two consecutive shipments to a distributor, as previously illustrated in equation (24). In particular the following new scenarios have been introduced and evaluated:

Worst, TO-$BE_{III,2}$. It is based on a time between two consecutive shipments four times the standard configuration (i.e. AS-IS and TO-$BE_{III,1}$). Given a generic branch, this hypothesis corresponds to a safety stock (SS) of about 40% of the mean demand quantified in a fulfilment period.

Bad, TO-$BE_{III,3}$. It is based on a time between two consecutive shipments two times the standard configuration (i.e. AS-IS and TO-$BE_{III,1}$). It corresponds to a SS of about 150% of the mean demand quantified in a fulfilment period.

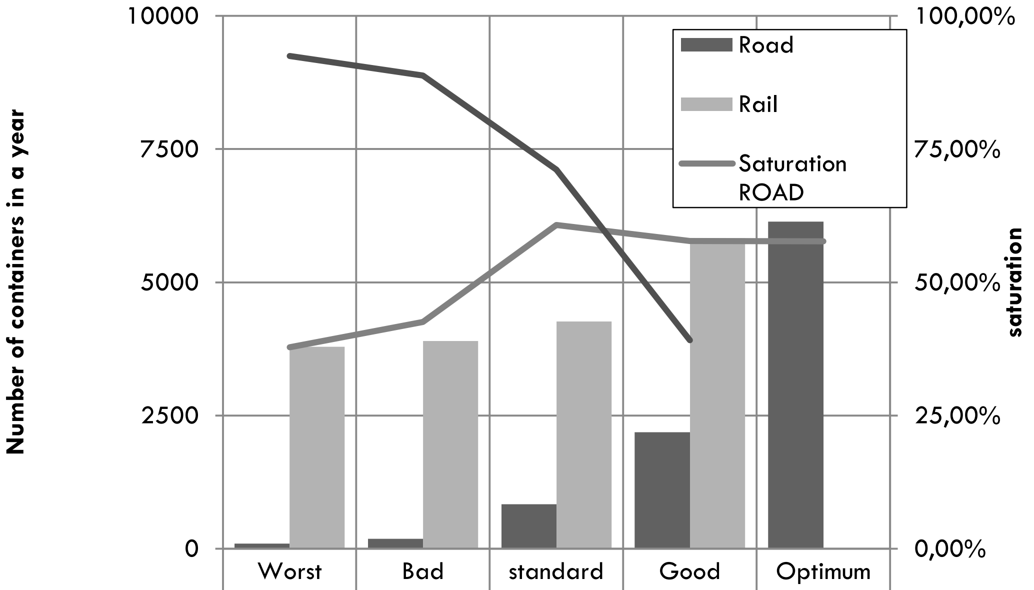
Good, TO-BE$_{III,4}$. It is based on a time between two consecutive shipments an half of times adopted in the standard configuration (i.e. AS-IS and TO-BE$_{III,1}$). The SS is about 3 times the mean demand.

Optimum,TO-BE$_{III,5}$. It is based on time between two consecutive shipments an half of times adopted in the standard configuration (i.e. AS-IS and TO-BE$_{III,1}$). The SS is about 4 times the mean demand.

	AS-IS$_{III}$	TO-BE$_{III,1}$	TO-BE$_{III,2}$	TO-BE$_{II,3}$	TO-BE$_{II,4}$	TO-BE$_{II,5}$
VARIABLE PRODUCTION COSTS	67652	67652	67652	67652	67652	67652
FIXED PRODUCTION COSTS	16009	16009	16009	16009	16009	16009
VARIABLE HANDLING COSTS IN DCs	2573	2573	2573	2573	2573	2573
FIXED COSTS IN DCs	10055	10055	10055	10055	10055	10055
STORAGE/HOLDING COST DC level	2719	2719	2719	2719	2719	2719
TRANSPORTATION COST I DCs – distributors	12141	7451	7133	7272	8174	12319
TRANSPORTATION COST II DCs – distributors	2367	3442	2700	2825	5287	3427
FIXED COSTS distributors	39037	18369	18369	18369	18369	18369
VARIABLE COSTS distributors	8702	10508	10538	10784	11010	10351
STORAGE/HOLDING COST distributors level	701	661	951	1052	458	298
TRANSPORTATION COSTS distributors - demand points	23006	23357	23330	23096	22944	23514
TOTAL COST	184968	162801	162035	162412	165255	167292
number of sources	2	2				
number of demand points	464	464				
number of DC kept open	1	1				
number of available DC	1	1				
transportation modes	2	2				
number of used distributors	33	20				
number of distributors kept open	168	22				
number of available distributors	168	168				

Table 3: Strategic model III, case study.

By Table 3 the global cost does not change significantly passing from a system configuration to another. In particular the "Optimum" cost is +2.76% if compared with the "Standard", while the "Worst" cost is -0.47% when compared with "Standard". Figure 13 reports the number of containers for all system configurations and for different transportation modes. The mean saturation levels of the container are also quantified. In the Optimum configuration the use of road is preferred to the use of rail which reveals better when the customer service level is lower.



	Worst	Bad	standard	Good	Optimum
Road	97,5	182	832	2184	6136
Rail	3789,5	3900	4264	5824	0
Saturation ROAD	37,80%	42,53%	60,76%	57,73%	57,70%
Saturation RAIL	92,46%	88,80%	71,18%	39,14%	

Figure 13: Strategic model III. Number of containers and saturation levels

Similarly to what illustrated when discussing about Model I and Model II, it is possible to run the mixed integer linear solver to find the best configuration of the distribution system in presence of a larger number of available DCs and distributors, in order to find their best locations and minimize global costs.

2.6. Operational management optimization, case study

To reduce the problem complexity it can be useful to accept a few of the locations and assignments generated by the strategic planning step illustrated in Section 2.2: this can significantly reduce the number of problem' variables.

Figure 14 exemplifies the trend of the cycle and SS levels in a DC for the period of time *T* made of 7 weeks. The cycle stock is the portion of stock available, or planned to be available, in a given period, excluding excess stock and SS.

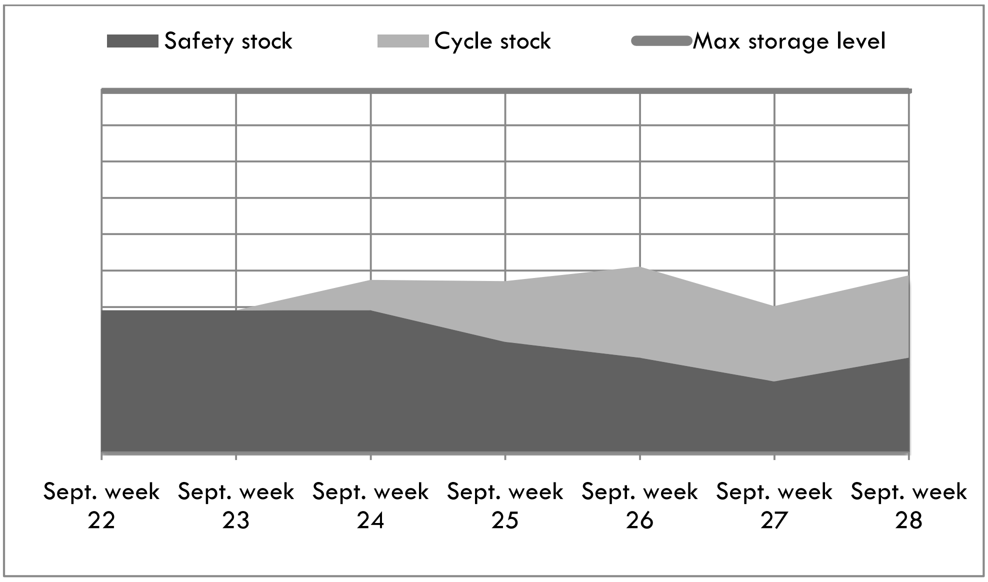


Figure 14: Cycle and safety stock levels by the operational mixed integer model. Case study

Figure 15 illustrates the location of counties as no zero demand points given a period of time *t* corresponding to an exemplifying week. Different colours correspond to different distributors assignments. Consequently it can be used as the input for the definition of trips of vehicles from distributors to customers points of demand by conducting a Cluster Analysis and applying clustering heuristics.

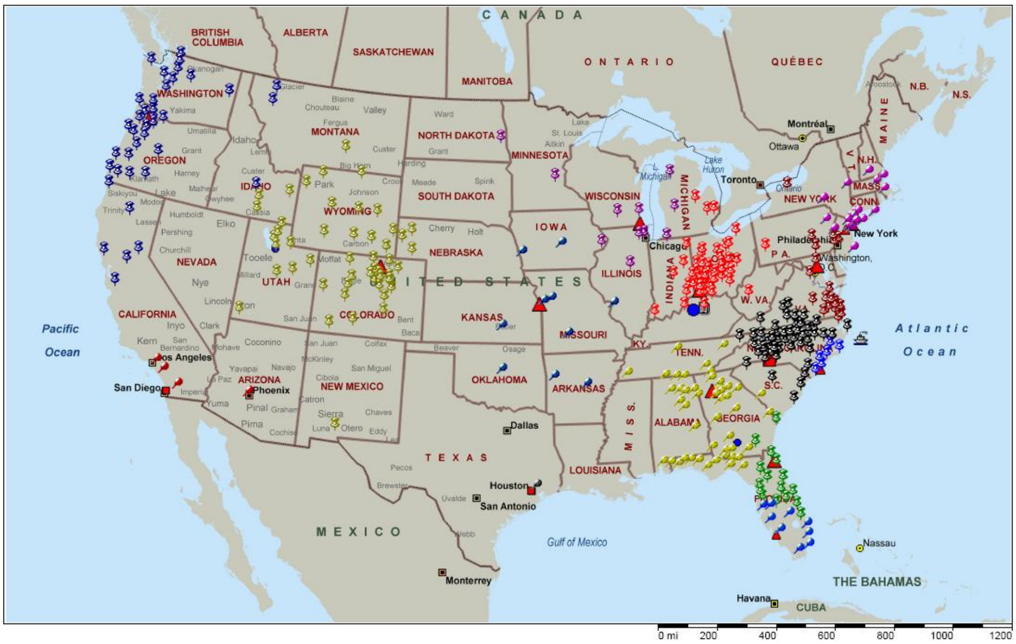


Figure 15: Location and allocation of counties in a period of time t. Case study. Microsoft® MapPoint

Figure 16 exemplifies the dendrogram generated by the application of the Complete Linkage algorithm to the matrix of similarity indices between the no zero points of demand Zip Codes supplied by a "distributor branch" located in Maryland. By selecting a threshold limit value of similarity corresponding to a maximum admissible distance between two members of the same cluster it is possible to identify the set of disjunctive trips, i.e. clusters. In particular Figure 16 propose to cut the dendrogram at 200 miles generating 4 groups, all supplied by Maryland branch. The groups are identified by the Zip Codes clustered in accordance to the different line formats and colours as reported in Figure 16.

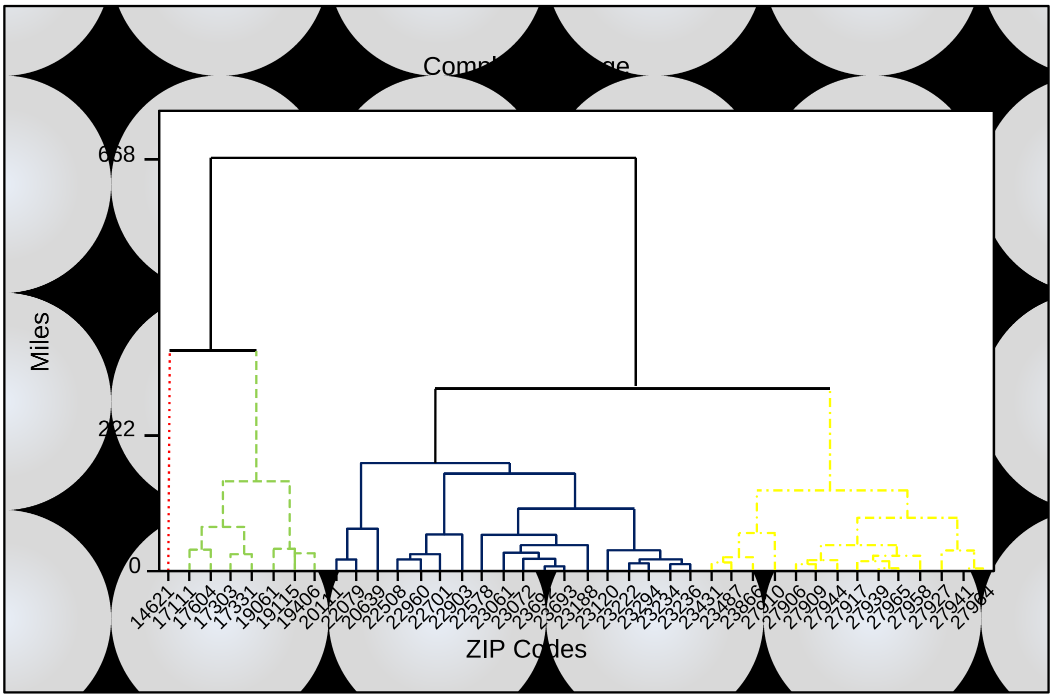


Figure 16: Dendrogram, threshold value equal to 200 miles. Case study.

Figure 16 exemplifies the identification of the minimal Hamiltonian circuit generated by the application of a TSP procedure to a group of locations whose Zip Codes are reported in Figure 15 from 23487 to 27964 and identified by the yellow colour. Similarly all trips planned in a period of time can be organized in terms of the number of containers and vehicles and the roads to travel in the geographic map.

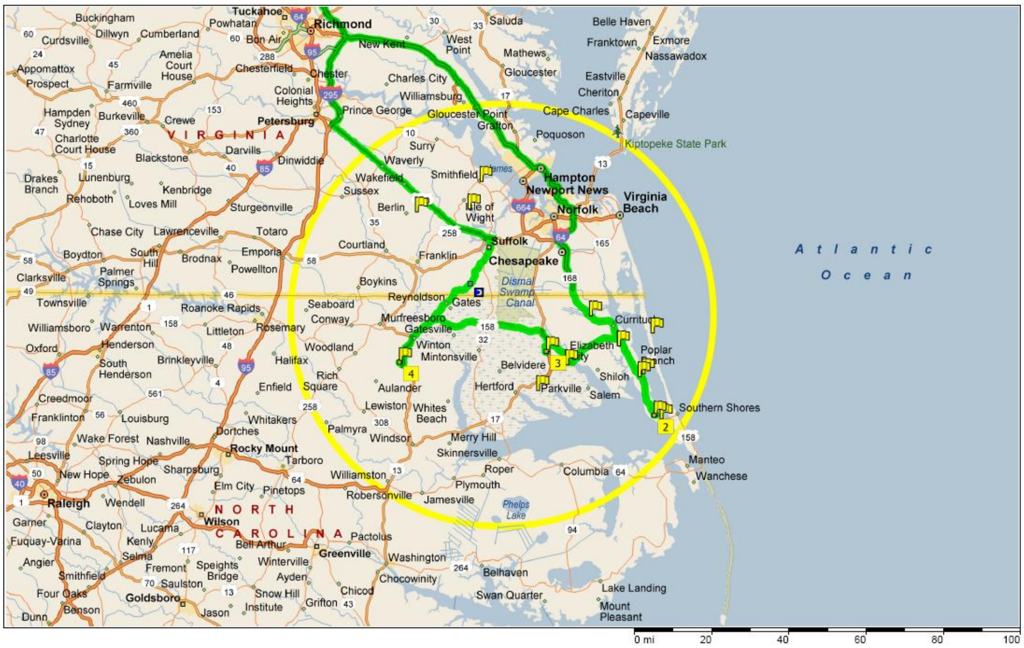


Figure 17: Hamiltonian circuit – TSP for a cluster nearby Norfolk. Microsoft® MapPoint

2.7. Conclusion and further research

This study propose a new effective approach for the integration of managers decisions regarding the configuration of a logistic network, the number and locations of facilities, e.g. DCs, distributors, production plants, raw materials sources, etc., the allocation of the generic demand points to the available suppliers, the choice of transportation modes, and the optimization of trips and vehicles/containers loading across roads, railways and other available transportation infrastructures. Actually literature does not present studies discussing models and methods to integrate effectively and efficiently all these decisions. This approach proposed and exemplified by the authors reveals an effective framework for developing further research in this field. In particular new models, methods and applications are achieved also integrating other crucial activities and decisions affecting the performance of a logistic system. A few examples are: vehicles loading and scheduling, reverse logistics decisions, etc., in conjunction to the access to the multi modal transportation modes, GPS technologies, identification platforms for the traceability of products and in general to all technologies and resources for supporting the synchronous management and control of logistics activities. This ambitious perspective is going to integrate the activities of planning, design, executing, management, control, and optimization in general of multi echelon and multi level production distribution systems operating worldwide.

3. A tool for the strategic, operational and tactical design of a distribution network

This chapter presents a tool for the design, planning, managing and control of a multi-level multi-period supply chain distribution network. This problem involves a very large number of interrelated decisions, including facility location, demand allocation, capacity, inventory, production, routing, and transportation modes. Optimality cannot be guaranteed with full integration of all these decisions (Melo et al. 2009): the proposed approach and models implemented by LD-LogOptimizer help the manager to find feasible solutions closed as possible to the optimality.

Actually, the proposed automatic platform for the full integration of management decisions in SCM does not yet consider planning decisions on reverse logistics and recovery activities. The introduction of a new layer, we call level, of disposal facilities is necessary in further development of the platform. Then the introduction and control of intra-layer flows is achieved.

Finally new models and tools to best optimize the decisions both in strategic planning, tactical planning and operational planning activity are achieved. To this purpose, the application of LD-LogOptimizer to significant case studies and the definition of new experimental analyses are also achieved.

Figure 18presents the main menu of the automatic platform LD-LogOptimizer for the execution of the strategic planning. It does not differ from the main menu of the tactical planning. This menu introduces a few basic network settings:

- Number of products. It can be 1 and we obtain the single product optimization problem, otherwise the problem is called multi product;
- Number of periods. It can be 1, the so called single period optimization problem, or greater, the multi period problem. In particular, the multi period problem is called dynamic in case a lot of time periods are modelled (Manzini et al. 2008). Consequently, a dynamic model can support logistic managers to take operational decisions such as "which the best allocation of the demand of product X in the unit time period t, e.g. a week, to the available set of suppliers, e.g. DCs, distributors, wholesalers, etc.?
- Number of stages. It can be up to 3 which corresponds to 4 levels, including the production (or source) level (named Plant), made of production plants and/or raw materials suppliers, the central distribution centers - CDC level, the distributors level (regional distribution centers - RDCs), made of branches, shops and wholesalers, and finally the customers level, made of the point of demands (Pods). The generic production plant can be also a distribution plant, i.e. a warehousing system supported by material handling devices and storage/retrieval systems.
- Demand typology. It is fractionable or nonfractionable: fractionable in case the demand coming from a demand point in a unit time period can be supplied by more than one supplier; nonfractionable in presence of only one supplier given a demand quantity.

These settings significantly influence the dimension of the instance to be solved, the complexity of the optimization problem and the availability/unavailability of effective solving techniques and tools, e.g. the mixed integer programming, heuristic algorithms, the clustering analysis, etc. (Manzini and Bindi, 2009). For example in presence of 5 products, a planning period of time made of 52 time units, i.e. 52 weeks for one year, 1000 customers and 30 wholesalers, there are at least 7,800,000 variables which refer to quantities (material flows) for each product from the generic supplier to the generic demand point in each unit time period. Then it is necessary to introduce many thousands of boolean variables which refer to the use/activation (or the non activation) of the available facilities (e.g. production plants, distribution centers, distributors, etc.) and the determination of their best geographical location.

LD-LogOptimizer interactively supports the user to find the optimal solution to the optimization problem or to find the best solution assuming a few simplifications, which reduce the original computational complexity of the problem and the related solving time increasing the efficiency of the decision, i.e. the time the solver finds the optimal solution.

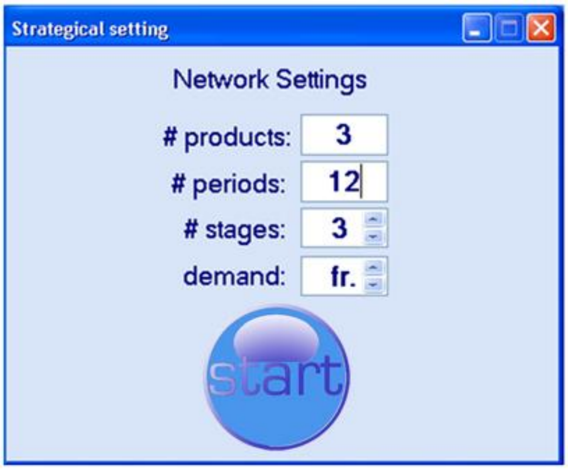


Figure 18: Main network settings. Data entry

The following sections presents the approach proposed and applied by LD-LogOptimizer by the illustration of a few forms of the tool when applied to a case study of a multi-echelon production distribution system operating in USA.

3.1. Strategic planning module

The terms network design and SC network design are usually synonymous of strategic supply chain planning. The strategic level deals with decisions that have a long-lasting effect on the firm (Simchi-Levi et al. 2004).

Melo et al. (2009) classify the literature on strategic planning in accordance with some typical SC decisions: capacity decisions, inventory decisions, procurement decisions, production decisions, routing decisions, and the choice of transportation modes. Additional features of facility locations models in SCM environment are: financial aspects (e.g. international factors, incentives offered by governments, budget constraints for opening and closing facilities), risk management (uncertainty in customer demands and costs, reliability issues, risk pooling in inventory management), and other aspects, e.g. relocation, bill of material (BOM) integration, and multi period factors. To avoid sub-optimization, these decisions should be regarded in an integrated perspective (Melo et al. 2009).

Object of a strategic planning, i.e. the strategic design and optimization of a production-distribution logistic system, is the determination of the best location of production/distribution facilities, the allocation of customer demands, i.e. the activation (non activation) of links and flows between two generic entities of different levels, e.g. a central DC and a regional DC. Other decisions deal with the determination of the best handling and storage capacities of the available set of production and/or distribution facilities. The adopted model is generally single period in order to minimize the complexity of the decision problem and to refer to a long-term planning horizon (e.g. 3-5 years).

Figure 19 illustrates the strategic input data opening process in detail. In particular, data on Plants, CDCs, RDCs, Pods, transportation modes and vehicle specifications are necessary. All input data can be saved and open as part of one project that is associated to an instance of the optimization problem, i.e. to a specific logistic network.

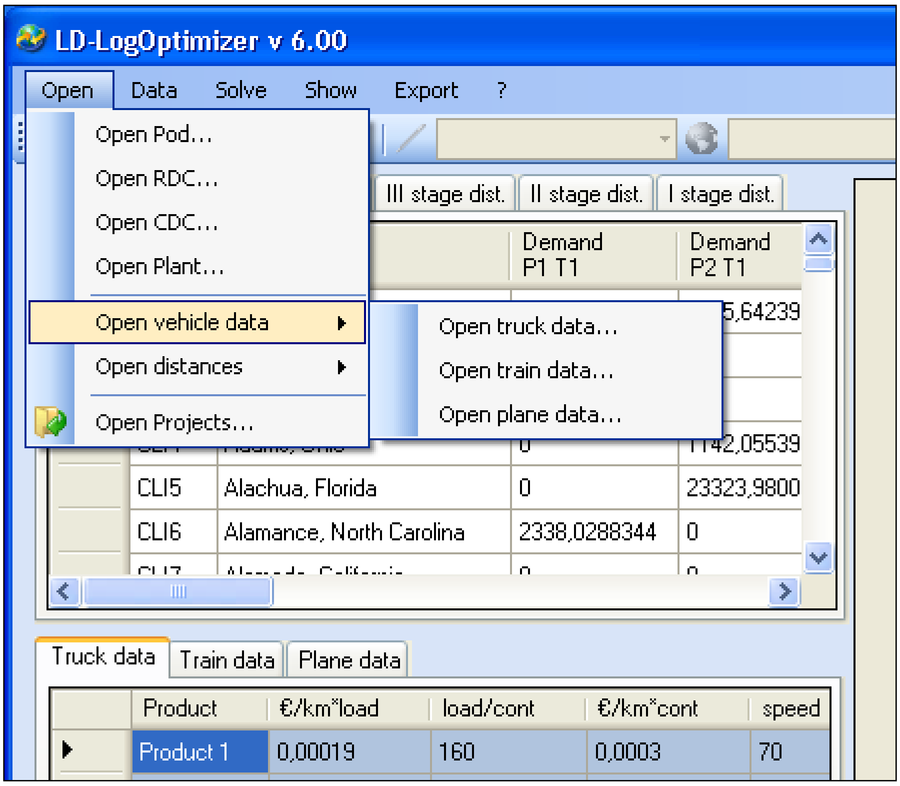


Figure 19: Data entry, open task

Figure 20 illustrates the summary form for the strategic design and optimization in LD-LogOptimizer: all available facilities and entities (CDCs, RDCs, Pods and Sources/Plants), called “points of interest” find their locations on a geographical map. Minimum distances and/or travelling times between all couples of locations are also quantified. LD-LogOptimizer faces the problem of designing the distribution network by modelling it as a mixed integer linear programming (MILP) problem. LD automatically generates an instance of the optimization problem and tries to solve it by the application of a linear solver.

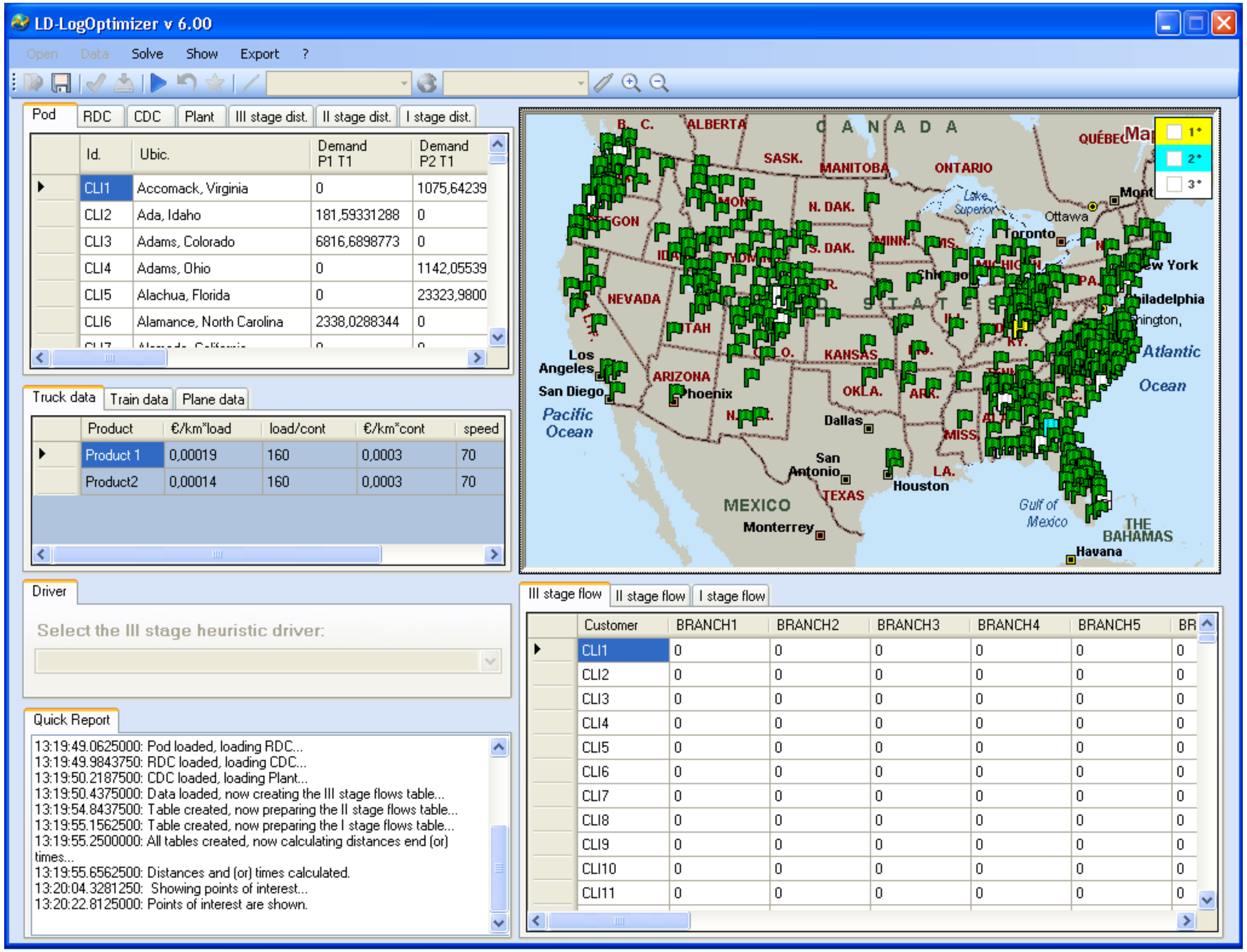


Figure 20: Strategic design set up

In case the solver fails to find the optimal solution in accordance with the solving time as expected by the user, it is possible to choose for a set of available heuristic approaches to find admissible solutions to the optimization problem more quickly. In particular, the user can choose a rule from a set of original heuristics, presented in subsection 3.1, to solve the assignment of customers, i.e. the points of demand - Pods, to the available RDCs (see the tab named "Driver" in Figure 5). In fact, the proposed constructive and greedy rules operate on the last stage of the network, which usually counts a lot of facilities and a large number of possible assignments. This stage is generally supposed to be supplied by one transportation mode, the road, and consequently there is not the problem of choosing the best transportation mode among a set of available ones.

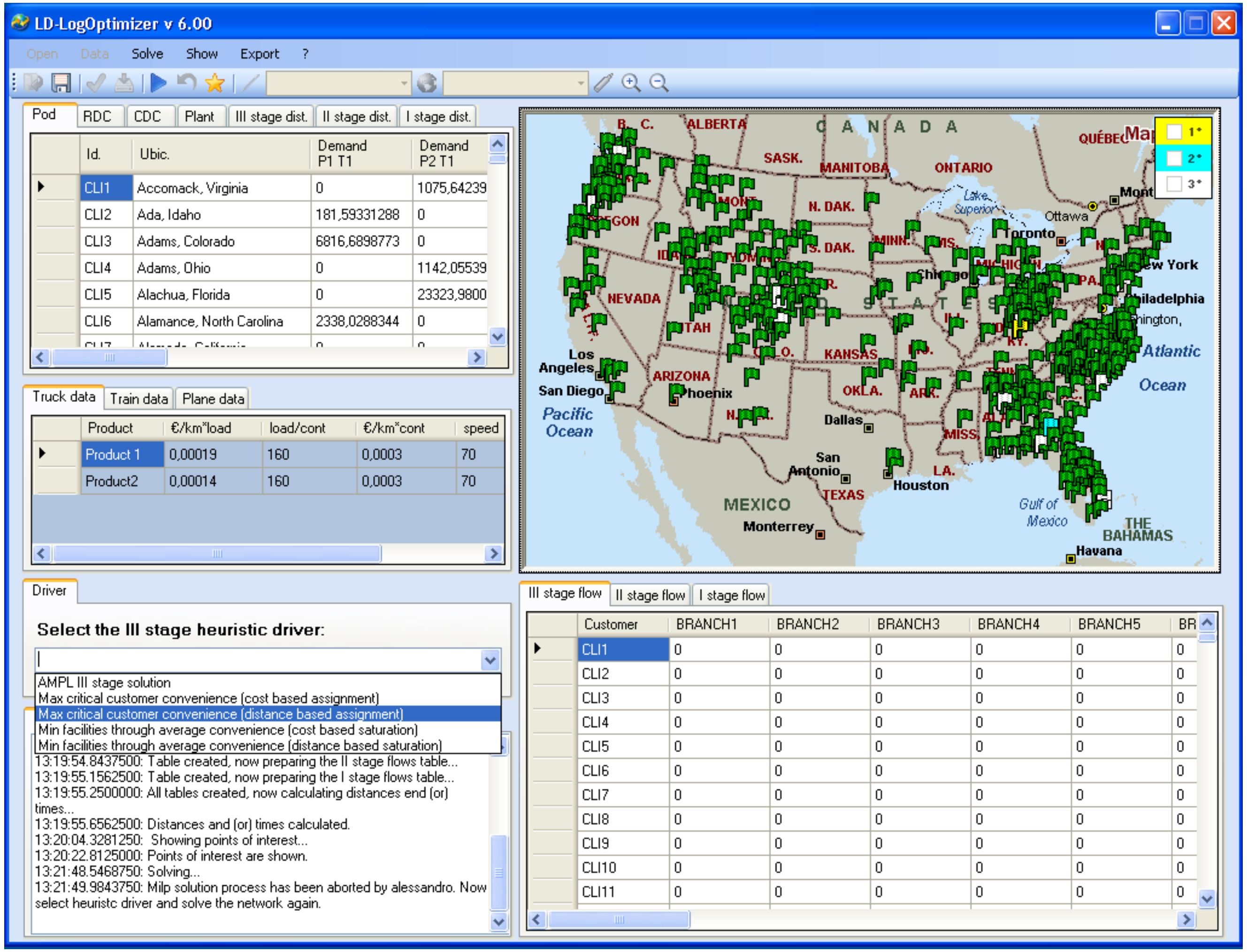


Figure 21: Heuristic driver selection.

3.1.1. Heuristic rules for the assignment of customers demand to the RDC level

A brief illustration of the main decision steps executed by the heuristics to reduce the computational complexity of the original MILP strategic model follows. These rules (see the "Driver" tab in Figure 21 named "Select the III heuristic driver:") are implemented by the platform LD-LogOptimizer.

- *Max critical customer convenience (cost based assignment).*

  This rule is focused on customers. The customer demand is supposed to be fractionable.

  Step 1. In presence of more than one product demand. The product with highest demand is selected. This is the most critical product.

  Step 2. Given the most critical product. All customers are ordered in descending order of the product demand.

  Step 3. Given the customer with the greater value of demand, the available RDC, i.e. the RDC with available capacity, are ordered in an ascending order in accordance to the following measures.

  in case the RDC is not yet activated, the adopted measure of cost is:

$$f^{RDC} / PC^{RDC} + c_{RDC,i}^{load,3°lev} + v^{RDC} \quad \text{Eq. 72}$$

Where:

f^{RDC}	fixed operating cost using the RDC. The unit of measure is [$/year] when the single period of time is one year;
PC^{RDC}	maximum admissible handling capacity of the RDC in the single period of time. The unit of measure is [load/year];
v^{RDC}	variable unit cost of handling, [$/load];
$c_{RDC,i}^{load,3rd\ stage}$	variable unit cost for the transportation of the one load from the RDC to the Pod i.

in case the RDC is already activated, the adopted measure of cost is:

$$c_{RDC,i}^{load,3rd\ stage} + v^{RDC} \qquad \text{Eq. 73}$$

RDC are ranked and the first one is selected. It is the so-called "first candidate" RDC.

Step 4. Customer demand is assigned to the first candidate RDC as much as possible. In case the capacity of the RDC is not sufficient, another RDC candidate is evaluated.

Step 5. A new customer is selected. Go to Step 3.

Step 6. A new product is selected. Go to step 2.

- *Max critical customer convenience (distance based assignment)*

  This rule is "costumer focused". The customer demand is supposed to be fractionable.

  See steps 1 - 2 in the previous rule. The cost measure in step 3 is the distance, i.e. given a customer the demand is assigned to the nearest RDC (minor distance from the Pod). Steps 4-6 are the same as the previous.

- *Min facilities through average convenience (cost based saturation)*

  This rule is focused on the RDC level because it minimizes the use, i.e. the activation, of the available facilities. The customer demand is supposed to be fractionable. In presence of multiple products the generic RDC has a maximum admissible capacity for each product.

Step 1. The RDCs with available capacity are selected and ranked in accordance to the ascending values of the following term:

$$\sum_{i=1}^{m}\left[d_i^{residual} \cdot \left(c_{RDC,i}^{load,3rd\ stage} + v_{RDC}\right)\right] \qquad \text{Eq. 74}$$

Where:

i the generic Pod

m the number of Pods

$d_i^{residual}$ the customer (Pod i) demand not yet assigned, called "residual", to an RDC.

In Eq. 74 the term $d_i^{residual}$ includes all requested products in presence of multiple products.

Step 2. Given the first candidate RDC, all customers are ordered in accordance with the ascending measures of cost in Eq. 73.

The first customer is selected. The residual demand of the selected customer is assigned to the RDC as much as possible.

Step 3. A new customer is considered till the capacity of the RDC is completely committed. A new RDC is considered till all customers are assigned.

In presence of multiple products: given the most critical one, the customer demand is assigned to the RDC till the available capacity for the selected product is saturated. A new RDC is considered till all customers demanding that selected product are assigned to an RDC.

- Min facilities through average convenience (distance based saturation).

  Similarly to the previous rule, this is focused on the RDCs but the measure of cost used to select a customer given an RDC is substituted by the measure of distance RDC-Pod.

These heuristic assignment procedures can significantly reduce the computational complexity of the optimization problem especially in presence of many Pods and RDCs. As a result, now the optimization problem only involves two stages: by the application of these rules a very large amount of variables, in particular integer variables, assume a specific value significantly reducing the complexity of the whole optimization problem and the time necessary to find the solution.

The obtained solution is the best proposed by the solver when applied to the simplified minimization problem and it is an admissible solution for the original and more complicated decision problem.

Anyway, the user can arbitrary stops the research of the optimal solution to the original MILP based on the use of a linear solver, and call one of these heuristic rules.

3.1.2. Output of the strategic planning module

Figure 22 summarizes the main planning activities as illustrated above and as implemented by LD-LogOptimizer for the strategic design of a supply chain network.

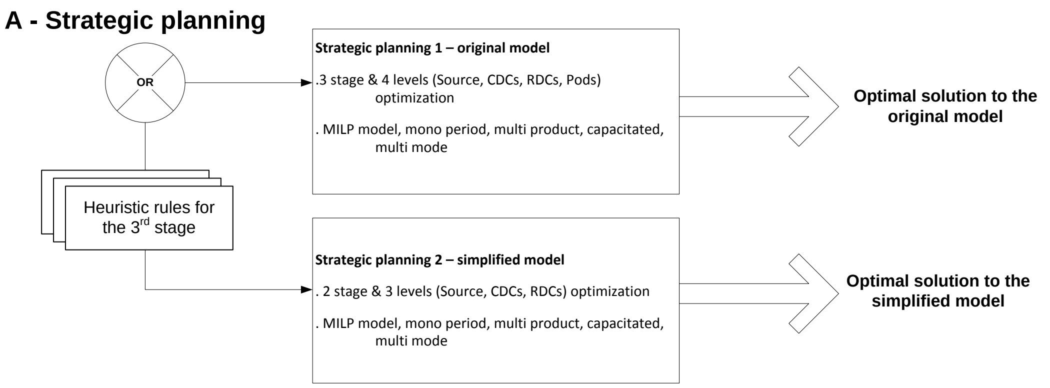


Figure 22: Strategic planning.

The form illustrated in Figure 23 presents main results obtained by the application of the proposed strategic optimization. For each product it is possible to show the materials flows in each stage of the network, i.e. between two generic locations (for example a central DC and a regional DC). In particular the map in Figure 23 presents the "active" links and flows between the entities at the first two stages (between Plants & CDCs, and between CDCs & RDCs). The tab "II stage flow" in Figure 23 shows the measures of flows from RDCs, called in the instance of example Branch1, Branch2, etc., to the CDCs, called CDC1, CDC2, etc. Similarly, flows between Sources/Plants & CDCs, and RDCs & Pods can be shown both in tables and in the map.

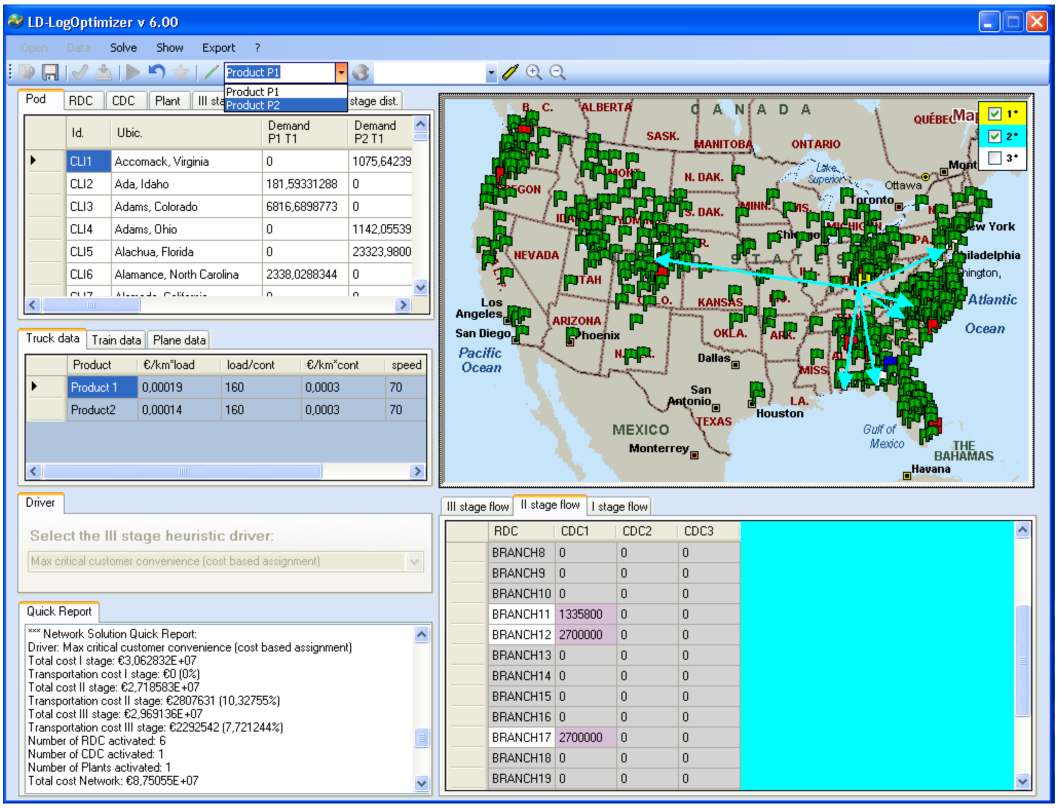


Figure 23: Results from the strategic analysis

Figure 24 exemplifies the large number of flows between an RDC and many Pods when a specific product is selected in a multi-product environment: this is the third distribution stage.

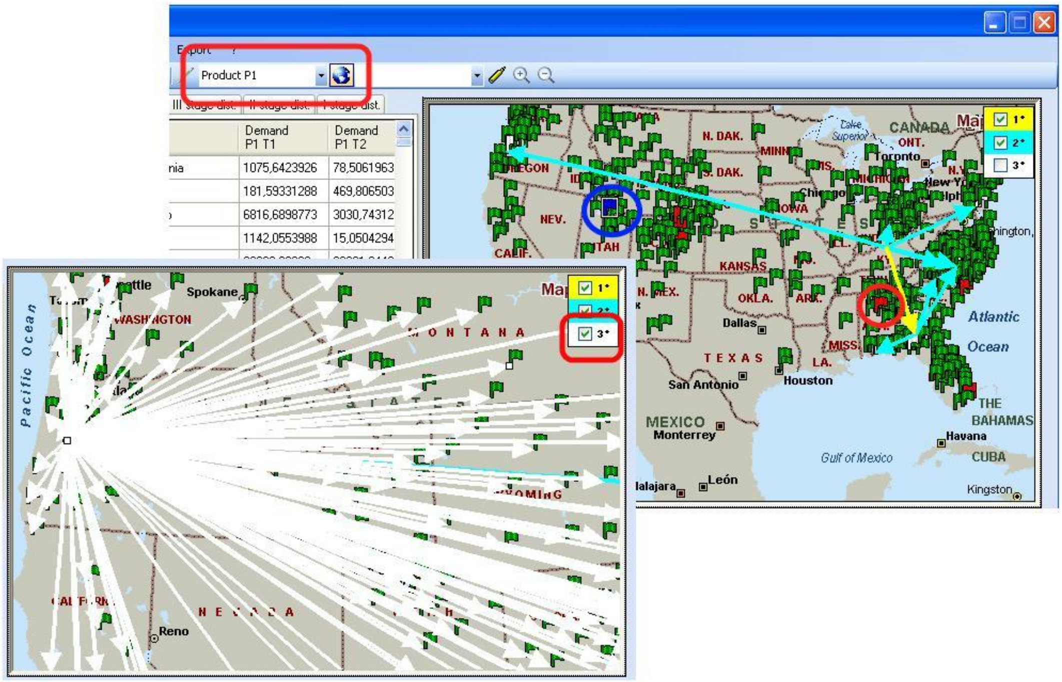


Figure 24: Strategic flows at the third stage

The text report, called Quick Report in Figure 24, reports the logistic cost generated at each level and stage. Non used, i.e. non selected, entities (e.g. a CDC, RDC or a plant) are coloured in a different way both in the tables and in the maps. What-if analysis can be conducted by the application of different simulation analyses.

LD-LogOptimizer supports the export of the results in several ways, e.g. tabs, ad-hoc reports, graphs and maps. For example, Figure 25 shows the total costs of the system as fixed costs, transportation costs and variable costs.

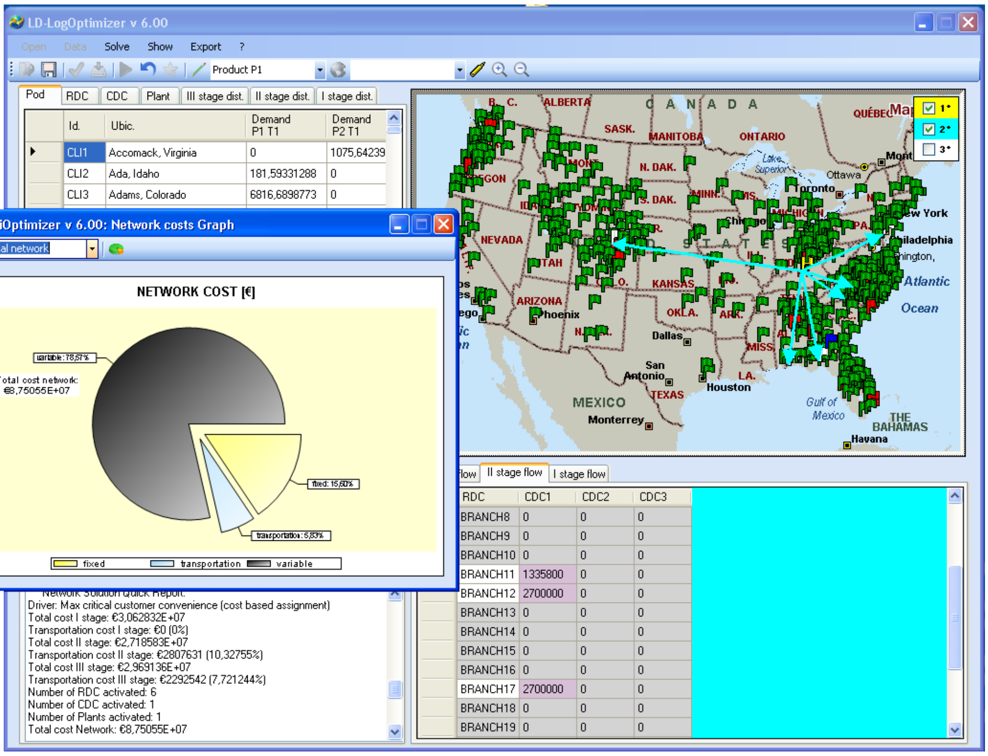


Figure 25: Network costs

3.2. Tactical planning module

Object of a tactical planning of a production-distribution logistic system is the determination of the best fulfilment-scheduling list of deliveries between two generic facilities in a supply chain (SC) system. This planning is multi period and the duration of the planning horizon of time is generally 3 months or 1 year. Different transportation modes are available. Storage, handling and production capacities are modelled at the distribution/production centers.

Even if the tactical planning is generally a multi-product and multi-period short-term planning, it can support also a long-term planning. Consequently the mixed integer optimization model is dynamic, i.e. time dependent, and counts a very large number of continuous and integer/boolean variables. The computational complexity can be very high and it could ask for "non optimal approaches", such as heuristics rules, metaheuristics techniques, etc.

The approach proposed and adopted by the authors of this chapter to face the tactical planning has been implemented by the software platform LD-LogOptimizer and can be optimum or "near-optimum". It is optimum when the user chooses to use a MILP solver to find the best solution to the multi-period, multi-product, production-distribution optimization problem that we call "original dynamic model". The approach is near optimum when a presetting modelling of the original dynamic MILP model is executed, followed by the application of a solver to the simplified dynamic, i.e. time based, MILP model.

Figure 26 summarizes the main functions and activities of the tactical planning in LD-LogOptimizer.

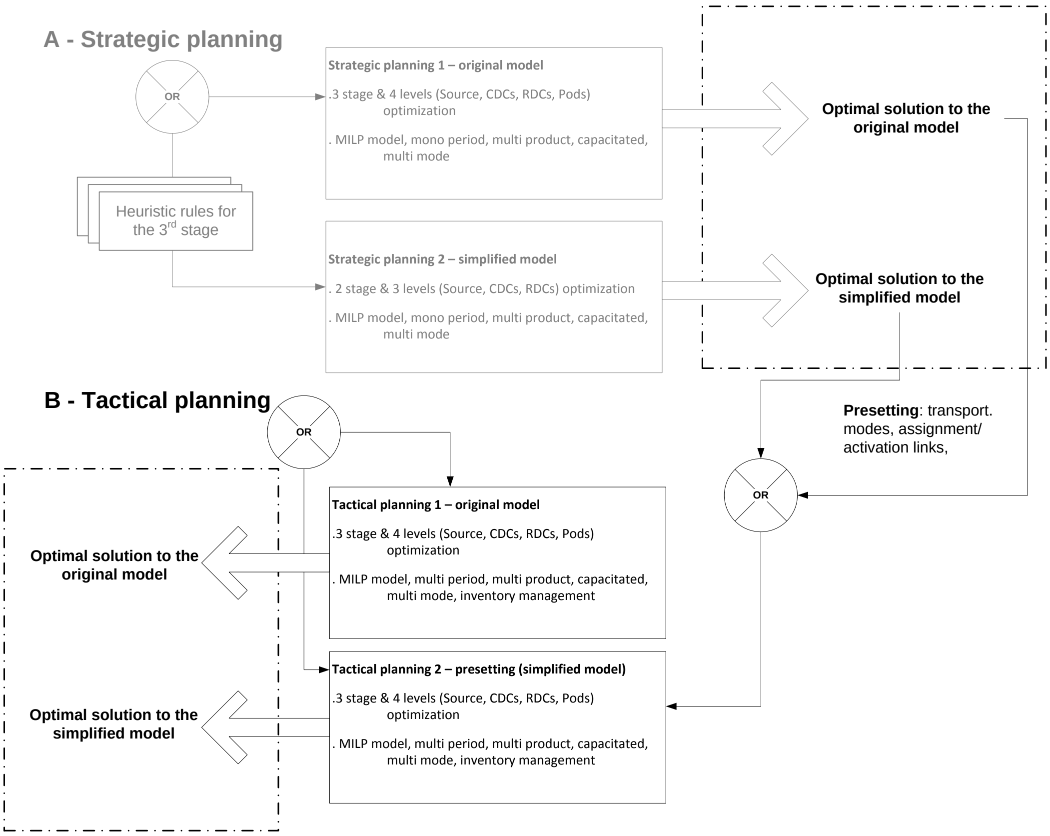


Figure 26: tactical planning.

The presetting activity consists in accepting a part of the results generated at the strategic planning, e.g. the assignment of RDCs to the CDCs or the CDCs to the Plants/Sources, the load flows, the transportation modes adopted, etc. To this purpose Figure 27 illustrates the input and the set up form for the tactical planning in LD-LogOptimizer. In particular, see the tab "Settings" for the presetting task. Obviously, the presetting activity significantly reduces the complexity of the original dynamic MILP model simplifying the calculus of the solver. The solver finds the optimum solution to the simplified MIL model that is admissible and hopefully much closed to the optimal solution of the original dynamic model.

Figure 27 presents the results of the tactical planning by the execution of a presetting and a MILP solver on the simplified model: the map shows the flows at the first and second stages when a specific period is selected. A list of deliveries between a specific central distribution center, called CDC1, and a set of RDCs is also reported always considering an exemplifying point in time, called T3.

Similarly, for each point in time t within the planning period, for each product and for each stage of the logistic network it is possible to define optimal deliveries with the specification of the products quantities, the location of the generic supplier and the location of the generic demand point. This is a schedule of deliveries in a planning period in accordance with the availability of different transportation modes and capacities, production and storage capacities in each point in time t.

LD-LogOptimizer generates several graphs illustrating the trends of the inventory levels, material handling levels and production levels at the generic facility, in accordance with the available capacities (maximum admissible values in a specific point in time of the planning period). To exemplify Figure 28 shows the trend of the obtained handling values in a specific central DC, called CDC3, while Figure 29 shows the expected trend of the costs due to handling and inventory management in different periods for a specific regional DC, called BRANCH4.

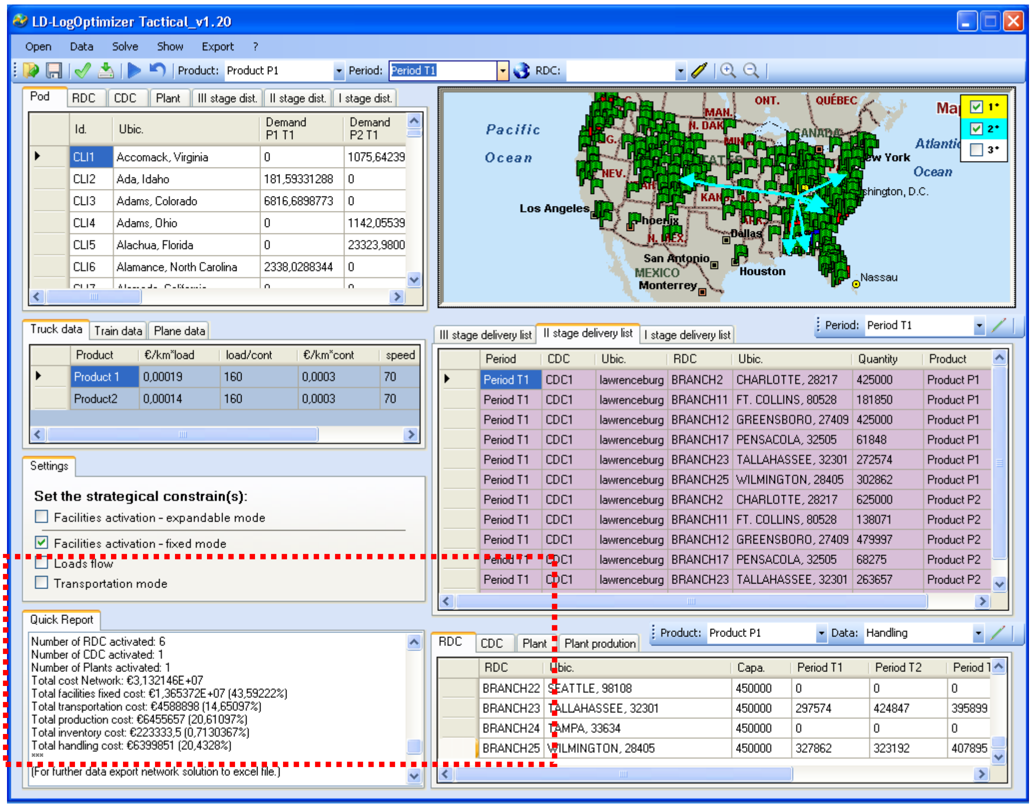


Figure 27: Results from the tactical planning

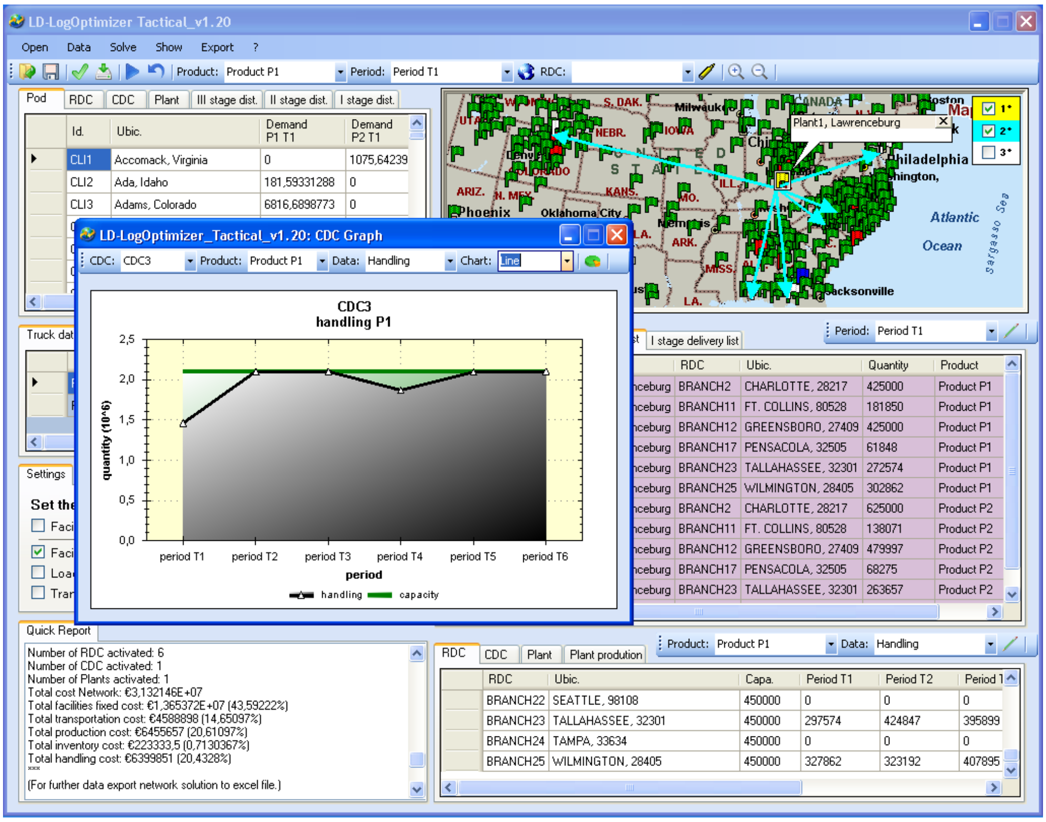


Figure 28: Material handling trend in a CDC. Tactical planning.

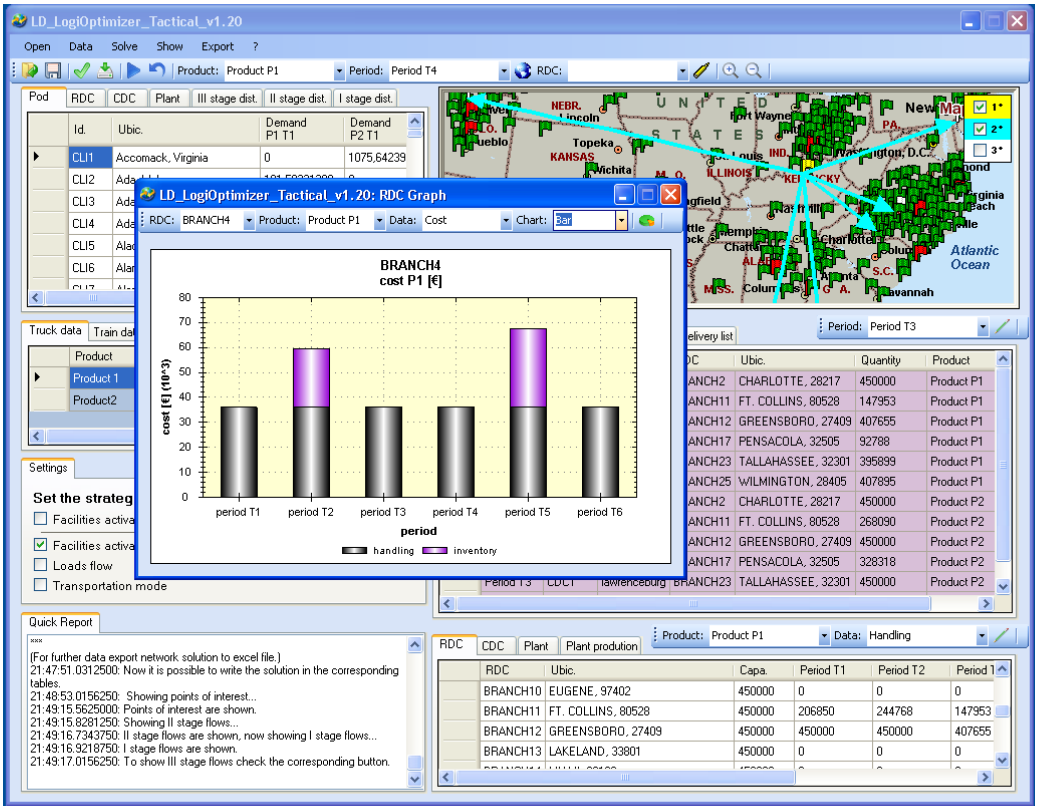


Figure 29: Costs in a RDC. Tactical planning

3.2.1. Operational planning of a production-distribution logistic system

The aim of the operational planning is the daily organization of vehicles fleet and routings to supply products from the sources and production plants to the customers (Pods) in accordance with a very large number of constraints, e.g. handling, inventory and production capacities at the Plants/sources and CDCs/RDCs.

The input data for the operational planning is a schedule of deliveries covering a period of time T, e.g. a few weeks or months. This is a list of orders from CDCs to RDCs (the second stage of the SC), and from RDCs to Pods (the third stage of the SC). Each order is made of different products and is based on a specific transportation mode. The generic order starts from a supplier and supplies a specific customer in a point in time t.

In case the groupage strategy can be adopted, LD-LogOptimizer groups different orders in clusters: a single vehicle in an optimized route visits each cluster of demand points. This is the vehicle capacitated routing problem VRP (Dantzig and Ramser, 1959) which seeks to service a number of customers with a fleet of vehicles minimizing the transportation costs. In particular, LD-LogOptimizer adopts a set of different two-stage heuristics for the optimization of the use of vehicles fleet and the vehicle routings. The first stage adopts a similarity based clustering rule (Manzini and Bindi 2009) supported by the availability of different similarity indices specifically introduced by the authors to best optimize the transportation issues. Given a cluster, the travelling salesman problem (TSP) is adopted and the best Hamiltonian circuit can be identified in presence of a few stops for each vehicle in a trip, i.e. in a pool of delivery requests.

The clustering process adopts a hierarchical heuristic algorithm, e.g. the CLINK, known as the farthest neighbourhood rule, or the single linkage method (SLINK), known as the nearest neighbourhood rule. The meaning and role of the similarity indices, dendrograms, similarity threshold-cut values, and clustering algorithms, is not object of this chapter. The authors deeply illustrate similar hierarchical clustering techniques in others studies when applied to different decision problems: cellular manufacturing (CM) & group technology (Manzini et al. IN PRESS 2010), and allocation of products in a less than unit load order picking system (OPS) (Bindi et al. 2009).

Figure 30 summarizes the main steps for the operational planning a implemented by LD-LogOptimizer. *Appendix A* summarizes the whole logic scheme of the proposed multi-modular tool: each module has been illustrated in previous sections.

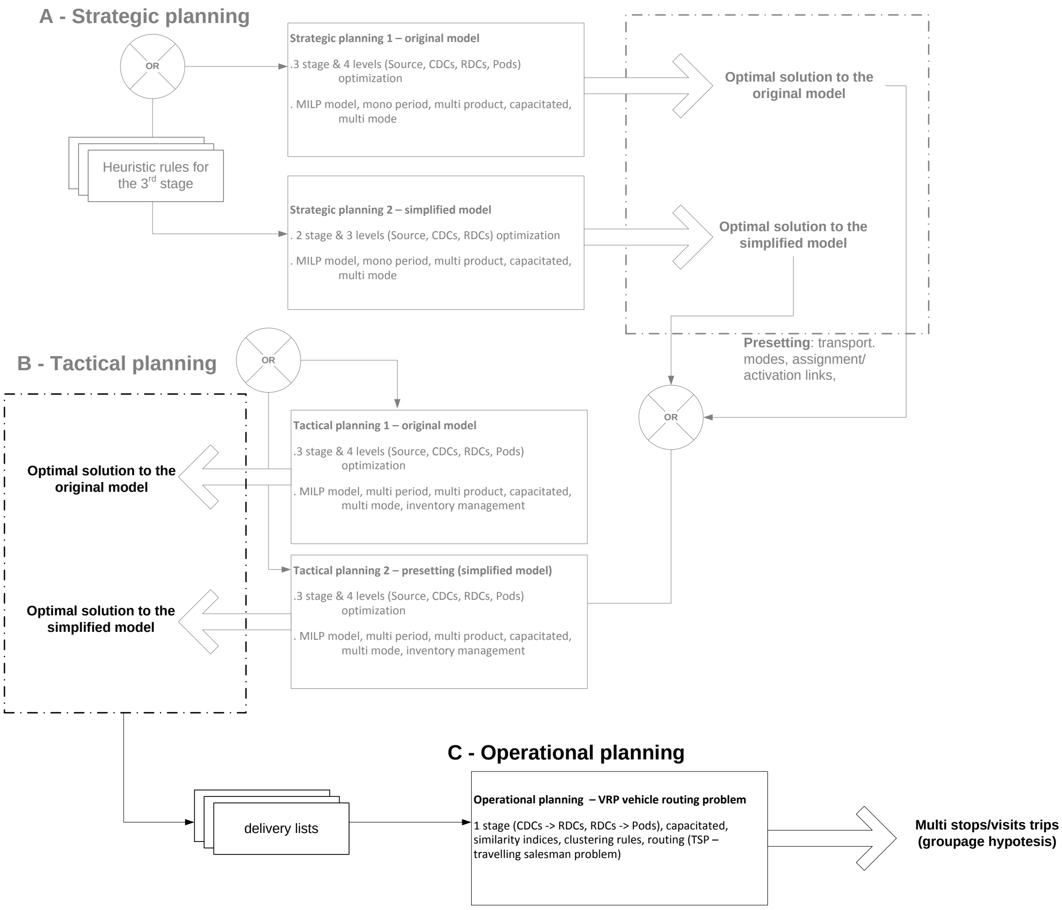


Figure 30: operational planning.

Figure 31 presents the main form of LD-LogOptimizer for the optimization of the operational planning, and exemplifies a few results. All demand quantities are preliminary grouped in time brackets and than grouped in distinct clusters by the adoption of the similarity based heuristics. Each cluster is assigned to a vehicle and defines a vehicle trip, i.e. a travelling mission. In particular, Figure 31 shows a few obtained clusters for the time bracket n°1 which includes two points in time, e.g. Monday and Tuesday of the same week. The maximum obtained number of stops per trip is 4, i.e. 4 visits (stops) for each vehicle. The generic stop corresponds to a customer location with non null demand.

All routes can be showed in a geographical map: for example see route 6 in Figure 31 and in Figure 32 (a detailed view). It consists of a trip which starts from and finishes to the RDC "BRANCH11" visiting Pods "CLI16", "CLI3" and "CLI9". The related transportation cost is about 507 km and the trip can be studied by the driver looking for the detailed instructions, e.g. "take ramp", "turn right", "keep left", and the sequence of roads in a map.

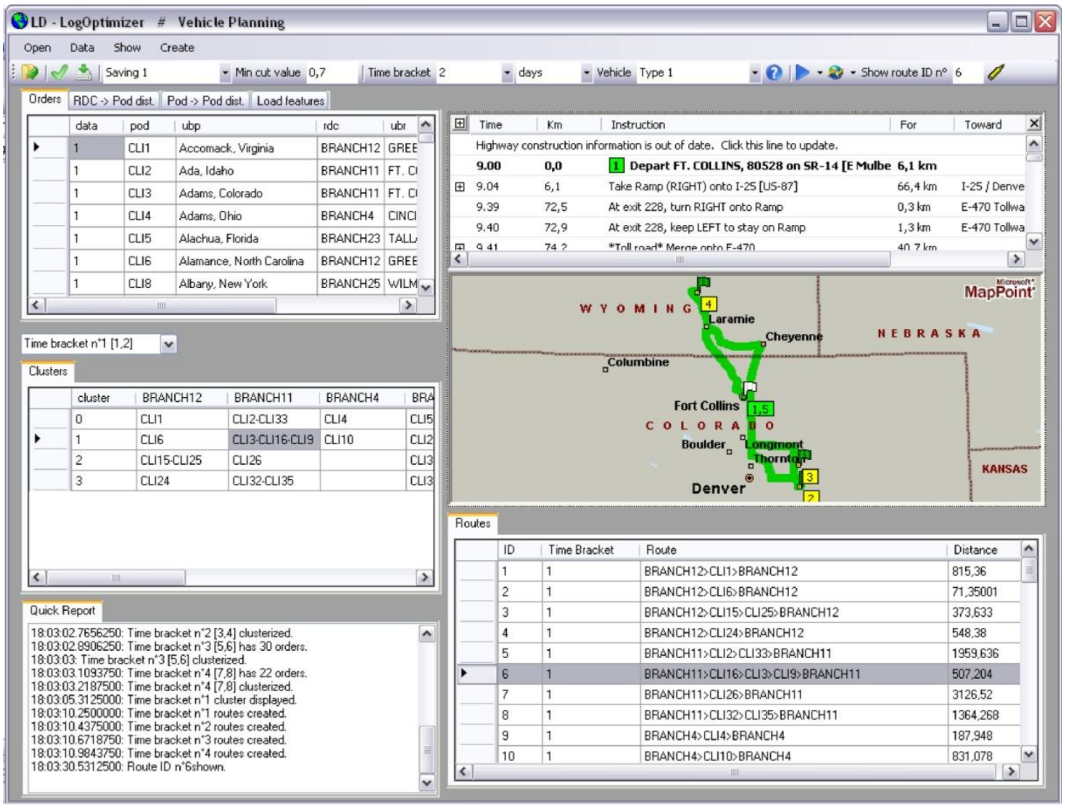


Figure 31: Operational Planning.

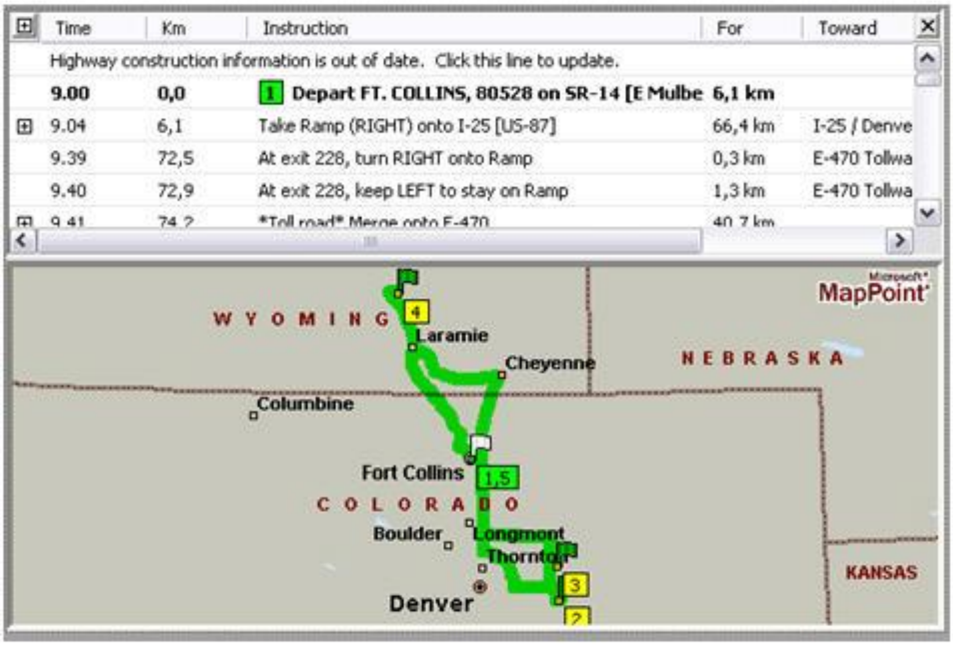


Figure 32: Results from the operational planning, a detailed view.

4. Warehouse as a Crucial Link in Supply Chain

Warehousing and the relative order picking process are an essential component of any supply chain. Approaches to improve order picking efficiency often also reduce customer response time in supply chain, decrease overall costs and improve related customer service level.

In the following sections a brief introduction to warehousing is conducted. The role in the supply chain, the main operations and functions, the general equipment, and the order picking process of a storage system are outlined.

4.1. Role of a Warehouse

In a recent survey the consulting company AT Kearney (ELA/AT Kearney survey 2004) states that there are more than 900,000 warehouse facilities worldwide from retail to service parts distribution centers , including state-of-art, professionally managed warehouses, as well as company stockrooms and self-store facilities. Warehouses frequently involve large expenses such as investments for land and facility equipment for the storage and the handling, costs connected to the labour and for the information system. So firstly it is necessary to understand the role a warehouse serves in a supply chain and which services it generally provides. Lambert et al. (1998) identify the following missions:

- Achieve transportation economies (e.g. combine shipment, full-container load).
- Achieve production economies (e.g. make-to-stock production policy).
- Take advantage of quantity purchase discounts and forward buys.
- Maintain a source of supply.
- Support the firm's customer service policies.
- Meet changing market conditions and again uncertainties (e.g. seasonality, demand fluctuations, competition).
- Overcome the time and space differences that exist between producers and customers.
- Accomplish least total cost logistics commensurate with a desired level of customer service.
- Support the just-in-time programs of suppliers and customers.
- Provide customers with a mix of products instead of a single product on each order (i.e. consolidation).
- Provide temporary storage of material to be disposed or recycled (i.e. reverse logistics).
- Provide a buffer location for trans-shipments (i.e. direct delivery, cross-docking).

Bartholdi and Hackman (2008) conversely recognize three main uses:

- Better matching the supply with customer demands.
  Nowadays there is a move to smaller lot-sizes, point-of-use delivery, order and product customization, and cycle time reductions. In distribution logistics, in order to serve customers, companies tend to accept late orders while providing rapid and timely delivery within tight time windows (thus the time available for order picking becomes shorter).

- Consolidating products.

  The reason to consolidate products is to better fill the carrier to capacity and to amortize the fixed cost for any product is transported. These costs are extremely high when the transportation mode is ship, plane or train. As a consequence a distributor may consolidate shipments from vendors into large shipments for downstream customers by an intermediate warehouse.
- Providing Value-added processing.

  Pricing, labelling and light assembly are simple examples of value added processing. In particular the assembly process is due for a manufacturing company adopting the postponement policy. According to this policy products are configured as close to the customers as possible.

As a result warehouses are necessary and play a significant role in the companies' logistics success.

4.2. Type of warehouses

Various factors directly influence the design of a warehouse and the decision making process. Any choice/decision became a constraint and is connected to the next choice in cascade. At the same time any decision strongly impacts on the final configuration of the warehouse and moreover on the performance and on the logistic costs. As a consequence it is fundamental find the right synergy between the main factors.

While there are many types of warehouses along a supply chain they may be categorized by the customers they serve (Bartholdi & Hackman, 2008):

- *Retail Distribution Center* typically serves product to retail stores. The direct customer of the distribution center is a retail store, which is likely to be a regular customer receiving shipments on regularly scheduled days. A typical order might comprise hundreds of items and the total flow of products is huge.

- *Service Parts Distribution Center* is probably the most complex system to manage. They hold spare parts for expensive capital equipment with a huge investment in inventory. It is not unusual to find a facility with tens of thousands of parts. The demand for any part is hard to predict due to the large variance in request both in time and quantity. As a consequence they hold large quantity of safety stocks. The shipment should be very fast because almost all the time the request of spare parts is very urgent

- *Catalog Fulfillment or E-commerce Distribution Center* receives small orders from individuals. Orders are typically 1-3 items and they are to be filled and shipped immediately after receipt.

- *Third Part Logistics Warehouse* is one to which a company might outsource its warehousing operations. Because it serves sometimes more than one customers from one facility it takes advantage of economy of scale.

4.3. Storage systems

There are many modes to store items into a warehouse, anyway the common modes include: pallet rack for bulk storage, carton flow rack for high-volume picking, and static shelving for slower, lower volume picking. Pallet systems are used to store large products or for handling large quantities of products. Cases are used for handling smaller quantities of product. Sometimes a warehouse contains some combination of pallet, case and individual product handling. For example, incoming pallet may be stored initially on pallets. After a while a pallet is moved to the case picking area. Orders containing large quantities of the product can be satisfied by retrieving a full case from this area. Orders with one or a few products are satisfied from the item picking area (Yoon & Sharp 1995; Bartholdi & Hackman 2008).
The simplest way of storage is *block stacking*. According to this system, the warehouse is one open space in which pallets, filled with products, are stored on the floor or on top of each other (e.g. a typical example is the storage of end products for the ceramic tile industry). A more advanced way to store pallets is with the use of *pallet racks*. A pallet rack is a metal structure that makes it possible to stack pallets higher than with block stacking while keeping the opportunity to manually access the pallets on the lower levels directly. Usually, several racks are placed in rows with aisles in between where vehicle or people can move for handling the pallets. Pallet racks can be *single-deep*, *double-deep*, or also *multi-deep*. Figure 33 illustrates a single-deep rack.

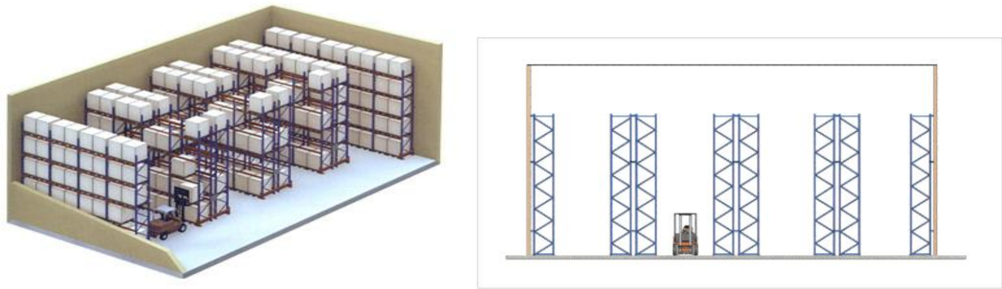


Figure 33: Single-deep racks.

Another way to store several pallets behind each other is the so called *drive-in or drive-through racks*.

Where the throughput is very high, it may be a good choice to use *pallet flow racks*. In these systems each position can contain multiple pallets, which are positioned behind each other. Products are retrieved from one side of the rack and refills are done from the other side. Pallets roll on a conveyor from one side of the rack to the other.

Then there are also systems in which products are not stored on pallets, often in quantities that are less than a full unit load. These systems include shelves, storage drawers, and gravity case flow racks.

There are many issues involved in designing and operating a warehouse to meet these requirements. Resources, such as space, labor, and equipment, need to be allocated among the different warehouse functions, and each function needs to be carefully implemented, operated, and coordinated in order to achieve system requirements in terms of capacity, throughput, and service at the minimum resource cost.

A scheme to classify warehouse design and operation planning problems is shown in Figure 34 (Jinxiang Gu et al., 2007).

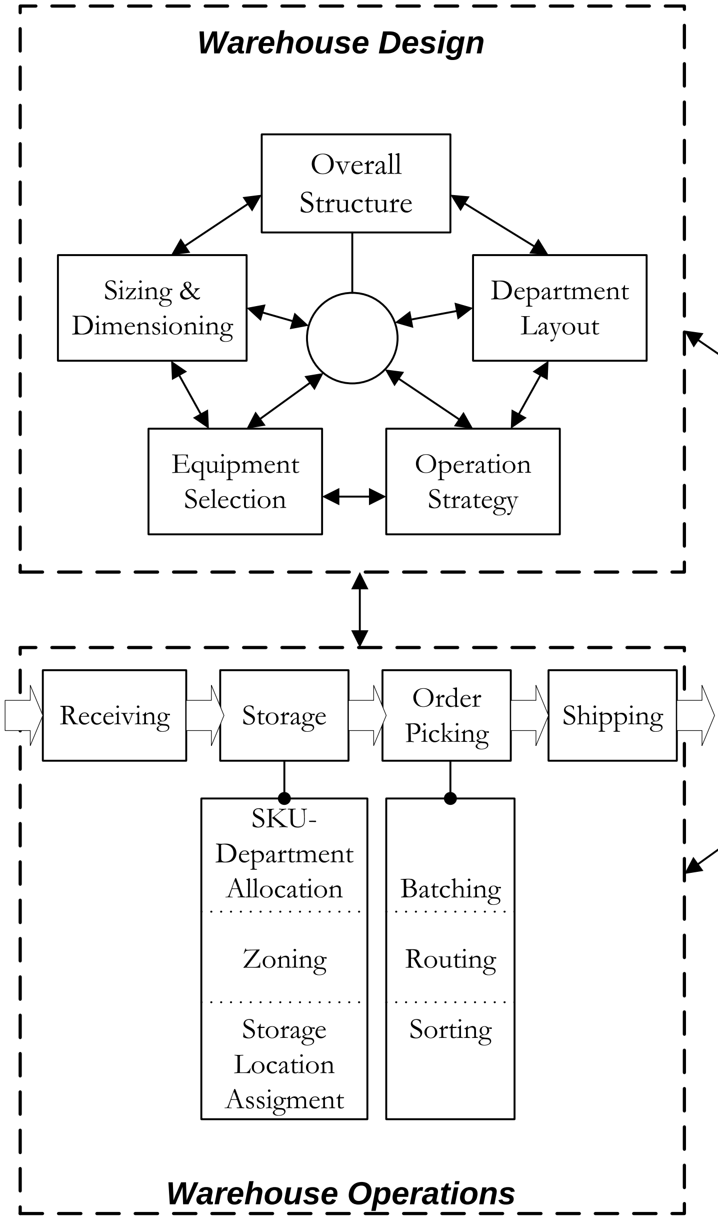


Figure 34: Framework for warehouse design and operation problems

A more detailed description of each problem category identified is given in Table 4. This paper will focus mostly on the operation planning problems.

Design and operation problems			Decisions
Warehouse design	Overall structure		• Material flow • Department identification • Relative location of departments
	Sizing and dimensioning		• Size of the warehouse • Size and dimension of departments
	Department layout		• Pallet block-stacking pattern (for pallet storage) • Aisle orientation • Number, length, and width of aisles • Door locations
	Equipment selection		• Level of automation • Storage equipment selection • Material handling equipment selection (order picking, sorting)
	Operation strategy		• Storage strategy selection (e.g., random vs. dedicated) • Order picking method selection
Warehouse operation	Receiving and shipping		• Truck-dock assignment • Order-truck assignment • Truck dispatch schedule
	Storage	SKU-department assignment	• Assignment of items to different warehouse departments • Space allocation
		Zoning	• Assignment of SKUs to zones • Assignment of pickers to zones
		Storage location assignment	• Storage location assignment • Specification of storage classes (for class-based storage)
	Order picking	Batching	• Batch size • Order-batch assignment
		Routing and sequencing	• Routing and sequencing of order picking tours • Dwell point selection (for AS/RS)
		Sorting	• Order-lane assignment

Table 4: Description of warehouse design

The design of real Order Picking Systems is often complicated, due a wide spectrum of external and internal factors which impact design choices. According to Goetschalckx and Ashayeri (1989) external factors that influence the OP choices include marketing channels, customer demand pattern, supplier replenishment pattern and inventory levels, the overall demand for a product, and the state of economy. Internal factors include system characteristics, organization and operational policies of OP systems. System characteristics consist of mechanization level, information availability and warehouse dimensionality (see Figure 35). Decision problems related to these factors are often concerned at the design stage. The organization and operational policies include mainly five factors: routing, storage, batching, zoning and order release mode. Figure 35 also shows the level of difficulty of OP systems; it is proportional to the distance of the representation of this problem in the axis system to the origin. In other words, the farther a system is located from the origin, the harder the system is to design and control.

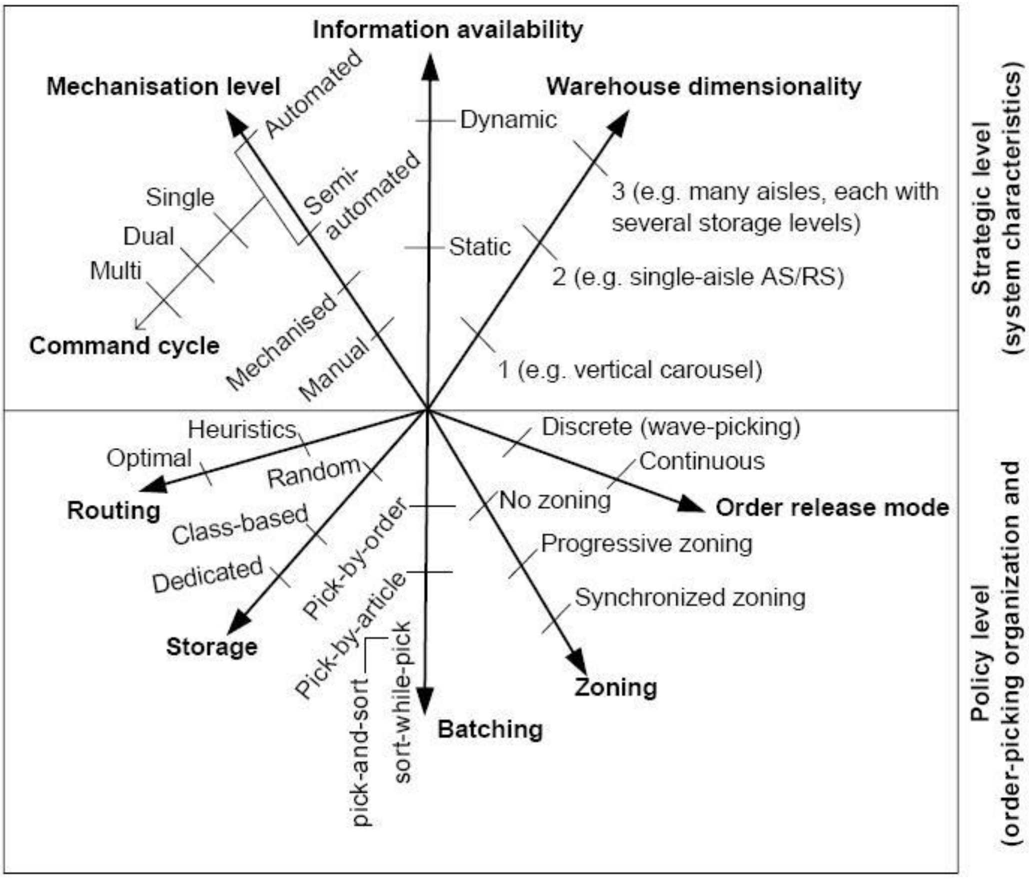


Figure 35: Complexity of OP systems (based on Goetschalckx and Ashayeri 1989)

4.4. Useful metrics

Storage systems as any others business process have some useful metrics. They are essential to estimate the overall performance of a warehouse and to benchmark with its peers, as well to describe the feature. Some of the most popular are here described:

1. **Area Saturation ratio**

$$I_s = \frac{A_u}{A_t}$$

It is defined as the ratio between the effective committed area for storage and the total area of the warehouse. The ratio I_s provides information about the degree of utilization for the area of a storage system.

2. Cubic Saturation ratio

$$I_v = \frac{V_u}{V_t}$$

It identifies the ratio between the effective committed volume for storage and the total volume of the warehouse.

3. Selectivity ratio

$$S = \frac{M_u}{M_t}$$

It is intended to summarize the ratio between the number of direct handling M_u and the total number of necessary handling M_t for each slot of rack, identifying the accessibility to the slot and the degree of easiness to place in or place out an item to/from that position. Selectivity ratio is equal to one for single-deep rack.

4. Balancing Height ratio

$$H = \frac{V_u}{A_t}$$

It is intended to evaluate the ratio between the effective committed volume for storage and the warehouse total area. Adopting a fluid model, the ratio identifies the ideal height of a warehouse.

5. Labor Index

It is generally quantified in a defined horizon t as the ratio between the number of products, pick-lines, cartons, pallets and the person-hour.

6. Energy ratio

It is the ratio between the number of products, pick-lines, cartons, pallets and the electric power installed or consumed in a defined horizon t.

7. ...and others operational key performance indices KPI following the typical ratio:

unit of output achieved / units of input required

- Response time index measured as order cycle time (minutes per order)
- Accuracy index measured as fractions of shipments with returns
- Operating costs as a percentage of sales

4.5. Typical warehouse operations

Here are the main operations and functional areas within a general warehouse: receiving, transfer and put away, order picking/selection, accumulation/sorting, cross-docking, and shipping. Figure 36: Typical warehouse operations (Inspired by: Tompkins et al., 2003) shows the flows of product and identify the typical storage areas and relative movements.

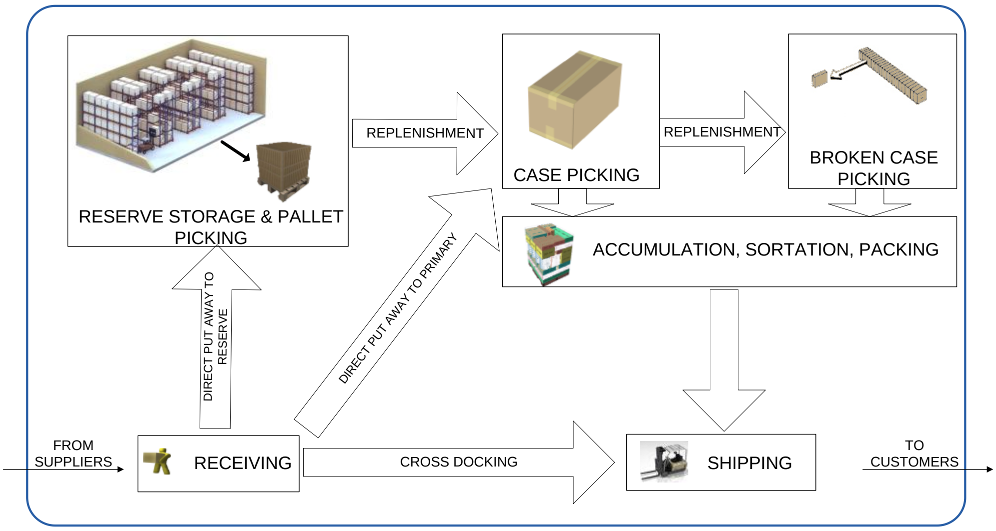


Figure 36: Typical warehouse operations (Inspired by: Tompkins et al., 2003)

- The receiving activity includes the unloading of products from the transport carrier, updating the inventory record, inspection to find if there is any quantity or quality inconsistency. The transfer and put away involves the transfer of incoming products to storage locations. It may also include repackaging (e.g. full pallets to cases, standardized containers), and physical movements (from the receiving docks to different functional areas, between these areas, from these areas to the shipping docks). The order picking/selection involves the process of obtaining a right amount of the right products for a set of customer orders. It is the major activity in most warehouses. The accumulation/sorting of picked orders into individual (customer) orders is a necessary activity if the orders have been picked in batches. The cross-docking activity is performed when the received products are transferred directly to the shipping docks (short stays or services may be required but no order picking is needed).
- The storage function is the physical containment of products while they are awaiting customer demands. The form of storage will depend on the size, quantity

of the products stored, and the handling characteristic of products or their product carriers (Tompkins et al., 2003).

Generally the whole warehouse activities are tracked and managed by an information system. Sometimes this task is performed by a Warehouse Management System *WMS,* which is basically just a software built around an industrial relational database. At least It tracks on the database all product arriving and all product shipped out, fundamental information for the financial transaction. Warehousing information (inventory level, stock-keeping locations, customer data, inbound, outbound shipments, etc.) is not only important for managing the warehouse operations itself but also for the efficiency of the whole supply chain.

4.6. Order Picking

Order picking *(OP)* can be defined as the retrieval of items from their warehouse locations in order to satisfy demands from internal or external customers (Petersen, 1999). As a warehouse function order picking arises because incoming items are received and stored in (large-volume) unit loads while customers order small volumes (less than unit loads) of different products as simply shown in Figure 37. Typically, thousands of customer orders have to be processed in a distribution warehouse per day.

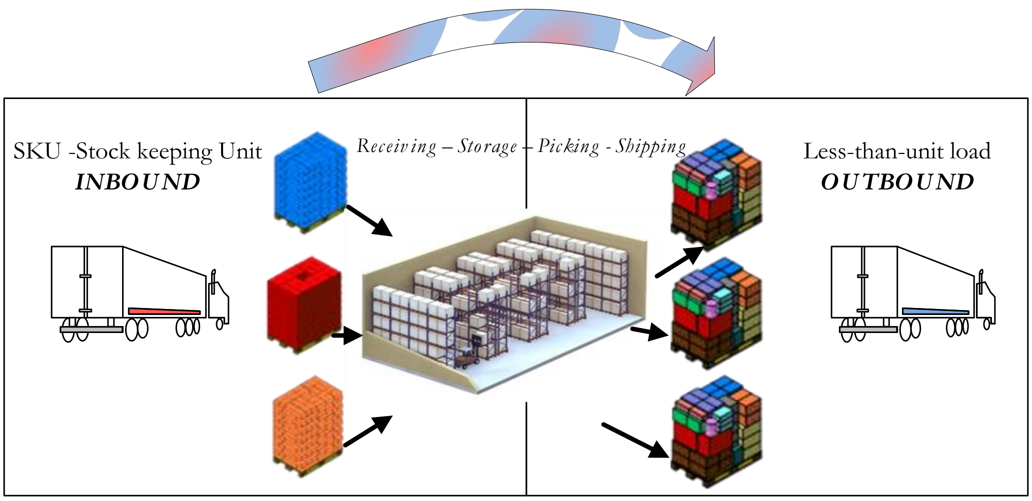


Figure 37: From SKUs to customer orders

Even thought there have been various attempts to automate the picking process, automatic systems are rarely found in practice. Order picking, like many other material handling activities, still is a repetitive and labour-intensive activity. Order picking systems, which involve human operators can be generally organized in two ways, namely as a parts-to-picker system in which the requested products are delivered automatically to a person at an input/output (I/O) point, or as a picker-to-parts system in which the order picker travels to storage locations in order to bring together the required products. Figure 38 gives a comprehensive classification of order picking systems.

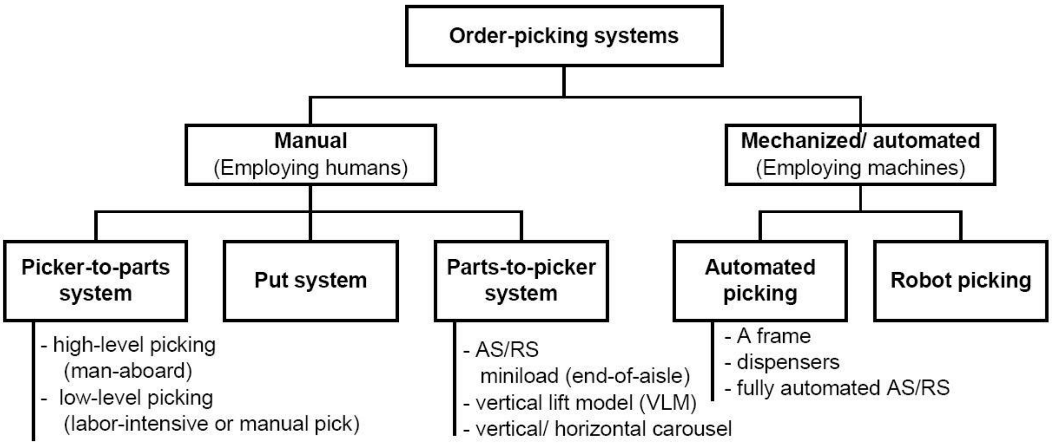


Figure 38: Classification of order-picking systems (based on De Koster 2004)

It can be distinguished two types of picker-to-parts systems: low-level systems and high-level systems. In low-level order picking systems, the picker picks requested items from storage racks or bins. Due to the labour intensity, low level systems often are called manual order picking systems. Some other order picking systems have high storage racks; order pickers travel to the pick locations on board of a stacker or order-pick truck, or a crane. The crane mechanically stops in front of the correct pick location and waits for the order picker to execute the pick. This type of system is called high-level or man-aboard system. Parts-to-picker systems include automated storage and retrieval systems (AS/RS), using mostly aisle-bound cranes that retrieve one or more unit loads (e.g. of bins: mini-load system, or pallets) and carry the loads to a pick station (i.e. I/O point). At this station the order picker picks the right quantity requested by the customer order, after which the residual stock quantity is stored again. This type of system is also called unit-load order picking system. The automated crane can work under different functional modes: single, dual and multiple command cycles. The single-command cycle means that either a load is moved from the I/O point to a rack location or from a rack location to the I/O point. In the dual command mode, first a load is moved from the I/O point to the rack location and next another load is retrieved from the rack. In multiple command cycles, the S/R machines have more than one shuttle and can pick up several loads in one cycle, at the I/O point or retrieve them from rack locations. For example, in a four-command cycle (described in Sarker et al., 1994), the S/R machine leaves the I/O point with two storage loads, travels to the first storage location to store the first load. Then it proceeds to a retrieval location to retrieve a load by the recently-emptied shuttle, and travels to the next storage location to unload the remains storage load. And then it travels to a pick location to retrieve the second load. Finally it returns to the I/O point, after two storages and two retrievals. Other systems use modular vertical lift modules (VLM), or carousels that also offer unit loads to the order picker, who is responsible for taking the right quantity. There exist systems which combine the principles of parts-to-picker and picker-to-parts OP systems (referred as put systems in Figure 38). First, items have to be retrieved, which can be done in a parts-to-picker or picker-to-parts manner. Second, the carrier (usually a bin) with these 'parts' is offered to an order picker who distributes the parts over customer orders. Put systems are particularly popular in case a large number of customer order lines have to be picked in a short time window (for example at e-commerce warehouses) and can result in about 500 picks on average per order picker hour (for small items) in well managed systems (De Koster, 2004).

Manual-pick picker-to-parts systems are the most common (De Koster, 2004). The basic variants include picking by article (batch picking) or pick by order (discrete picking). In the case of picking by article, multiple customer orders (the batch) are picked at the same time by an order picker. Many in-between variants exist, such as picking multiple orders followed by immediate sorting (on the pick cart) by the order picker (sortwhile- pick), or the sorting takes place after the pick process has finished (pick-and-sort).

Another basic variant is zoning, which means that a logical storage area (this might be a pallet storage area, but also the entire warehouse) is split in multiple parts, each with different order pickers. Depending on the picking strategy, zoning may be further classified into two types: progressive zoning and synchronized zoning. Under the progressive (or sequential) zoning strategy, each batch (possibly of one order) is processed only in one zone at a time; at any particular point in time each zone processes a batch that is dissimilar from the others. Hence, the batch is finished only after it sequentially visits all the zones containing its line items. Under the synchronized zoning strategy, all zone pickers can work on the same batch at the same time. There may be some idle time of zone pickers waiting until all other zone pickers finish the current batch. This harmonization of pickers intends to keep the batches from being mixed, and so to lessen the complexity of the following stages such as the accumulation and sorting. The term wave picking is used if orders for a common destination (for example, departure at a fixed time with a certain carrier) are released simultaneously for picking in multiple warehouse areas. Usually (but not necessarily) it is combined with batch picking. The batch size is determined based on the required time to pick the whole batch completely, often between 30 minutes to 2 hours (see Petersen, 2000). Order pickers pick continuously the requested items in their zones, and a next picking-wave can only start when the previous one is completed.

5. Design of Order Picking Systems

Today distribution warehouses need to process a far higher volume of smaller orders of multiple products which considerably increases logistics costs. These are the so-called order picking systems where products have to be picked from a set of specific storage locations by an order picking process usually driven by production batches or customer orders. Order picking is often very labour intensive and its efficiency largely depends on the distance the order pickers have to travel, which therefore needs to be minimized. Minimizing this distance is affected by several factors e.g. facility layout, shape of storage area, and especially the storage assignment strategy. Products that are frequently ordered together in multi-item less than unit load customer orders should be stored near each other: this is the correlated storage assignment strategy. The following sections of this chapter develop, test, and compare a set of different storage allocation rules based on the application of original similarity coefficients and clustering techniques. Lastly, a case study demonstrates the effectiveness of the proposed rules in minimizing logistic costs.

5.1. Literature review

The design and control of real OPSs is very complicated due to the large number of critical factors affecting tactical and operational level decisions (De Koster et al. 2007, Min 2006). These common decisions have been extensively investigated in the literature which contains significant studies on OPS optimization for the following main areas and problems:

- Plant layout design, and storage area configuration & dimensioning. This area concerns two main problems. The first is the so-called facility location problem that determines the best location for all system departments e.g. receiving, picking, storage area, sorting and shipping (Tompkins et al. 2003; Heragu et al. 2005). The second problem concerns the determination of the number of blocks and bays, and the length, width, and number of aisles in each picking block, that is, the so called internal layout design or aisle configuration problem (Petersen 2002; Caron et al. 2000).
- Storage assignment problem i.e. where and how to locate incoming products in warehousing systems. There are several strategies for assigning products to storage locations in forward and reserve storage areas. The literature includes several studies presenting heuristic models and policies to support management decisions, as illustrated in the next section (Petersen et al. 2004; Jarvis and McDowell 1991; Manzini 2006b).
- Batching problem, that is, the method of grouping a collection of customer orders into a number of subsets, each of which can be picked by the order picker in one single tour. Many batching heuristics for minimizing picking travel time have been developed and illustrated in the literature (Chen and Wu 2005; Gademan and Van de Velde 2005; Hsu et al. 2005; Won and Olafsson 2005).
- Routing and sequencing problem, this deals with the optimization of the vehicle routes through the system. Several heuristics and algorithms have been proposed and compared in the literature (Petersen and Aase 2004; Hwang et al. 2004; Roodbergen and de Koster 2001a).

In the following sections we focus on issues affecting layout design and storage assignment decisions in OPSs.

5.2. Storage assignment strategies

The Storage assignment problem, that is the assignment of product to storage locations, was formally introduced by Cahn in 1948. Successively it was recalled by Frazelle et al. in 1989 showing that the storage assignment problem is in the class of NP-hard problems for which the optimal solution is computationally infeasible to obtain in problems of practical sizes. After that study, successive literature have been focusing on heuristic procedure based on the formulation of storage assignment policies. These policies are generally a set of rules which can be used to assign products to storage locations and they primarily aim to provide ways for allocating items in an order picking system so that order picking time will be reduced (Muppani and Adil 2008, Manzini et al. 2005; Manzini et al. 2006a; Van Den Berg 1999). As described in Gu et al. (2006) the storage assignment problem could formally be defined as follows:

Given:

(1) Information on the storage area, including its physical configuration and layout.

(2) Information on the storage locations, including their availability, physical dimensions, and location.

(3) Information on the set of items to be stored, including their physical dimensions, demand, quantity, arrival and departure times.

Determine:

The physical location where present and incoming items will be stored.

Subject to performance criteria and constraints such as:

(1) Storage capacity and efficiency.

(2) Picker capacity and efficiency based on the picker cycle time.

(3) Response time.

(4) Compatibility between products and storage locations and the compatibility between products.

(5) Item retrieval policy such as FIFO (first-in, first-out), LIFO (last-in, first-out), BFIFO (batch first-in, first-out). When using the BFIFO policy, items that arrived in the same replenishment batch are considered to be equivalent.

Although different storage systems may adopt different rules depending on the specific sku profile and storage technology in use, storage assignment policies can be divided into the following four broad categories, each of which has a different impact on the travel time required to retrieve products from storage areas in response to customer requests (Petersen 1997, Manzini et al. 2005, Van Den Berg et al. 1999, Dallari et al. 2000):

- **Randomized storage**

Every incoming pallet or an amount of similar products are assigned to a location selected randomly in the storage area. The incoming product is generally stored at the first empty location closest to the input/output area (the so-called depot area). The random storage policy is widely used in many warehouses because it is simple to use, often requires less space than other storage methods, and results in a better level of utilization of all picking aisles.

- **Dedicated storage**

  Items are assigned to predetermined locations based on throughput and storage requirements. It follows that a location is reserved even for products that are out of stock. It requires more storage space since sufficient storage locations must be reserved for the maximum inventory of each products. On the other hand, as an advantage, the order pickers become familiar with product locations. Sometimes, dedicated storage can be useful if products have different weights. Heavy products need to be on the bottom of the pallet and light products on top. By storing products in order of weight and routing the order pickers accordingly, a good stacking sequence is obtained without additional effort.

- **Class-based storage**

  This policy provides an alternative that is between and has the benefits of both dedicated and randomized storage. The implementation of class based storage (i.e., the number of classes, the assignment of products to classes, and the storage locations for each class) has significant impact on the required storage space and the material handling cost in a warehouse. Research on this problem has been largely focused on AS/RS, especially single command AS/RS. Hausman et al. (1976) show that for single-command AS/RS with the Chebyshev metric, the ideal shape of storage regions is L-shaped. Bynzer and Johansson (1996) in their paper provided a storage assignment strategy originating from the product structure to reduce the picking time by using variant features as picking information in the construction of a logical assignment policy. Rosenblatt and Eynan (1989) developed an algorithm involving a one-dimensional search for obtaining the boundaries for any desired number of classes in an automated warehouse. Results show that this one-dimensional search procedure is very effective in solving most practical problems. Frazelle (2002) punctually states the two most frequently used criteria that can be used to assign a product (class) to storage locations: popularity and COI cube per order index.

- **Correlated Storage**

  The idea of this type of storage assignment policy is that the allocation of products within a storage area can be based on different types of correlation subsisting between products. Once the correlation has been calculated for all pair of products, the couples with the highest value of correlation are stored together. For example, customers may use to order a certain item together with another item. These products might reasonably have high correlation and it may be useful to locate these two products close together within the system and by doing so the travel distance will be reduced. In order to group products, the statistical correlation between them should be known or at least be predictable as described in Frazelle and Sharp (1989), and Brynzér and Johansson (1996). Ballou (1992) introduced three considerable principles for supporting the grouping of products for the storage location assignment: *complementary, compatibility* and *popularity*. Complementary refers to the idea that items ordered together should be located near to each other. Compatibility is whether items can be practically located next to each other. Popularity is for emphasizing that products have different turnover rates in a storage system, and the ones requiring a large number of trips should be located close to the depot area. Successively Wascher (2004) extended these principles to two methods for the correlated storage assignment. The first method is called the *complimentary-based* method, which contains two major phases. In the first phase, it clusters the items into groups based on a measure of strength of joint demand (i.e. complimentary). In the second phase, it locates the items within one cluster as close to each other as possible. The second method is called *contact-based* and it uses *contact frequencies* to cluster items into groups. It pretends to integrate routing problem in the evaluation of correlation between products. For example, given an optimal routing solution, a contact frequency between generic item i and item j is defined as the number of times that an order picker picks either item i directly after item type j, or item j directly after item i. However, the routing decision is dependent on the location of the item types, which demonstrates the strong interrelationship between item location and routing. Due to the fact that finding a joint optimal solution for both problems is not a realistic approach for real applications, contact-based solution methods alternate between the two problem types.

The literature presents several studies on storage location strategies and rules, but there is little discussion on the opportunity to correlate assignments. Moreover many of the existing papers provide performance evaluation comparing only at least a couple of rules and almost always the proposed method is compared only to the randomized storage rule, ignoring that popularity is the criterion most widely adopted as class-based storage for current warehousing practice (Frazelle 2002). Furthermore, literature argue widely on low-level forward reserve order picking system thus lacking in system where the forward pick area is spread over several higher levels. This is the case of typical storage systems for niche industrial sector managing medium to high volume items, with high unit value, low turn, and few pick lines per order (e.g. ceramic, glass, wood decoration sector). So the purpose of this study is firstly to present innovative storage assignment rules based on correlated storage policy and embracing the complimentary principle. Secondly test and compare all these rules with the standard rules adopted in real world warehousing practice. Finally discuss the results obtained by experimental analysis on case studies.

5.3. Popularity, COI and Turn as storage assignment rules

According to the previous introduced class-based storage policy, in this research three different criteria which can be used to assign a product (class) to storage locations have been taken as references: Popularity, Cube per order Index (COI), and Turn.

- The Popularity Assignment rule (P) simply considers the demand frequency of the item types. Usually the popularity is defined for an item as the number of times it appears in a customer order during a specific period of time. Product classes are ranked by decreasing popularity and the classes with the highest popularity are assigned the most desirable locations. Malmborg (1996) argues that it can be expected that the distribution of popularity has a direct influence on the extent to which alternative storage policies affect picking time and costs.
- The COI Assignment rule (C) is based on COI index. For an item the index is defined as the ratio of the number of storage addresses in the order picking area that are reserved for the item, to the average number of transactions per order picking period (Haskett, 1963) .The COI index takes into consideration both a sku's popularity and its storage space requirement. According to (C) the product classes are ranked by increasing COI value and the classes with the lowest COI are stored in the most desirable locations (Malmborg 1995).

- The Turn is defined as the ratio of the average stock quantity of a product, to its total movement, both of which are quantified for a certain period of time T.

$$\text{Turn} = \frac{\text{total movement}}{\text{average stock quantity}} \qquad \text{Eq. 75}$$

According to the related Turn Assignment rule (T) product classes are ranked by increasing turn value and then the classes with the lowest turn value are assigned to the most desirable locations.

5.4. Order Closing assignment rule

Inspired to the *Order Completion* principle introduced by Bartholdi and Hackman (2003), in this dissertation a storage assignment rule is introduced, named Order Closing Assignment rule (OC). It is based on an index, called for simplicity *Order Completion Index,* evaluating the strength of a generic item to take part to the completion of an order. It can be estimates as the sum of the fraction of order the generic item performs.

Suppose as an example to have six different items and five customer orders, as shown in Table 5. It follows that in the following incident matrix if the generic Item1 belongs to Order1 and at the same time other 3 different items belong to the same order, so the Item1 has a ¼ of fraction of Order 1. The Order Completion index for item 1 is the sum of all fraction related to all the orders that is equal to 7/4 in the example.

	Order 1	Order 2	Order 3	Order 4	Order 5	Sum
Item 1	1/4	1/2	0	1	0	7/4
Item 2	0	1/2	1/3	0	0	5/6
Item 3	1/4	0	0	0	0	1/4
Item 4	0	0	1/3	0	0	1/3
Item 5	1/4	0	0	0	0	1/4
Item 6	1/4	0	1/3	0	0	7/12

Table 5: Evaluating Order Closing OC on a exemplified customer order

According to the previous hhypothesis the Order Completion Index for a certain Item has:

- Minimum value = 1/ Total Number of Items

when the item belongs to all the customer orders

- Maximum value = number of order

when the item is the one and only to belong to all the customer orders

If two items that are frequently request together also frequently comprise the entire order, then one can conveniently convert the two-line order to a single line order by storing these two products together. Then the order picker will be able to pick both products in a single tour to their common locale, and be done with the order. The benefits of completing orders quickly include reduced work to consolidate orders before shipping.

Once the Order Completion Index has been evaluated for the entire product mix, according to the OC the items are sorted in a decreasing order of these indices, while, on the other hand, the available locations are sorted in an increasing order with respect to their distance from the I/O point (i.e. the so called *desirability ranking* of locations).

5.5. A systematic approach for the order picking problem using product correlation

According to the complementary-based principle previously illustrated, an approach for the correlated assignment storage has been developed for the present research. The proposed systematic approach provides managers and practitioners with an effective solution to the OPP. The approach is composed of two consecutive processes: the first is named Family Grouping, followed by the second named Storage Allocation. As illustrated in Figure 39, both processes involve two steps (called phases):

PROCESS 1. *Correlation analysis* (phase 1.1) and *clustering* (phase 1.2) in the Family Grouping process;

PROCESS 2. *Priority list* (phase 2.1) and *product locations* (phase 2.2) in the Storage Allocation process.

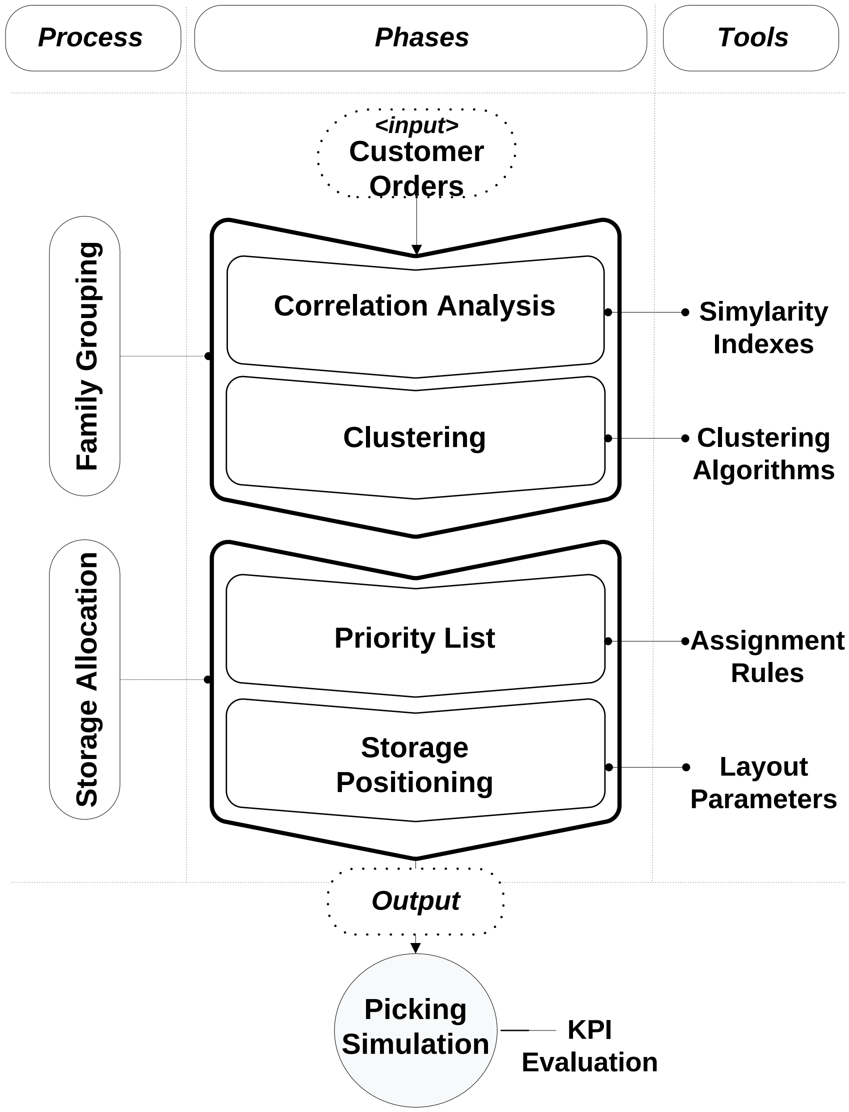


Figure 39: Conceptual framework of the proposed approach.

Each phase is carried out by using a supporting decision making tools (ref. Figure 39, third column) which is composed of a set of strategies, rules, parameterizations, and supporting decision making techniques (e.g. clustering algorithms).

The proposed approach obtains information about customer orders in input and generates the storage locations for products in output by applying the set of supporting decision making tools. The storage locations obtained can be used to simulate historical OP orders to evaluate key performance indicator targets and properly define the best system configuration.

5.5.1. Family Grouping process

The ***first phase*** is named Correlation Analysis and determines the degree of correlation, also called similarity, between the products in the product mix. The literature presents several different measurements or similarity indices to quantify the correlation between pairs of objects. This decision step is very critical because the obtained results influence the number and configuration of the clusters generated since some products may be close to one another according to one measurement but further away when a different similarity index is used.

In literature are two main types of similarity indices:

- **General purpose indices**

  This type of index is uniquely based on information concerning the belonging of different products to common picking orders (so-called belonging frequency information - BFI). As a rule, this information is formalized in the well-known incidence matrix (see Figure 40), a Boolean representation of the presence of the products in the different orders.

Customer Orders	Products							
	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6	Product 7	Product 8
Order 1	1	0	1	0	0	0	1	0
Order 2	1	0	0	1	0	1	1	1
Order 3	1	1	0	0	0	0	1	0
Order 4	0	0	1	0	1	0	0	0
Order 5	0	0	1	0	0	0	0	1
Order 6	0	1	0	0	1	0	0	0
Order 7	1	0	1	0	0	0	0	0
Order 8	0	0	0	0	0	1	1	0
Order 9	1	0	0	1	0	1	0	0
Order 10	0	0	0	0	1	1	0	0
Order 11	0	0	0	1	0	1	0	0
Order 12	1	0	0	0	0	0	1	1

Figure 40: An example of Incidence Matrix

  In general, the incidence matrix is a matrix that shows the relationship between two classes of objects. If the first class is X and the second is Y, the matrix has one row for each element of X and one column for each element of Y. The entry in row x and column y is 1 if x and y are related (called incident in this context) and 0 if they are not. In particular, if X is the class of customer orders and Y the set of products, the entry in row x and column y is 1 if product y belongs to the order x, i.e. a customer in the order x needs the product y to be picked from the OPS.

  Several similarity indices are presented in the literature and are widely used in a great many disciplines e.g. genetics, medical science, data mining, and mathematics. Some examples are: Jaccard, Hamman, Yule, Simple matching, Rogers and Tanimoto coefficients (Mosier et al. 1997, Shafer and Rogers 1993). In particular, the Jaccard coefficient is widely used because of its simplicity and effectiveness. For two generic products *i* and *j* with *n* customer orders, the Jaccard coefficient is defined as follows:

$$S_{ij} = \frac{a}{a+b+c} \qquad \text{Eq. 76}$$

subject to the following *BFI*:

$$a = \sum_{k=1}^{n} a_{ij}* \qquad \text{Eq. 77}$$

$$b = \sum_{k=1}^{n} b_{ij}* \qquad \text{Eq. 78}$$

$$c = \sum_{k=1}^{n} c_{ij}* \qquad \text{Eq. 79}$$

where:

k= 1,..n multi products order;

n number of orders

$$a_{ij}* = \begin{cases} 1 \text{ if both products i and j belong to the same order} \\ 0 \text{ else} \end{cases} \qquad \text{Eq. 80}$$

$$b_{ij}* = \begin{cases} 1 \text{ if only product i belongs to the order k} \\ 0 \text{ else} \end{cases} \qquad \text{Eq. 81}$$

$$c_{ij}* = \begin{cases} 1 \text{ if only product j belongs to the order k} \\ 0 \text{ else} \end{cases} \qquad \text{Eq. 82}$$

- **Problem oriented indices**

In addition to the incidence matrix information, this type of index evaluates the degree of similarity between two products using several specific measurements of suitability for the problem (e.g. production and/or logistics information). For example, two products can be similar if frequently ordered together, if they have a similar bill of material, if they have the same physical dimensions, or if they are manufactured and/or assembled by visiting the same resources (e.g. workstations, CNC machines), i.e. they follow a similar work cycle, etc..

An original problem oriented similarity index is introduced in this dissertation. It measures the level of correlation between products, and supports storage location assignment activity in OPS. More in particular, the performance of the "*Proposed*" index has been compared to the Jaccard coefficient. The first is based on two types of logistic parameter quantified for each product of the generic couple *i* and *j*:

- *BFI* introduced by equations Eq. 77, Eq. 78, Eq. 79;
- *Production information.* The *Proposed* similarity index evaluates the correlation of two products in addition to the *BFI* by using the measurement of suitability represented by the *Turn* value, illustrated in Eq. 75.

The *Proposed* similarity index is defined by the following:

$$S_{i,j} = \frac{a}{a + \frac{1}{4}(b+c)} \times \frac{\min\{Turn_i;Turn_j\}}{\max\{Turn_i;Turn_j\}} \qquad \text{Eq. 83}$$

where:

a, b, c	refer to Eq. 77, Eq. 78, Eq. 79;
$Turn_i$	Turn value for the product *i*;
$Turn_j$	Turn value for the product *j*.

Figure 41 represents the block diagram of the *Proposed* similarity index. Its value ranges from *0* when two products are "completely dissimilar" to *1* when they are "fully similar".

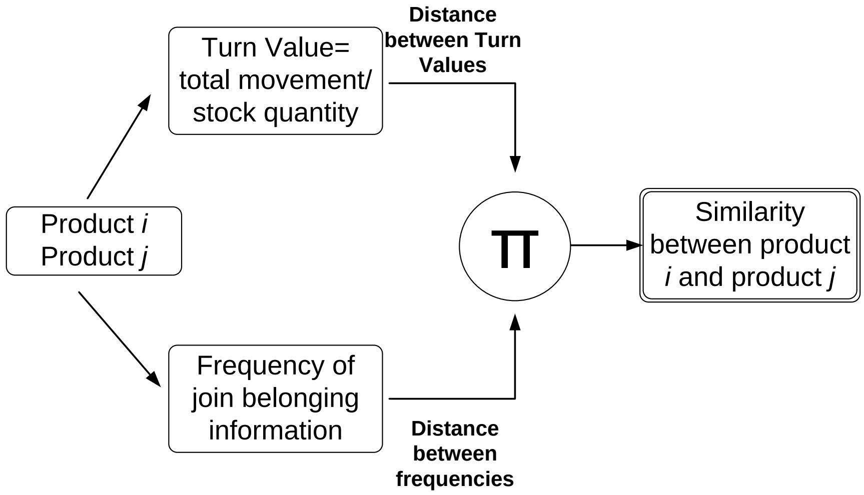


Figure 41: Block diagram of the similarity index

In the first term of the equation the parameter ¼ reduces the impact of coefficients *b* and *c*. In other words it contributes to treating very dissimilar products (i.e. with high values of *b* and *c*) appropriately. The second term estimates the similarity between product *turn* values. This ratio is higher when the *turn* values of two products are similar. It follows that two products have high value of this similarity index if they are similar in both frequency belonging and in *turn* values. A later discussion about the features of the *Proposed* similarity index is provided at the end of this chapter.

The ***second phase*** in the Family Grouping process is the Clustering analysis. Clustering is the organization of products into different clusters (or families) so that the products in each cluster have high values of similarity/correlation. The clustering algorithms are specific supporting decision management tools used in executing this phase (see Figure 39).

These algorithms can be either hierarchical or partitional. Hierarchical algorithms are generally constructive and greedy heuristics which step by step generate clusters applying an agglomerative approach, whereas partitional algorithms decompose directly the products into a set of disjoint clusters. The present research focuses on two well known clustering algorithms to perform this phase: the farthest neighbor clustering (*fn*) and the nearest neighbor clustering (*nn*) algorithm (Aldenderfen et al. 1984). The nn algorithm is based on a scheme that erases rows and columns in a similarity matrix as old clusters are merged into new ones. The similarity matrix D (dimension N x N, see Figure 42 for an example) contains all the correlations between the products d(i,j), calculated according to a chosen similarity index as described in the previous phase.

	Product 1	Product 2	Product 3	Product 4	Product 5	Product 6	Product 7	Product 8
Product 1	1,00							
Product 2	0,17	1,00						
Product 3	0,43	0,86	1,00					
Product 4	0,26	0,31	0,99	1,00				
Product 5	0,00	0,00	0,09	0,26	1,00			
Product 6	0,00	0,00	0,09	0,26	0,40	1,00		
Product 7	0,01	0,01	0,00	0,00	0,42	0,09	1,00	
Product 8	0,00	0,09	0,00	0,00	0,21	0,00	0,00	1,00

Figure 42: An example of Similarity matrix

To the clusterings are assigned sequence numbers 0,1,…, (n − 1) and L(k) is the level of the k-th clustering. A cluster with sequence number m is denoted (m) and the correlation between clusters (r) and (s) is denoted d[(r),(s)]. The algorithm is composed of the following points:

1. Begin with the disjoint clustering having level L(0) = 0 and sequence number m = 0.
2. Find the least dissimilar pair of clusters in the current clustering, say pair (r), (s), according to:

$$d[(r),(s)] = \min d[(i),(j)] \qquad \text{Eq. 84}$$

   where the minimum is over all pairs of clusters in the current clustering.
3. Increment the sequence number: m = m + 1. Merge clusters (r) and (s) into a single cluster to form the next clustering m. Set the level of this clustering to:

$$L(m) = d[(r),(s)] \qquad \text{Eq. 85}$$

4. Update the similarity matrix D by deleting the rows and columns corresponding to clusters (r) and (s) and adding a row and column corresponding to the newly formed cluster. The correlation between the new cluster, denoted (r,s) and old cluster (k) is defined as:

$$d[(k),(r,s)] = \min d[(k),(r)], d[(k),(s)] \qquad \text{Eq. 86}$$

5. If all products are in one cluster, stop. Else, go to point 2.

The fn algorithm is based on the same scheme, with equation in point 4 modified as follows:

$$d[(k),(r,s)] = \max d[(k),(r)], d[(k),(s)] \qquad \text{Eq. } 87$$

A representation of the clusters arrangement generated by a clustering algorithm is a tree diagram, called dendrogram, with individual products at one end and a single cluster containing all items of the product mix at the other (Aldenderfer and Blashfield 1984). An example of a dendrogram is illustrated in Figure 43.

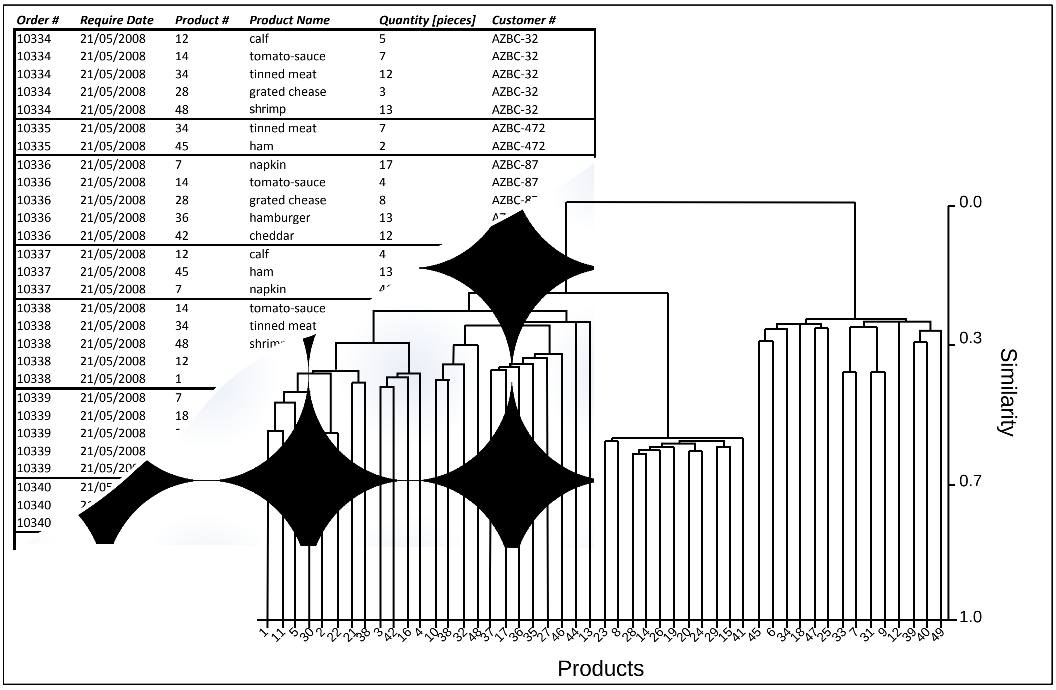


Figure 43: An example of a Dendrogram in correlated storage assignment

Anyway the results of the clustering analysis depend on the minimum admissible level of correlation adopted for the generic group of clustered items. Consequently, the choice of a threshold group correlation measurement strongly influences the number and formation of groups of products. In the present study we adopt the percentile-based threshold value proposed by the author in a previous paper (Manzini and Bindi, 2010-IN PRESS), that is a range of group similarity measurements which cuts the dendrogram at the percentile number of aggregations identified by the clustering rule, as follows:

$$T\_value_{\%p} \in \left] \text{simil}\{\lceil \%_p \times L(m) \rceil\}, \text{simil}\{\lfloor \%_p \times L(m) \rfloor\} \right] \qquad \text{Eq. } 88$$

Where $\%_p$ is the percentile of aggregations, expressed as a percentage; L(m) the level of the clustering; simil{L(m)} the similarity value which corresponds to the level L(m). The percentile-based threshold value is particularly suited when a comparison between different clustering results should be made.

5.5.2. Storage Allocation process

The **first phase** of the Storage Allocation process is the development of an insertion list, named priority list, of products where the previously obtained clusters of products (ref. Family Grouping process in Figure 39) are arranged in agreement with the so-called assignment rule adopted.

The assignment rule establishes the insertion order of the clusters and consequently of products in the insertion list.

- *Cluster Based* rule *(CB)*. Once cluster analysis has been completed, every product belongs to a cluster. The quantity of products grouped together defines the cluster dimension called *power*. This rule inserts the clusters in the list by starting from those with minimal power (equal to 1) and then following an ascending order of power. Consequently, larger clusters are assigned to the less desirable area of the storage systems (see Figure 44).

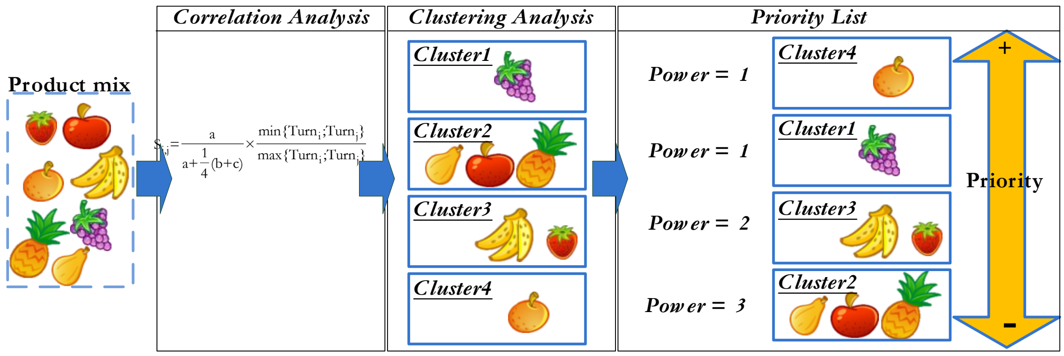


Figure 44: An example of CB rule

- *Cluster & Turn* rule (C&T). This rule arranges the products in the priority list by applying two sequential sorting activities based on the turn value. Firstly, the C&T rule arranges clusters according to their turn values. Then it sorts the products in each cluster according to turn values in descending order of values. Consequently, this rule assigns products to the priority list by using cluster and turn data simultaneously.
- Cluster & COI rule (C&C). This rule arranges the products in the priority list with the same two sorting activities than the previous C&T using COI as value for the ranking instead of the turn value.
- Cluster & Popularity rule (C&P). This rule arranges the products in the priority list with the same two sorting activities than the previous using Popularity as value for the ranking (see Figure 45).

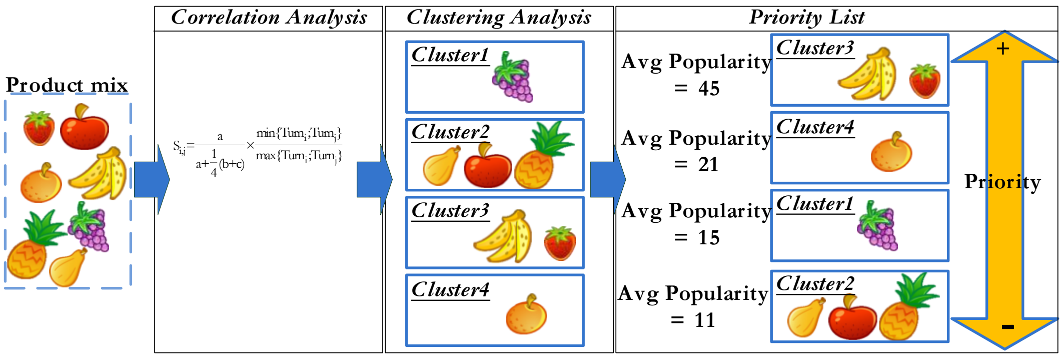


Figure 45: An example of C&P rule

- Cluster & Order Closing (C&OC). This rule arranges the products in the priority list with the same two sorting activities than the previous using Order Completion as value for the ranking.

As described above the CB rule is exclusively resulting from the grouping process, while the C&T, C&C, C&P, and C&OC rules arrange products combining the grouping process respectively with Turn, COI, Popularity, and Order Completion data.

Once all of the products have been listed in order of priority, they can be positioned in the storage areas: this is the so called *Product Allocation* phase, **second phase** of the Storage Allocation process (phase 2.2). In this phase the products are located in the sequence shown on the previously defined priority list, and the correct storage quantities are assigned to each product. Both layout and operational parameters (e.g. shape factor for the storage area, routing policy, load capacity, etc.) play a significant role in this decision step (Manzini et al. 2006b). Each parameter strongly impacts on the generation of logistic costs in terms of travel distance.

The most important operational decision variables (i.e. the degrees of freedom of the decision and optimization process) can be summarized as follow:

- *Positioning rules*. After all products have been ordered in the priority list, they can be located in the most suitable way within the storage areas. Managers can decide the exact locations for each product according to the sequence defined by the list, and to a chosen *positioning rule*. This rule identifies a specific layout for the products under assignment across the shelves of a warehousing system. Furthermore, these rules are strictly connected to the *assignment rule* previously illustrated.

  In the literature two general classes of positioning rules are argued: the first is the one that consider the exact distances between the available locations and the I/O input output point, the second is the so called *storage-allocation patterns* according to which items types are assigned to locations following three different areas of high, medium and low frequency (Petersen 1999, Jarvis et al. 1991, Wascher 2004). The *storage allocation patterns* are depicted in Figure 46.

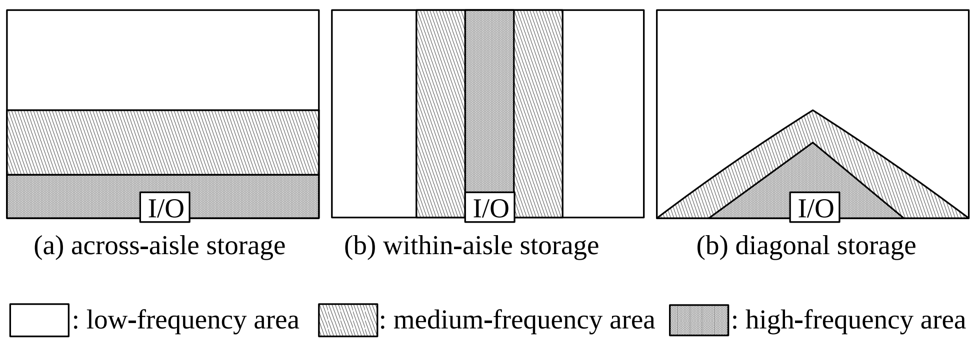


Figure 46: Storage allocation patterns (based on: Wascher 2004).

The *positioning rules* adopted in this study have been developed to perform well with the correlated storage assignment strategies. In particular they are based on an exact correspondence between product quantities and space available in the storage system. Moreover these rules try to maintain together each other products that should be stored together according to the family grouping process. It follows that adopting a storage assignment rule based on product correlation brings certainly the user to choose a subsequent positioning rule under some constraints. For example the within-aisle storage rule described in Figure 46 defines two areas with the same medium frequency skipping from an aisle to another. That rule doesn't match exactly with the product correlation requirement called *subsequent positions nearness*, producing de facto a disconnected progress positioning of product. Indeed it may occur that a product *i* that belongs to a cluster with product *j* (i.e. they have high level of correlation) could be stored in different aisles.

The following two positioning rules are especially developed for the low-level order picking system, satisfying the correlation requirement of subsequent nearness positioning nearness:

a. *Zig-zag rule.* The products in the priority list are positioned on the shelves according to a layout running in zigzags across the aisles of the system. The positioning process starts from the bottom left of the system (see start point in Figure 47).

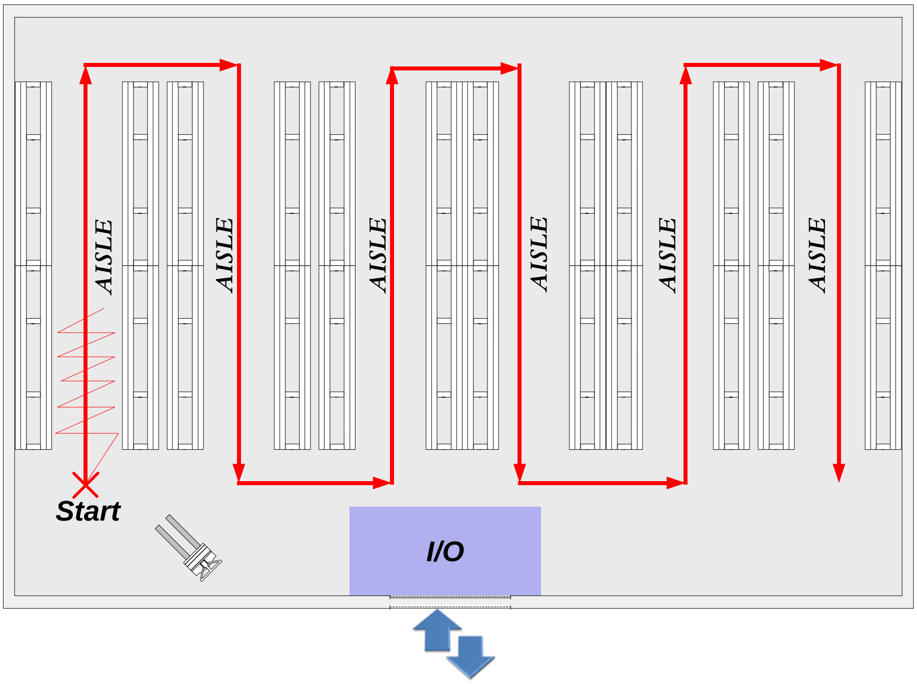


Figure 47: Zig-Zag positioning rule

b. Parametric stripes rule. In agreement with the priority list, the products are positioned on the shelves across aisles following a "breadthwise" configuration. The positioning process starts from the shelves at the bottom left and concerns a specific number of slots in the shelves. This is why this positioning rule is called *parametric stripes*. The correct value of the width of the stripes (i.e. the number of slots in the generic shelves involved) must be quantified accurately (see Figure 48). It can be seen as an extension of the *across-aisle storage pattern*. Choosing a number of

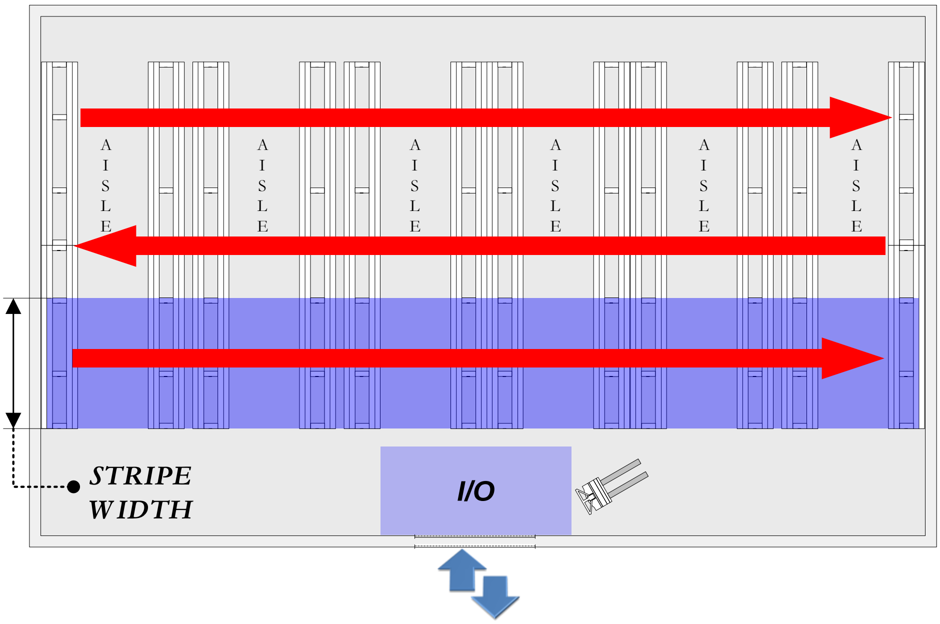


Figure 48: Stripes positioning rule

Literature defines positioning rules mostly for low-level forward reserve order picking system thus lacking in high-level system where the forward area is spread over several higher levels. In Yu and De Koster (2009a and 2009b) the authors argue some attempts to develop positioning rules for a three dimensional high-level storage system but the approach is not suited for assignment rules based on clustering.

Some innovative positioning rules are introduced by the author to overcome this constraint and to become a useful set of recommendations for supporting the design and control activities of managers and practitioners:

c. The first positioning rule, called *Stripes*, divided the storage system in equal width stripes (i.e. three and an half spans) following an across-aisle storage policy. As showed in Figure 49, products according to the priority list are allocated side by side in the slots of shelf 1 and shelf 2 following the path identified by the red arrow (for a better comprehension it can be seen also by the sequential number printed on the skus). Once the 98 slots from the first three and an half spans are completely filled the same procedure skip to the next aisle. Then the procedure is repeated to the end.

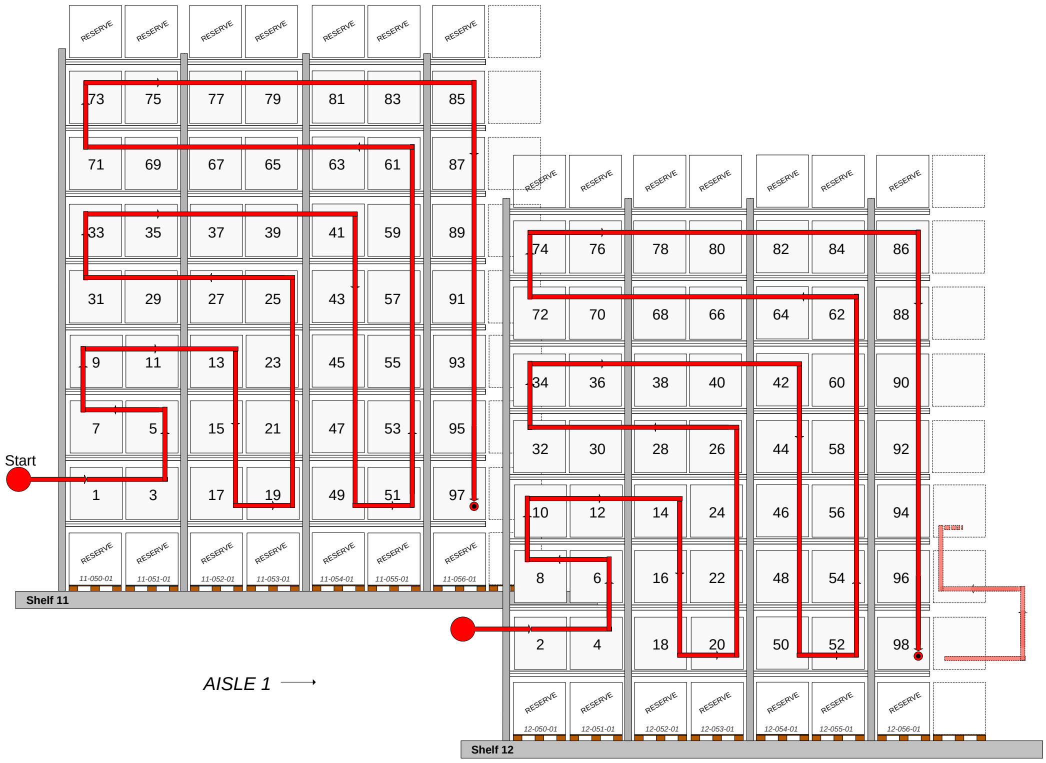


Figure 49: Stripes positioning rule (side view of the shelves)

The second and the third positioning rules have been developed for a particular case study (presented in the following sections) and are based on the iso time mapping. Warehouse locations are divided into iso time areas according to the necessary total travel time considering the speed profile of the material handling equipment in use to reach the locations belonging to that area from the I/O point. The exact number of iso time areas is generally a choice for the user according to the features and characteristic of the system studied.

The positioning rule Isotime 1 has three iso time areas, while Isotime 2 has six according to the rule introduced in Sturges (1926) for the identification of the optimal number of classes. As shown in Figure 50, locations from the area A in Isotime 1 have a travel time lower than 10.9 seconds, locations from area B have a travel time comprised between 10.9 and 22.3 seconds, while locations from area C have a travel time comprised between 22.3 and 33.6 seconds.

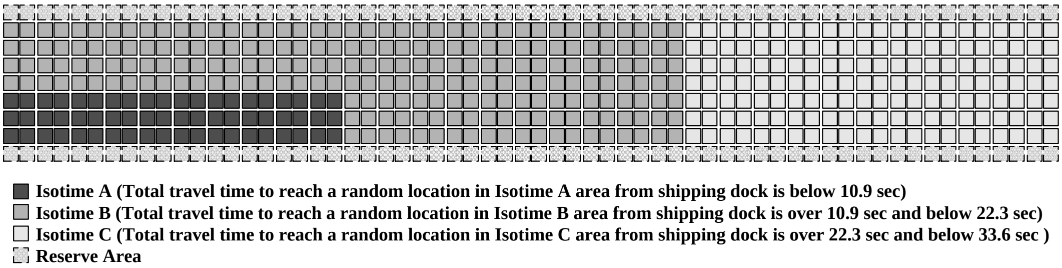


Figure 50: Isotime 1 Positioning rule – side view of the shelf

Similarly Figure 51 describes the iso time areas for the Isotime 2 positioning rule. The adopted procedure for establish the definitive position of each product is the same used in the Stripes rule. For simplicity the followed path is not introduced in the figure.

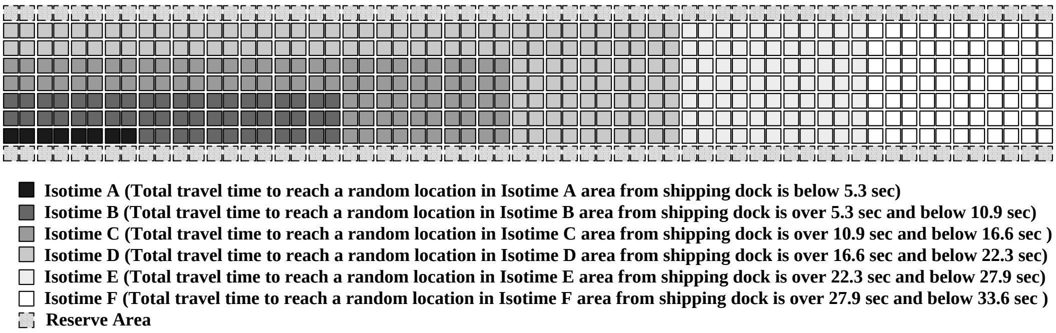


Figure 51: Isotime 2 Positioning rule – side view of the shelf

Even if the previous positioning rules are specifically designed for a particular case study, in any case these positioning rules can be extended for other systems, following the same criteria.

- *Shape factor*. This refers to the planimetric dimensions of the storage area and can be defined as the ratio between the length and width of a warehouse (e.g. L/W in Figure 52). Warehouses frequently have a shape ratio of 1 or 0.5. This factor is very critical because warehouse dimensions strongly influence the total travel distance in storage and retrieval activities.
- *Load capacity* of a picker. In OPS the picker travels to picking locations and picks products until the load capacity of the vehicle is full, then the picker returns to the input/output area (the depot area) to unload the products and continue the OP activities.
- *Routing policy*. There are three main routing policies in OPSs: *return, traversal*, and *composite*. The literature presents extensive studies of the performance of these policies, particularly

in unit load OPSs (Hwang et al. 2004; Petersen 1997; Caron et al. 1998; Hwang et al. 2003). In traversal policy, also called S-shape policy, the picker enters at one end of an aisle containing at least one pick and exits at the other end. In return policy the picker can enter and exit at the same end of an aisle. The composite policy combines elements from both traversal and return policies; aisles with picks are either entirely traversed or entered and left at the same end.

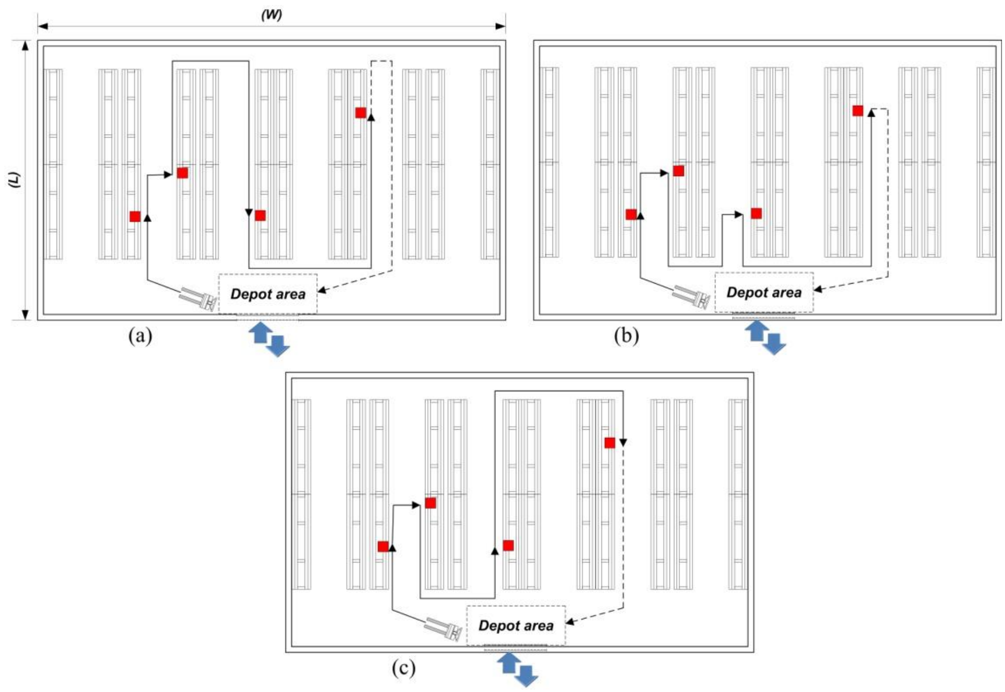


Figure 52: (a) Traversal, (b) return and (c) composite policies

- *Aisle layout*. Basic aisle layout alternatives are the *lengthwise* and the *breadthwise*. In lengthwise (or longitudinal) OPS stocking aisles run perpendicular to the warehouse front-end (as illustrated in Figure 52). Roodbergen and De Koster (2001b) call this configuration "basic warehouse layout". In breadthwise OPS stocking aisles run parallel to the warehouse front-end where the depot area is located.

5.6. Experimental Simulation & ANOVA statistical testing analysis

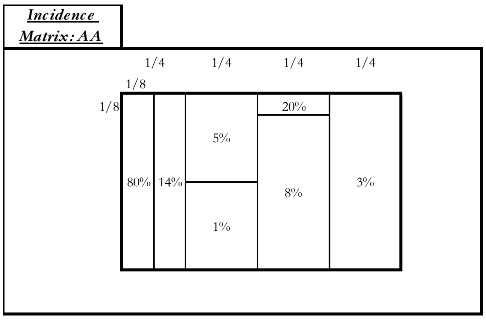
This section illustrates an experimental simulation conducted to identify the relative level of influence for the designing factors. The aim of this simulation is to find a set of fewer more important factors to which concentrate on during the design and control of order picking system.

5.6.1. Simulation Set Up

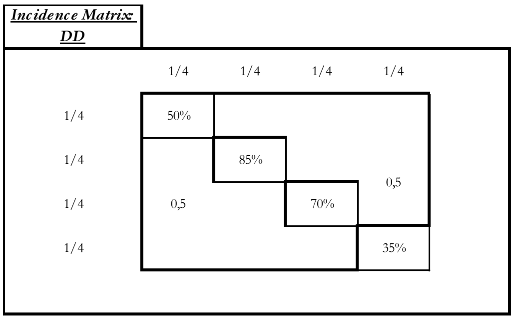
The picking environment in this simulation experiment is a rectangular warehouse. Assuming each storage span location of the rack is 3 meters and 1 meter in depth, and the I/O point is in the lower right corner or midpoint of the warehouse, respectively, the picker starts from point I to pick products from the picking point, and after finishing picking operation, goes back to point O and starts picking for the next order. Some other assumptions are shown below:

1. Aisle width is 3 meters.
2. Every storage location has "*no stock out*" hypothesis.
3. There are enough locations in the warehouse to store the product mix generated
4. The average moving speed of the material handling equipment is 2,5 m/sec.
5. The material handling equipment and warehouse system has no downtime.

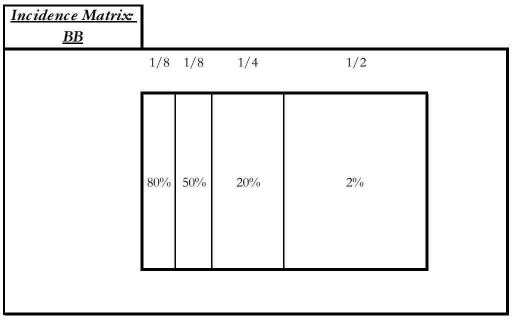
About four hundred orders are generated randomly by a computer. The turn rate and the similarity of products are analyzed. In each test combination, the products data is transformed to corresponding same storage locations in order to calculate picking distance. Numerous combination of factors are performed such as nine storage allocation rules, two types of positioning rules (ref. to low level system), two types of order picking policy, five types of picking density. The density of picking generated is practically visible on the incidence matrix. More presences of products on the incidence matrix identify a higher density of picking. Just to be clear, the density as introduced in this research is not related to the general picking density inside the aisle. So it is not referable to congestion issue. Table 6 illustrates the five different picking densities on the related incidence matrix, called AA, BB, CC, DD, and EE.



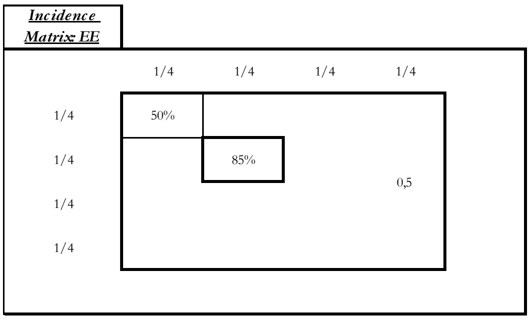
Presence of 15,6% of products on the overall matrix



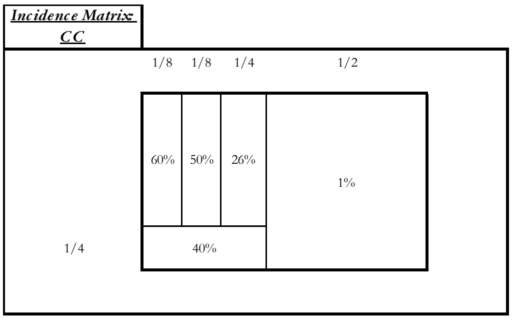
Presence of 18% of products on the overall matrix



Presence of 17% of products on the overall matrix



Presence of 12% of products on the overall matrix



Presence of 19% of products on the overall matrix

Table 6: Different densities of picking.

Range Turn	Density	I/O	Positionig rule	Capacity	Routing	Policy	Storage Allocatio	Algorith m	Similarity Index	Shape	Cut Value	Total Travel	Δ% Sav. Ref. *R*	Δ% Sav. Ref. P
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	R	/	/	1-1	/	2029846	/	5,37
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	P	/	/	1-1	/	1926482	-5,09	/
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	C	/	/	1-1	/	1896681	-6,56	-1,55
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	CB	nn	Proposed	1-1	0,5	1928834	-4,98	0,12
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	OC	/	/	1-1	/	1883271	-7,22	-2,24
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	C&C	nn	Proposed	1-1	0,5	1829143	-9,89	-5,05
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	C&T	nn	Proposed	1-1	0,5	1769503	-12,83	-8,15
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	C&OC	nn	Proposed	1-1	0,5	1738015	-14,38	-9,78
[0.3,2]	AA	midpoint	Stripes	1 m^3	off	RETURN	C&P	nn	Proposed	1-1	0,5	1701503	-16,18	-11,68

Table 7: Extract of results for density AA

Specifically the density/presence called *AA* can be identified by a density equal to 15.6% of total presences of product on the matrix. The other relative patterns of density are: DD for a total presence of 18%, BB 17% of density, CC 19%, and EE a density equal to 12%. Even if the percentage of density are all similar, the distribution on the matrix, so the relative correlation between products, is completely different. In fact density EE has a presence of products completely concentrated on few orders. On the other hand density AA has a more uniform presence on the orders.

The current simulation system collects the related evaluation index data, for example, the overall travel picking distance. Then the collected average overall picking distance data from the simulation is arranged and variance analysis is performed. Table 7 shows the comparison of average overall picking distance for density AA. From Table 8, it can be clearly seen that the routing, storage assignment rules, similarity indices, density and threshold cut value all have obvious different effects on the average overall picking distance.

Factors	D.F.	SS	MS	F test	*p* -value
a	1	13007030.8	13007030.9	2516.1	< .0001*
b	1	46314.1	46314.2	9.4	0.0023*
a*b	1	50008.36	50008.3	10.1	0.0016*
c	2	2408785.8	1204391.2	234.3	< .0001*
a*c	2	6951007.1	3475503.5	700.1	< .0001*
b*c	2	270067.5	135033.8	26.9	< .0001*
a*b*c	2	171726.5	85863.7	17.2	< .0001*
d	1	226417.4	226417.3	46.5	< .0001*
a*d	1	181.3	181.4	0.1	0.8486
b*d	1	46128.6	46128.7	9.2	0.0024*
a*b*d	1	75141.2	75141.3	14.9	0.0001*
c*d	2	63255.3	31267.6	6.3	0.0018*
a*c*d	2	268487.8	134243.5	27.0	< .0001*
b*c*d	2	141427.7	70712.7	13.9	< .0001*
a*b*c*d	2	137971.5	68987.9	13.8	< .0001*
e	10	1173055.4	1173055.4	23.6	< .0001*
a*e	10	55436.5	5543.6	1.1	0.3470
b*e	10	55465.9	294.6	0.1	1.0000
a*b*e	10	2938.9	512.7	1.4	0.9998
c*e	20	5182.1	518.6	0.3	0.1070
a*c*e	20	140305.3	7051.1	0.1	0.9959
b*c*e	20	35667.7	1768.9	0.1	1.0000
a*b*c*e	20	2624.1	130.9	0.1	1.0000
d*e	10	2657.4	128.6	3.6	< .0001*
a*d*e	10	181179.6	18118.5	0.3	0.9951
b*d*e	10	10635.6	1064.3	0.2	0.9854
a*b*d*e	10	10635.2	1193.4	0.2	0.9921
c*d*e	20	13877.2	4156.1	0.8	0.6705
a*c*d*e	20	11949.2	1002.7	0.2	0.9999
b*c*d*e	20	20045.1	573.4	0.1	1.0000
a*b*c*d*e	20	6409.6	320.5	0.1	1.0000
Total	1451	78927483.5			*P< 0.05

a: routing b: storage assignment rule c: similarity index d: density e: threshold cut value

Table 8: Results for relative travel distance (Anova)

Figure 53 shows the Pareto chart of the effect obtained as result of the simulation analysis. Routing and assignment rule are the factors having the higher impact on the system response. Similarity index has a moderate impact. Density and cut value have a slight but relevant influence too. Moreover it can clearly seen that are present interactions among those five factors such as picking density, routing, similarity indices, cut value and storage assignment planning. From the simulation result verification, we know that appropriate

Storage assignment rule accompanied with routing planning has a distinguished effect in reducing the overall picking distance.

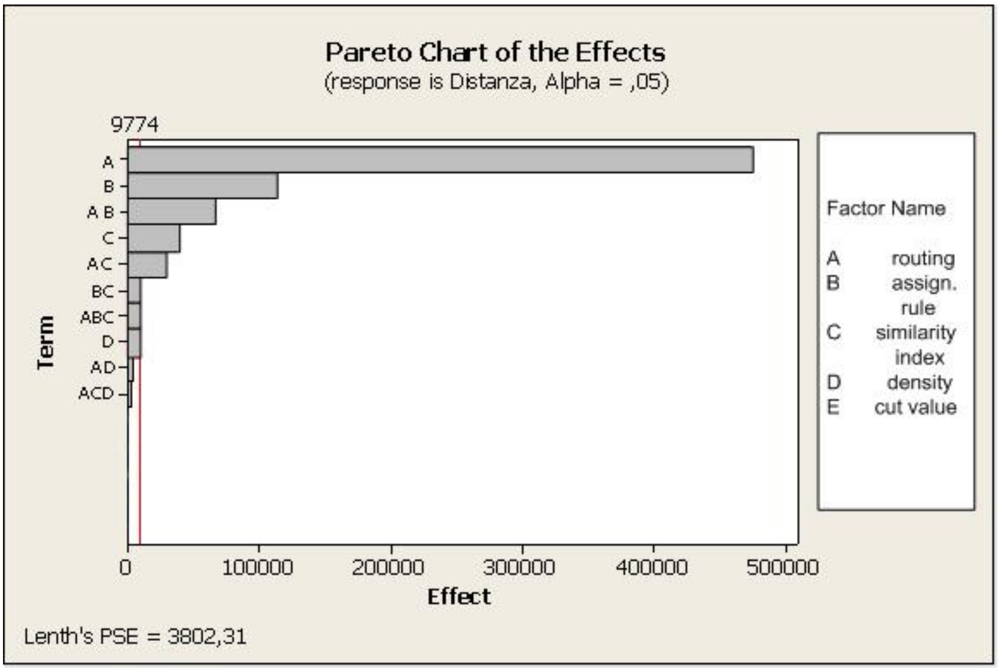


Figure 53: Pareto chart of the effects

Through system simulation experiments, we verify that we can find optimum combination for warehouse design in different environment and better performance is found. It is hoped that this approach can be a practical and useful reference to the industry in the design and planning of an order picking system in a warehouse system.

5.7. Case Study I: low-level order picking system

The proposed and previously illustrated supporting decision approach was applied to the design of a new warehousing system in an Italian food service company with particular emphasis on the allocation of products within the storage areas. This storage plant is 15000 m² and serves Central and Northern Italy. Figure 54 shows a view of the storage system configuration.

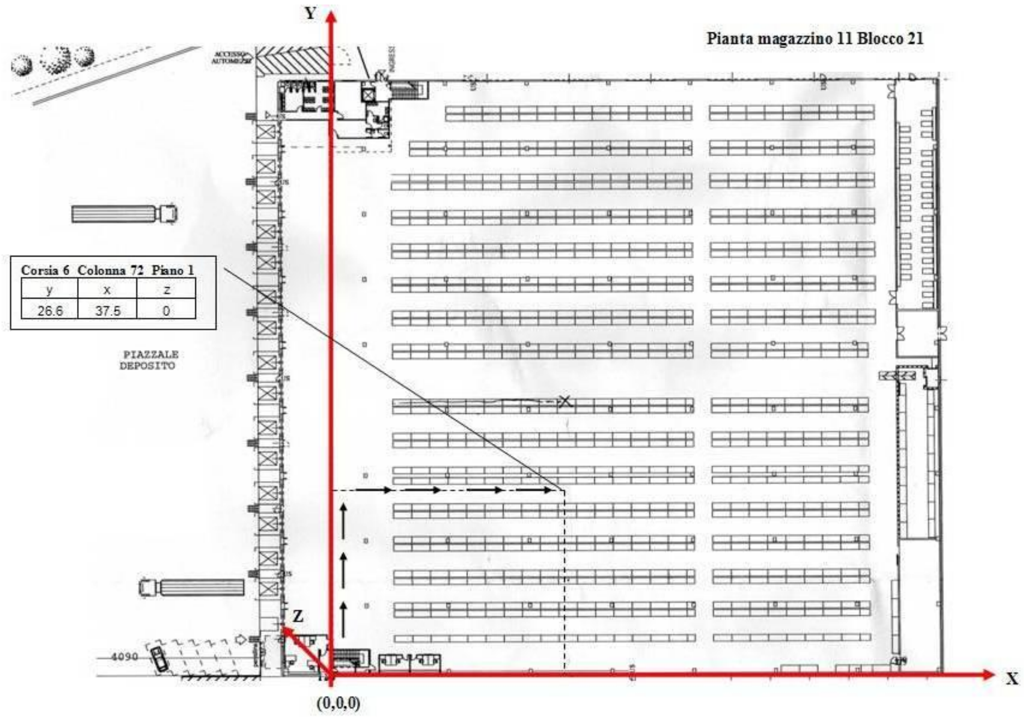


Figure 54: Layout of the storage system

Figure 55: Front of the Picking Aisles

Figure 56: Picking equipment

Figure 55 shows a picture taken in front of the picking aisles. Figure 56 shows the picking equipment.

The total quantity of outbound products in the system in a time period of a week is approximately 2200 m^3. The average quantity of customer orders is approximately 4100 orders/week and the number of less than unit load picking requests is approximately 59000 rows/week. Figure 57 and Figure 58 show the histogram of order lines and movement.

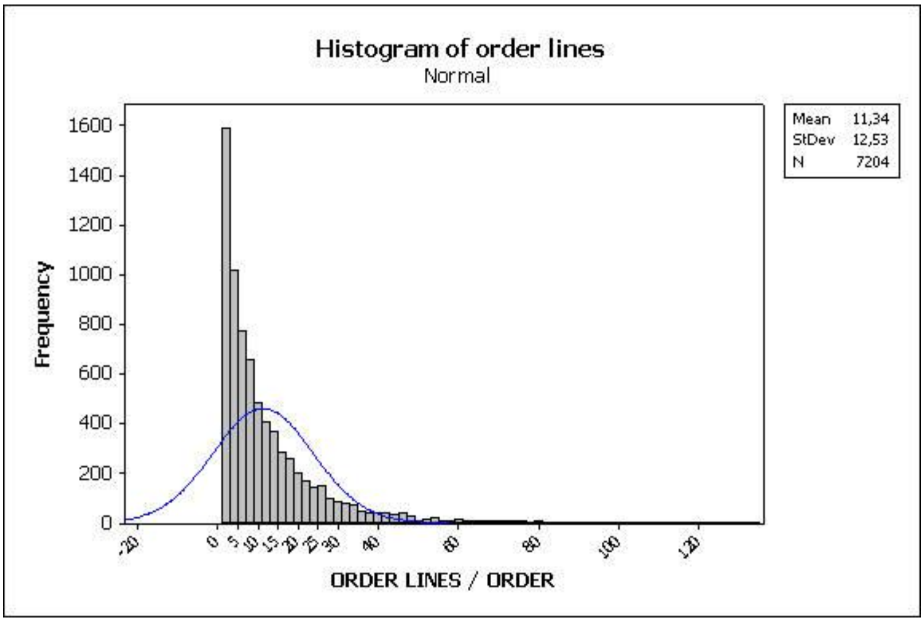


Figure 57: Histogram of order lines (order lines/order)

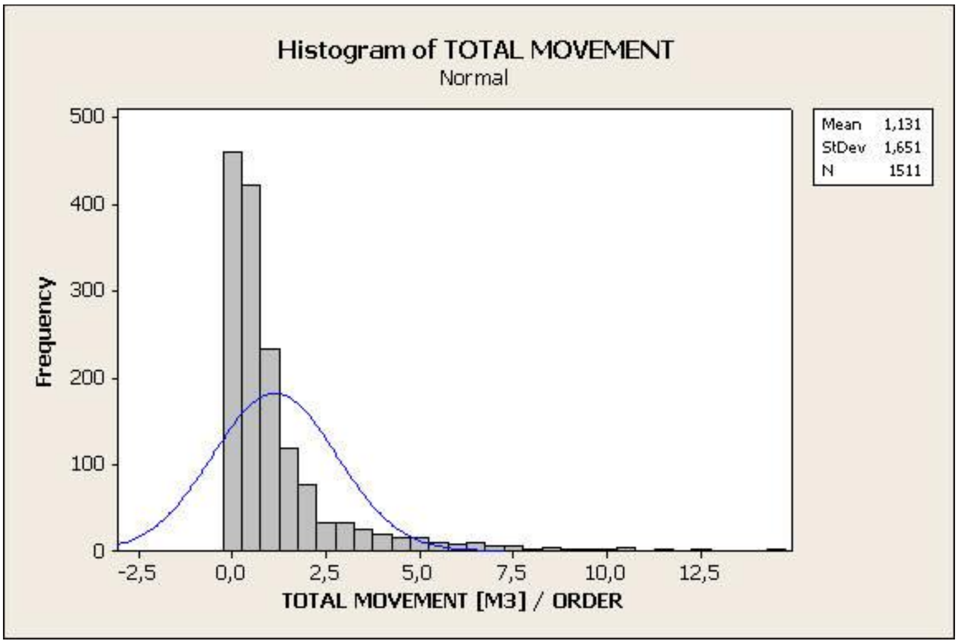


Figure 58: Histogram of total movement

The product mix of the company is composed of 2500 different items. As usual, this system follows the Pareto's 20/80 principle: 80 percent of the stock quantity is generated by the 20 percent of the product mix. Figure 59 shows the Pareto's curve for the storage system.

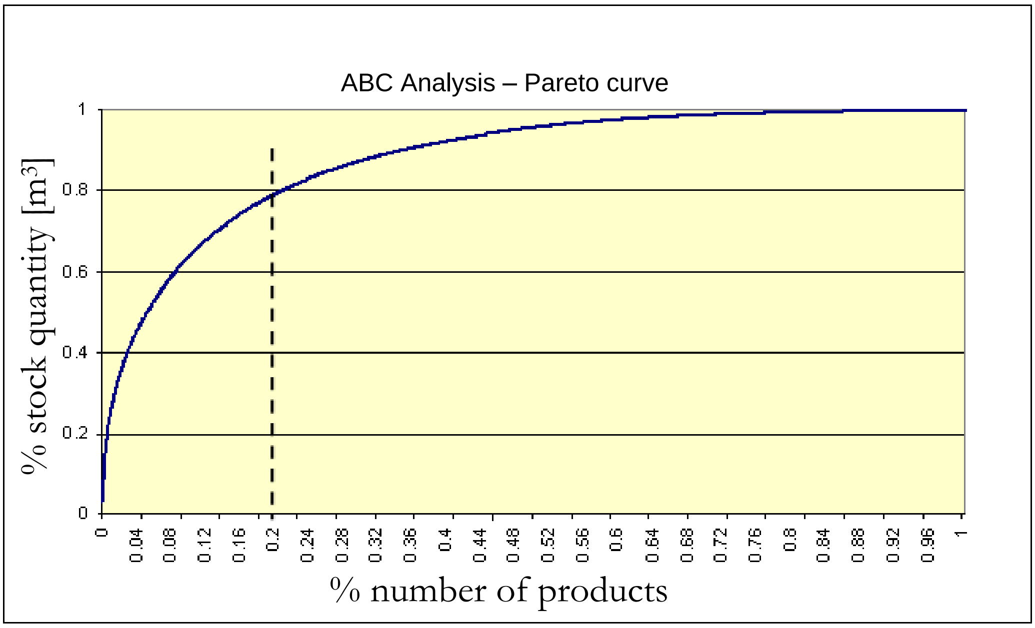


Figure 59: Pareto Analysis

A multi scenario what if analysis was carried out in order to identify the best configuration of the system and minimize the total travel distance assuming a lengthwise configuration of the system layout. It follows the list of factors and related levels assumed in the factorial analysis:

Factor	***Level***
Shape [L-W]	1-1; 1-2
Load Capacity [m3]	1; 1,5
Routing Policy	Traversal; Return
Positioning Rule	ZigZag; Parametric Stripes
Assignment Rule	Randomized (R); Populairty (P); COI (C); Turn (T); ClusterBased (CB); Cluster&Popularity (cp); Cluster&Turn (C&T): Order Closing (OC); Cluster&OrderClosing (C&OC)
Similarity Index	Poposed (B1); Jaccard (J)
Routing	on (O); off (S)
Threshold cut value	4; 10,5

The study pays particular attention to comparing the performance of distinct *similarity indices*, different storage *assignment strategies* (e.g. random, class based, and correlated), and different *assignment rules*. The approach introduced in this chapter is tested on the case study. The initial data have been divided into two sets, the *training set* and the *test set*. The training set has been used to train the approach and define the storage allocations, while the test set is used to simulate the retrieval of customer order from the obtained forward storage area and to evaluate the results (see Figure 60). The splitting of initial data is a necessary step in order to avoid the so called "*overfitting*" data problem and outcome bias.

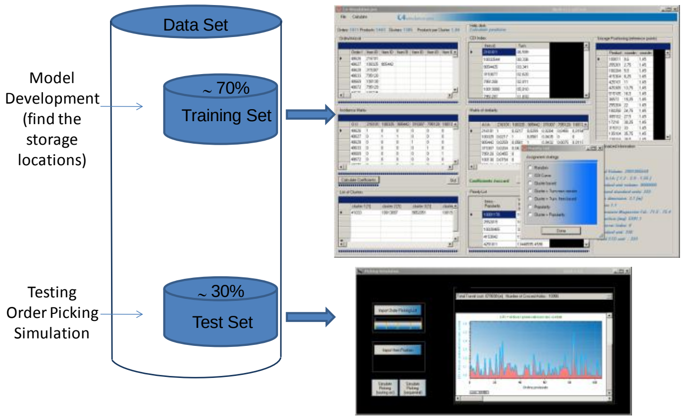


Figure 60: Preliminary data processing

Table 9 lists an extract of the arrangement of product according to the popularity index.

RANKING ACCORDING POPULARITY	ITEM	ITALIAN DESCRIPTION	ENGLISH DESCRIPTION
1	132463	RISORIBE PARB. KG5 SCOTTI	RICE
2	2552015	OLIO EXTRA V.OLIVA LT. 1BOTT.	EXTRA VERGIN OIL
3	1232445	LATTE PARMALAT UHT P.S. LT1	ultra-heat treatment MILK
4	4153042	C.D. ZUCCHERO IN PACCHI KG.1	SUGAR
5	4251011	D.A. SALE M. GROSSO GEMMA KG10	SALT
6	4253054	D.A. ACETO BIANCO LT.1	VINEGAR
7	5151055	PELLICOLA PER ALIMENTI MT.300	PROTECTIVE FILM
8	36573	LATTE UHT INTERO LT1	WHOLE MILK
9	2552042	OLIO OLIVA LT.1BOTTIGLIA	OIL
10	324495	OLIO SEMI DI SOIA LT.5 PET SAN MARCO	SOYA BEAN OIL
11	3051021	F.L. FARINA BIANCA TIPO 00 KG.1	FLOUR 00
12	17218	F.L. FIOCCHI PURE' KG.2 BUITON	PUREE
13	3153121	P.D. GRISSINTORIN STIRAT.GR12X40	BREADSTICK
14	1351049	ACQUA NAT. LT1.5 PET S.BEN.	WATER
15	2281047	L.R. PELATI KG.3 NORMALI	PEELED TOMATOES
16	3051011	F.L. FARINA BIANCA TIPO0 KG1	FLOUR 0
17	5055220	SALVIETTE 33X33 2V. CAMST X2400 PZ	NAPKINS
18	1257082	V. BRICK BIANC LT.1BRICCHELLO	WINE
19	4253061	D.A. ACETO BALSAMICO LT.0,5 LA VILLA	BALSAMIC ACEITE
20	4151045	CAFFE' MACINATO GR.250	COFFE
21	2852030	PANNA UHT LT. 1/2	CREAM
22	10000000	GUANTI LATTICE PICCOLI X100PZ	LATEX GLOVE
23	4251024	D.A. SALE FINO KG.1	SALT
24	4152309	C.D. ORZO SOLUB.RISTORA GR.500	BARLEY
25	5054012	STUZZICADENTI IMBUST. CAMST X 1000 PZ	toothpick
26	2552069	OLIO EXTRA V.OLIVA LT5 PET OLICAF	OIL
27	9054510	SALE DEPURAZ. PASTIGLIE Kg. 25	SALT FOR DISHWASHER
28	3153077	P.D. BIFETTA PANCOLUSSI GR.14X240	RUSK
29	4153021	C.D. ZUCCH BIANCO BUST PERS.CAMST	SUGAR
30	3153048	P.D. CRACKERS MONOP.GR.25 X100 PZ	BISCUIT
31	7951164	P.S. FARFALLE F19 GRANAR.	PASTA

Table 9: Popularity ranking (first 31 products)

The correlation analysis conducted with the Proposed similarity index and the successive clustering process has generated 1440 levels of clustering/group at different values of similarity as shown in Figure 61. It may be seen clearly from figure that similarity levels out for the first 50 clusterings, after that it dramatically falls to similarity value equal to 0,5. Therefore the general similarity of the product mix is not strong. As a consequence choosing a high threshold cut value could results in few clusters having power greater than one.

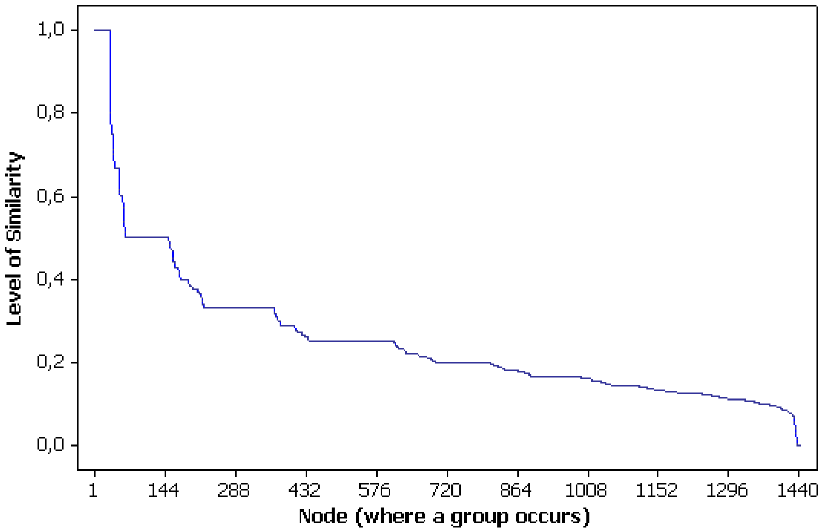


Figure 61: Values of similarity at different clustering levels.

Table 10 lists an extract of resulting clusters after the grouping analysis. It is peculiar to see that the cluster with id equal to 1362 groups together a certain type of "pasta" and a certain kind of red sparkling wine (hope it is at least a good match!).

Features				Cluster id	Products Description
1340	10029384	472522	0,4725223	1338	10029384 P.I. PASTINA TEMPESTINA GR.350 MELLIN
1341	10000522	502242	0,502242	1338	10000522 C.D. CAMOMILLA HOUSE OF TEA AST.50 FILTR
1342	10020098	684191	0,6841906	1338	10020098 BISC. PLASMON GRAN. SENZA GLUT. GR.340X2
1343	10024250	3552640	3,5526399	1338	10024250 BICCHIERE K200 X 700 PZ
1344	10008052	364615	0,3646154	1338	10008052 D.A. ESTR.DI CARNE 5% STAR KG.1
1399	1155057	194471	0,1944709	1365	1155057 WHISKY JACK DANIELS LT.1
1400	4253059	135957	0,1359573	1365	4253059 D.A. ACETO 0,250 ROSMARINO
1397	1154007	191806	0,191806	1364	1154007 GRAPPA BIANCA CORREZION.LT.1,5
1398	1152036	80437,2	0,0804372	1364	1152036 AMARO LUCANO 3/4
1395	2161020	434696	0,4346961	1363	2161020 F.S. CILIEGIE SCAT. KG.1
1396	35214	494842	0,4948416	1363	35214 P.D. MOUSSE CIOCC. BIANCO GR.750
1393	7952060	835221	0,835221	1362	7952060 P.U. PENNETTE F158 GRANAR
1394	1252091	935623	0,9356228	1362	1252091 V. PIGNOLETTO FRIZZ. LT 0.375
1391	7956016	3574646	3,5746458	1361	7956016 P.B. CONCHIGLIE BIO GR.500 ALCE NERO
1392	10009465	101466	0,1014656	1361	10009465 P.I. OMO MELA BIO GR.100 YO GRANDE
1424	18616	1349534	1,3495344	1376	18616 P.U. FETTUCCINE UOVO KG1 CT X6 BARILLA
1425	4252014	48178,1	0,0481781	1376	4252014 D.A. CANNELLA MACINATA GR.500
1422	1161081	76441,4	0,0764414	1375	1161081 RHUM BACARDI C. BIANCA LT.1
1423	1161093	87475,4	0,0874754	1375	1161093 RHUM PAMPERO ESP.GOLD CL.70
1420	10022012	489914	0,4899143	1374	10022012 P.B. MACCHERONI RIG. BIO GR500 ALCE NERO
1421	1152032	49970,1	0,0499701	1374	1152032 AMARO JAGERMAISTER LT.1,5
1418	5053118	3699542	3,6995417	1373	5053118 COPP.MACED PP OTTAG X 1600 PZ
1419	10003330	1197840	1,1978397	1373	10003330 P.I. OMOG. NIPIOL FORMAGGINO IPOLIP GR80

Table 10: an extract of resulting clusters

The grouping analysis has generated about 60 clusters at a threshold cut value equal to 0.6 and according to the nn algorithm. It follows that each cluster has an average of 2,17 products. Only the 8% of the total number of skus belongs to a cluster with power greater than 1 as illustrated in the following dotplot.

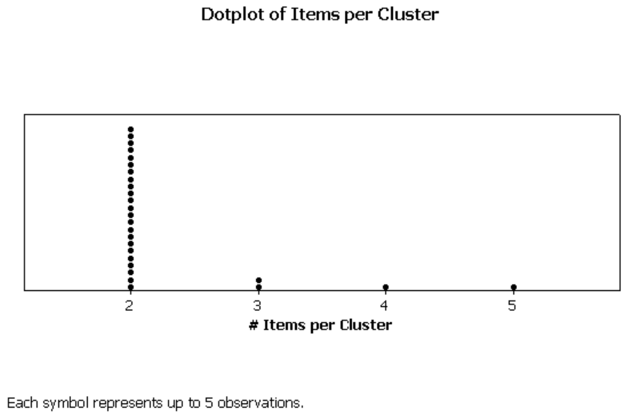


Figure 62: Dotplot of items per cluster.

The *what-if* analysis is based on more than one hundred different simulated scenarios. For each scenario simulated, the total travel distance associated with retrieving products from the storage area in response to real customer requests is quantified. *Appendix B* is an extract of the results obtained in terms of the total travel distance [m/week] for different system configurations. The antepenult column of Appendix B reports the percentage saving compared to the *popularity assignment strategy*.

The generic travelled distance [m/week] can be converted in a variable cost [$/week] and contributes to quantify fixed costs related to the necessary number of workers and picking vehicles in the system.

Storage Assignment Rule	Avg. Saving* (ref. Popularity)
Turn	0,94
Cluster&Turn	-2,19
Cluster&Popularity (Proposed similarity Index)	-4,41
Cluster&Popularity (Jaccard similarity coefficient)	-3,88
ClusterBased	1,17

* obtained on the average values of the simulation

Table 11: Comparing average results with popularity assignment strategy

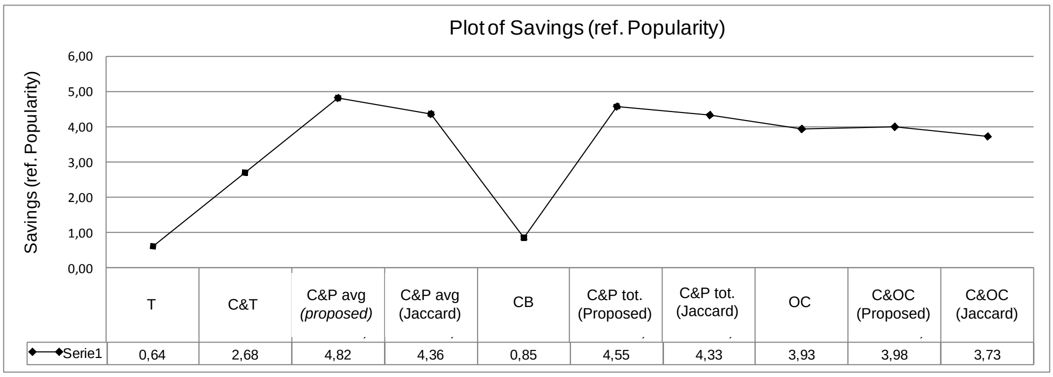


Figure 63: Plot of savings (ref. popularity)

The obtained results (see Figure 63) demonstrate that both the Jaccard coefficient and the *Proposed* similarity index guarantee significant logistic cost saving. Consequently, the *correlated storage assignment* performs better than *popularity* and *class based storage strategies*. Nevertheless, there are several system configurations where the *Proposed* similarity index has the largest percentage reduction in travel distance compared to the Jaccard. Figure 64 presents the main effects plot for travel distance (i.e. average travel distance in all simulated scenarios), and compares different assignment strategies and rules. The Cluster&Popularity rule results the best performing. Indeed, it makes an average saving of approximately ten per cent on total travel distance compared to the *popularity rule*.

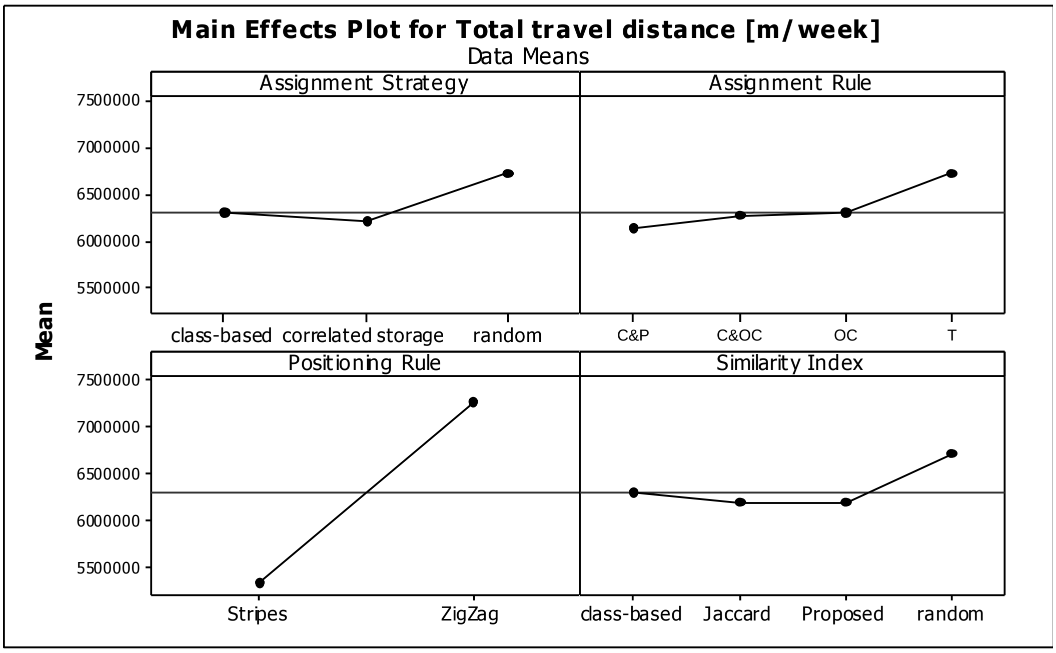


Figure 64: Main effect plot for total travel distance

Figure 65 represents the density of picking on the system layout (the diameter of the spheres is proportional to the density strength) firstly when products are located randomly (Figure 65a) and secondly when they are located according to the correlated strategy and when the C&P rule is adopted (Figure 65b). In particular, the second figure shows that the demand density is higher for shelves closer to the depot area justifying the results and the best performance obtained: correlated products with high level of demand are appropriately located near the depot area.

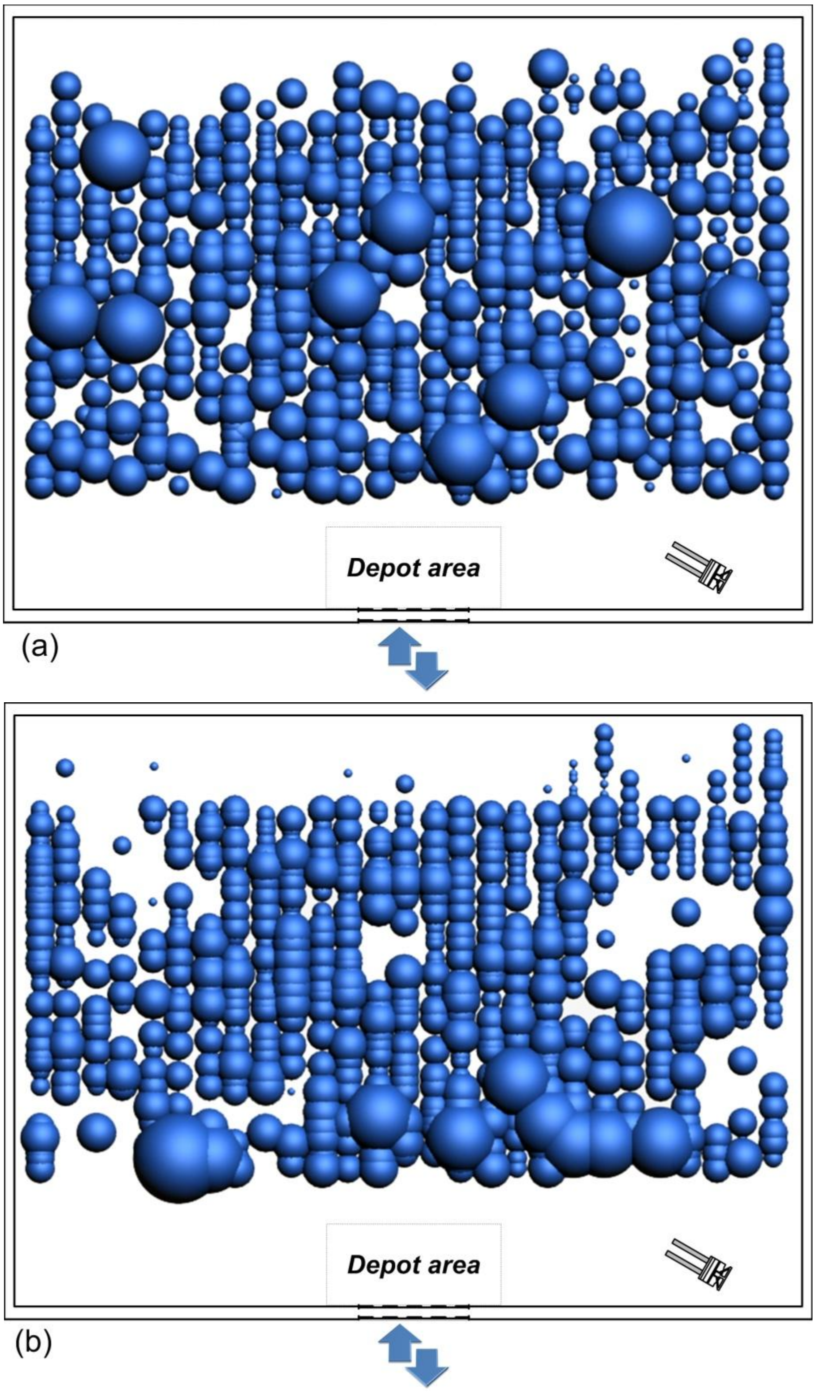


Figure 65: Picking density, (a) randomized, (b) C&P rule

These results refer to the specific case study the proposed approach was applied to. It demonstrates the effectiveness of the similarity based techniques. In fact the case study illustrated in this section relates to not high levels of correlations between products as previously argued.

5.8. Case Study II: high-level order picking system

The proposed approach has been tested on sku re-profiling for an Italian leading manufacturing company operating in the ceramic sector for flooring and tiles at the luxury high end of the market. The case study is focused on the storage system for the business unit of ceramic decorations.

5.8.1. Current Operation

The total footprint of the current picking zone is 630 square meters; 90 meters long and 7 meters wide. The width of picking aisle is 1.8 meters. Each picking aisle has 1116 stock keeping unit locations. The layout of the ceramic broken-case picking zone is shown in Figure 66.

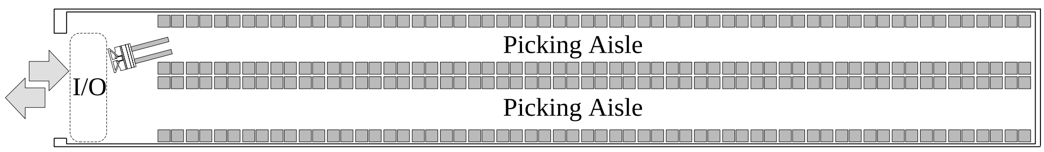


Figure 66: Layout of picking zone

The layout configuration is set up according to a length-wise shape of the racks. It can be seen that the overall ceramic decoration picking zone is organized with two aisles and the I/O point located in the middle. The order picker travels down the picking aisle from I/O point till the pick location adopting a return routing policy, so it can enter and exit at the same side of an aisle. The current storage system is a simple pallet rack with 9 levels. The company has established that the reserve area includes the level 1 and level 9 of the rack, while the forward pick area comprises the level 2, level 3, level 4, level 5, level 6, level 7, and level 8. Once the forward area has been emptied, a *restocker* refills it by dropping/arising the products from the two reserve levels during a shift completely dedicated to the refilling process. A schematic side view of the rack is depicted in Figure 67.

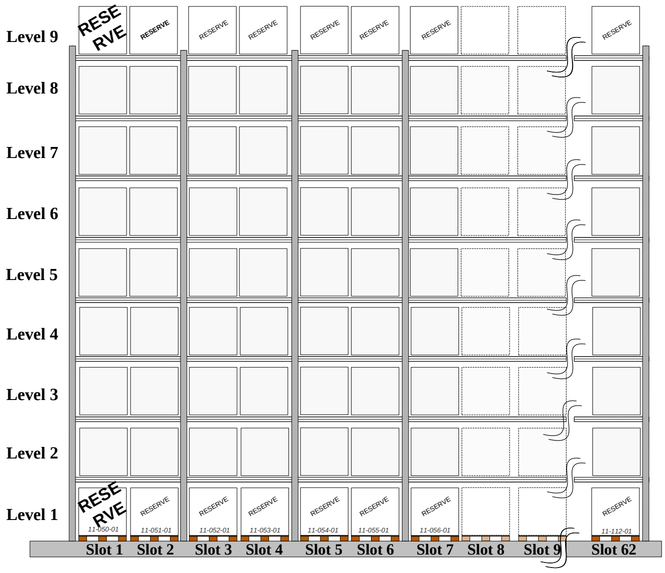


Figure 67: side view of rack

The current picking method is single order picking, i.e. retrieval of one customer order per trip. Trilateral stackers are used as retrieval equipment. The capacity of the picking stackers, set according to the fragility of the products and limitations on stacking, only allows the picker to pick 0.8 cubic meters per picking trip. The speed profile of the trilateral stackers depicted in Figure 68 has two speed segment respectively of 2.5 m/sec and an acceleration/deceleration of 0.55 m/sec^2 for travelling and 0.45 m/sec and an acceleration/deceleration of 0.08 m/sec^2 for raising/lowering the forks of the stacker. It is noticeable that the raising/lowering speed has a terrific impact on the total travel time for the order picking. As a consequence the vertical drive has been taken into account for the computation of the total travel time.

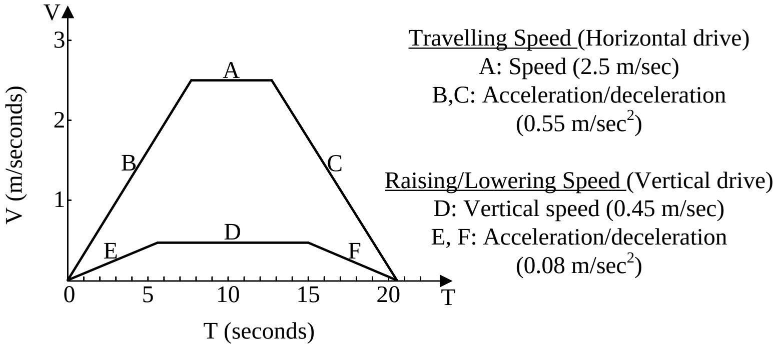


Figure 68: Speed profile of the trilateral stackers.

5.8.2. Analyzed Data

The horizon time for the analysis embraces 18-month order profile data. The initial data have been divided into two sets, the *training set* (15 months) and the *test set* (3 months). The training set has been used to train the approach and define the storage allocations, while the test set is used to simulate the retrieval of customer order from the obtained forward storage area and to evaluate the results. The splitting of initial data is a necessary step in order to avoid the so called overfitting data problem and outcome bias.

The average number of orders dispatched per day was 103. The standard deviation of the number of orders processed per day is 44. Therefore it can be concluded that the picking operation is small and demand variability is high, so a flexible order picking system is preferred.

The distribution of the number of lines per order (see Figure 69) suggests that almost all the orders have more than 8 lines; the most frequent order size falls in the range between 8 and 15. Mulcahy (1997) defines large orders as those that have more than 10 lines and recommends that single order picking may yield an efficient picking tour for large orders. He also suggests that batch picking is especially effective for small orders that have 1 up to 5 lines. Therefore, seen from the distribution of order lines, batch picking may not be appropriate for the operation but single order picking may be suitable.

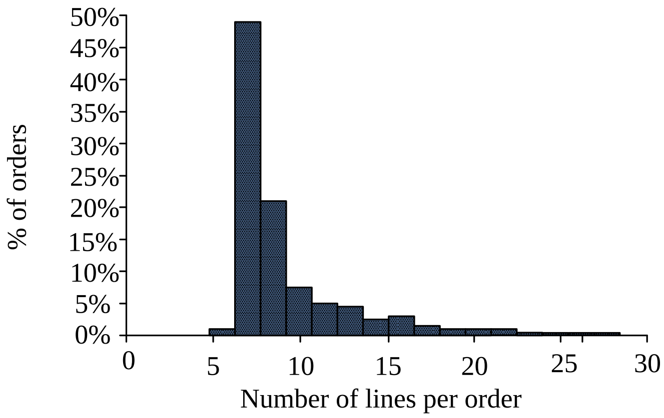


Figure 69: Distribution of lines per order

5.8.3. Factors and Levels

The study involves the main critical factors for an order picking system. In particular Figure 70 describes the most important factors and related values combined in the study.

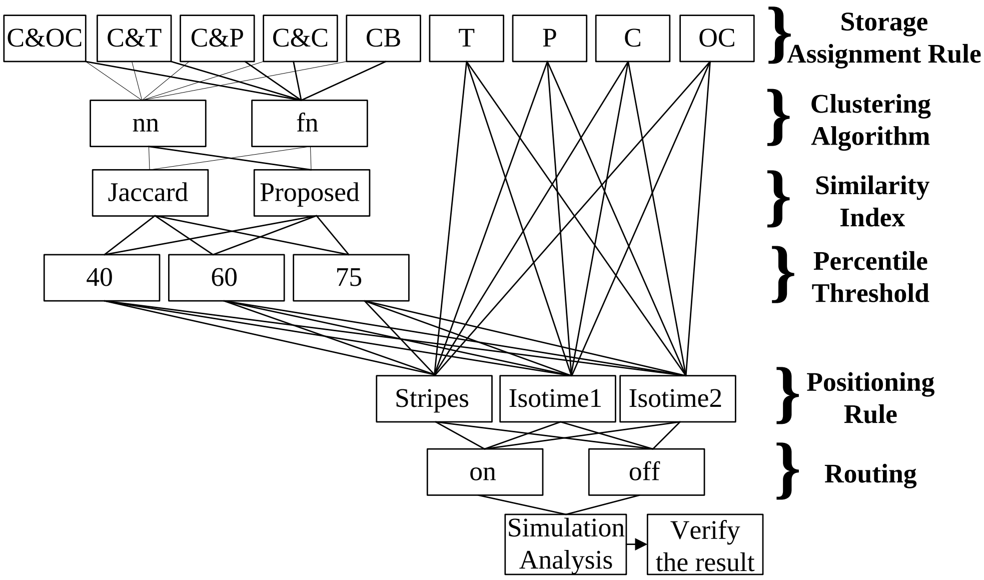


Figure 70: Combination relationship of six experimental factors with different levels

The combination relationship is composed of:

- nine different storage assignment rules (i.e. all the previously introduced storage allocation rules – *C, T, P, OC, CB, C&T, C&P, C&C, C&OC*);
- two clustering algorithms (*fn* and *nn* clustering algorithms);
- two types of similarity indices (*Jaccard coefficient* and the *Proposed similarity index*);

- three percentile threshold cut values (*40°, 60°, 70°* related level of correlation obtained with equation (6));
- two modes of routing ("*off*" identify a not ordered picking list, "*on*" an arranged picking list with an optimal routing);
- three positioning rules (*"stripes", "isotime1"* and *"isotime2"* described in the rest of this section).

These factors are combined in a what-if analysis and the best system configuration in terms of travel distance and travel time is identified. The what-if analysis is based on 384 different simulated scenarios. For each scenario simulated, the total travel distance (vertical drive + horizontal drive), the travel time, and the total number of visited aisles associated with retrieving products from the storage area in response to real customer requests is quantified.

The three positioning rules introduced for the case study are an extension of the *storage allocation patterns* presented in this chapter.

The first positioning rule, called *Stripes*, divided the storage system in equal width stripes (i.e. three and an half spans) following an across-aisle storage policy. As showed in Figure 49, products according to the priority list are allocated side by side in the slots of shelf 1 and shelf 2 following the path identified by the red arrow (for a better comprehension it can be seen also by the sequential number printed on the skus). Once the 98 slots from the first three and an half spans are completely filled the same procedure skip to the next aisle. Then the procedure is repeated to the end.

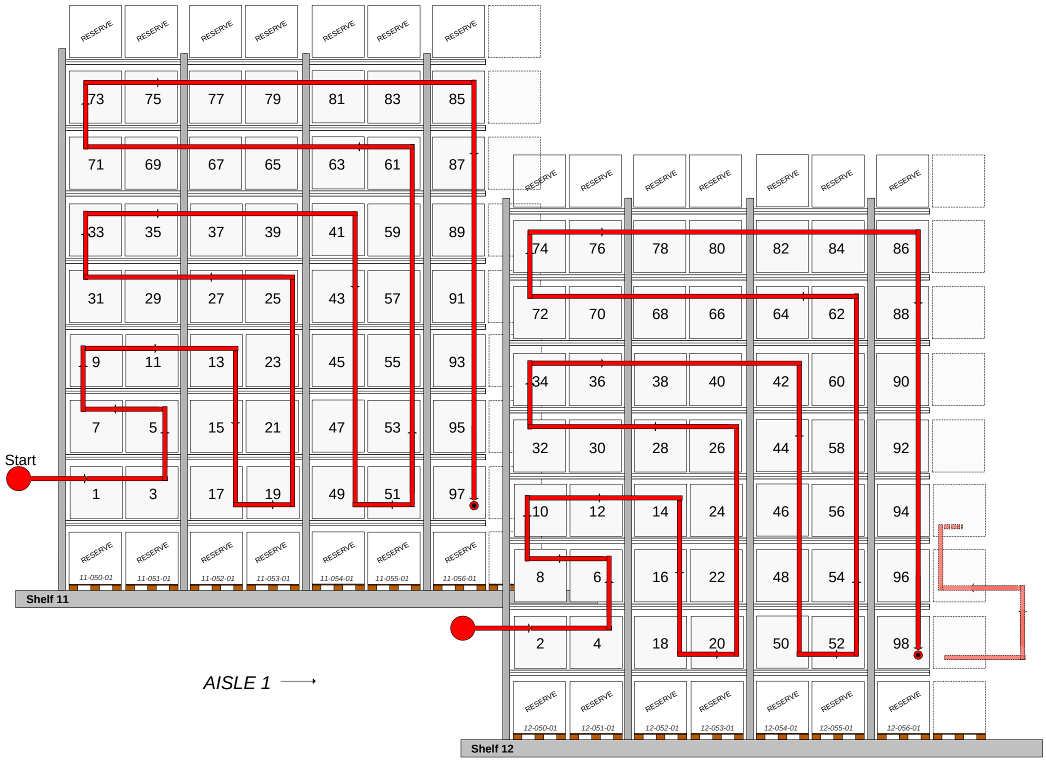


Figure 71: Stripes positioning rule (side view of the shelves)

The second and the third positioning rules developed for the case study are based on the *iso time mapping*. Warehouse locations are divided into iso time area according to the necessary total travel time considering the speed profile (see Figure 68) to reach the locations belonging to that area from the I/O point. The positioning rule Isotime 1 has three iso time areas, while Isotime 2 has six according to the rule introduced by Sturges (1926) for the identification of the optimal number of classes. As shown in Figure 50, locations from the area A in Isotime 1 have a travel time lower than 10.9 seconds, locations from area B have a travel time comprised between 10.9 and 22.3 seconds, while locations from area C have a travel time comprised between 22.3 and 33.6 seconds.

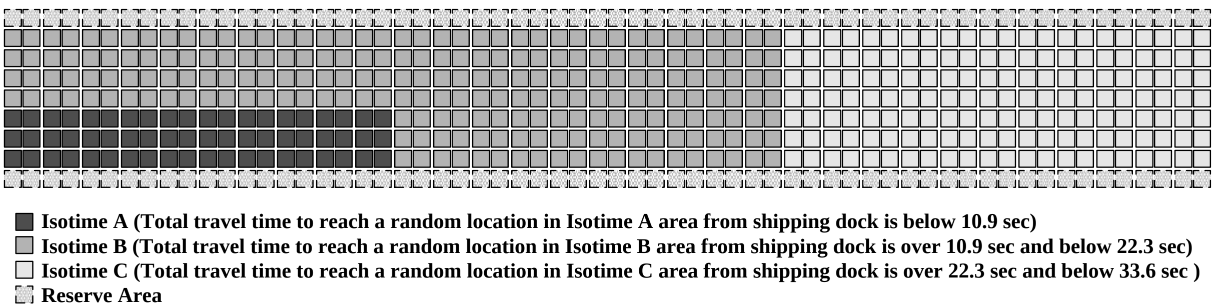


Figure 72: Isotime 1 Positioning rule – side view of the shelf

Similarly Figure 51 describes the iso time areas for the Isotime 2 positioning rule. The adopted procedure for establish the definitive position of each product is the same used in the Stripes rule.

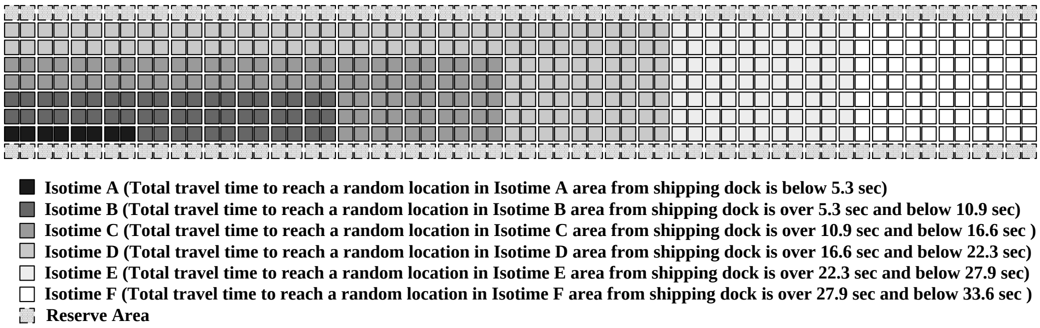


Figure 73: Isotime 2 Positioning rule – side view of the shelf

5.8.4. Results

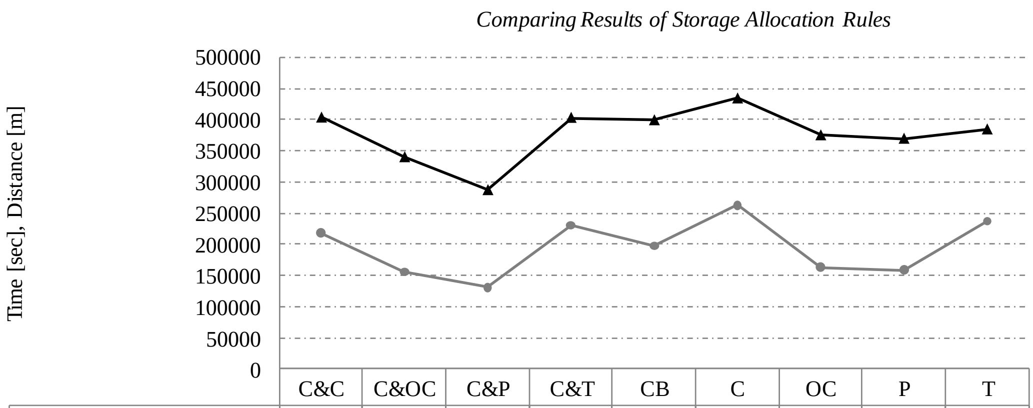
Table 12 is an extract of the results obtained in terms of the total travel time [sec/month], total travel distance [m/month], travelled aisles [visits], raising/lowering distance [m/month] for different system configurations, ordered by the adopted storage allocation rules. *Appendix C* lists all the 384 results from the simulations analysis.

Storage Allocation	Similarity Index	Total Travel Time [sec]$^+$	Total Travel Distance [m]$^+$	Travelled Aisles [visits]$^+$	Raising/Lowering Distance [m]$^+$
C&C	Jaccard	404975	218090	4435	11862
	Proposed	403208	240285	4646	11919
C&OC	Jaccard	348098	219329	4562	9780
	Proposed	345247	163124	4425	9571
C&P	Jaccard	310268	153503	4513	9320
	Proposed	287981	131316	4590	8642
C&T	Jaccard	403372	263609	4543	11633
	Proposed	402856	230191	4597	11627
CB	Jaccard	409874	197373	4945	12529
	Proposed	398990	257350	4903	12066
OC	*	375079	173340	5051	11014
P	*	369624	159096	5035	10931
T	*	384430	237133	5160	11344
C	*	433627	262868	5110	12864

+ minimum value obtained on 384 simulations

Table 12: Extract of the results obtained

Considering the minimum value obtained on 384 simulations the C&P allocation rule performs better than the other, especially when the Proposed similarity index is used to estimate the correlation between products. As demonstrated by results in Table 12 the C&P rule referring to the P rule obtains a total travel time reduced by 22% and it guarantees a global savings of about 16% on total travel distance. It can also be seen that the storage allocation rules adopting clustering obtain better results for the Proposed similarity index than the other using Jaccard coefficient. Furthermore it is interesting observing the value of the travelled aisles: the storage allocation rules considering the notion of product correlation have a general lower value compared to the other rules. That result could be reasonably explained referring to the influence of the product correlation. Products with high correlation are indeed stored together resulting in less visited aisle. As a consequence congestion may occur and hence it is a natural extension to consider the waiting times between two pickers for future study.



	C&C	C&OC	C&P	C&T	CB	C	OC	P	T
Total Travel time (sec)	403208	340247	287981	402856	398990	433627	375079	369624	384430
Total travel distance (m)	218090	156124	131316	230191	197373	262868	163340	159096	237133

Figure 74: Comparing results (travel time, travel distance)

Figure 74 outlines the results obtained as average of the 384 simulations for total travel time and distance. Both the lines of distance and time collapse considerably and reach a low point in correspondence of the C&P assignment rule, demonstrating the effectiveness of the proposed approach.

Table 13 compares results obtained for different storage assignment rules with and without the acceleration/deceleration effect of the stackers. It can be seen firstly that a reduction in travel time happens for all the rules in the results not considering the acceleration/deceleration effect. But while the storage assignment rules considering the product correlation have a moderate increase, the other rules result in a considerable rise. As a consequence conduct a simulation for a three dimensional storage system not considering the acceleration/deceleration effect could produce an incorrect performance evaluation, undervaluing the performance gap between the storage allocation rules adopting product correlation and the others.

Storage Assignment rule	Average of Total Travel time considering acceleration/ deceleration effect [sec]	Average of Total Travel time without considering acceleration/ deceleration effect [sec]	Δ (%)
C&C	697574	663393	4,9
C&OC	658150	631166	4,1
C&P	574313	549617	4,3
C&T	707658	676521	4,4
CB	709489	665501	6,2
C	723295	669048	7,5
OC	605508	564939	6,7
P	600234	554616	7,6
T	672245	617793	8,1

Table 13: Evaluation of acceleration/deceleration effect

In order to get a complete comprehension of the main factors and the optimal configuration for the case study we have then conducted an analysis as reported in Figure 75 and in Figure 76. From the main effect plot for total travel distance and the interaction plot for total travel time it can be seen that:

- *Isotime2* rule performs better referring to the other positioning rules.
- Using an ordered picking list and an optimal routing obviously may reduce the travel distance.
- *Fn* clustering algorithm obtains on average a reduced travel distance for the storage assignment based on the clustering process.
- The simulations conducted adopting the Proposed similarity index result in a lower total travel distance referring to the simulations adopting Jaccard coefficient as the correlation measurement.
- 40° percentile cut value should be preferred.
- C&P performs better than the other storage assignment rules.

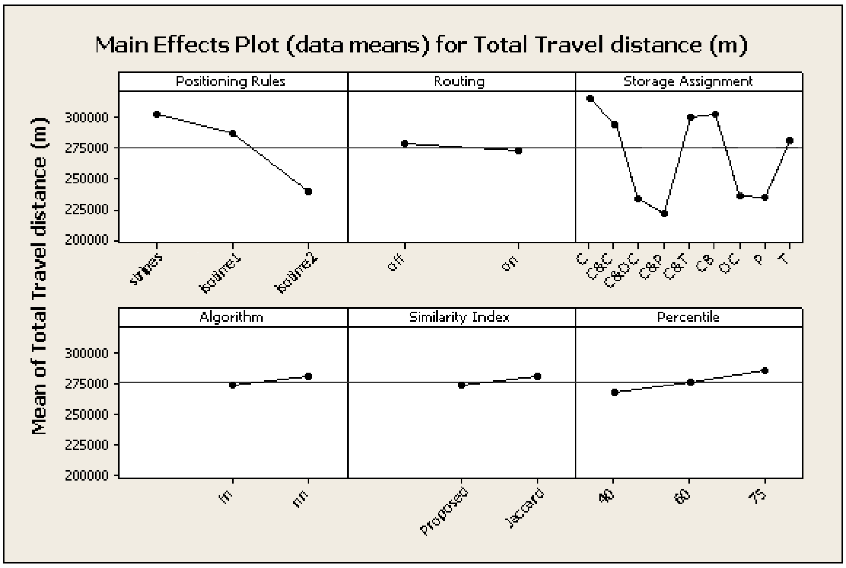


Figure 75: Main effects plot (ref. total travel distance)

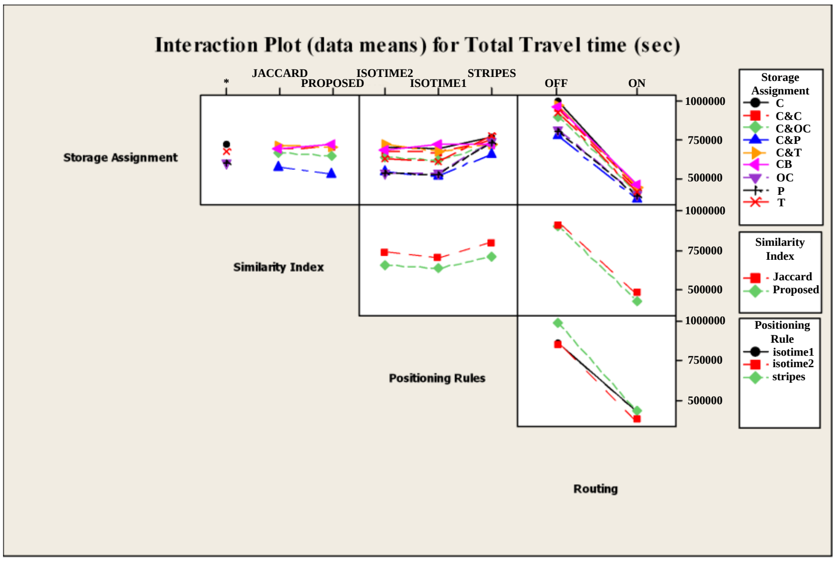


Figure 76: Interaction Plot for total travel time

5.8.5. Visualization of the results

Similarly to the *Case Study I*, the effect of the assignment rules can be visualized in the storage system adopting the proposed representation. As previously anticipated, the diameter of the spheres is proportional to the density strength. Thus, it represents the density of picking on the system layout when products are located according to the correlated strategy and when the C&P rule is adopted. Figure 77 shows a perspective view of the racks. In particular, it shows that the picking density is higher for locations closer to the depot area justifying the results and the best performance obtained. The close green spheres are products which belong to the same relative cluster. It can be clearly seen that correlated products with high level of picking density are appropriately located near the input/output point.

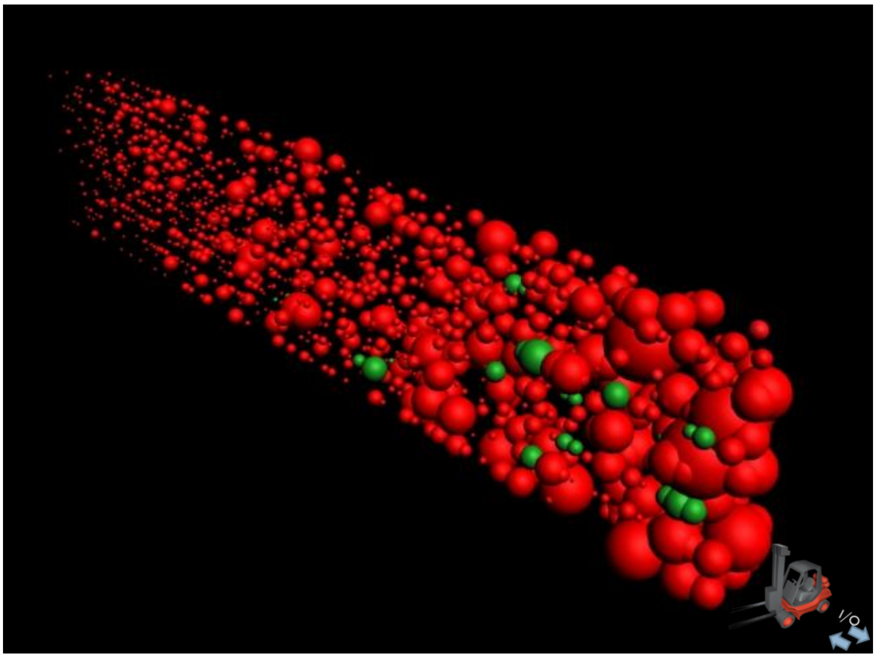


Figure 77: Perspective view of the racks (ref. C&P rule)

Figure 78 shows the left side view of the racks. It's simple to recognize the seven different levels of the rack. Spheres with greater diameter are concentrated on the right side of the picture, where is located the I/O point.

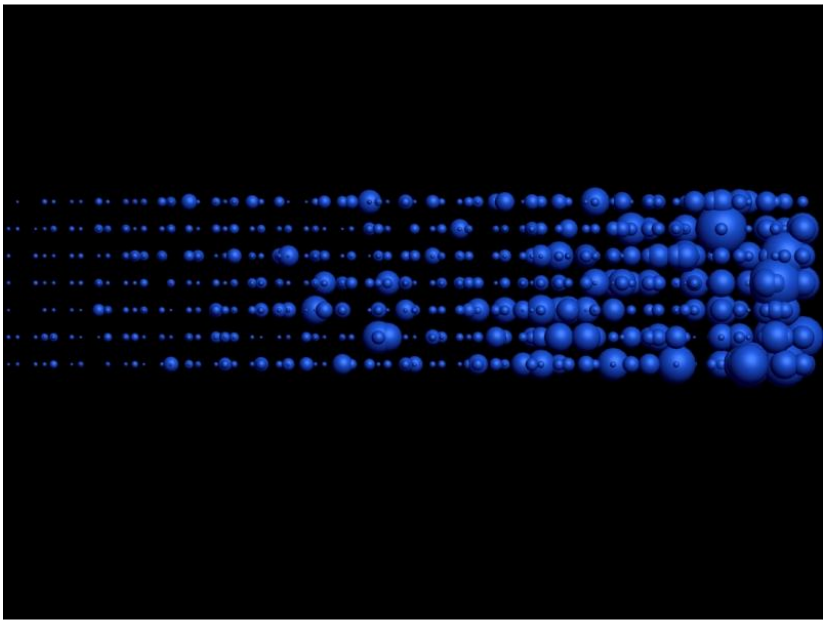


Figure 78: Left Side view of the racks (ref. C&P rule)

5.9. Close examination on C&P rule

As the *C&P* results to be the best performer storage allocation rule when adopted in association with the *Proposed* similarity index (see Eq. 83), this section examines the reason of such performance analysing a simple example.

The *C&P* assignment rule takes advantage of using Eq. 83 to evaluate product correlation. This advantage has a particular impact when the C&P rule is used in storage systems where the forward area is shared between products and different product quantity are assigned for distinct skus. This suggests that, the more different quantity assigned for distinct skus and variance between them, the more important is the effect of the C&P rule.

A simple example is presented in the following to better understand the potential benefits of the C&P rule compared to P rule.

Assume to have a simplified ten customer orders as the historical data for the examined storage system, and 4 distinct products as product mix. On the left side of Table 14, order lines are listed. Each customer order consists of at least one product of the product mix. On the right side of the same table are listed the stock quantity in the forward area for each product and the average movement expressed using *slots* as measurement units.

Customer Orders

Order	*Product*
Order1:	2
Order2:	2, 3, 1
Order3:	2, 1
Order4:	3, 4
Order5:	2
Order6:	1
Order7:	2, 3
Order8:	3, 4, 2
Order9:	1
Order10:	3, 4

Stock Quantity in Forward Picking Area

Product	*Assigned Forward Pick Area*
1	3 slots
2	1 slots
3	2 slots
4	2 slots

Average Movement

Product	**Average Quantity**
1	1/4 slot
2	1/4 slot
3	1/2 slot
4	1/2 slot

Table 14: Historical customer orders, stock quantity in forward area, average movemnt

Before arrange the products in the priority list as discussed in section 5.5, BFI coefficients and the similarity matrix obtained by the Eq. 83 must be evaluated. Table 15 shows an extract of the BFI coefficients computation, and the similarity matrix for the analyzed product mix.

Coefficients *a, b, c* :

Product *i*	Product *j*:	*a*	*b*	*c*
1	1	3	0	0
1	2	1	2	5
1	3	1	2	4
1	4	0	3	3
2	1	1	5	2
2	2	6	0	0
2	3	3	3	2
2	4	1	5	2
…	…	…	…	…
4	4	3	0	0

Similarity Matrix

Product *i* \ Product *j*	1	2	3	4
1	1			
2	0,0636	1		
3	0,0504	0,5082	1	
4	0	0,2545	0,4319	1

Table 15: BFI Coefficients, and Similarity Matrix

Adopting the *nn algorithm* for the grouping process, 3 levels of clustering are obtained. Table 16 shows the three levels and the relative groups of product at different similarity.

Level L(m)	Group 1	Group 2	Similarity	Objects in group
1	Product2	Product3	0,508	2
2	L(1)	Product4	0,432	3
3	Product1	L(2)	0,064	4

Table 16: Levels of Clustering

The same output can be seen in the dendrogram diagram of Figure 79. It can be seen from the diagram that product3 and product2 have high level of correlation, indeed they are grouped at a value of similarity equal to 0,50. Then a second clustering is the one grouping product4 with the previous group at a value of similarity equal to 0,43. Product1 has the lowest value of similarity.

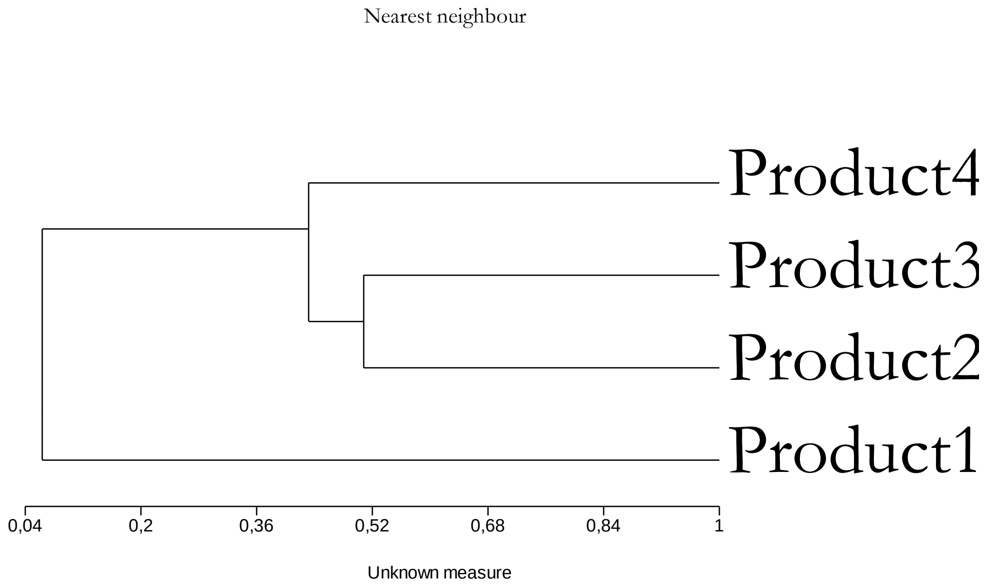


Figure 79: Dendrogram

It is chosen to adopt the threshold cut value equal to 0,36. According to the *C&P* assignment rule the ranking in the priority list is : product2, product3, product4, product1. At the same time the popularity of each product is evaluated and illustrated in Table 17. The last column in Table 17 defines the ranking in the priority list according to the *P* assignment rule.

Popularity		
Product	***# of recurrences***	***Ranking according to P rule***
1	4	3
2	6	1
3	5	2
4	3	4

Table 17: Popularity of the product mix

Assuming to have a single pick aisle and a single rack, and to store the products exclusively at the bottom of the rack, two storage configurations can be identified according to the P assignment rule and the C&P as shown in Figure 80.

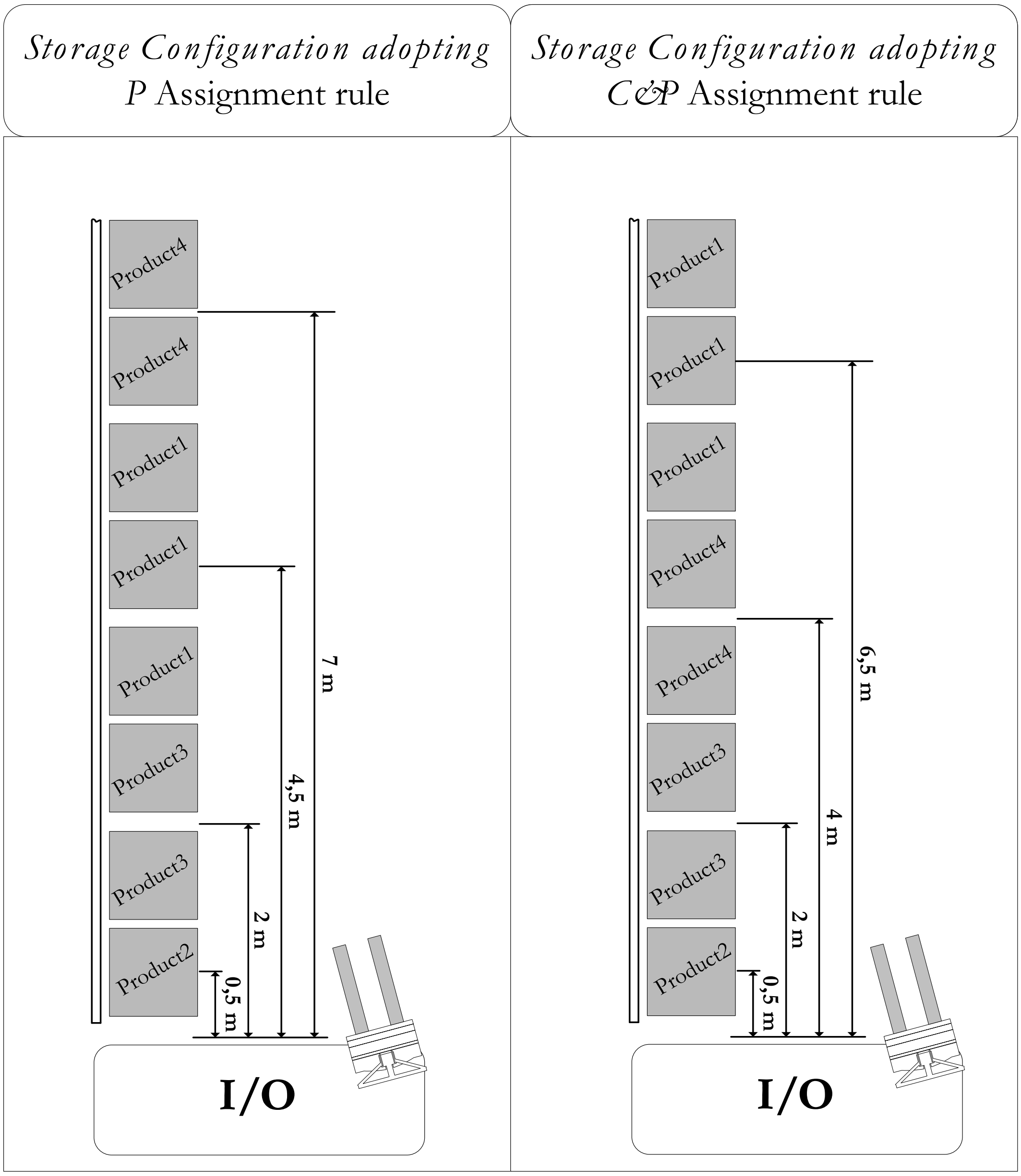


Figure 80: Storage configurations

Total travel distance to retrieve customer orders can be evaluated. Table 18 lists the total travel distance and the travel distance for each order. It can be seen that C&P obtains a lower value of travel distance.

The results of this simple example suggest that C&P rule may properly consider the effect of the different volume reserved for products in the forward area. It is particularly effective when simultaneously the storage area is fixed and the space is a limited critical resource.

Customer Order	Travel distance adopting the *P* assignment rule [m]		Travel distance adopting the *C&P* assignment rule [m]
Order1	1		1
Order2	10		13
Order3	1		1
Order4	14		8
Order5	1		1
Order6	9		13
Order7	4		4
Order8	14		8
Order9	9		13
Order10	14		8
	77	**>**	**70**

Table 18: Comparing total travel between P and C&P assignment rule

6. A tool supporting design of OPS

The chapter 6 illustrates a tool supporting the design and optimization of OPS. In particular the approach introduced in section 5 and all the combination of parameters and factors previously identified for the design of an OP are included and extended in the proposed tool. Following the same scheme adopted in section 2 for the design of distribution network, the present tool has the intention to become a framework to integrate the interrelated decisions situated at a strategic, tactical and operational level. The tool consists of a set of modules which can be extended to model a wider variety of order picking systems. The following sections outline the main features of the tool.

6.1. Design and scope of tool

The purpose of this project is to develop a tool that allows the simulation of order picking in a person-aboard storage system. It allows the logistics manager and the practitioner investigating the impact of different product and order profile, levels of correlation, storage assignment rules, routing, and physical configuration. The main aim was to keep the tool as flexible as possible and enable easy extension to model a wide variety of existing systems. Indeed the tool outlines how to conduct simulation either for existing systems or for desired custom configuration of the systems (i.e. *experimental simulation* profile). The flexibility is achieved by splitting the tool into different modules, each performing a certain task in the system. For each type of module the user has the opportunity to select the parameters and features available that is most appropriate for the purpose of the simulation.

Figure 81 and Figure 82 show the framework of the tool supporting the proposed approach.

The proposed framework is capable of capturing at the same time the four basic types of system parameters that directly influence the operating performance of order picking systems (Malmborg and Al-Thassan, 2000). The first is item parameters such as transactions demand levels, item space requirements, and item assignment constraints, e.g. compatibility. The second type includes the functional specifications of storage equipment such as vehicle travel speeds and movement patterns, e.g. routing strategies, vehicle routing, capacity of the retrieval equipment, etc. The third type includes system operating rules which determine interleaving discipline, transaction sequencing and item locations. Finally the physical configuration of the storage area including the height, depth and number of storage aisles, and the unit load size represent the fourth category of system parameters directly related to operating performance. To accurately model the operating performance of an order picking system in term of its three essential measures of total space requirements, throughout capacity and service level, the interdependencies among these parameters must be reconciled.

The framework proposed runs through a certain number of consecutive phases typical of a design process: concept, data acquisition, functional specification, technical specification, selection of means and equipment, layout and selection of planning and control policies. Alternatively, these decisions may be situated at a strategic, tactical or operational level. Similarly to the framework presented for the design of a distribution network in chapter 2, most decisions are interrelated but the hierarchical framework outlined above reflects the horizon of the decisions (i.e. long term, medium term, short term) while solutions chosen at a higher level provide the constrains for lower level design problems.

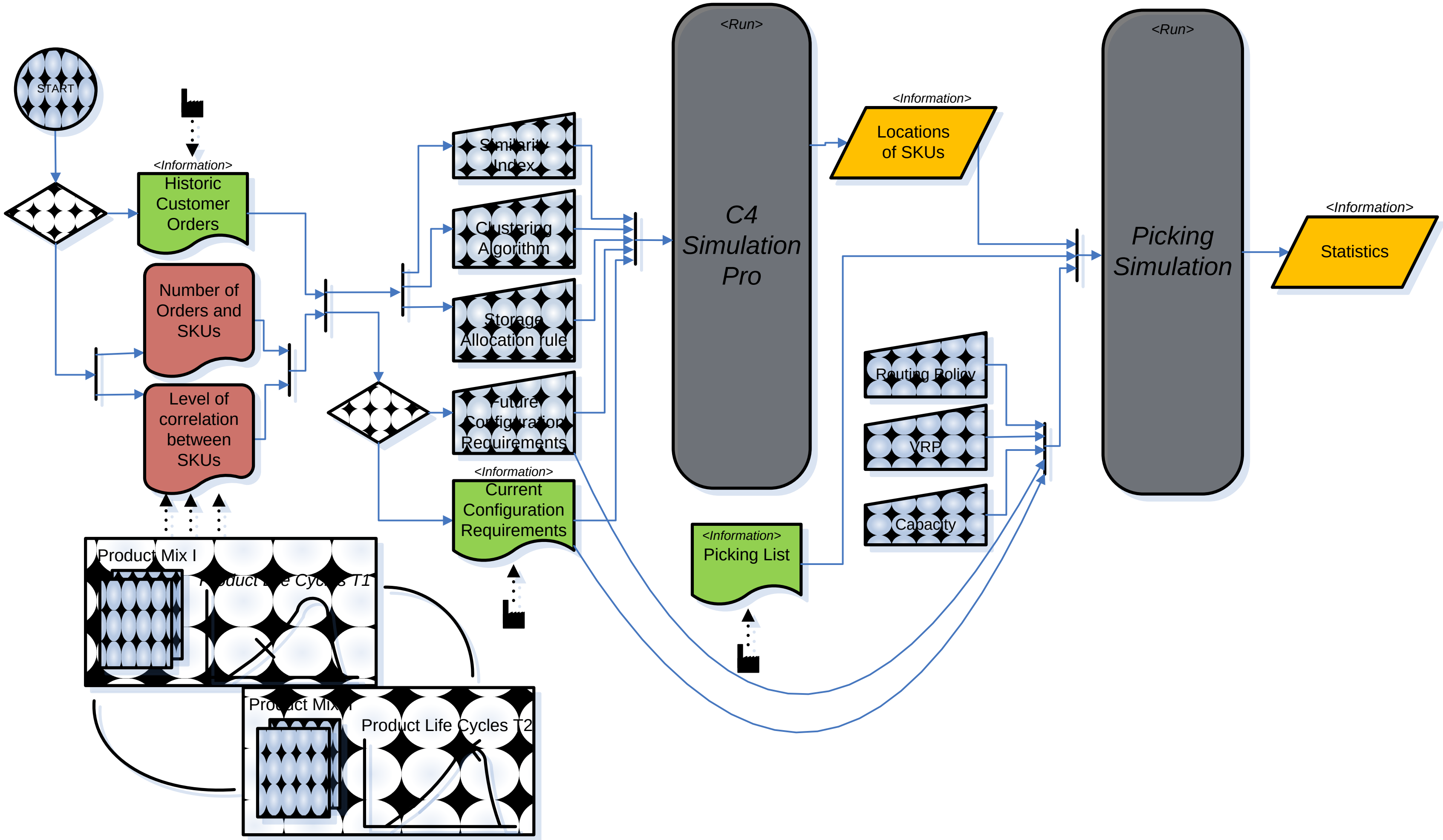


Figure 81: Framework of the tool supporting the proposed approach

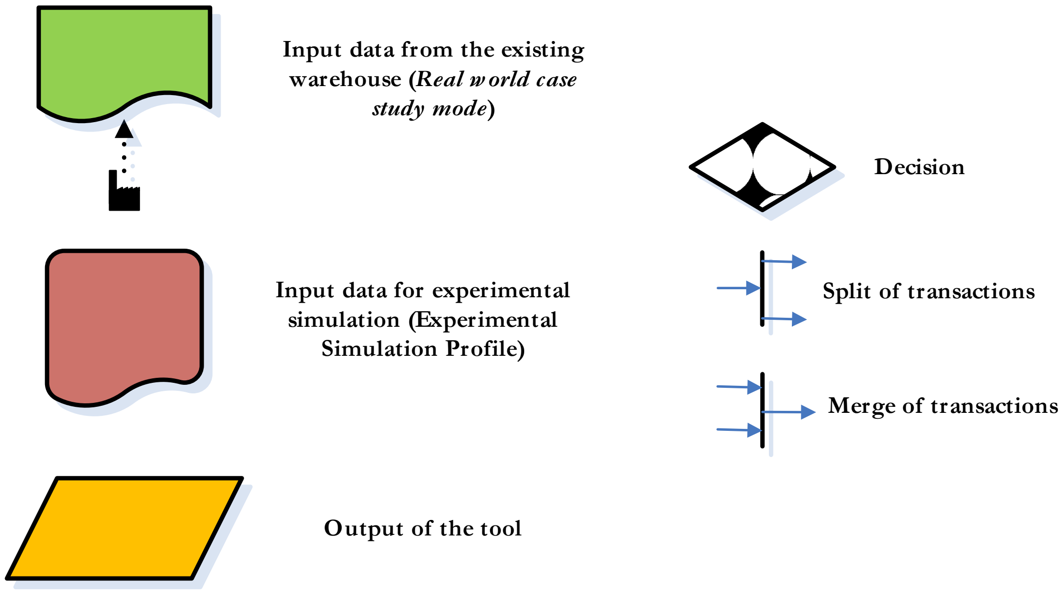


Figure 82: Explanatory list for Figure 81

Several general assumptions were made for the tool proposed as listed below:

- There is only one vehicle operating in the storage system. This assumption may not hold in real systems. In systems with multiple order pickers, vehicle congestion can take place in aisles with high picking activity, thus deteriorating picking performance. Anyway a congestion indicator for the system provided by the tool is the number of visited aisle as widely discussed in the previous chapter.
- The warehouse has only one I/O point at which storage orders are picked up or retrieval orders are dropped by the picker.
- The stock out of forward pick area during the retrieval is not admitted. It is assumed that every time a quantity of a line item is requested for retrieval the quantity is available in the storage system. Likewise enough capacity is available in the storage area for incoming skus.
- The picking travel time is estimated as a net time of travelling. Neither searching time, nor products set up are considered. Conversely the speed profile, specifically the acceleration/deceleration effect, is considered for travelling and arising/lowering forks of the lift.

The framework supports two distinct run profiles/modes. The first is the analysis of a real case study, so called *existing warehouse profile*, while the second profile is called *experimental simulation profile,* permitting to simulate a wide variety of different applications (see Figure 82).

6.2. User Interface Overview

The user interface is subdivided into seven forms, one form for different type of data assuming a similar *logistics dashboard* aspect. Figure 83 shows the user interface as it appears when launched before the run starts and the main module is invoked.

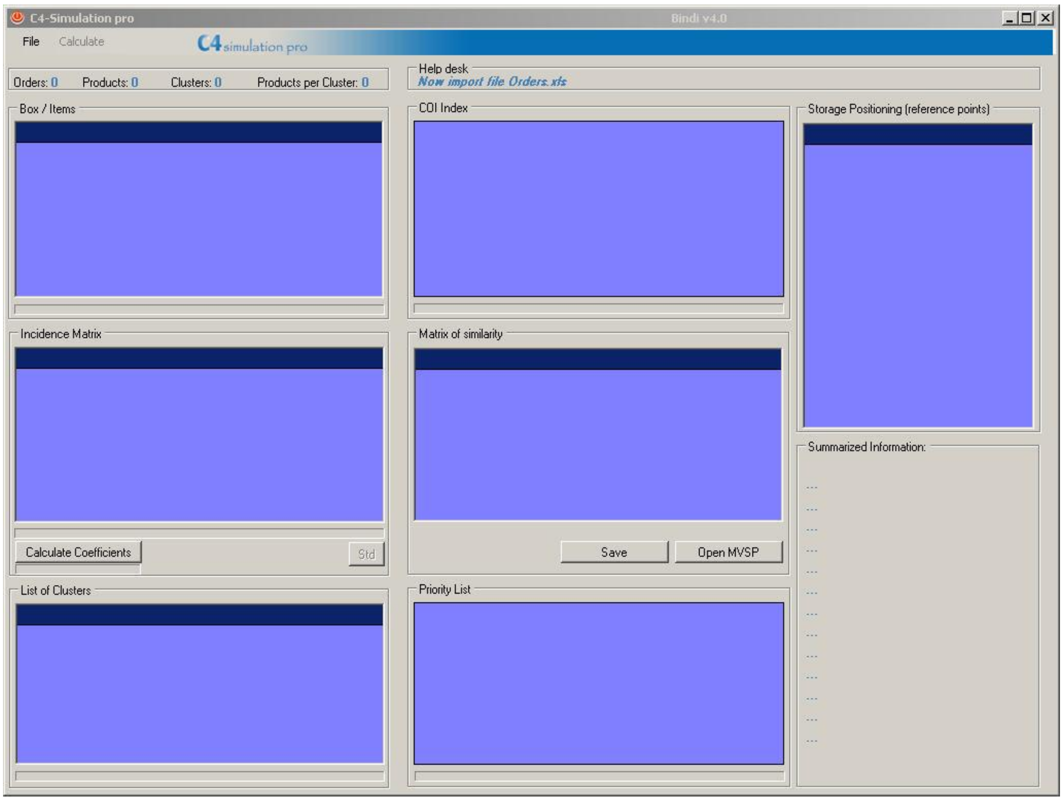


Figure 83: User Interface

The first form on the upper left corner shows the historical (or experimentally generated, if it is set up under the experimental analysis profile) customer orders and the included products. The next form shows the evaluation of the COI Index for the entire product mix. It can be chosen by a drop down list box to change metrics and to show in the same form different indices, e.g. Turn, Order-Closing, Popularity, etc. The third form shows the incidence matrix, useful to evaluate the BFI coefficients. The fourth form shows the matrix of similarity according to the chosen similarity index. On the lower left corner the clusters resulting from the grouping process are listed in the fifth form. The sixth form shows the priority list of products after they are arranged in according to a chosen storage assignment rule. The last and seventh form shows the real product positions in the system (existing system or experimentally designed).

Figure 84 illustrates the interface as it appears when pressed the drop down list of similarity indices.

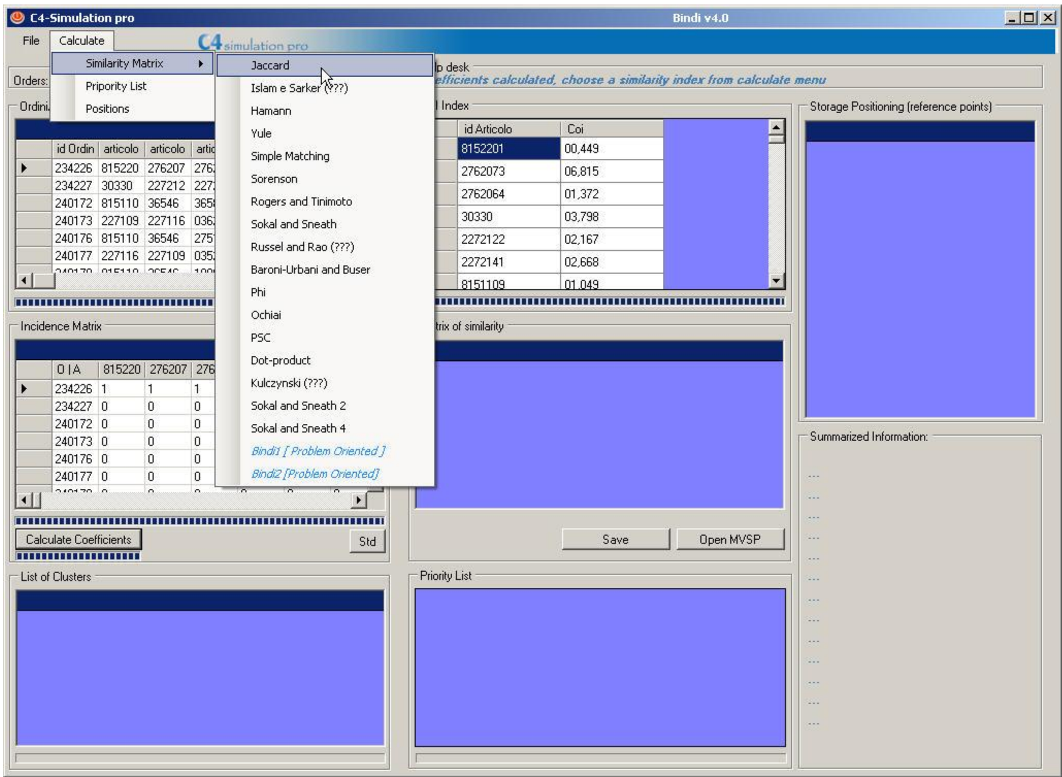


Figure 84: Interface – drop down list for similarity indices

Figure 85 shows the interface as it appears at the end of the run process. Each form is displaying its data. On the lower right corner a text box summarizes information about the system configuration and useful metrics as discussed in section 4.4.

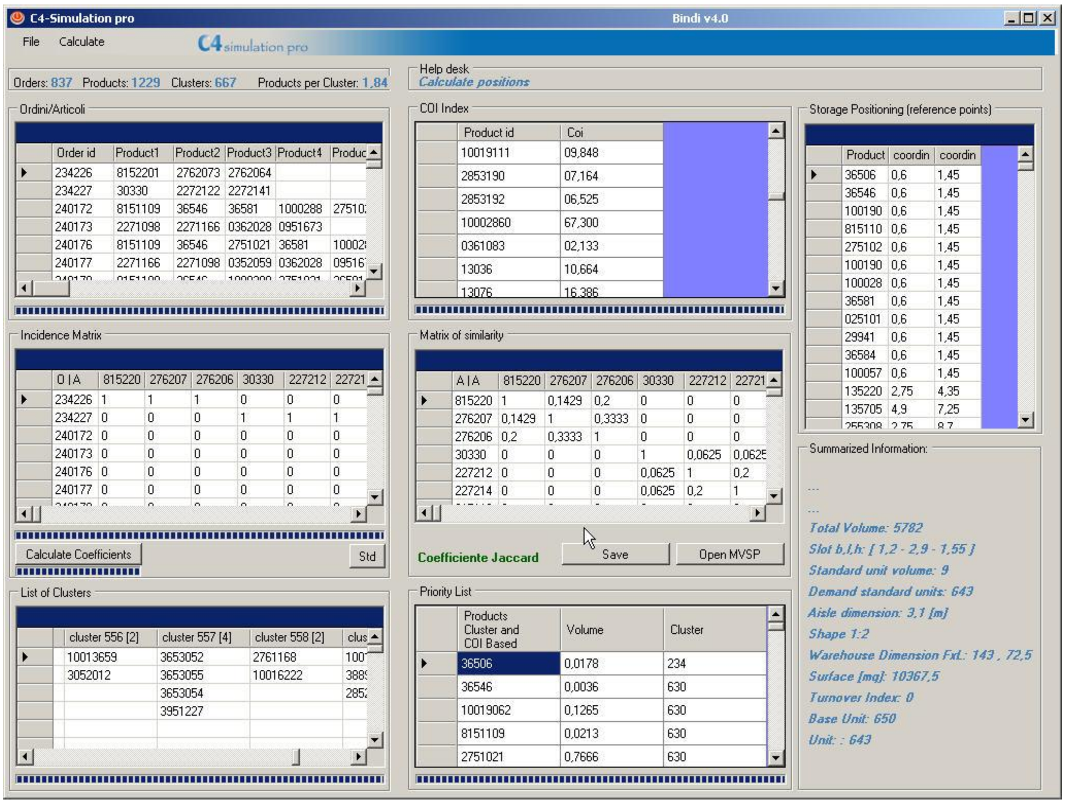


Figure 85: Interface – end of run.

Once the product positions have been evaluated the tool outlines the storage system and the real positions of each product. Figure 86 shows a bird eye view of the storage systems. The black triangles on the form identify the product positions.

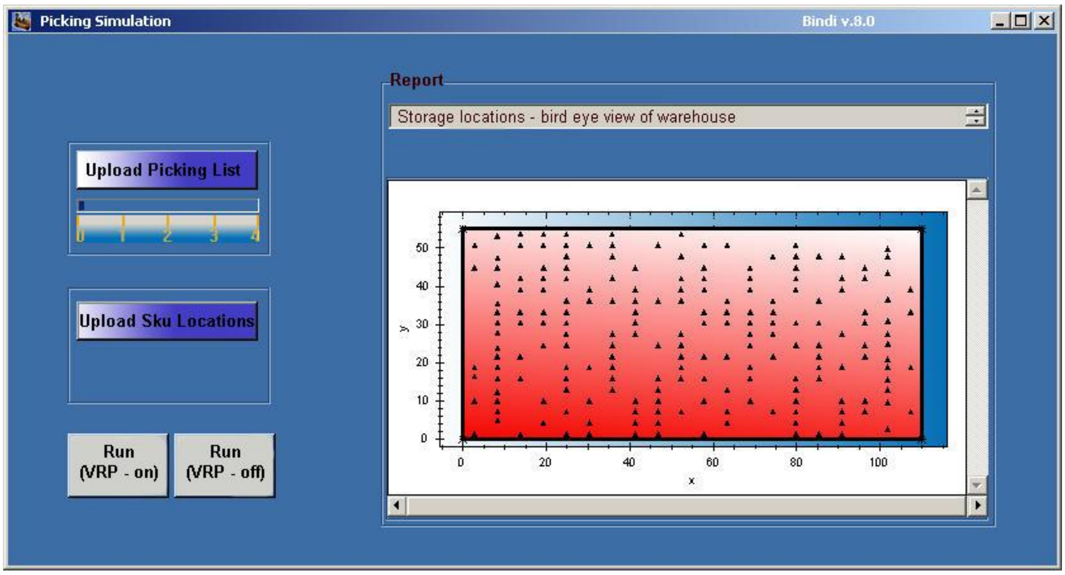


Figure 86: Picking simulation module – warehouse bird eye view

The *picking simulation* module performs the computation of the distance between each product in the storage system and the travel time. The function of the travel distance is called by the routing module to determine the shortest route connecting the pick and drop location. On the other hand, the travel time function using the speed profile of the lift equipment determines the net total time to reach each location considering the acceleration/deceleration effect. Figure 87 shows the report of the picking simulation module. Specifically it illustrates in the figure a graph about a particular KPI defined as the ratio between the Number of SKUs retrieved per order and the visited aisles per order. Higher values of that KPI identify efficient retrieval operation. This is particularly true and recurrent when the KPI is evaluated for a storage assignment based on clustering.

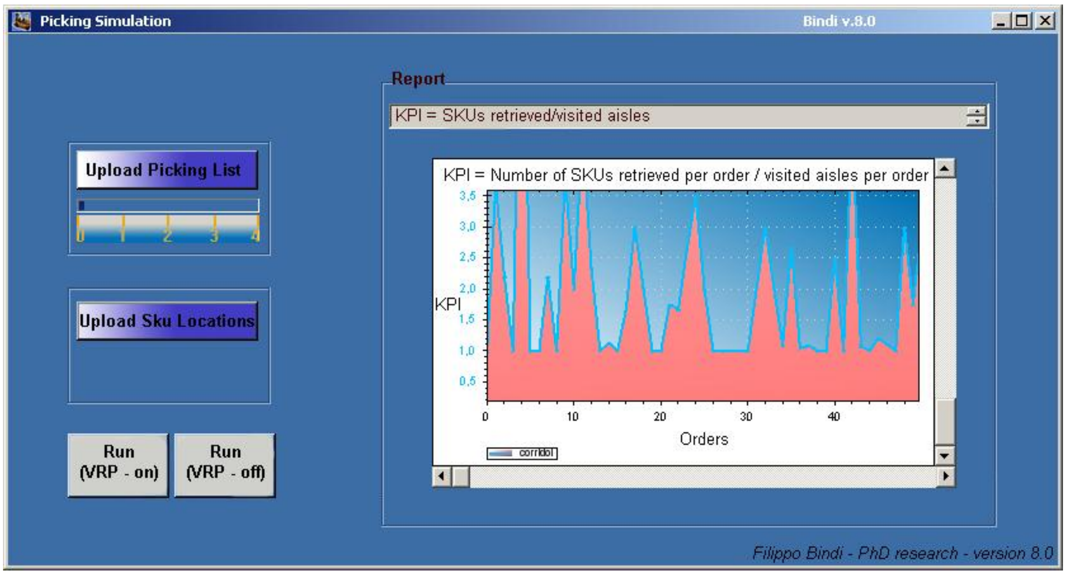


Figure 87: Picking simulation module – KPI evaluation

6.3. Integrating framework

As seen in the previous sections, the tool presented in this chapter could be taken as framework to integrate the interrelated decisions situated at a strategic, tactical and operational level for the design and control of order picking systems. The hierarchical framework identified by the tool reflects the horizon of the decisions (long term, medium term, short term) while solutions chosen at a higher level provide the constraints for lower level design problems.

At the strategic level we consider decisions that have long term impact, mostly decisions that concern high investments. The two main collections are the decisions concerning the selection of the types of storage systems and the design of the process flow.

On the tactical design level, a number of medium term decisions are to be made, based on the outcomes of the strategic decisions. The tactical decisions have a lower impact than the strategic decisions, but still require some investments and should therefore not be reconsidered too often. Tactical decisions generally interest the dimensions of resources, e.g. storage system sizes and the picking equipment, determination of a layout and a number of organizational issues, e.g. storage allocation rules. The relation between the various problems is less resolute than at the strategic level. Nevertheless, the different storage rules are strongly interrelated. The storage rules are also related to the other organizational policies, since they all impact on the maximum throughput of the storage system, and cannot be optimized independently. The results of the decisions made at this tactical level have a strong impact on the remaining problems to be solved at the operational level.

At the operational level, processes have to be carried out within the constraints set by the strategic and tactical decisions made at the higher levels. Interfaces between different processes are handled within the design problems at the strategic and tactical level. It follows that at the operational level policies have less interaction and therefore can be analyzed independently. The main decision at this level concerns assignment and control problems, e.g. the assignment of incoming products to available storage locations.

The proposed framework adopted by the tool could be taken as a complete reference model and design approach for warehousing systems. As demonstrated, it integrates the decisions along the three axes strategic, tactical and operational. Finally a complete set of performance evaluation parameters allow the final objective comparison of alternative scenarios and the identification of the best configuration of the system and the operational issues.

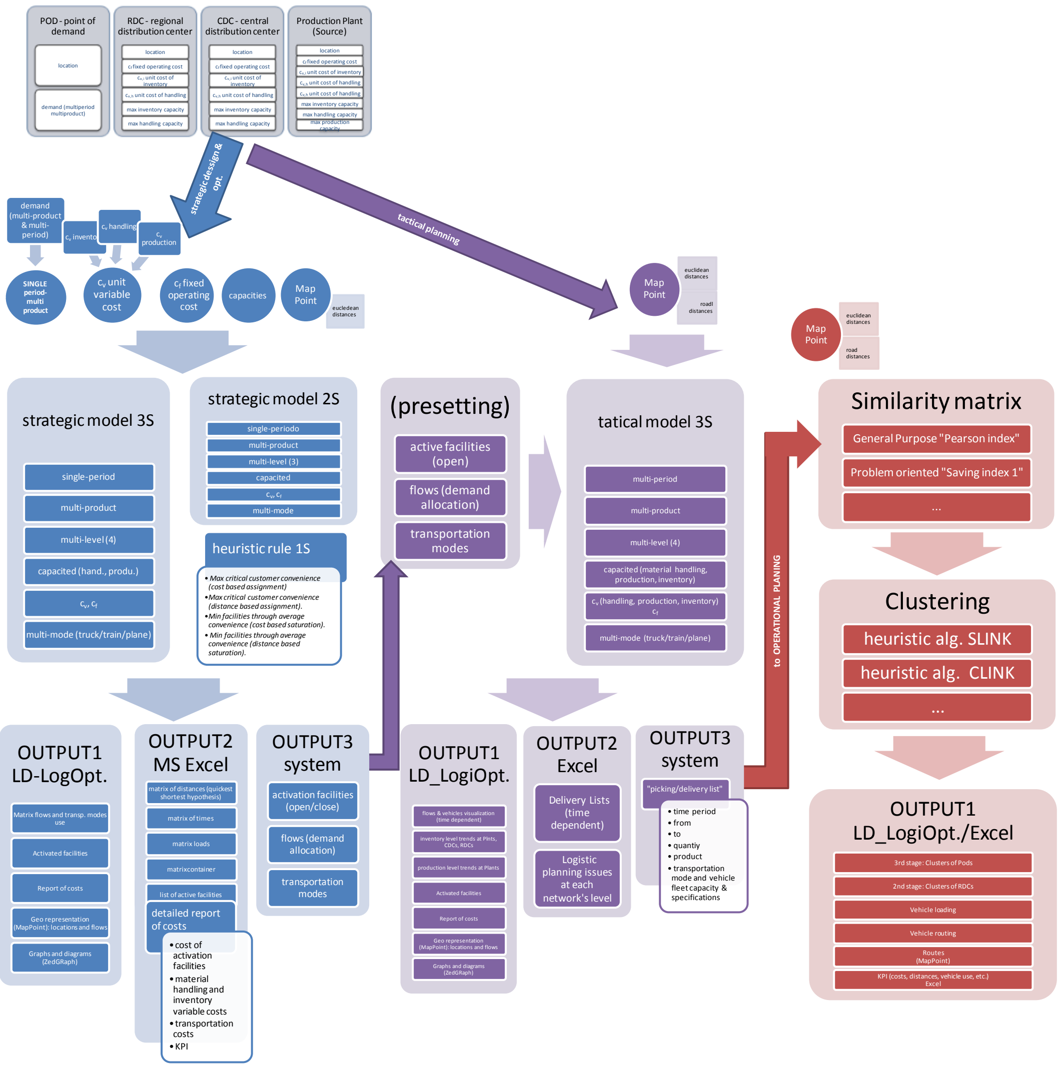
7. Conclusions

SC are increasingly global and complex, as company aspire to support a variety of strategies, such as entering new markets, increasing speed to customer, and lowering costs. The first part of this thesis presents advanced models and tools for planning and design complex supply chain networks, made of hundreds entities among production plants, distribution centers, wholesalers, customers, etc.. Many companies operating worldwide have to simultaneously face some of the following critical issues: the determination of the best number and location of production and/or distribution plants, e.g. distribution centers, transit points and hubs; the assignment of customers and points of demand to distributors and wholesalers; the management of inventory systems; the determination of the best transportation modes, e.g. rail, road and air; the vehicles fleet management with attention to the loading, scheduling & routing critical and expensive activities, etc.. The set of methodological hierarchical approaches and methods introduced in the present research aim to become a modeling system for integrating the main supply chain management decisions. In particular this modeling system groups concepts about integrated planning. Indeed it refers to functional coordination within the firm, between the firm and its suppliers, and between the firm and its customers. It also refers to inter-temporal coordination of supply chain decisions as they relate to the firm's operational, tactical and strategic plans. The modeling system for the design, management and control of logistic networks introduced in the first part of this thesis is based on the simultaneous applications of different mixed integer linear programming, cluster analysis, and heuristics algorithms. The proposed models have been implemented in an automatic tool to help logistic professional and practitioners in decision making. *Appendix A* summarizes the whole logic scheme of the proposed multi-modular tool: each module has been illustrated in chapter 3. The illustrated case study demonstrates the effectiveness of the proposed approach and automatic tool.

Following a top down approach for the design of the logistic distribution network and aiming to find a global optimum, in the second part of the thesis the focus is on the crucial links of the supply chain: warehouses and distribution centers. Warehouses are needed for a number of reasons such as to facilitate the coordination between production and customer demand, by buffering products for a certain period of time, to accumulate and consolidate from various producers for combined shipment to common customers, and to provide value added activities, such as packaging, labeling, marking and pricing. A wide description of the functions and typical features of warehouses are discussed in chapter 4.

Chapter 5 describes several new concepts to improve order picking in warehouses. *Order picking (OP)* concerns the retrieval of products from storage to meet customer orders. The OP process is often one of the most laborious and time consuming activities in a warehouse. The efficiency of this process depends on factors such as warehouse layout and storage assignment. The design, control, and optimization of an OP system is a very complex activity because there are several factors that simultaneously affect the process of retrieving products from a storage system. In chapter 5 *correlated assignment strategy* is discussed. It suggests basically that products that are frequently ordered together in multi-item orders should be stored near each other. A set of different storage allocation rules are presented in the chapter, some of them are based on the application of an original approach based on product correlation. It uses ad-hoc developed similarity coefficient for the estimation of the similarity between products and clustering techniques for the family grouping process. Through system simulation experiments, a combination model for combining factors such storage allocation rules, density of picking, shape and routing is introduced. The aim of that model is to explore and verify a suitable approach for finding the optimal combination for warehouse design in different environment. Two meaningful case studies are then discussed. One based on a low-level order picking system, the second a man aboard high-level order picking system. The effectiveness of the proposed approach and the significance of the assignment rules and the similarity coefficient are shown. Finally a tool presenting an integrated framework supporting the design and control of OP is presented in chapter 6.

The hierarchical frameworks, approaches and advanced tools presented in this thesis allow the logistics planner and managers to design inbound and outbound logistics simultaneously optimizing the various problems at different levels of decision in order to reach a global optimum.


POD - point of demand
RDC - regional distribution center
CDC - central distribution center
Production Plant (Source)
strategic design & opt.
tactical planning
SINGLE period-multi product
unit variable cost
fixed operating cost
capacities
Map Point
strategic model 3S
single-period
multi-product
multi-level (4)
capacited (hand., produ.)
multi-mode (truck/train/plane)
strategic model 2S
heuristic rule 1S
(presetting)
active facilities (open)
flows (demand allocation)
transportation modes
tatical model 3S
multi-period
multi-product
multi-level (4)
multi-mode (truck/train/plane)
to OPERATIONAL PLANING
Similarity matrix
General Purpose "Pearson index"
Problem oriented "Saving index 1"
...
Clustering
heuristic alg. SLINK
heuristic alg. CLINK
...
OUTPUT1 LD-LogOpt.
Matrix flows and transp. modes use
Activated facilities
Report of costs
Geo representation (MapPoint): locations and flows
Graphs and diagrams (ZedGRaph)
OUTPUT2 MS Excel
matrix of times
matrix loads
matrixcontainer
list of active facilities
detailed report of costs
cost of activation facilities
material handling and inventory variable costs
transportation costs
KPI
OUTPUT3 system
activation facilities (open/close)
flows (demand allocation)
transportation modes
OUTPUT1 LD_LogiOpt.
OUTPUT2 Excel
Delivery Lists (time dependent)
Logistic planning issues at each network's level
OUTPUT3 system
"picking/delivery list"
time period
from
to
quantity
product
transportation mode and vehicle fleet capacity & specifications
OUTPUT1 LD_LogiOpt./Excel
3rd stage: Clusters of Pods
2nd stage: Clusters of RDCs
Vehicle loading
Vehicle routing
Routes (MapPoint)
KPI (costs, distances, vehicle use, etc.) Excel

I/O	Storage Positioning	Capacity [m3]	Routing? [Sequencial/ Routing on]	Policy [Traversal/ Return]	Assignment Strategies[Rand/Turn/ ClusterBased/ Clus+Turn, Clus+Pop, Popularity]	Clustering Algorithm	Similarity Index	Shape	Threshold	Percentile cut value	Total Travel Distance [m]	Savings KPI 1: [%]	Aisles crossed	Savings KPI 2: [%]
c	S(2vani)	1,0	S	r	r	NN	/	1-1	/	/	791791	0,00	10359	-0,47
c	S(2vani)	1,0	S	r	p	NN	/	1-1	/	/	759783	0,00	10408	0,00
c	S(2vani)	1,0	S	r	c4	NN	J	1-1	0,6	4	742088	-2,33	10424	0,15
c	S(2vani)	1,0	S	r	c1	NN	/	1-1	/	/	745555	-1,87	10333	-0,72
c	S(2vani)	1,0	S	r	cb	NN	J	1-1	0,6	4	759629	-0,02	10185	-2,14
c	S(2vani)	1,0	S	r	c4	NN	B1	1-1	0,62	4	701709	-7,64	10406	-0,02
c	S(2vani)	1,0	S	r	cp	NN	B1	1-1	0,62	4	691433	-9,00	10433	0,24
c	S(2vani)	1,0	S	r	cp	NN	J	1-1	0,6	4	692755	-8,82	10421	0,12
c	S(2vani)	1,0	S	r	cp	NN	J	1-1	0,49	10,5	691295	-9,01	10341	-0,64
c	S(2vani)	1,0	S	r	cp	NN	B1	1-1	0,526	10,5	684777	-9,87	10244	-1,58
c	S(2vani)	1,5	S	r	r	NN	/	1-1	/	/	782934	8,88	10176	-0,48
c	S(2vani)	1,5	S	r	p	NN	/	1-1	/	/	719052	0,00	10225	0,00
c	S(2vani)	1,5	S	r	c4	NN	J	1-1	0,6	4	707675	-1,58	10241	0,16
c	S(2vani)	1,5	S	r	c1	NN	/	1-1	/	/	717303	-0,24	10150	-0,73
c	S(2vani)	1,5	S	r	cb	NN	J	1-1	0,6	4	744940	-4,85	10002	-2,18
c	S(2vani)	1,5	S	r	c4	NN	B1	1-1	0,6	4	736773	2,46	10223	-0,02
c	S(2vani)	1,5	S	r	cp	NN	J	1-1	0,6	4	679485	-5,50	10238	0,13
c	S(2vani)	1,5	S	r	cp	NN	B1	1-1	0,526	10,5	676219	-5,96	10229	0,04
c	S(2vani)	1,5	S	r	cp	NN	B1	1-1	0,62	4	676101	-5,97	10236	0,11
c	S(2vani)	1,5	S	r	r	NN	/	1-2	/		764403	9,98	10451	-0,01
c	S(2vani)	1,5	S	r	p	NN	/	1-2	/		695017	0,00	10452	0,00
c	S(2vani)	1,5	S	r	c4	NN	J	1-2	0,6	4	681511	-1,94	10447	-0,05
c	S(2vani)	1,5	S	r	c1	NN	/	1-2	/		705993	1,58	10361	-0,87
c	S(2vani)	1,5	S	r	cb	NN	J	1-2	0,6	4	708390	1,92	10247	-1,96
c	S(2vani)	1,5	S	r	c4	NN	B1	1-2	0,62	4	710641	2,25	10406	-0,44
c	S(2vani)	1,5	S	r	CP	NN	J	1-2	0,6	4	696992	0,28	10480	0,27
c	S(2vani)	1,5	s	r	CP	NN	B1	1-2	0,62	4	696357	0,19	10469	0,16
c	S(2vani)	1,5	O	r	r	NN	/	1-2	/		406077	16,79	6489	-0,31
c	S(2vani)	1,5	O	r	p	NN	/	1-2	/		347687	0,00	6509	0,00
c	S(2vani)	1,5	O	r	c4	NN	J	1-2	0,6	4	345671	-0,58	6567	0,89
c	S(2vani)	1,5	O	r	c1	NN	/	1-2	/		365435	5,10	6451	-0,89
c	S(2vani)	1,5	O	r	cb	NN	J	1-2	0,6	4	356149	2,43	6445	-0,98
c	S(2vani)	1,5	O	r	c4	NN	B1	1-2	0,62	4	363448	4,53	6538	0,45
c	S(2vani)	1,5	O	r	cp	NN	B1	1-2	0,62	4	346160	-0,44	6488	-0,32
c	S(2vani)	1,5	O	r	cp	NN	B1	1-2	0,526	10,5	344501	-0,92	6474	-0,54
c	S(2vani)	1,5	O	r	cp	NN	J	1-2	0,526	10,5	345559	-0,61	5529	-15,06
c	S(2vani)	1,5	O	r	r	NN	/	1-1	/		424433	5,26	5478	0,27
c	S(2vani)	1,5	O	r	p	NN	/	1-1	/		403213		5463	
c	S(2vani)	1,5	O	r	c4	NN	J	1-1	0,6	4	416245	3,23	5480	0,31
c	S(2vani)	1,5	O	r	c1	NN	/	1-1	/		409663	1,60	5481	0,33
c	S(2vani)	1,5	O	r	cb	NN	J	1-1	0,6	4	403900	0,17	5392	-1,30
c	S(2vani)	1,5	O	r	c4	NN	B1	1-1	0,62	4	402368	-0,21	5519	1,03
c	S(2vani)	1,5	O	r	cp	NN	B1	1-1	0,62	4	375170	-6,95	5539	1,39
c	S(2vani)	1,5	O	r	cp	NN	B1	1-1	0,526	10,5	372010	-7,74	5527	1,17
c	S(2vani)	1,5	O	r	cp	NN	J	1-1	0,526	10,5	375670	-6,83	5535	1,32
c	ZIGZAG	1,0	S	r	r	NN	/	1-1	/	/	853791	14,07	10359	9,50
c	ZIGZAG	1,0	S	r	p	NN	/	1-1	/	/	748482	0,00	9460	0,00
c	ZIGZAG	1,0	S	r	c4	NN	J	1-1	0,6	4	749721	0,17	9915	4,81
c	ZIGZAG	1,0	S	r	c1	NN	/	1-1	/	/	780050	4,22	9909	4,75
c	ZIGZAG	1,0	S	r	cb	NN	J	1-1	0,6	4	747719	-0,10	9755	3,12
c	ZIGZAG	1,0	S	r	c4	NN	B1	1-1	0,62	4	782684	4,57	9886	4,50
c	ZIGZAG	1,0	S	r	cp	NN	J	1-1	0,6	4	741273	-0,96	9505	0,48
c	ZIGZAG	1,0	S	r	cp	NN	B1	1-1	0,62	4	740160	-1,11	9450	-0,11
s	ZIGZAG	1,0	S	r	r	NN	/	1-2	/		793427	5,99	10634	12,41
s	ZIGZAG	1,0	S	r	p	NN	/	1-2	/		748614	0,00	9460	0,00
s	ZIGZAG	1,0	S	r	c4	NN	J	1-2	0,6	4	722237	-3,52	10310	8,99
s	ZIGZAG	1,0	S	r	c1	NN	/	1-2	/		720007	-3,82	10224	8,08
s	ZIGZAG	1,0	S	r	cb	NN	J	1-2	0,6	4	750112	0,20	10076	6,51
s	ZIGZAG	1,0	S	r	cp	NN	B1	1-2	0,62	4	713989	-4,63	10256	8,41
s	ZIGZAG	1,0	S	r	cp	NN	J	1-2	0,6	4	714995	-4,49	10247	8,32

Positioning Rules	Routing	Storage Assignment	Algorithm	Similarity Index	Percentile	Total Travel time (sec)	Travelled Aisles	Total Travel distance (m)	Total raising/lowering distance (m)
stripes	off	C	*	*	*	1081963	5322	277430	43020
stripes	on	C	*	*	*	460975	5026	262868	14514
isotime1	off	C	*	*	*	953980	5142	359133	37855
isotime1	on	C	*	*	*	451820	4910	342112	13238
isotime2	off	C	*	*	*	957404	5320	334343	37932
isotime2	on	C	*	*	*	433627	5030	317497	12864
stripes	off	C&C	nn	Proposed	60	1006575	4826	276278	40263
stripes	on	C&C	nn	Proposed	60	449985	4702	267235	13853
stripes	off	C&C	nn	Proposed	75	1052693	4829	299051	42160
stripes	on	C&C	nn	Proposed	75	461845	4703	290586	13951
stripes	off	C&C	nn	Proposed	40	1056420	5040	250969	42301
stripes	on	C&C	nn	Proposed	40	436467	4843	240285	13765
isotime1	off	C&C	nn	Proposed	60	917396	4795	312622	36644
isotime1	on	C&C	nn	Proposed	60	461380	4690	302106	13865
isotime1	off	C&C	nn	Proposed	75	957041	4725	357355	38188
isotime1	on	C&C	nn	Proposed	75	482893	4646	345020	14154
isotime1	off	C&C	nn	Proposed	40	884146	4980	306228	35291
isotime1	on	C&C	nn	Proposed	40	425048	4804	294955	12602
isotime2	off	C&C	nn	Proposed	60	936303	4775	310483	37417
isotime2	on	C&C	nn	Proposed	60	454867	4690	300442	13641
isotime2	off	C&C	nn	Proposed	75	1012946	4969	345943	40471
isotime2	on	C&C	nn	Proposed	75	475729	4807	335235	13958
isotime2	off	C&C	nn	Proposed	40	873384	5063	299171	34844
isotime2	on	C&C	nn	Proposed	40	418860	4874	289334	12383
stripes	off	C&C	fn	Proposed	60	995032	5019	277020	39796
stripes	on	C&C	fn	Proposed	60	449974	4890	269241	13853
stripes	off	C&C	fn	Proposed	75	1052712	5119	300278	42161
stripes	on	C&C	fn	Proposed	75	458572	4985	288611	13851
stripes	off	C&C	fn	Proposed	40	1080571	4889	250732	43246
stripes	on	C&C	fn	Proposed	40	443057	4940	242855	13970
isotime1	off	C&C	fn	Proposed	60	894785	5035	320770	35718
isotime1	on	C&C	fn	Proposed	60	459702	4878	300396	13814
isotime1	off	C&C	fn	Proposed	75	956722	5056	359948	38175
isotime1	on	C&C	fn	Proposed	75	487893	4785	348702	14299

isotime1	off	C&C	fn	Proposed	40	870371	5279	307584	34732
isotime1	on	C&C	fn	Proposed	40	403208	4756	270703	11919
isotime2	off	C&C	fn	Proposed	60	838719	4821	290888	33042
isotime2	on	C&C	fn	Proposed	60	447911	4878	307262	13429
isotime2	off	C&C	fn	Proposed	75	950585	4968	337074	37816
isotime2	on	C&C	fn	Proposed	75	477612	4807	345149	14013
isotime2	off	C&C	fn	Proposed	40	865523	5359	308188	34528
isotime2	on	C&C	fn	Proposed	40	417892	4679	304154	12354
stripes	off	C&C	nn	Jaccard	60	1059786	4711	253482	42270
stripes	on	C&C	nn	Jaccard	60	457010	4620	245800	14275
stripes	off	C&C	nn	Jaccard	75	1062361	4812	293384	42337
stripes	on	C&C	nn	Jaccard	75	468581	4709	284340	14234
stripes	off	C&C	nn	Jaccard	40	1066798	4987	233125	42506
stripes	on	C&C	nn	Jaccard	40	448844	4822	223880	14326
isotime1	off	C&C	nn	Jaccard	60	899288	4842	277476	35730
isotime1	on	C&C	nn	Jaccard	60	417041	4707	267097	12436
isotime1	off	C&C	nn	Jaccard	75	961061	4779	349605	38175
isotime1	on	C&C	nn	Jaccard	75	474660	4658	337009	13831
isotime1	off	C&C	nn	Jaccard	40	855816	4973	285051	33978
isotime1	on	C&C	nn	Jaccard	40	407494	4798	276121	11970
isotime2	off	C&C	nn	Jaccard	60	830526	4810	301190	33000
isotime2	on	C&C	nn	Jaccard	60	420372	4699	292562	12278
isotime2	off	C&C	nn	Jaccard	75	989848	4853	328700	39326
isotime2	on	C&C	nn	Jaccard	75	478306	4720	319657	14172
isotime2	off	C&C	nn	Jaccard	40	859980	4983	292892	34135
isotime2	on	C&C	nn	Jaccard	40	404975	4825	281636	11862
stripes	off	C&C	fn	Jaccard	60	1004756	4805	230720	39955
stripes	on	C&C	fn	Jaccard	60	450987	4435	245952	14084
stripes	off	C&C	fn	Jaccard	75	1060231	4820	297221	42252
stripes	on	C&C	fn	Jaccard	75	452768	5039	285943	13737
stripes	off	C&C	fn	Jaccard	40	1000654	5002	218090	39696
stripes	on	C&C	fn	Jaccard	40	445001	4870	229899	14202
isotime1	off	C&C	fn	Jaccard	60	900567	4987	279967	35781
isotime1	on	C&C	fn	Jaccard	60	420192	4698	266637	12529
isotime1	off	C&C	fn	Jaccard	75	960123	4731	350733	38138
isotime1	on	C&C	fn	Jaccard	75	472031	4984	340246	13754
isotime1	off	C&C	fn	Jaccard	40	850234	5172	290938	33755
isotime1	on	C&C	fn	Jaccard	40	406999	5134	279218	11955
isotime2	off	C&C	fn	Jaccard	60	802321	4940	302207	31834
isotime2	on	C&C	fn	Jaccard	60	420039	4558	307062	12268
isotime2	off	C&C	fn	Jaccard	75	976273	5198	337648	38779
isotime2	on	C&C	fn	Jaccard	75	479985	4673	329870	14222
isotime2	off	C&C	fn	Jaccard	40	834528	5240	293201	33094

isotime2	on	C&C	fn	Jaccard	40	410076	4680	289857	12010
stripes	off	C&OC	nn	Proposed	60	1012468	4819	256826	40576
stripes	on	C&OC	nn	Proposed	60	446169	4692	251130	13665
stripes	off	C&OC	nn	Proposed	75	1051855	4967	233653	42137
stripes	on	C&OC	nn	Proposed	75	455910	4810	227891	14395
stripes	off	C&OC	nn	Proposed	40	1052412	4931	199474	42150
stripes	on	C&OC	nn	Proposed	40	435803	4764	192814	14181
isotime1	off	C&OC	nn	Proposed	60	1009515	4851	334284	40316
isotime1	on	C&OC	nn	Proposed	60	434392	4699	323893	12371
isotime1	off	C&OC	nn	Proposed	75	927229	4836	302538	37022
isotime1	on	C&OC	nn	Proposed	75	421038	4731	292265	12331
isotime1	off	C&OC	nn	Proposed	40	804062	4736	314746	32063
isotime1	on	C&OC	nn	Proposed	40	391060	4609	302364	11035
isotime2	off	C&OC	nn	Proposed	60	873415	4984	269414	34853
isotime2	on	C&OC	nn	Proposed	60	387143	4802	261528	11357
isotime2	off	C&OC	nn	Proposed	75	846145	4861	283569	33766
isotime2	on	C&OC	nn	Proposed	75	405114	4740	276153	11805
isotime2	off	C&OC	nn	Proposed	40	803107	4946	287775	31991
isotime2	on	C&OC	nn	Proposed	40	382614	4787	278425	10988
stripes	off	C&OC	fn	Proposed	60	934869	5060	241853	37208
stripes	on	C&OC	fn	Proposed	60	418055	4786	229090	12746
stripes	off	C&OC	fn	Proposed	75	953043	4917	226623	37768
stripes	on	C&OC	fn	Proposed	75	437646	4858	233662	13794
stripes	off	C&OC	fn	Proposed	40	906325	4882	176124	35356
stripes	on	C&OC	fn	Proposed	40	417912	5097	191344	13574
isotime1	off	C&OC	fn	Proposed	60	904684	4832	331697	35644
isotime1	on	C&OC	fn	Proposed	60	419868	4699	323215	11943
isotime1	off	C&OC	fn	Proposed	75	905594	5029	311232	36138
isotime1	on	C&OC	fn	Proposed	75	421104	4873	294710	12333
isotime1	off	C&OC	fn	Proposed	40	654578	4878	280463	24741
isotime1	on	C&OC	fn	Proposed	40	345247	4425	257796	9571
isotime2	off	C&OC	fn	Proposed	60	741874	4981	191113	28642
isotime2	on	C&OC	fn	Proposed	60	387060	4850	259002	11355
isotime2	off	C&OC	fn	Proposed	75	717736	5207	200415	27722
isotime2	on	C&OC	fn	Proposed	75	404070	4693	280146	11774
isotime2	off	C&OC	fn	Proposed	40	745488	5451	244508	29518
isotime2	on	C&OC	fn	Proposed	40	381481	4691	289460	10955
stripes	off	C&OC	nn	Jaccard	60	1038391	4801	254453	41400
stripes	on	C&OC	nn	Jaccard	60	459674	4677	248982	14054
stripes	off	C&OC	nn	Jaccard	75	957792	4837	259216	38175
stripes	on	C&OC	nn	Jaccard	75	448930	4707	253091	13650
stripes	off	C&OC	nn	Jaccard	40	1070607	5054	225370	42671
stripes	on	C&OC	nn	Jaccard	40	449628	4871	219329	14289

isotime1	off	C&OC	nn	Jaccard	60	1023203	4728	307517	40703
isotime1	on	C&OC	nn	Jaccard	60	440449	4615	298186	12854
isotime1	off	C&OC	nn	Jaccard	75	901546	4872	323871	35846
isotime1	on	C&OC	nn	Jaccard	75	434371	4732	314701	12365
isotime1	off	C&OC	nn	Jaccard	40	807964	4657	299503	32076
isotime1	on	C&OC	nn	Jaccard	40	387668	4562	287418	11034
isotime2	off	C&OC	nn	Jaccard	60	936433	4896	310332	37160
isotime2	on	C&OC	nn	Jaccard	60	420296	4745	301269	12031
isotime2	off	C&OC	nn	Jaccard	75	957431	4827	289796	38077
isotime2	on	C&OC	nn	Jaccard	75	406762	4669	280712	11715
isotime2	off	C&OC	nn	Jaccard	40	845866	4992	279627	33564
isotime2	on	C&OC	nn	Jaccard	40	399253	4823	270429	11691
stripes	off	C&OC	fn	Jaccard	60	921973	5137	225161	36172
stripes	on	C&OC	fn	Jaccard	60	450234	4771	255830	13759
stripes	off	C&OC	fn	Jaccard	75	960213	5127	257682	38271
stripes	on	C&OC	fn	Jaccard	75	450232	4848	258158	13689
stripes	off	C&OC	fn	Jaccard	40	1000951	5256	224560	39702
stripes	on	C&OC	fn	Jaccard	40	440567	4920	225203	13995
isotime1	off	C&OC	fn	Jaccard	60	950765	4775	285288	37602
isotime1	on	C&OC	fn	Jaccard	60	410230	4707	272074	11907
isotime1	off	C&OC	fn	Jaccard	75	910239	4908	328241	36188
isotime1	on	C&OC	fn	Jaccard	75	433941	5016	314726	12353
isotime1	off	C&OC	fn	Jaccard	40	656998	4890	227847	24706
isotime1	on	C&OC	fn	Jaccard	40	348098	4699	280728	9780
isotime2	off	C&OC	fn	Jaccard	60	895974	5191	272293	35474
isotime2	on	C&OC	fn	Jaccard	60	419941	4982	310037	12021
isotime2	off	C&OC	fn	Jaccard	75	908730	5011	252569	36035
isotime2	on	C&OC	fn	Jaccard	75	406129	4996	287236	11697
isotime2	off	C&OC	fn	Jaccard	40	800323	5185	257573	31654
isotime2	on	C&OC	fn	Jaccard	40	398936	4919	282146	11682
stripes	off	C&P	nn	Proposed	40	941210	4859	167786	37772
stripes	on	C&P	nn	Proposed	40	395562	4720	161896	13102
isotime1	off	C&P	nn	Proposed	40	670664	4957	236435	27535
isotime1	on	C&P	nn	Proposed	40	332694	4781	226244	10151
isotime2	off	C&P	nn	Proposed	40	643010	5061	229815	26352
isotime2	on	C&P	nn	Proposed	40	325962	4874	220856	9891
stripes	off	C&P	fn	Proposed	40	777595	4762	146674	31112
stripes	on	C&P	fn	Proposed	40	357086	4720	151258	12019
isotime1	off	C&P	fn	Proposed	40	651364	5033	245066	26559
isotime1	on	C&P	fn	Proposed	40	311234	4590	215723	9158
isotime2	off	C&P	fn	Proposed	40	632875	5200	228012	25791
isotime2	on	C&P	fn	Proposed	40	287981	4923	131316	8642
stripes	off	C&P	nn	Jaccard	40	927928	4803	159632	38153

stripes	on	C&P	nn	Jaccard	40	396193	4654	153503	13478
isotime1	off	C&P	nn	Jaccard	40	645998	4946	232650	26359
isotime1	on	C&P	nn	Jaccard	40	329423	4767	223843	9966
isotime2	off	C&P	nn	Jaccard	40	625837	5004	218443	25511
isotime2	on	C&P	nn	Jaccard	40	316105	4852	210043	9504
stripes	off	C&P	fn	Jaccard	40	904495	5091	164289	37165
stripes	on	C&P	fn	Jaccard	40	388742	4980	155060	13220
isotime1	off	C&P	fn	Jaccard	40	640693	5015	241655	26115
isotime1	on	C&P	fn	Jaccard	40	320219	4720	212855	9679
isotime2	off	C&P	fn	Jaccard	40	627814	5152	223734	25594
isotime2	on	C&P	fn	Jaccard	40	310268	4792	209081	9320
stripes	off	C&P	nn	Proposed	60	971929	4991	199515	38947
stripes	on	C&P	nn	Proposed	60	414809	4814	193915	13288
isotime1	off	C&P	nn	Proposed	60	814071	4916	280885	32485
isotime1	on	C&P	nn	Proposed	60	380998	4778	271112	11077
isotime2	off	C&P	nn	Proposed	60	752026	4952	243910	29950
isotime2	on	C&P	nn	Proposed	60	370772	4817	236165	11082
stripes	off	C&P	fn	Proposed	60	806183	5041	175881	30940
stripes	on	C&P	fn	Proposed	60	408028	5055	199515	13067
isotime1	off	C&P	fn	Proposed	60	674998	5005	243451	26731
isotime1	on	C&P	fn	Proposed	60	349274	4890	255288	10070
isotime2	off	C&P	fn	Proposed	60	656928	5167	225822	25990
isotime2	on	C&P	fn	Proposed	60	328333	4854	198577	9641
stripes	off	C&P	nn	Jaccard	60	947614	4639	175985	37802
stripes	on	C&P	nn	Jaccard	60	410500	4559	170817	13266
isotime1	off	C&P	nn	Jaccard	60	749286	4723	240726	29719
isotime1	on	C&P	nn	Jaccard	60	360994	4616	230914	10586
isotime2	off	C&P	nn	Jaccard	60	677238	4852	224228	26812
isotime2	on	C&P	nn	Jaccard	60	337809	4727	216668	9858
stripes	off	C&P	fn	Jaccard	60	920938	4964	176084	36707
stripes	on	C&P	fn	Jaccard	60	419872	4513	175024	13562
isotime1	off	C&P	fn	Jaccard	60	667019	4955	239174	26414
isotime1	on	C&P	fn	Jaccard	60	350071	5153	230356	10255
isotime2	off	C&P	fn	Jaccard	60	647980	5093	222588	25615
isotime2	on	C&P	fn	Jaccard	60	329875	4732	217501	9601
stripes	off	C&P	nn	Proposed	75	1039237	4964	233137	41629
stripes	on	C&P	nn	Proposed	75	451432	4805	227254	14229
isotime1	off	C&P	nn	Proposed	75	926115	4838	302997	36971
isotime1	on	C&P	nn	Proposed	75	421274	4733	292907	12332
isotime2	off	C&P	nn	Proposed	75	850088	4859	283093	33916
isotime2	on	C&P	nn	Proposed	75	402577	4735	275464	11723
stripes	off	C&P	fn	Proposed	75	825722	4815	190795	30865
stripes	on	C&P	fn	Proposed	75	417887	4901	220004	13087

isotime1	off	C&P	fn	Proposed	75	685552	4946	247217	27151
isotime1	on	C&P	fn	Proposed	75	407188	4740	292120	11905
isotime2	off	C&P	fn	Proposed	75	668152	5063	228262	26463
isotime2	on	C&P	fn	Proposed	75	377050	4756	232500	10922
stripes	off	C&P	nn	Jaccard	75	1011640	4834	224206	40333
stripes	on	C&P	nn	Jaccard	75	448798	4700	218059	14177
isotime1	off	C&P	nn	Jaccard	75	870107	4832	280269	34584
isotime1	on	C&P	nn	Jaccard	75	412240	4715	270816	12150
isotime2	off	C&P	nn	Jaccard	75	826819	4695	263948	32847
isotime2	on	C&P	nn	Jaccard	75	391293	4590	254929	11504
stripes	off	C&P	fn	Jaccard	75	908374	4840	217411	35748
stripes	on	C&P	fn	Jaccard	75	400534	4982	189002	12469
isotime1	off	C&P	fn	Jaccard	75	678813	4955	242589	26866
isotime1	on	C&P	fn	Jaccard	75	398721	4801	270021	11738
isotime2	off	C&P	fn	Jaccard	75	668194	5091	223477	26456
isotime2	on	C&P	fn	Jaccard	75	354218	4610	249202	10203
stripes	off	C&T	nn	Proposed	60	1006762	4909	263582	40313
stripes	on	C&T	nn	Proposed	60	434773	4765	257601	13211
stripes	off	C&T	nn	Proposed	75	1057749	4960	235972	42376
stripes	on	C&T	nn	Proposed	75	457153	4803	230191	14418
stripes	off	C&T	nn	Proposed	40	1019617	5029	274535	40815
stripes	on	C&T	nn	Proposed	40	463913	4833	266233	14419
isotime1	off	C&T	nn	Proposed	60	1015078	4942	318858	40541
isotime1	on	C&T	nn	Proposed	60	419282	4770	309084	12042
isotime1	off	C&T	nn	Proposed	75	941462	4836	299050	37605
isotime1	on	C&T	nn	Proposed	75	419713	4731	288801	12332
isotime1	off	C&T	nn	Proposed	40	951810	4922	360081	38006
isotime1	on	C&T	nn	Proposed	40	419332	4759	348408	1635
isotime2	off	C&T	nn	Proposed	60	897751	4981	298384	35849
isotime2	on	C&T	nn	Proposed	60	406592	4802	290464	11778
isotime2	off	C&T	nn	Proposed	75	838715	4862	287447	33469
isotime2	on	C&T	nn	Proposed	75	402856	4739	279918	11658
isotime2	off	C&T	nn	Proposed	40	957352	5060	323384	38173
isotime2	on	C&T	nn	Proposed	40	422626	4864	313356	12267
stripes	off	C&T	fn	Proposed	60	976328	4811	268698	39056
stripes	on	C&T	fn	Proposed	60	426908	4760	255690	12968
stripes	off	C&T	fn	Proposed	75	985022	5258	234125	39247
stripes	on	C&T	fn	Proposed	75	449034	4755	232235	14157
stripes	off	C&T	fn	Proposed	40	965135	5280	271614	38511
stripes	on	C&T	fn	Proposed	40	418991	4881	253631	12873
isotime1	off	C&T	fn	Proposed	60	964090	5239	291759	38397
isotime1	on	C&T	fn	Proposed	60	915752	4722	310129	18571
isotime1	off	C&T	fn	Proposed	75	942384	4872	303476	37642

isotime1	on	C&T	fn	Proposed	75	419990	4968	292586	12340
isotime1	off	C&T	fn	Proposed	40	941248	4873	366315	37580
isotime1	on	C&T	fn	Proposed	40	417301	4997	353441	1627
isotime2	off	C&T	fn	Proposed	60	896962	5180	307115	35817
isotime2	on	C&T	fn	Proposed	60	408714	4802	287890	11839
isotime2	off	C&T	fn	Proposed	75	837805	5008	294766	33433
isotime2	on	C&T	fn	Proposed	75	402856	4597	287138	11658
isotime2	off	C&T	fn	Proposed	40	954183	5041	330386	38046
isotime2	on	C&T	fn	Proposed	40	419868	4873	315309	12186
stripes	off	C&T	nn	Jaccard	60	1033425	4879	287754	41187
stripes	on	C&T	nn	Jaccard	60	472649	4730	281263	14282
stripes	off	C&T	nn	Jaccard	75	971667	4831	269712	38725
stripes	on	C&T	nn	Jaccard	75	449809	4703	263609	13535
stripes	off	C&T	nn	Jaccard	40	1072850	5001	294084	42713
stripes	on	C&T	nn	Jaccard	40	467554	4833	285106	14257
isotime1	off	C&T	nn	Jaccard	60	1040889	4880	340734	41378
isotime1	on	C&T	nn	Jaccard	60	452163	4733	331836	12935
isotime1	off	C&T	nn	Jaccard	75	955940	4872	311551	38011
isotime1	on	C&T	nn	Jaccard	75	430978	4732	302404	12422
isotime1	off	C&T	nn	Jaccard	40	1029172	4881	353457	40921
isotime1	on	C&T	nn	Jaccard	40	447968	4732	342811	12808
isotime2	off	C&T	nn	Jaccard	60	968478	4877	329212	38427
isotime2	on	C&T	nn	Jaccard	60	428669	4735	321491	12083
isotime2	off	C&T	nn	Jaccard	75	948308	4840	287903	37708
isotime2	on	C&T	nn	Jaccard	75	403372	4680	278667	11633
isotime2	off	C&T	nn	Jaccard	40	991868	5036	342943	39416
isotime2	on	C&T	nn	Jaccard	40	443351	4870	332972	12771
stripes	off	C&T	fn	Jaccard	60	999345	4781	286628	39782
stripes	on	C&T	fn	Jaccard	60	470129	5014	287920	14205
stripes	off	C&T	fn	Jaccard	75	968002	5121	268659	38578
stripes	on	C&T	fn	Jaccard	75	430876	4750	265100	12940
stripes	off	C&T	fn	Jaccard	40	991239	5351	293673	39196
stripes	on	C&T	fn	Jaccard	40	441256	5123	279808	13407
isotime1	off	C&T	fn	Jaccard	60	957032	4734	321582	37752
isotime1	on	C&T	fn	Jaccard	60	430923	4780	305358	12297
isotime1	off	C&T	fn	Jaccard	75	958009	5067	316803	38093
isotime1	on	C&T	fn	Jaccard	75	431239	4543	306391	12430
isotime1	off	C&T	fn	Jaccard	40	955961	4893	343046	37787
isotime1	on	C&T	fn	Jaccard	40	443400	4732	347603	12676
isotime2	off	C&T	fn	Jaccard	60	963786	5218	338356	38239
isotime2	on	C&T	fn	Jaccard	60	427861	4830	325505	12060
isotime2	off	C&T	fn	Jaccard	75	958990	5130	289368	38128
isotime2	on	C&T	fn	Jaccard	75	407810	5008	277146	11760

isotime2	off	C&T	fn	Jaccard	40	989789	5187	347282	39333
isotime2	on	C&T	fn	Jaccard	40	441546	4967	337812	12719
stripes	off	CB	nn	Proposed	60	1017537	4847	290175	40737
stripes	on	CB	nn	Proposed	60	446061	4727	281509	13490
stripes	off	CB	nn	Proposed	75	1041605	4802	290575	41723
stripes	on	CB	nn	Proposed	75	454025	4692	282694	13761
stripes	off	CB	nn	Proposed	40	1070181	5038	292806	42812
stripes	on	CB	nn	Proposed	40	467111	4847	279836	14550
isotime1	off	CB	nn	Proposed	60	942586	4739	366126	37625
isotime1	on	CB	nn	Proposed	60	505528	4652	354755	14952
isotime1	off	CB	nn	Proposed	75	946325	4670	357127	37778
isotime1	on	CB	nn	Proposed	75	489609	4603	344527	14452
isotime1	off	CB	nn	Proposed	40	937651	4925	366714	37401
isotime1	on	CB	nn	Proposed	40	490914	4768	352699	14458
isotime2	off	CB	nn	Proposed	60	1019898	4975	333510	40719
isotime2	on	CB	nn	Proposed	60	486486	4812	322603	14603
isotime2	off	CB	nn	Proposed	75	1009631	4994	343609	40305
isotime2	on	CB	nn	Proposed	75	493695	4814	333162	14750
isotime2	off	CB	nn	Proposed	40	973096	4915	341579	38833
isotime2	on	CB	nn	Proposed	40	478948	4785	329934	14261
stripes	off	CB	fn	Proposed	60	973650	4992	273315	38901
stripes	on	CB	fn	Proposed	60	406867	5011	276701	12190
stripes	off	CB	fn	Proposed	75	975231	4787	276276	38883
stripes	on	CB	fn	Proposed	75	417713	4974	280500	12565
stripes	off	CB	fn	Proposed	40	975081	4887	271413	38637
stripes	on	CB	fn	Proposed	40	398990	4944	257350	12066
isotime1	off	CB	fn	Proposed	60	935401	4786	373881	37336
isotime1	on	CB	fn	Proposed	60	487669	4699	363301	14404
isotime1	off	CB	fn	Proposed	75	946254	4997	357486	37775
isotime1	on	CB	fn	Proposed	75	490536	4741	354124	14479
isotime1	off	CB	fn	Proposed	40	836773	5122	334620	32892
isotime1	on	CB	fn	Proposed	40	448707	5054	328485	13098
isotime2	off	CB	fn	Proposed	60	992552	5224	343203	39592
isotime2	on	CB	fn	Proposed	60	478573	5101	331200	14362
isotime2	off	CB	fn	Proposed	75	995056	5001	343726	39714
isotime2	on	CB	fn	Proposed	75	484953	4814	336813	14483
isotime2	off	CB	fn	Proposed	40	964916	4964	345175	38504
isotime2	on	CB	fn	Proposed	40	467960	5120	332535	13926
stripes	off	CB	nn	Jaccard	60	1036239	4809	250384	41325
stripes	on	CB	nn	Jaccard	60	462434	4700	243139	14556
stripes	off	CB	nn	Jaccard	75	1038987	4795	268718	41423
stripes	on	CB	nn	Jaccard	75	465921	4691	260649	14399
stripes	off	CB	nn	Jaccard	40	1028857	4791	237993	40987

stripes	on	CB	nn	Jaccard	40	441134	4682	228617	13991
isotime1	off	CB	nn	Jaccard	60	883840	4725	319386	35061
isotime1	on	CB	nn	Jaccard	60	458454	4630	309161	13629
isotime1	off	CB	nn	Jaccard	75	939882	4720	304815	37353
isotime1	on	CB	nn	Jaccard	75	466638	4629	293996	14087
isotime1	off	CB	nn	Jaccard	40	848881	4726	325401	33691
isotime1	on	CB	nn	Jaccard	40	470576	4663	281808	14503
isotime2	off	CB	nn	Jaccard	60	934414	4914	311627	37104
isotime2	on	CB	nn	Jaccard	60	470950	4761	301702	14198
isotime2	off	CB	nn	Jaccard	75	940061	4875	319340	37349
isotime2	on	CB	nn	Jaccard	75	460916	4740	309470	13654
isotime2	off	CB	nn	Jaccard	40	942404	4796	292517	37463
isotime2	on	CB	nn	Jaccard	40	470576	4663	281808	14503
stripes	off	CB	fn	Jaccard	60	978456	4953	249209	38885
stripes	on	CB	fn	Jaccard	60	410321	4720	197373	12707
stripes	off	CB	fn	Jaccard	75	980145	4891	253914	38936
stripes	on	CB	fn	Jaccard	75	412356	4926	198098	12529
stripes	off	CB	fn	Jaccard	40	980123	4935	229420	38949
stripes	on	CB	fn	Jaccard	40	409874	4822	226460	12924
isotime1	off	CB	fn	Jaccard	60	880490	4536	320367	34928
isotime1	on	CB	fn	Jaccard	60	453097	4445	310434	13468
isotime1	off	CB	fn	Jaccard	75	910934	4767	305690	36166
isotime1	on	CB	fn	Jaccard	75	462047	4632	295891	13947
isotime1	off	CB	fn	Jaccard	40	840201	4631	326674	33343
isotime1	on	CB	fn	Jaccard	40	451045	4476	282681	13875
isotime2	off	CB	fn	Jaccard	60	934789	4914	315630	37119
isotime2	on	CB	fn	Jaccard	60	470021	5094	304286	14170
isotime2	off	CB	fn	Jaccard	75	940925	5168	328360	37383
isotime2	on	CB	fn	Jaccard	75	459992	4598	314874	13626
isotime2	off	CB	fn	Jaccard	40	940367	4940	292333	37382
isotime2	on	CB	fn	Jaccard	40	459123	4756	288866	14141
stripes	off	OC	*	*	*	1042687	5096	173415	39536
stripes	on	OC	*	*	*	439714	4862	163340	14824
isotime1	off	OC	*	*	*	691667	5215	257676	27313
isotime1	on	OC	*	*	*	377150	4949	244991	11900
isotime2	off	OC	*	*	*	706752	5311	232454	27096
isotime2	on	OC	*	*	*	375079	5023	222090	11014
stripes	off	P	*	*	*	1033286	5066	167328	41148
stripes	on	P	*	*	*	434890	4832	159096	14530
isotime1	off	P	*	*	*	701790	5161	255748	27718
isotime1	on	P	*	*	*	369624	4896	243904	10931
isotime2	off	P	*	*	*	687436	5312	236495	27125
isotime2	on	P	*	*	*	374376	5027	225609	11904

stripes	off	T	*	*	*	1091445	5248	248811	43431
stripes	on	T	*	*	*	454831	4991	237133	14636
isotime1	off	T	*	*	*	858713	5249	319778	34079
isotime1	on	T	*	*	*	407206	4988	305427	11943
isotime2	off	T	*	*	*	836842	5375	295133	33160
isotime2	on	T	*	*	*	384430	5065	281389	11344

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Waves crash down
8:am
Morning mist
Hot sun burning
Colourful boards rising
from the sand
camp stove coffee
smelling good
Fuel for the engine
Rhythm of the windsurf
Drums of the sea
One by one
into the ocean
throwing our bodies into
the liquid of life
Souls set free
standing on our hearts
twisting and turning
propelled by ocean
into the white light of peace
exhilaration
fear the only obstacle
adrenaline the reward
sweat is our offering
baptized in the waters of
our creator
cleansed of our sins
given strength
to carry our message of
an infinite calm
a silence within
as day begins
the sound of the windsurf
dawn of the drums

Adapted by *Sound of Surf - Ralph Alfonso*