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Integrated Models and Tools for Design and Management of Global Supply Chain

Modelli e Strumenti Integrati per la

Progettazione e Gestione di Filiere Logistico-Distributive Globali

Direttore della Scuola: Chiar.mo Prof. Paolo Colombo

Coordinatore d'Indirizzo: Chiar.mo Prof. Alberto Trevisani

Supervisore: Chiar.mo Prof. Arrigo Pareschi

Dottorando: ing. Riccardo Accorsi

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Abstract

In modern and global supply chain, the increasing trend toward product variety, level of service, short delivery delay and response time to consumers, highlight the importance to set and configure smooth and efficient logistic processes and operations.

In order to comply such purposes the supply chain management (SCM) theory entails a wide set of models, algorithms, procedure, tools and best practices for the design, the management and control of articulated supply chain networks and logistics nodes.

The purpose of this Ph.D. dissertation is going in detail on the principle aspects and concerns of supply chain network and warehousing systems, by proposing and illustrating useful methods, procedures and support-decision tools for the design and management of real instance applications, such those currently face by enterprises.

In particular, after a comprehensive literature review of the principal warehousing issues and entities, the manuscript focuses on design top-down procedure for both less-than-unit-load OPS and unit-load storage systems. For both, decision-support software platforms are illustrated as useful tools to address the optimization of the warehousing performances and efficiency metrics. The development of such interfaces enables to test the effectiveness of the proposed hierarchical top-down procedure with huge real case studies, taken by industry applications.

Whether the large part of the manuscript deals with micro concerns of warehousing nodes, also macro issues and aspects related to the planning, design, and management of the whole supply chain are enquired and discussed.

The integration of macro criticalities, such as the design of the supply chain infrastructure and the placement of the logistic nodes, with micro concerns, such the design of warehousing nodes and the management of material handling, is addressed through the definition of integrated models and procedures, involving the overall supply chain and the whole product life cycle.

A new integrated perspective should be applied in study and planning of global supply chains. Each aspect of the reality influences the others. Each product consumed by a customer tells a story, made by activities, transformations, handling, processes, traveling around the world. Each step of this story accounts costs, time, resources exploitation, labor, waste, pollution. The economical and environmental sustainability of the modern global supply chain is the challenge to face.

Sommario

Nelle moderne filiere logistiche-distributive globali, la crescente varietà dei prodotti, il livello di servizio e la rapidità nel rispondere alla domanda del cliente, impongono una seria e ponderata progettazione ed organizzazione dei processi intra-inter aziendali. Con l'obiettivo di rispondere a tali criticità, le teorie di supply chain managment (SCM) propongono una vasta gamma di modelli, algoritmi, procedure, e strumenti per la progettazione, la gestione e il controllo delle articolate supply chain e dei principali nodi logistici.

Uno dei principali obiettivi di questa tesi di dottorato è approfondire nel dettaglio i processi e gli aspetti principali della filiera logistica e dei suoi principali buffer (i.e. sistemi di stoccaggio), illustrando metodi, modelli, procedure e sistemi di supporto decisionale per la progettazione e gestione di istanze reali, quotidianamente affrontate dalle aziende di tutto il mondo.

In particolare, dopo una completa rassegna della letteratura sui sistemi di stoccaggio, la tesi si concentra sulla descrizione di procedure decisionali top-down per la progettazione ed il controllo di sistemi di stoccaggio a prelievo frazionato (i.e. Order picking systems) e sistemi di stoccaggio ad unità di carico intere. Per entrambe le tipologie di sistemi, sono illustrati strumenti informatici di supporto alle decisioni per la valutazione e l'ottimizzazione delle prestazioni logistiche - operative. Lo sviluppo di tali interfacce permette di testare l'efficacia dei modelli e delle procedure decisionali proposte su significativi casi di studio di origine industriale.

Se la prima parte del manoscritto si concentra sugli aspetti micro intra-nodo della filiera distributiva, l'ultimo capitolo affronta le tematiche macro di filiera relative alla pianificazione, progettazione e gestione della infrastruttura della supply chain.

L'integrazione di macro criticità, come la locazione dei nodi logistici di produzione e distribuzione e l'instradamento dei flussi fisici lungo ed attraverso il network della supply chain, con micro criticità, inerenti la progettazione di nodi distributivi e di stoccaggio e la gestione del material handling, si realizza attraverso la definizione di modelli integrati di pianificazione strategica per l'ottimizzazione dell'intera filiera, lungo tutto il ciclo di vita del prodotto.

Una nuova prospettiva integrata deve essere applicata allo studio e la progettazione di articolate supply chain globali. Ogni aspetto della realtà dipende ed influenza gli altri lungo la filiera. Ogni prodotto acquistato e consumato dal cliente finale racconta una storia, fatta di attività, processi,

trasformazioni subite, movimentazioni e trasporto in giro per il mondo. Ogni step di questo percorso richiede tempo, risorse, manodopera, generando costi, scarti, inquinamento.

In tale contesto, la sostenibilità economica ed ambientale delle moderne supply chain globali rappresenta la principale sfida da affrontare.

Acknoledgement

This Ph.D. dissertation is the summary and the result of long and tough path leading a young and irresolute engineering student from the age of college to the age of work. This is not just the report of the main research topics and projects carried out during the last three years, but also the effective and concrete proof of what I hope, have been my improvements, the achieved expertise, and my own maturation. Nothing I have done would ever have been possible without the support a some friends I want to mention.

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Thank you all.

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Riccardo Accorsi

Integrated Models and Tools for Design and Management of Global Supply Chain

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Riccardo Accorsi

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&

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To those who follow a lifelong ambition,
to dogged, stubborn and hell-bent ones,
to those falling and raising,
to those always trying and never giving up,
because they do look forward,
they do always experience,
they do believe in future,
and never stop dreaming.

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1. Introduction

Nowadays, warehouses represent the crucial operative nodes throughout the supply chain and distribution network. In modern and global supply chain, the increasing trend toward product variety, level of service, short delivery delay and response time to consumers, highlight the importance to set and configure smooth and efficient logistic processes and operations. These operations play a critical role in addressing enterprises competition, whilst logistics is currently renowned as the most concrete tool to reduce overall supply chain costs. Indeed, the outdated perspective considering logistics a no value-added aspect of the supply chain is worldwide disappeared.

According to the principles of supply chain management, modern enterprises attempt to achieve high-volume production and distribution of large variety of products i.e. stock keeping units (SKUs) and customized items using minimal inventories throughout the network and delivering within a short response time. In a further attempt to decrease the total inventory costs, many companies set, design and plan new integrated and extensive distribution networks by replacing several relatively small distribution centers (DCs) to few large DCs. Often an entire continent, such as North America or Europe, is served by a small number of huge DCs located to strategic sites.

The complexity of the supply and distribution network depends on the number of partners, the involved nodes, the objective customers, the sites of extraction of raw material. The modern global market compels enterprises to break down national barriers, and implements innovative methodologies to manufacture, store, retrieve, ship, and deliver products over global scale. Global economy makes products travelling along the supply chain from the manufacturer to final customer at the other side of the world, being available almost in every place and at every time. The modern supply chains strive for sundering manufacturing district (e.g. the so-called cheap labor country) from consumption sites (e.g. developed country) and the performance of the chain is measured by the quality of delivered products, the overall costs efficiency and the time of response to demand.

The efficiency and effectiveness in supply chain networks largely depend both by the configuration of the network and the activities and operations within nodes and hubs of the network. Supply chain management (SCM) is the integration of key business processes from end-user through original suppliers (Lambert et al. 1998). Relevant concerns of SCM are the definition of the optimal logistic network configuration and the identification of the best management rules and operational procedures. Many enterprises worldwide operating currently face the following critical issues:

- the definition of the number of manufacturing, processing and/or distribution facilities (e.g. DCs, transit points and hubs, wholesalers);
- the choice of their geographical locations;
- the allocation of sets of logistic nodes (e.g. suppliers, DCs, wholesalers) to sets of points of demand (e.g. customers/consumers);
- the design of warehousing systems (i.e. DCs);
- the operative management of storage system and the inventory inbound/outbound operations;
- the definition of the best transportation modes (e.g. rail, road, water, air)
- the operative management of vehicles fleet with particular focus on loading, scheduling and routing.

These issues deal with the strategic configuration of a logistic network on one hand and the management and the operative control of the distribution chain on the other. These two categories of problems compel the decision maker (i.e. industry manager, practitioner, academician) to consider and analyze a wide sub-set of decisions focusing on macro and micro aspects of the supply chain and distribution network.

Macro concerns deals with the strategic design and tactical planning of the network, by setting the site of logistic nodes and by assigning a set of points of demand (PODs) to be fulfilled by each node, by defining the proper shipping policy and strategy.

Micro concerns mainly focus on the design of the logistic nodes (i.e. warehousing system), the configuration of stock-keeping-units (SKUs) storage, the selection of the best performing inbound/outbound operations to let the SKUs quickly flowing through the node.

Figure 1 illustrates the change of perspective of decision makers in facing the articulated problem of supply chain management. The conceptual scheme represents different stage and level of analysis, characterized by different grade of detail. The higher the detail, the wider the set of decisions to be taken, the larger the number of entities and data to consider, the more far by the optimum the solution of the problem is.

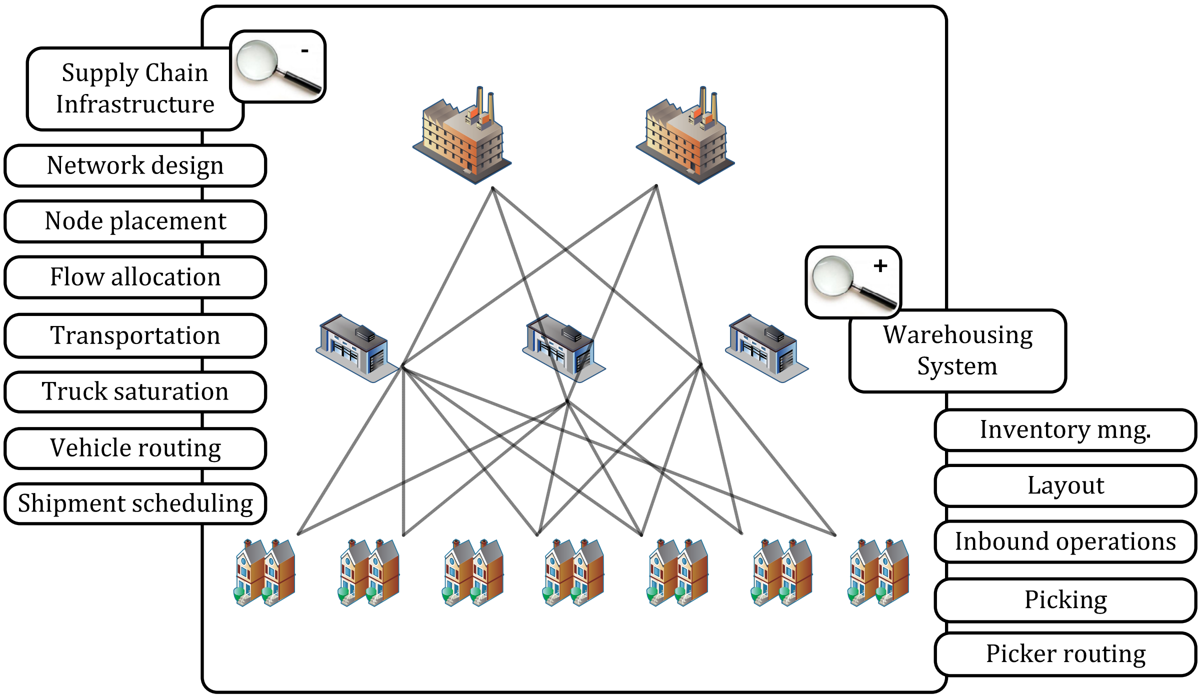


Figure 1. Macro-issues of supply chain.

At first level of analysis the decision maker overviews the configuration of the chain network by considering the set of PODs to serve, the potential candidate logistic facilities to activate for both manufacturing and distribution activities, and their geographical locations. Literature debates these topics through the formalization of the following main problems and decisions: the so-called facility location problem (FLP) and the so-called allocation problem (AP).

In FLP the selection of the sites where new facilities are to be established is restricted to a finite set of candidates. The simplest approach to solve such a problem consists on the so-called p-median problem, where some facilities, equivalent in opening-setup costs, are selected to minimize the overall weighted distances for supplying customer demands (Melo et al. 2009). Many different mixed-integer linear programming (MILP) models have been proposed by the literature in order to suggest the best location of logistic nodes under different constraints and hypotheses. These models are summarized in several meaningful surveys (Nagy et al. 2007, Melo et al. 2009): the so-called uncapacitated (UFLP) or capacitated location problems (CFLP), or single and multi-period location problems considering customer demand changing over time in a predictable way.

The second level of analysis involves a set of decisions concerning with the design and management of storage node or warehousing system over processes, resources, and organization perspectives (Rouwenhorst et al. 2000). Generally, products arriving at a warehouse are subsequently handled through a set of activities and processes. Resource refers to the wide list of physical entities treated, utilized and processed within the warehouse. This list includes SKUs, rack, storage/retrieving vehicles and equipments, operators, bay, aisle, etc. Finally, organization involves all the design, planning techniques, procedures, strategies and policies applied to run and control the storage system.

Warehouse major roles include buffering material flow along the chain to comply variability due to demand seasonality, production or distribution batching; consolidation of SKUs from suppliers to fulfill customer demand; efficient and effective material handling through the system; value-added-processing such as sorting, kitting, pricing, labeling and sometimes product customization (Gu et al. 2007).

Therefore, it is not surprising that the research on warehousing system gained interest in research in 1970s, since those years experience a shifting interest from the problem of productivity efficiency improvement to the problem of inventory reduction (Van den Berg 1999). The development of information systems allowed the implementation of tool and techniques, e.g., to match both upline and downline the manufacturing process with the storage and inventory step. As instance, the manufacturing resource planning (MRP), developed at the beginning of 1970s and further implemented in thousands enterprises until 1980s, is a software-based production planning and inventory control system used to manage manufacturing and inventory processes. This approach provides a set of supporting decision tool to match manufacturing issues, distribution issues and inventory control.

On the other hand, emerging philosophies suggest innovative outlines and new approaches to take into account in SCM and warehouse design and inventory control. As instance, in 1980s from Japan a new management philosophy emerged: the so-called Just-In-Time (JIT) production. JIT attempts to achieve high-volume production by utilizing minimal inventories of parts arrived just in time.

Current trends in warehousing and distribution logistics are those dealing with the Efficient Consumer Response (ERC) as a main driver for SCM. In particular, ECR pursues a demand-driven organization of the supply chain with small inventories and reliable short response times to the costumers. Such an organization requires a close cooperation among the companies along the chain. Furthermore, information technology enables these developments through Electronic Data Interchange (EDI) and software systems such as the Enterprise Resource Planning (ERP) and Warehouse Management Systems (WMS) (Van den Berg 1999).

Nowadays, the current increasing sensibility to environment and environmental solutions involve each aspect of supply chains and in general society. This new environmental care perspective compels enterprises to organize and design green distribution and green supply chain, characterized by reduced material flows and inventory, reduced wastes and purpose for material recovery strategies and policies. Furthermore, the new interest in quality coerces warehouse managers to examine operations aiming to minimize product damages, establish short and reliable transaction times and providing demand-fulfillment accuracy.

These trends in procedures, routines, technologies and perspectives require a change in approaching warehouse and supply chain issues. The challenge to tackle are the fulfillment of customer needs by reducing volumes handled through the logistic nodes of the supply chain, by frequently deliver with shorter response time, by manage wider and wider variety of SKUs.

The warehousing systems are in the meanwhile the source of problems and the solution. The more efficient the management of time and space in warehouse operations, the faster the material flow through the logistic node. The faster the flow through the node, the quicker the response of the supply chain to the final consumer demands. The quicker the response to costumers, the lower the required stock of product. The lower the product inventory, the fewer the warehousing system to be involved along the supply chain, and so on. Therefore, a wide range of interdependent decisions, concerns and issues affect both the warehouse node and the distribution network, and the performance of the former influences the effectiveness and the efficiency of the latter. Figure 2 briefly illustrates the links among the potential aspects, decisions and issues on supply chain caused by the proper or improper design and management of warehouse nodes.

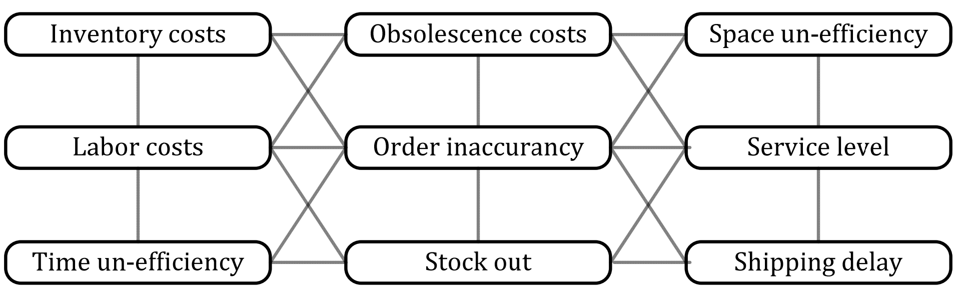


Figure 2. Micro-issues due to warehouse nodes

The main question to be answer by reading this manuscript is the even simplest: *why dealing with warehousing systems at all?*

A warehouse produces material lock-up, requires labor, capital (e.g. land, facility building, storage-handling equipments, etc.) and information systems, which mean costs for supply chain actors and costumers. Distribution storage nodes represent one of the main sources of wastes and costs throughout the whole supply chain, and are responsible on average of 50% of distribution costs (Bartholdi and Hackman 2012).

Thus, the second question arises: *are there any methods, methodologies and/or procedures to avoid such costs?*

Unfortunately, for most operations the answer is no. Indeed, warehouses enable to match supply and manufacturing with customer demand, respond to products and demand seasonality, consolidate product reducing transportation costs, and finally provide useful added-value services, which are unlikely to vanish under the current global economy.

The present manuscript analyses SCM approaches, techniques, methods, models and tools focusing on different aspects and issues of warehousing and distribution systems as essential components of any supply chains. On one side, integrated procedure, approaches and methodologies to tackle multi-dimensions and multi-purposes warehousing and distribution concerns are illustrated and presented in comparison with the wide set of models and contributions proposed by literature. On the other, a set of decision support systems, informative instruments and mathematical models are introduced and described in detail as useful and comprehensive tools for industry, managers, practitioners and academicians in addressing warehouse and distribution related issues and pointing out design and management guide lines.

1.1 Thesis outline

This chapter as introduction of the manuscript presents the majors and the objectives of the proposed contents. The inbound and outbound supply chain operations represent the main topics of this dissertation with particular focus on warehouse and storage systems design and management. The reminder of the manuscript is organized as follows, and the integration among chapters is illustrated in Figure 3.

- **Chapter 2.** The second chapter presents a detailed and comprehensive literature reviews dealing with the main aspects, issues and features of logistic distribution chain, and storage warehousing systems. The whole set of processes, operations, activities and steps driving the products through the node and throughout the chain are classified and reported. This chapter also regards with the storage recourses (i.e. operators), storage modes and equipments (i.e. rack typologies, retrieving vehicle, manual or automatic storage/retrieving systems) and summarizes a panel of decisions and concerns to be considered per each case. A brief description of the main typologies of storage systems is proposed, in order to point out how different products and demand profiles deeply affect the characteristics of the distribution system. Finally, a classification of problems and decisions with related solving methods and approaches is illustrates.

Chapter 2 attempts to clarify the complexity of such a context of analysis by summarizing the articulated list of approaches provided by literature. Outline of this section is considering the warehouse design and management as a multi-purpose and multi-technique problem, where mathematical optimal formulations often fail in addressing real industry cases. In particular, two subsets of warehouse systems are illustrates and further complied and treated respectively in Chapters 3-5 and Chapters 6: less-than-unit load order picking systems or Order Picking Systems (OPS) and unit-load retrieving systems.

- **Chapter 3**. The third chapter responses to the criticalities and lacks highlighted in the previous literature reviews, by proposing a hierarchical top-down procedure for decisions supporting of design and management of warehousing systems. In particular, the procedure involves different steps of analysis and considers aspects such as the layout and system configuration, storage allocation (i.e. the strategy to devote the proper inventory of each product within the system), storage assignment (i.e. the strategy to define the problem location of each product within the system), and routing strategies (i.e. the strategy to visit the locations within the system). The hierarchical procedure addresses to the principle warehouse operations concerns aiming to select the combined multi-purposes and multi-drivers strategy or policy in order to reduce the overall handling costs. This chapter mainly reports and summarizes the contents of recent published works of the author (Accorsi et al. 2012, Manzini et al. 2011, Accorsi et al. 2011, Accorsi et al. 2010).

- **Chapter 4**. The fourth chapter presents and illustrates in detail a support-decision tool for the design, management and control of a warehousing system. The proposed informative system, implementing the top-down hierarchical procedure proposed in Chapter 3, takes into account both issues of warehouse design and warehouse operations. As a computerized platform, it implements support-decision models, analytical methods and algorithms to comply most relevant warehouse issues concerning with put-away, replenishment and order picking, the latter responsible of 55% of overall costs within a distribution centre. Resulting by the adoption of the this decision-support tool is a dashboard of key performance indicators (KPIs) of space and time efficiency allowing warehouse providers, practitioners, managers, as well as academics and educators to tackle real case studies and to pin down useful guidelines in keeping control of a storage system. The chapter presents the data management architecture of the tool, a picture of code structures, and a selection of graphic user interfaces (GUIs) to show the potential functionalities enabling the application of real data-oriented analysis. This chapter mainly reports and summarizes the contents of recent published works of the author (Accorsi et al. 2012).

- **Chapter 5**. The fifth chapter presents and illustrates in details some real less-than-unit load warehousing system cases faced by the adoption of top-down hierarchical procedures and the support-decision tool presented respectively in Chapter 3 and Chapter 4. In particular, the proposed case study deals with a spare parts management system for the automotive industry. A logistic firm operating worldwide provides the logistics services of transportation (inbound & outbound) and warehousing for an important automotive company in order to supply the demand of spare parts to hundreds of Italian customers and dealers. Results in terms of operative performances in inbound and outbound warehouse operations are summarized to point out the interdependency of specific products and demand profiles in determining the best sets of operative strategies and policies to adopt.

- **Chapter 6**. The sixth chapter focuses on the design and management of pallet picking operations warehouses, in which pallets load (i.e. unit-load) are moved in, through and out the system (Van den Berg and Zijm 1999). These systems are the simplest to design and manage since layout and operation concerns are suitable to mathematical approach and modelization. Pallet-load storage systems typically handle commodities and other products characterized by large volume demand and high throughput. There are many enterprises and general industry sectors adopting these common and simple storage systems formats such as tissue, beverage, dry food, etc. The goal of this section is to present an original hierarchical top-down procedure for the design and management of unit-load storage/retrieving system. The procedure gains traction by literature static mathematical models (Bartholdi and Hackman 2011) to define the system layout implications in terms of storage mode to adopt and lanes depth. The lane is a common pallet placement strategy bases on homogeneous (i.e. holding the same SKU) queue (or line) of pallet facing the aisle by one or both sides. Aisles provide accessibility, but this empty space is not revenue-generating for the warehousing system. By storing SKUs in lanes, additional pallet positions can share the same space amortizing the cost. The definition of layout entails a wide set of issues, but the most important one is the effective utilization of space. This is the principle goal of the proposed top-down hierarchical procedures.

A second section of this chapter presents and illustrates in detail a support-decision tool for the design, management and control of a unit-load warehousing system. As a computerized platform, it implements support-decision models, analytical methods and algorithms to comply most relevant layout issues concerning with lane depth optimization, space efficiency, put-away and retrieving operations. As for Chapter 4, this section presents the data management architecture of the tool, a picture of code structures, and a selection of graphic user interfaces (GUIs) to show the potential functionalities enabling the application of real data-oriented analysis.

The final section of this chapter illustrates in details some real unit-load warehousing system case studies faced by the adoption of top-down hierarchical procedures and the support-decision tool. As for Chapter 5, this section reports the analyses conducted on real industry cases and applications in order to validate the effectiveness of the proposed methodologies and tools. Remarks from the analyses are the obtained improvements in terms of space and time efficiency of warehouse layout and operations in comparison with the AS-IS benchmark. Even though, the illustrated results only refer to the specific case study and are not generalized, the aim of the section is to gather a set of guidelines for industry managers, practitioners and researcher in facing real instances and applications.

- **Chapter 7**. The seventh chapter draws the general links between the warehousing nodes, deeply treated in this manuscript, and the supply chain network from the gathering of raw materials across manufacturing, distribution to the final consumer and the end-of-life treatments. In order to address quality, sustainability and efficiency of products and operations the supply chain network should be treated and studied as a whole, involving even concerns and processes at the top (i.e. land use, raw material collection) and at the bottom (i.e. end-of-life scenarios, products and package disposal, recycling, recovery) of the supply chain. The purpose of this section is to present a set original of support-decision models for the strategic planning and design of a sustainable supply chain and distribution network. The proposed MILP models aim (1) to define the proper use of land for the collection of raw materials, (2) to establish the set of processing and logistic nodes (i.e.

manufacturing node, warehousing node, collection site and transformation site) to activate along the chain, and (3) to assign the product flows to the proper set of nodes in response to the consumer demands. Objective functions attempt to minimize environmental and economical costs of the overall chain. The food supply chain (FSC), more than others, fits for the application of these models, since entails the multiple-purposes decisions of land use allocation (i.e. agriculture), the consolidation of raw material (i.e. harvesting and stowing) the manufacturing and distribution, the recovery and recycling of products and waste (i.e. packages). However, the generality of such decision-support models allows their application to the design and planning of any typologies of efficient and sustainable supply chains and distribution network.

- **Chapter 8**. The eighth and final chapter draws the conclusions of the manuscript by highlighting the most relevant models, procedures and decision-support tools for the strategic design and operative management of supply chain and distribution networks and nodes. Conclusions dealing with the efficiency, quality, sustainability of the chain as whole are illustrated and discussed, as well as general tips and guide lines or suggestions for further developments and research challenges.

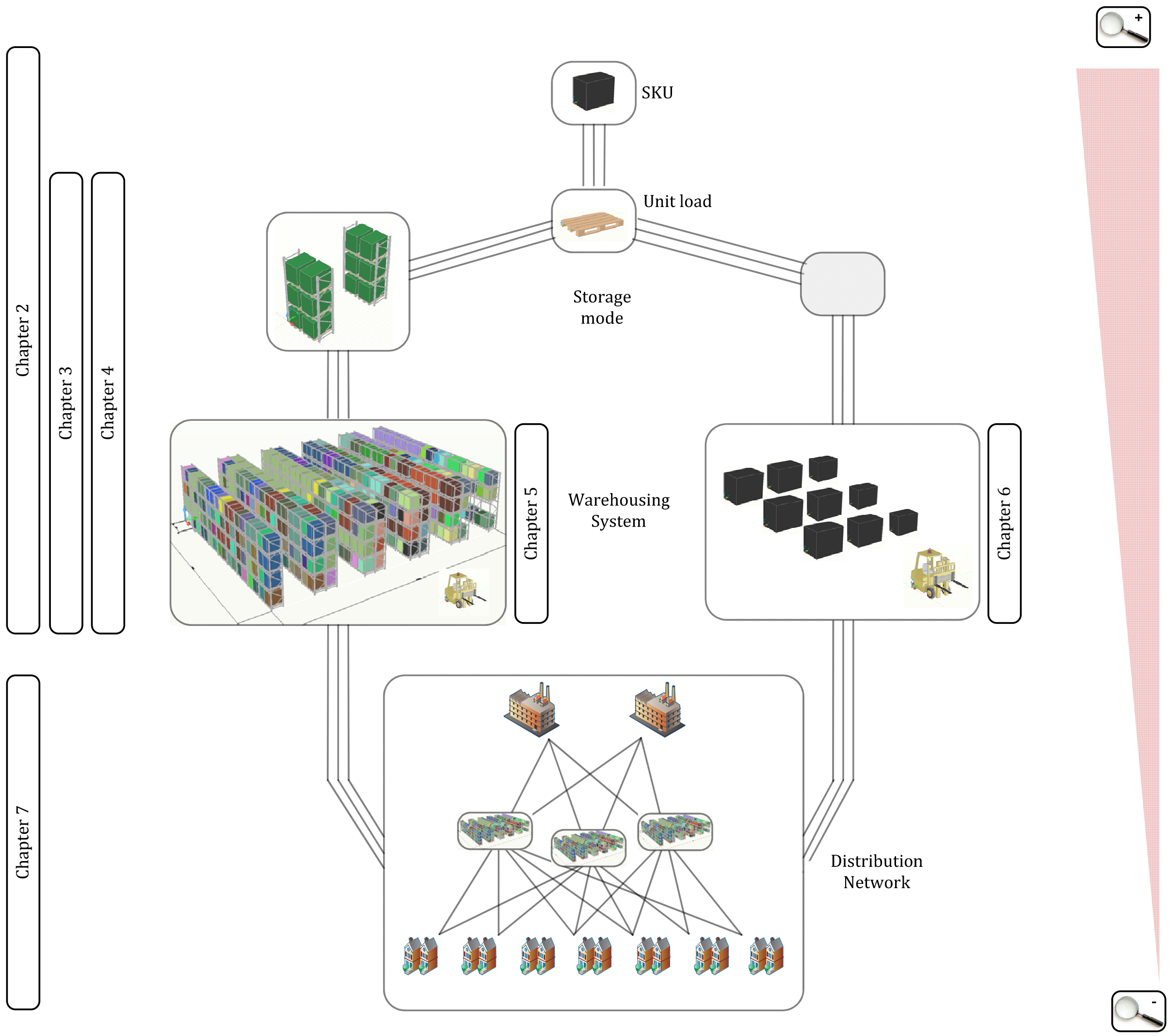


Figure 3. Manuscript outline

2. Warehousing Systems

Warehouses are the nodes throughout the supply chain where products pause, are touched and handled (Bartholdi and Hackman 2011). This handling process consumes both space and time, affecting respectively capital and labor costs. The goal of this manuscript is to develop procedures, mathematical models, decision-support tools for the design and management of warehousing systems and the reduction of space and time. First, a detailed overview of the role played by warehouses in supply chain, the warehouse typologies, processes, operations is necessary. This chapter presents a comprehensive picture of about what is a warehouse and what happens within.

2.1 Role of warehousing systems in supply chain

Inventory holding and warehousing systems play an important role in modern supply chains. A survey of logistics costs in Europe identifies the cost of inventory as being 13% of total logistics costs, whilst warehousing accounted for a further 24%. A similar study for USA context points out inventory costs significantly higher at 24%, with warehousing, at 22%, being close to the European picture (Baker 2007). The inventory holding encompasses all the cost drivers related to the reorder policy, the shortage, the product lock-up and obsolescence, whilst warehousing costs take into account infrastructure capital costs, material handling and operations. These costs represents on average 25% of product value, taken ad a rough approximation of the average holding expense for a year. This fraction is growing up in recent decades due to increasing velocity of products in supply chain. Therefore, inventory and warehousing are significant in cost terms, but much more important in terms of customer service, with product availability as crucial metric of effectiveness of warehousing in contributing to success or failure of many supply chains.

The main concept upon inventory holding is providing a buffer against uncertainty. Nowadays, the disadvantages of holding inventory are increasingly recognized, particularly with regard to the impacts on costs, wastes and inefficiencies throughout the supply chain. The supply chain is the sequence of processes leading products from their origin toward the consumers. Bartholdi and Hackman (2011) draw a metaphor to explain the main concept about the inventory holding along the supply chain: given a fluid modeling of the supply chain, warehouses represent storage tanks along the pipeline. The analogy with fluid flows remarks some substantial insights. A fluid flows faster in the narrower tube than in a wider. Thus, the wider the tube (i.e. the inventory held by the warehousing system) the slower the flow along the pipeline (i.e. the supply chain). Others useful conceptual remarks can be pointed out, such as: avoiding product pauses throughout the chain; avoiding warehouse layout impeding quick handling; identify and resolve bottlenecks. Thus, the JIT logistics and supply is roughly equivalent to reducing the diameter of the pipe, which means products flowing quickly and reduced in-transit inventory. These tips respond to the plumber troubles as well as to the current global supply chain criticalities.

Increasing globalization leads to long supply lead-times, which result in greater level of inventory to protect by uncertainty, to ward by stock-out risk and provide the same service levels (Baker 2007). There is a widely debated set of justifications to holding inventory, and some of these are economies scale, manufacturing batching, distribution issues, demand response, emergency, seasonal, uncertainty. The increasingly variability in customer demands, in both quality and products customization, matches with the more distant supply lines, the geographical spreading of consumers, the design and development of more complex distribution networks. The challenge is, on one side, to contain inventory costs and, on the other, to define the proper mix of supplying strategies and operations efficiency aiming to satisfy the demand.

There are some concerns in assessing and recognizing the set of costs referring to the inventory. Christopher (2005) highlights costs such as storage, obsolescence, damage, deterioration, shrinkage, insurance and management costs, as well as the more traditional holding costs, reorder costs and shortage (Goetschalckx 2003). The risk of underrating the inventory costs drives to inaccurate supply chain micro and macro decisions. The proper assessment of inventory impacts and cost drivers influences both the quantity of product to stock per logistic node (i.e. micro decision) and the geographical site of logistic nodes (i.e. macro decision).

In current lean supply chain perspective, inventory is considered as one of the most relevant source of waste of the overall system and it is held at few echelons (i.e. central or regional distribution centers), with goods passing through supply chain quickly to respond to changes in market demand (Christopher and Towill 2001). Many researchers point out the relevance of inventory reduction, even though they claim the proper quantity of stock along the chain as inevitable.

The definition of the proper inventory level at chain decoupling points make the warehousing system as a buffer, separating lean production activities from an agile response to volatile market places (Christopher and Towill 2001). Such inventory addresses customer demand, enabling the adoption of lean principles (e.g. JIT) to the processes of raw material supply, manufacturing and the distribution.

Whilst inventories provide some security against fluctuations in the level of customer demand, they affect the ability of supply chains to respond to changes in the nature of that demand. Inventories in international supply chains may therefore act as a buffer against one risk whilst increasing another type of risk. As instance, Etienne (2005) summarizes factors such as time-to-market for new products, responsiveness to new technology (leading to potential obsolescence of existing inventory), responsiveness to market niches, feedback time for quality issues, and "feed forward" time (e.g. speed of signal to the market, through actual use, that the product has been improved). The higher the level of stock, the higher the protection by variation of demanded volume, the lower the safeguard by the variation of product demanded.

The potential disadvantages of holding inventory are widely recognised and a number of inventory reducing strategies are proposed by literature. Baker (2007) gives a brief summary of these strategies:

- A reduction in production lead-times, for example, by means of shorter set-up times and smaller manufacturing runs (Harrison and van Hoek 2005).
- The manufacturing/assembling postponement (Van Hoek 1998).
- The visibility of supply chain actors on the consumer demand, aimed to reduce the noise and uncertainty due to bullwhip effect (Christopher 2005).
- Total cycle time compression, in both information and material flow lead times (Mason-Jones and Towill 1999).
- The centralization of inventory to a tight group of logistic nodes. For example, the level of safety stocks is reduced by centralizing inventory in a single European DC rather than holding inventory in several national DC (Sussams 1986).
- The flows of goods among warehouses at the same echelon level in the supply chain (Herer et al. 2002)
- Cross-docking goods to speed the flow of goods through the supply chain (Apte and Viswanathan, 2000). In this sense, cross-docking is defined as receiving goods at a warehouse and quickly transferring to despatch vehicles, without putting the goods away into stock.

The complexity of modern chains and distribution networks may reduce the benefits of the application of such strategies. International supply chains are affected by the geographic area covered, the dispersion of point of demand, the distance between product origination sites, manufacturing and product usage or consumption, the transport modes used, political/border factors and environmental issues (Prater et al., 2001). The wider the network and longer the chain, the higher the uncertainty to comply customer demand and the related risk are.

Aimed to contain risk, the use of inventory is generally recognized as one possible tool. Chopra and Sodhi (2004) consider the increase inventory as a risk mitigation approach, whereas Lee (2002) particularly emphasizes the role of inventory in situations of supply uncertainty. There are thus widely varying views about the role of inventory in the literature and some of these views appear to have conflicting goals. For example, the goal of traditional inventory control theory is the optimization of inventory levels, whereas the goal discussed in current trends (i.e. lean supply chains) is concentrated more on the minimization of inventory levels.

However, there is per each product, logistic node and supply chain an optimum level of inventory at all. The definition of such level is blended mix of strategic and operative decisions involving the manufacturing, distribution, marketing departments of a company. Such level determines the capacity, the layout and the operations of the warehousing system, the performance of the distribution network, the efficiency and the effectiveness of the manufacturing systems and the final level of service experienced by the consumer.

The identification of this level involves wider concepts than traditional inventory control theory and strategic supply chain management, and in particular inbound and outbound handling and distribution operations, or those related to what happens within the inventory holding node, the warehouse.

Even though enterprises are redesigning and planning their supply chain to respond to increasing customer service demands and warehousing node become smaller and smaller, they remain a fundamental component of the logistic system. The requirements of warehouse are significantly changing in comparison with those of a decade ago. Some of current roles played by warehouses (Baker 2007, Goetschalckx 2003, Bartholdi and Hackman 2011) are:

- Holding warehouses. Their main function is to store materials and products that do not have to be removed (e.g. nuclear waste). The main resource to manage is storage capacity and space efficiency and throughput and response time are of lesser or insignificant importance.
- Distribution warehouses. They attempt to reduce transportation costs and better arrange shipping processes. The main functions are to receive shipments from suppliers (i.e. manufacturing nodes or other distribution warehouses), to store and consolidate (i.e. make-bulk, break-bulk) products in inventory until are demanded, then to retrieve products in response to customers orders and thus ship toward them. The throughput, space and time

efficiency are all-important metrics of performance. Such warehouses receive large, less frequent and homogeneous delivery of products and fulfill customer orders that are typically small, more frequent, and heterogeneous in products quantity and variety. The homogeneity or heterogeneity in input flows are affected by the presence of long and complex chain and the flows provenience from manufacturing facility or from other distribution nodes. In the former, flows tend to be homogeneous whilst in the latter tend to be more miscellaneous. Generally, the larger input depends on the necessity to fit transportation and production economies of scale, especially in presence of larger distances and larger manufacturing batches. The small and frequent output is caused by the fulfillment of consumers requests, ever more varying, smaller and with closer due date.

The activity of retrieving products responding to a customer order, the so-called order picking, is a prime component of labor and costs in the warehouse. There many different typologies and layouts of order picking systems mostly depending by the products and inventory characteristics and the demand profile. The order picking can be carried out directly from the storage locations, whether the number of product is small, or from a concentrated forward picking area, while keeping the bulk of the inventory in a larger reserve storage area. Therefore the costs associated to the system refers to the storage (or put-away), the replenishment of the forward area and the retrieving.

- Cross-dock warehouses. They receive customer orders prepared and sorted by other actors of the chain (e.g. manufacturing nodes or other warehouses) and arrange shipments to destination. The good passes through the system without being modified. The main performance characteristics are the throughput capacity and the throughput of the flow time.
- Intermodal warehouses. They provide integrated infrastructure to combine multiple transportation modes. Such warehouses enable the transhipment of products, materials and orders mode by mode (e.g. from train to ship, from train to truck, from ship to truck, etc.).
- Work-in-process warehouses. They hold sub-components and partially manufactured products. The components arrive from the manufacturing facility or vendors and are shipped to production facility or distribution warehouse. By this way, warehouses provide opportunities to postpone product differentiation by enabling generic product to be configured close to the customer. This enables the manufacturer to satisfy many types of customer demand from a tight set of generic items, whit consequently higher demand aggregation, and more accurately forecasting. Furthermore, safety stock and overall inventory can be lower throughout the logistic nodes of the chain.

- Product-fulfilment warehouses. responding directly to final consumer (e.g. Internet fulfilment operations).
- Reverse warehouses. handling unwanted and damaged goods, as well as goods returning under environmental legislation such as for product recovery and packaging waste in order to manage and organize reverse chain collection and final disposal of products (i.e. landfill, recycling, reusing).
- Miscellaneous warehouses. They provide a large whole of functionalities as customer support, installation and repair services, products pricing or labeling.

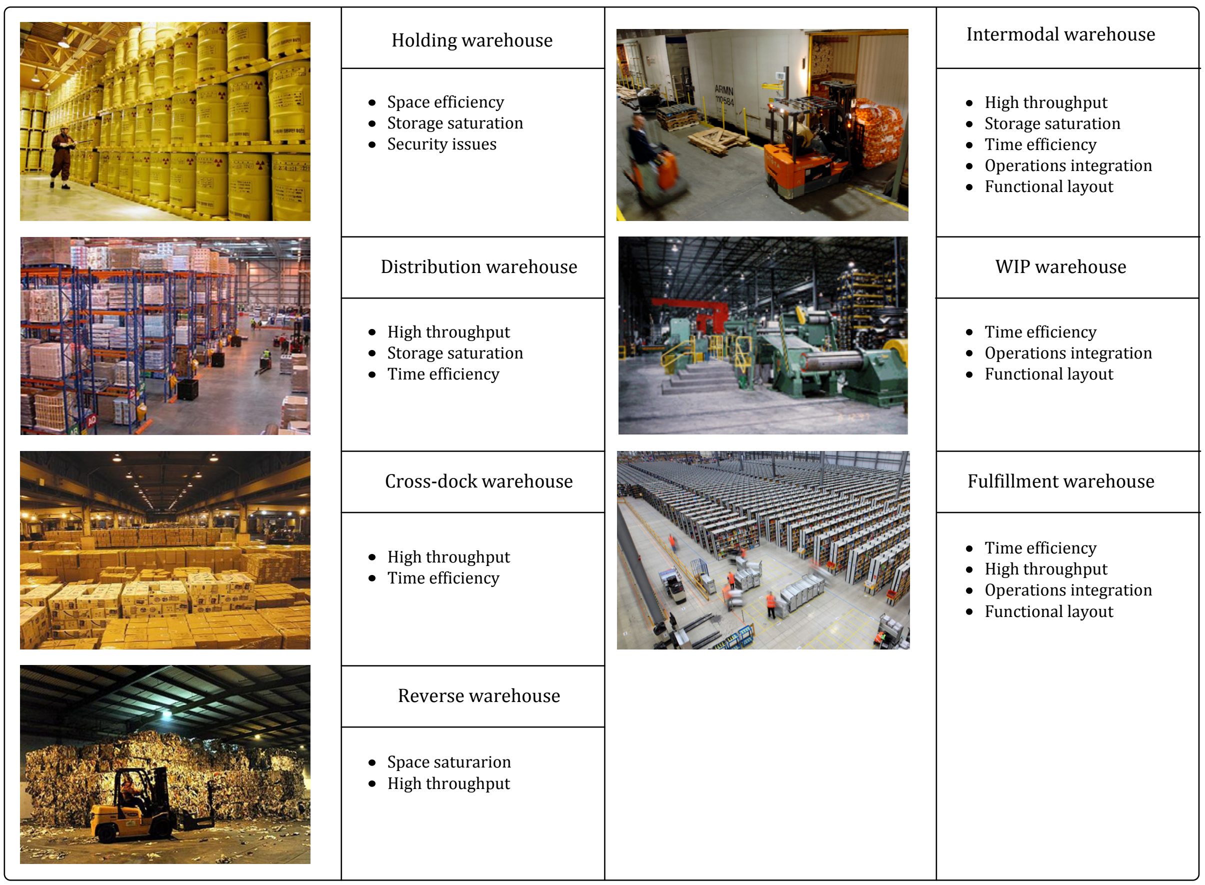


Figure 4. Warehouse roles.

Figure 4 illustrates a brief exemplification of the material flows through the listed warehousing systems with related sample pictures. Many different warehouses belonging to wide industry sectors and typologies combine and match a proper mix of these roles within the same logistic node. Generally, and independently of the type of system, the 50% of the floor surface of a warehouse is taken up by storage, with the most of the remaining area being used for the associated goods-in, order picking, packing and dispatch activities (Baker, 2004).

In spite of the steps and efforts taken to reduce inventory, the warehouses continue to be very crucial components of modern global supply chains. In light of this, a greater understanding is required as how these nodes work, how they are linked together, how they are organized and they manage their resources.

2.2 Warehousing systems characterization

Aiming to provide a comprehensive characterization of warehousing systems, a description upon processes, resource, organization, decision and type is proposed in follows. Products achieve logistic nodes of different *types* and experience a sequence of *processes* operated by and through *resources* (i.e. equipment and personnel) within an *organized* system, built on *decision* about design, planning and control of procedures and activities. To go in detail upon these four perspectives, an exhaustive summary of vocabulary of warehousing and storage is necessary.

2.2.1 Warehouses processes

Even though warehouses comply quite different goals and demands, most share the same general pattern of material flow (Bartholdi and Hackman 2011). Essentially, they receive bulk shipments, store them for quick retrieval, then in response to customer requests, retrieve and sort SKUs, and ship them out to customers. In warehouses and throughout the chain, a product is defined as a specific type of good, and is called item or stock-keeping-unit (SKU), whilst the combination of SKUs required by a customer is defined as an order. The organization of material flow within the system follows the sequence of these activities:

- Receiving.
- Storage.
- Order-picking.
- Checking and packing.
- Shipping.

Figure 5 gives a picture of the main processes and material flows within a warehouse. Each activity represents a micro step of the distribution chain, and entails a wide set of decisions on resources to adopt and organization.

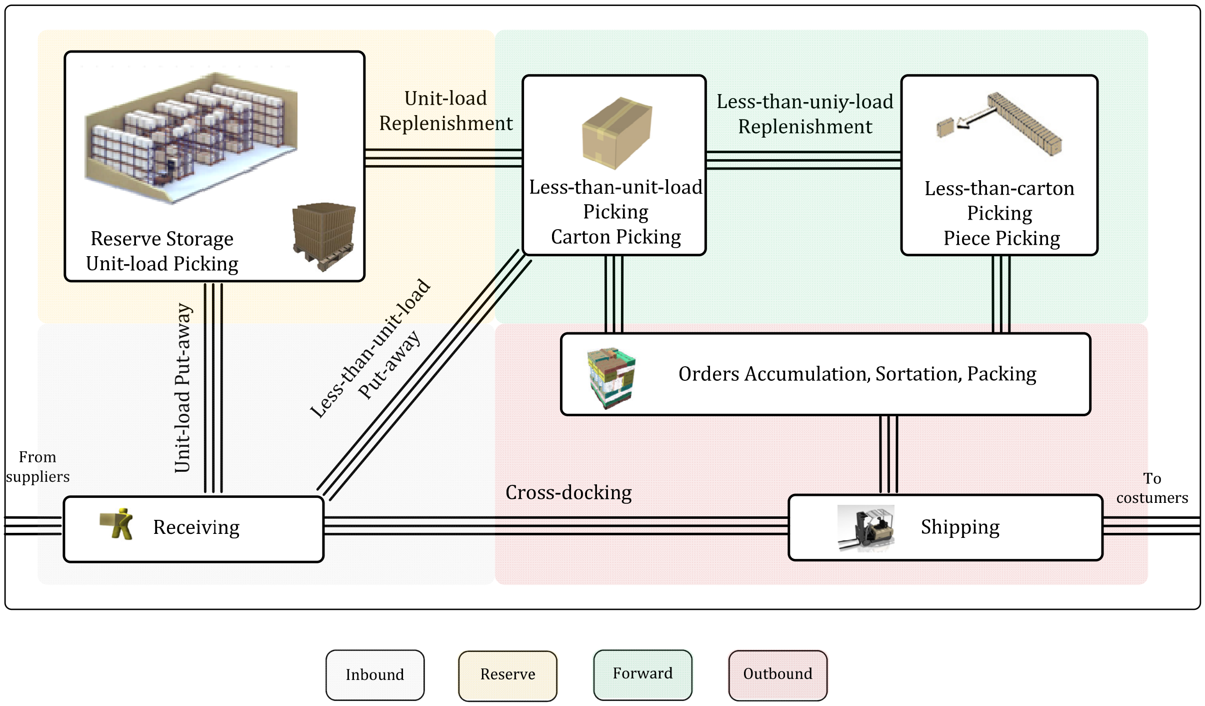


Figure 5. Warehouse flows.

2.2.1.1 Receiving

The receiving is the first process experienced by an arriving item. Products are received by truck, train, or other inbound transportation mode and are notified and checked. This allows the warehouse to schedule receipt and unloading according to the resources and the other activities. This stage attempt to scanner and register incoming items so that ownership is assumed and payments dispatched. At this point information of incoming shipment (e.g. arrival time and contents) are available in order to schedule the service of carriers at each dock and to manage the allocation and dispatching of material handling resources, such as labor and material handling equipment. Decision making in receiving is constrained by the level of prior knowledge about incoming flows. In some cases, no knowledge joins the material flows. In such scenario, the decision maker suffers for the trouble of not having any bases to assign carriers to docks, neither product to storage locations. Conversely, whether partial of perfect statistics of incoming flows are available, a wide set of tools, procedures, algorithms taken by research literature can applied to manage the receiving and following chained processes.

Products typically arrive in large units, such as unit-load, standard or custom containers, or pallets, so that related labor and handling activities are less expensive (Bartholdi and Hackman 2011). As previously treated dealing with the distribution role of warehouses, the complexity of receiving and unloading operations depends on the type of received product unit. Indeed, in long supply chain, distribution warehouses may serve other distribution nodes and heterogeneous pallets or loads, received from upstream, need to be broken out into separate SKUs and cartons.

Generally, receiving accounts for only about 10% of operating costs (Frazelle 2002) and enterprise information technologies such as Radio frequency Identification (RFID), GPS and advanced shipping notices (ASN) might further reduce this percentage.

2.2.1.2 Storage

Storage is the most significant warehouse function. Before managing all handling activities and procedure to place products from inbound docks to the rack, a proper storage location must be defined. Dealing with storage, Gu et al. (2007) highlight three fundamental decisions to be taken: how much inventory to hold for a SKU; how frequently replenish this inventory; where store a SKU within the warehouse. The first two question lead to considerations on system infrastructure, layout, overall inventory and other typical issues of inventory control.

The latter entails the definition of the storage location of a SKU, which is probably the most crucial decision to be taken in a warehouse since it affects the costs will occur in handling, retrieving and fulfilling customer orders. Two of the main criteria to establish the proper storage location per each SKU are the storage efficiency (i.e. holding capacity) and the access efficiency (i.e. resource spent by put-away and picking).

Storage task mainly asks to extend the knowledge about the system on, of course, product inventory or storage locations. The point is constantly determine how many, where and which kind of available locations are there, how large they are, how much weight they can bear and so on.

To address this purpose when products are put-away, the combination of product and storage location should be scanned and registered. Such information drives the arrangement of efficient order lists to guide the pickers in retrieving products.

Generally, the storage area consists of two parts as follows:

- Reserve area. In this area, products are stored in most economical way (bulk storage) typically per unit-load in pallet rack.
- Forward area. In this area, products stored in smaller amount in easily to access storage module to address picking. The items movement from reserve storage to forward is called replenishment.

The storage task requires more labor than receiving. The larger the system, the higher this cost (i.e. on average 15% of warehouse operating expenses)(Frazelle 2002).

2.2.1.3 Order picking

Order picking refers to the retrieval of items from their storage locations in response to a customer orders. Order picking accounts for 55% of warehouse operating costs and encompasses the following steps reported in Figure 6.

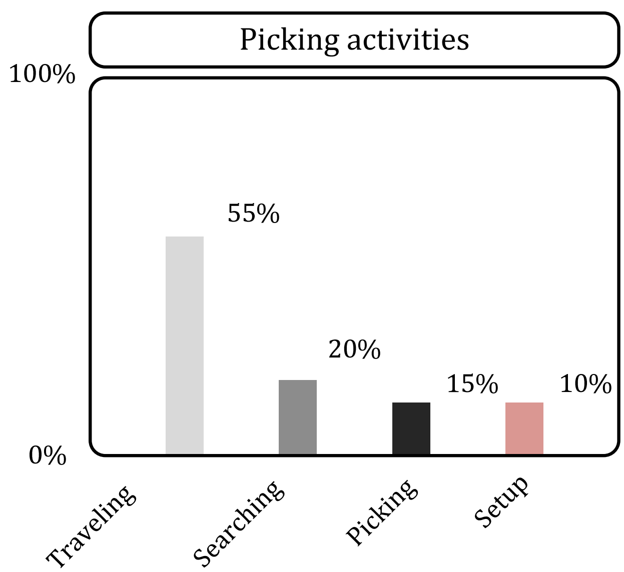


Figure 6. Typical distribution of picking costs

Traveling comprises the greatest part of the expense of order picking, which is itself the most expensive part of warehouse operating costs. The order picker processes an order list and travels within the aisles in order to retrieve the requested SKU in the proper quantity. Then the warehouse must provide pick lists to guide the order pickers and a set of labeling and shipping documentation to configure picking and shipping. The order lists are gathered from downstream and arranged as shopping lists and pick-lines each of them characterized by a SKU an ordered quantity, as illustrated in Table 1.

Date	*Order Code*	*SKU Code*	*Quantity*
2/1/2013	Order1	SKU1	1
2/2/2013	Order2	SKU1	2
2/2/2013	Order2	SKU2	3
2/2/2013	Order2	SKU5	1
2/2/2013	Order3	SKU2	5
2/2/2013	Order3	SKU3	1
2/2/2013	Order4	SKU4	5

Table 1. Sample of picking list

Pick-lines are instructions to the order-pickers, in terms of where and what to pick in what quantity and units of measure. Depending on the available technologies, the pick-list consists on a sheet of paper, a label, or a sequence transmitted by voice, light or radio frequency (RF). Each pick-line represents a location to be visited, and since travel is the largest labor cost, the number of pick-lines is an indication of the labor required.

Aiming to reduce traveling, the design and planning of an order picking system consider some critical metrics of performances dealing with both space efficiency and time efficiency. The most labor-intensive order picking is the less-than-carton picking, concerning with a broken-case ordered quantity. Broken-case picking is labor intensive, since requires to manage and handle small unit usually resistant to automation due to variability in size and shape. Conversely, carton-picking (i.e. picking of full cartons) is less labor intensive and can be seldom automated for the more regular shape of items (e.g. rectangular boxes).

In order to assess the order-picking performances Bartholdi and Hanckman (2011) summarize and report a brief set of metrics and indicators. The picking travelling, basically, account for the meters travelled within aisles during picking operations of a specific period. The pick face is the 2-dimensional surface, front of rack, from which pickers retrieve SKUs. In general, the higher the number of SKUs per area of pick face (e.g. square meter), the more less the travel required per pick. In order to fix this concept, SKU density counts the number of SKU available per unit of area of pick face. If a warehouse has a high SKU density, it likely achieves a high pick density, which is the number of pick per unit of area of pick face. These metrics can be proposed and computed even per order and not just per pick face. The SKU density (or pick density) is a measure of the number of SKU (or pick) per unit of distance along the aisle traveled by an order-picker. Pick density can be increased mainly by storing the most popular SKU together, in small and easy-accessible area, which means less walking. Other metrics to evaluate the total work related to an order are as follows: the average pick per person-hour, the average work per order, expressed in terms of picks and travelled distances.

The interdependency of time and space is demonstrated by the fact that the space efficiency in storage enables to reduce the travelling for picking, thus increasing the time efficiency. This relationship as fundamental aspect of warehouse design and management is further treated and discussed in Chapter 3.

Different order picking methods can be carried out in a warehouse generally depending of the characteristics of handled products and the type of demand profile. Some of these retrieving methodologies are single-order picking, batching and sort-while-picking, batching and sort-after-picking, single-order picking with zoning, batching with zoning (Yoon and Sharp 1996). The *single-order picking* consists on assign one order list to one picker since all the pick-lines are complied and fulfilled. This technique avoids double handling of products since the picker is responsible per one order a time and prepares the shipment load while retrieves. Moreover, the mistakes are minimized. The *batching* methodology consists on making a picker to retrieve multiple orders in one trip. It represents a very useful approach to increase pick-density and reduce traveling. However, batching requires retrieved SKUs be sorted into each order. The sorting occurs during picking or downstream. In the first case, pickers are slower since they have to pick and carry different boxes or totes, one per each order, and this consumes time and leads to mistakes. In the second case, particular equipments and warehouse devices (e.g. conveyor), as well as human resources have to be devoted to the final handling and sorting before shipping. Generally, there is a benefit in batching single-line orders, since there are easy to manage and to split or sort during picking activities. In assessing the benefit of batch orders, the size and shape of products play a crucial role, especially for large orders.

The zoning methodology consists on partitioning the warehouse into different zones corresponding to work stations. Pickers are assigned to zones and workers progressively assemble each order passing it along from zone to zone. Typically, each zone holds a particular group of SKUs, which share one or multiple characteristics or features in shape, weight, size of carton, size of load, size of fitting rack, demand frequency and order policy. The benefit of creating warehouse zones is that pickers tend to concentrate in one zone of the system, facing the typical handling and retrieving criticalities and experiencing learning curve. The main issue related to the zone-picking is balancing the system as a sort of assembling-line, where the order move forward the system and is assembled. Some storage equipments and devices, such as conveyor, can support the order flowing through the system zone by zone.

In order to support the order picking the replenishment of SKUs is necessary. The restockers move products in large unit-load (i.e. pallets) to respond to the lack of materials in forward picking area. A restock is more expensive than a pick since the unit-load are generally moved from the bulk storage area in a single command or dual command process. In forward-reserve order picking system the products are moved from the reserve (e.g. above storage levels) to replenish empty forward locations. In forward order picking system, there is a shared location between forward and reserve totally devoted to one SKU. In this context, the replenishment is called by the re-order level and is performed as a delivery of products from other warehouses throughout the supply chain. This system comply the pull theory and the JIT approaches, since the inventory is reduced at minimum throughout the chain. The restocker is responsible to prepare the stock for picking, to remove shrink-wrap from a pallet or eventually open carton or packages, to let individual pieces available.

All the proposed methods and procedures aim to reduce the flow time, which counts the elapsed time from the product receiving in the system to the product shipment. Warehouses tend to use the proper combination of several of these approaches.

2.2.1.4 Checking and packing

Checking and packing are labor-intensive operations occurring at the end of retrieving step. In many case the warehouse represents the last logistic node in the chain before the final consumer or the retailer. Notwithstanding the stage of the warehouse along the distribution chain, mistakes in order completion may seep out the network as a bullwhip effect. Inaccurate orders not only annoy customers, but they also generate returns; and returns are expensive to handle. Therefore, the accuracy in order completion is a crucial factor to determine the efficacy and the level of service ensured by the supply chain. Checking activities, usually joining even ticketing or labeling, represent a fundamental step before arranging shipments.

On the other hand, packing regards with the activity of preparing orders and products in a shape or package to address both transportation and customer requirements. Customers like to receive all pieces of their orders in one or few containers, but the picking system has to merge all parts (coming from different zones or pickers) in the outbound dock at the same time. At this step several considerations on products and package shape, size, weight need to be properly faced.

2.2.1.5 Shipping

Shipping is the last step of the material flow through the system. This process is usually carried out at the outbound docks and consists on truck loading and shipping scheduling. Shipping handle heterogeneous unit loads, labeled in accordance with the customer code and the list of ordered products. Shipping, as receiving, checking and packing activities do account for no travelling, but for handling and processing time. Good metrics of handling and scheduling shipping methodologies are the sum of the work contents of all the orders to go on the truck, or train or other carries, and the shipment integrity as the weighted sum of the orders accuracy for the shipped orders per carrier.

2.2.2 Warehouses resources

The warehouse resources are the entities handled, managed and utilized to design, control and configure a distribution system in a supply chain. Warehousing operations regard with operators (i.e. stockers, restocker, pickers and sorters) and physical entities (i.e. storage equipments, storage containers, SKUs, racks, etc.). The management of operators time, the scheduling and arrangement of procedure and activities match with the layout properties and features, the adopted storage modes and equipment, the SKUs features and characteristics, the turn of inventory, etc. Each entity contributes to affect and influence the relationships among operators and activities, and ought to be properly considered.

In such context, the huge amount of entities and related data represents a critical challenge to manage. Rouwenhorst et al. (2000) and Frazelle (2002) give a comprehensive picture of these entities distinguished as follows.

2.2.2.1 Stock-keeping-unit

The SKU represents the stored item within the warehousing system. Each product handled throughout the system is univocally recognized and identified by a specific alphanumerical string. The tracked characteristics of the SKU involve sales and marketing issues and, above all, packages (i.e. carton, piece, unit load) shapes and sizes, volume, weight, and, eventually, the zone where such product is stored. The logistics details regarding the SKU (e.g. size, volume, weight, etc.) are the crucial background to develop a real data-oriented analysis on the warehouse system.

2.2.2.2 Storage unit

The storage units are the handling units in which products may be stored. Examples of storage units are pallets, unit-load, carton boxes, plastic boxes, totes, etc. The storage unit gives an important insight on the type of handling processes experienced by each SKU along the chain. The smaller and more varying the size of storage unit, the higher the handling costs and labor. Generally, the storage system tends to assign products with similar storage units to the same zones, since they share the type of rack, of pick-face, and of retrieving routines. The warehouse is indeed devoted to the merging, packing and un-packing of products received and shipped in large or small, homogeneous or heterogeneous units. Figure 7 shows and exemplifies the most diffuse storage units.

Figure 7. Sample of logistic unit-load

In particular, the worldwide diffused and standardized storage and handling unit is the pallet, which is a rigid rectangular (or square) base to stack boxes. Most pallets are made of wood, plastic or even steel. Table 2 summarizes the wide range of standard pallets mainly available in two ways of handling mode. A 2-way pallet allows fork from a standard forklift on the smaller side, whilst the 4-way pallet has slots on both sides. Such pallet is more expensive, but ensures more flexibility in handling and often addresses space and time efficiency (Bartholdi and Hackman 2011).

Size	*Most diffused in*
800 x 1200 mm	Europe
1000 x 1200 mm	Europe, Asia
1100 x 1100 mm	Asia
1067 x 1067 mm	North America, Europe, Asia
1165 x 1165 mm	Australia
1219 x 1016 mm	North America

Table 2. Most common pallets (Bartholdi and Hackman 2011)

2.2.2.3 Order

The order mainly consists on a codified customer request expressed in term of SKU code and quantity per each SKU due to until a specific due date. The list of received orders within a specific temporal batch reports the order code, the code of customer, the SKU and demanded quantity, or weight or volume. In general, the unit of measure adopted to account picking and retrieving operations depends on the objective industry sector. As instance, in grocery and retail food supply chain the picking lines are expressed in term of retrieved weight (e.g. five kilograms of bread or potato), whereas in tile sector the picking lines are reported in term of square meters (e.g. five square meters of yellow tile) and so on.

The order is the principle entity booting the supply chain operations. The order triggers the informative and physical flows throughout the supply chain. The operations concern with the collection and exploitation of raw materials, their consignment, the manufacturing and transformation, the storage and distribution of finish good and work-in-progress (WIP), the final stage delivery to respond to a specific customer request. By tracking the order, the decision maker tracks the processes and activities throughout the distribution chain and figures out the impacts of each step on the overall performance and results.

2.2.2.4 Storage mode

The warehouse consists on multiple subsystems (i.e. storage system or zone) that hold different types of products. There is a wide range of different storage systems depending on the presence or not of racks (i.e. block storage), the level of automation and the types of adopted storage equipments. The setting of the proper combination of typologies of racks, storage mode and storage strategy defines and configures the system. The storage mode refers to the combination of equipment and operating policies applied to the storage/retrieving environment. As instances, common storage modes encompass pallet rack, carton flow rack for high-volume picking and static shelves for low-volume picking. Main differences emerge from the size of product and in particular the size of storage unit (i.e. big and small SKUs).

For large products, handled on pallets, the most simple storage mode is the block stacking, or block storage (or floor storage) which consists on storing pallets without racks on the floor, arranged in lanes.

Pallet racks are used for bulk storage and to support carton picking. The size of pallet suggests the proper rack to consider and the number of available slots per bay. The benefit of rack storage in lieu of floor storage consists on the exploitation of height of warehouse, and secondly, and in providing much greater access to the load, independent level by level. The most standard types of racks are summarized as follows:

- Selective rack. This rack stores pallet one deep, so that each pallet is independently accessible. It allows handling freedom but requires more aisle space.
- Double-deep rack. This rack consists on two selective racks, one behind the other. In order to avoid double-handling, each two-deep lane is entirely devoted to a single SKU, which entails some empty location whenever just the first pallet is shipped.
- Push-back rack. This rack is sort of extension of double-deep rack to typically 3-5 pallet positions. In order to make interior position accessible the rack in each lane pulls out like a drawer. Each lane (at any level) is independently accessible.
- Drive-In rack. This rack permits to a lift truck to drive within the rack and access interior loads. In order to avoid double-handling, all the levels of each lane are assigned to one SKU. In such mode, storage and retrieving are performed by the same aisle side according to last-in-first-out policy (LIFO).
- Drive-Through rack. This rack is similar to the Drive-In rack despite of the fact that the pallets enter from one side and leave from the other so that the first-in-first-out policy (FIFO) is complied. Drive-in and Drive-through racks replace the floor storage mode but for products that are not stackable at all. The adoption of this particular racks compels considering more resistant pallet (supported only by edge) and specific vehicle to access into the rack.

- Pallet flow rack. This rack is deep lane sloped rack, that allows the interior pallets moving forward whenever the front one leaves. Such rack enables to decoupling storage and retrieving operations preventing them to interfering each other. This type of rack fits with high-throughput facilities and SKUs.

Moreover, for small items bin shelving and modular storage drawers are usually adopted. A brief summary of the most typical shelves is given as follows:

- Bin shelving. This kind of rack is devoted to tiny parts. The small SKUs are organized within bins and they might be handled individually.
- Static shelving. This shelf is the most basic storage mode and is diffuse for small or medium size cartons. The shelves are shallow, thus a small inventory per SKU is stored. Otherwise larger quantity of one SKU spreads out along the pick face, reducing both SKU density and pick density. In such storage mode, picking and replenishment are performed by the same side.
- Gravity flow rack. This shelf is slanted and moves the interior cartons forward whenever the first is removed (as for pallet flow rack). This shelf is generally 1-3 meters deep, so that significant inventory per SKU is held, whilst only one location per SKU is available on the pick face. Such rack is often supported by pick-to-light system, where the informative system lights up signals at every location to warn the operator about the SKU to pick. Replenishment does not interfere with picking operations since is realized at opposite side. There are three principle shape of such rack: vertical frame, suited for full-case picking, layback frame, suited to pick from open cases varying in shape and size, and front-tilted frame, suited to pick from open cases similar in shape and size.
- Mezzanine. The mezzanine infrastructure allows exploiting the warehouse height to store small and tiny parts, which are manually retrieved and handled on ground floor by the operator.

Figure 8. Storage modes samples

Figure 8 gives some pictures of the most common rack typologies and bin shelves presented above.

2.2.2.5 Storage equipment

The storage and retrieval of SKUs is performed through manual, automated and automatic storage/retrieving systems and equipments. In these terms, the storage system, regarding with the storage units to handle, the features and characteristics of SKUs, the order profiles, suggest the proper equipment to utilize.

In particular, Van den Berg and Zijm (1999) distinguish three types of storage system: manual storage systems (picker-to-products systems), automated storage systems (product-to-picker systems) and automatic storage systems.

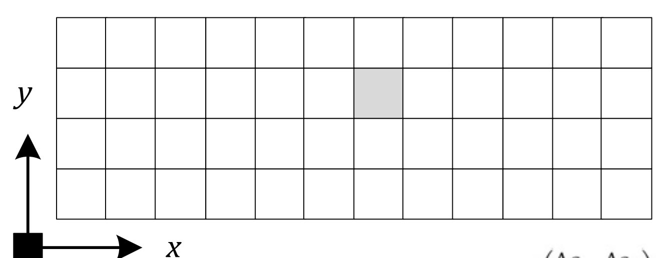
In a manual storage system (Bartholdi and Hackman 2011), the pickers ride vehicles from one pick location to another. Different types of lift truck are used to store and retrieve pallet from and to racks. The most common lift trucks are:

- Walkie stacker. This stacker enables the picker to stand on the vehicle and drop the retrieved products into the order pallet held by the forward forks. Such vehicle can be electric powered or pedestrian and are also classified as straddle walkie stacker, counter-balanced walkie stacker and reach walkie stacker.
- Counterbalance lift truck. This is the most worldwide diffuse type of storage and retrieving vehicle. The sit-down version requires an aisle width of 3.8-4.6 meters, with lift limit at about 6 meters, and an average speed of 0.3 meters per second. The standing version requires a narrower aisle width (i.e. 3-3.8 meters), the same height achieved with a bit slower travel velocity.
- Reach and double-reach lift truck. This particular mean is equipped with a reach mechanism that allows its forks extending as a spring. The double-reach truck accesses the interior position in a double deep rack. Each truck requires an aisle width of 2.1-2.7 meters, achieves levels 9 meters height and a travel speed of 0.2 meters per second.
- Turret truck. This vehicle consists on a turret that turns 90 degrees in both directions to storage and retrieve pallet on and from both sides of the rack. Since this mean does not turn itself within the aisle, an aisle width of just 1.5-2 meters in enough. The turret rises to 13 meters with an average speed of 0.4 meters per second. Because this truck allows such narrow aisle, some rails, wire or tape on the floor are necessary. It only operates with select rack, and is not easy to drive outside the aisle.

Dealing with the handling of small parts in manual systems, a wide set of order-picking carts join the operator during the order completion. Due to the high variability in shape and size of small parts a manual mean is more efficient and adaptable than any other automated.
In general, manual storage systems match with a picker-to-product systems. Automated warehousing systems conversely regard with product-to-picker systems. An almost comprehensive list of automated storage equipments are:

- Carousel. This is a computer-controlled storage equipment is used for storage and order-picking of small-to medium sized SKUs. A carousel holds many different products stored in bins or drawers that rotate around a closed loop. The order picker waits at fixed location at the front of the carousel. Whenever a SKU is ordered, the carousel automatically rotates until the selected item is available at picker location. The order picker may effectively use the rotation time of the carousel for activities such as sorting, packaging, labeling. There are both horizontal and vertical carousels. The latter allows the use of vertical space and are also adopted to limit the access to small, valuable product.

- Rotary rack. This storage equipment consists on a more expensive version of the horizontal carousel, with the extra feature that every storage level rotate independently, reducing significantly the waiting time of the order picking.
- Automated storage/retrieval systems (AS/RS). This is a typical parts-to-picker system consists of one or multiple parallel aisles with two high bay pallet racks alongside each side. Within each aisle there is a storage/retrieval (S/R) machine, the so-called stacker crane, designed to handle pallet loads up to 30 meters, while roof or floor installed tracks are adopt to guide the crane. The aisle width is about 0.2 meters wider than the unit load. In a typical configuration the stacker cranes carry at most one pallet a time. Pallets to be stored enter the system by an input station and wait at a sorter, accumulator conveyor until the crane is ready to retrieve and take them to the proper locations. Storages are performed according to a first come first store (FCFS) routine. By retrieving the machine pick pallets and lead them to the output station, after they are available for handling and shipping. The S/R machine has three independent drives for horizontal, vertical and shuttle movement. Due to the independency of horizontal and vertical travel times the S/R travel time is measured by the maximum of the horizontal and vertical travel times, according to the so-called Tchebyshev distances (see Figure 9). Tchebyshev distance is simply the maximum distance between two vectors taken on any of the coordinate dimensions.



$$d(x,y) = Max\left(\frac{\Delta s_x}{v_x}, \frac{\Delta s_y}{v_y}\right)$$

Figure 9. Tchebyshev distance

In many applications the S/R machine is confined to single lane, but there are mechanisms (i.e. curves in the rails connecting the aisles) to move the crane among the lanes.

Nevertheless, to maintain stability in giant construction, the crane has to reduce speed in the curves. Another method to share crane with multiple aisles is to install a shuttle that transfer the S/R machine between aisles.

Due to its unit-load capacity, the operational characteristics of the S/R machine are limited to single-command cycles and dual-command cycles. The single-command cycle means that a load is moved from the depot to a rack location or from a rack location to the depot. Thus, storage or a retrieval is performed between two consecutive visits of the input and output stations. In a dual-command cycle the S/R machine consecutively performs a storage, travel empty to a retrieval location and do a retrieval. The empty travel between the storage and retrieval location is named interleaving travel. Figure 10 illustrates the travel cycle of a S/R crane for single and dual-command operation.

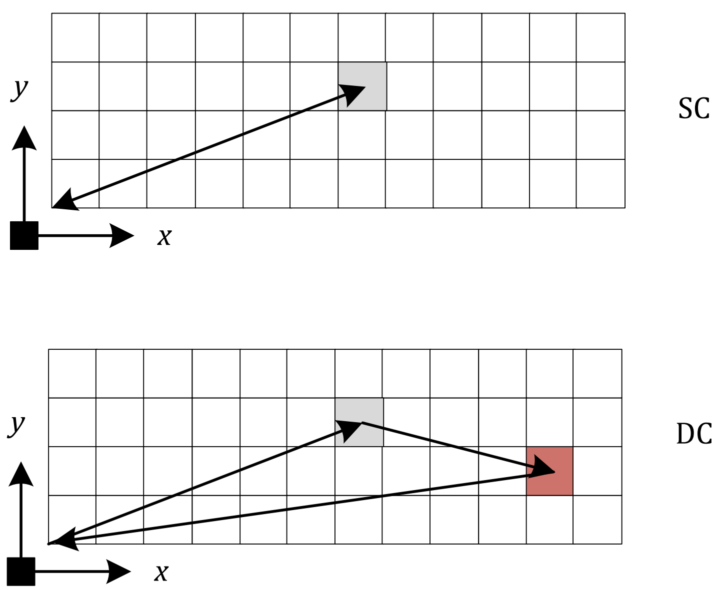


Figure 10. Single-Dual commands operations

- Automated storage/retrieval vehicle systems (AS/RVS). This is a high density pallet storage system based on automatic shuttle able to transform into an automatic warehouse all the drive-in racking systems, assuring the maximum use of the warehousing, making the facility more productive and efficient. The system consists of a pallet shuttle driveing into the rack through proper rails, responsible to put away and retrieve pallet from the lane. Each level of the rack is independently accessible. It is powered by an easy to recharge battery and managed by an interactive informative system, and moves goods on pallets into the drive-in channels. The shuttle can be placed in the proper channel by means of a standard fork lift or special purpose elevators.

- Mini-load. A mini-load is a typical AS/RS system but designed to handle small items. The SKUs are stored in modular storage drawers or in bins. These containers may be divided into multiple compartments each containing a specific SKU. In a typical mini-load AS/RS operation, the order-picker resides at the end of the aisle at a picking station. This station holds at least two container positions so that while the picker extracts the SKU from one location, the machine store the previous bins and let the next one available. A mini-load generally refers to an end-of-aisle order picking system, as opposed to in-the-aisle picking system performed through manual storage retrieving equipments.

The classification of storage and retrieving equipments also regards with automatic warehousing systems, which perform high-speed picking of small- or medium-sized non-fragile items to close rough uniform size and shape (e.g. books, pharmaceuticals, etc.). Van den Berg and Zijm (1999) report few examples of such systems as follows:

- A-frame machine. This automatic dispenser works totally without pickers and drops items onto a kind of conveyor. In detail, an A-frame consists of a conveyor belt with lanes arranged in a A-frame shape rack on either side of the belt. Each lane contains a powered mechanism that automatically dispenses items onto the belt. The order is assigned to a certain section, the so-called cell, on the conveyor. When the cell achieves the lane of the SKU to be picked, the proper quantity (i.e. number of pieces) of such item is automatically ejected upon the passing belt. At the end of the belt the items belonging to the same order fall down into a bin, a tote or a carton.
  A-frame are picking-labor-free, therefore are used when products are small but requested in very high volumes. The SKUs must fit with system features, so they need to be small and able to fall onto a conveyor without damaging it.
  One weakness of such systems is that all SKUs must be kept loaded, in order to avoid order inaccuracy, and significant labor is required to restock the machine.
- B-frame machine. This is an automatic dispenser performing as A-frame, but that presents two conveyor belts, one above the other. By this way, a higher variety of SKUs can be stored per linear meter and multiple orders might be processed at the same time.

Figure 11 gives a schematic picture of such automatic storage/retrieving systems highlighting the shape of racks and the manual operations to refill them.

Figure 11. Manual/Automated S/R systems

In a common warehousing system, there are even accumulation and sorting systems (ASSs) exploited to convey products and orders in picking, sorting and packing stations, to match and join different warehouse zones, and to establish order integrity when order are retrieved in batching or zoning. ASSs are available in various types, ranging from manual staging using kitting matrix to high volume automatic systems. These systems usually consist of closed-loop conveyors with automatic divert devices and collection lanes. Architecture of optical scanners allows the system to distinguish the proper lane to assign to each order. SKUs corresponding to the same order are then automatically sent to one lane.

The conveyors change the way the travel costs are accounted to processes and operations: storage locations close to the conveyor are, in terms of labor, close to shipping. Conveyors separate the warehouse into different zone of storage and picking, therefore the work among picking zones need to be balanced.

2.2.2.6 Computer system

A computer system is a fundamental resource in the management of warehousing system throughout the modern supply chain. The research into individual tools and computer aided solutions for the design, planning, and management of warehouses and related data is widely debated by literature, and industry practitioners. Indeed, the widespread implementation of new information technologies (IT), such as bar coding, radio frequency communications (RF), and warehouse management systems (WMS), provides new opportunities to improve warehouse operations. These opportunities include, but are not bounded to: real time control of warehouse operation, easy communication with the other parts of the supply chain, and high levels of automation. In general, there are specific and useful tool and computer based decision support systems for some steps but these do not seem to cover all the set of decisions. Rouwenhorst et al. (2000) conclude that the existing literature contributions focus on a small number of specific areas within the total warehouse design problems. A list of various computer systems and tools commonly adopted by warehouse design companies encompass is summarized by Baker and Canessa (2009) and proposed as follows:

- Database and spreadsheet models for data analysis.
- Spreadsheet models for considering equipments type.
- Formal spreadsheet models to calculate equipment capacities and quantities.
- Computer-aided design (CAD) software for drawing up the layouts.
- Simulation software and formal spreadsheet models for evaluation and assessment.

2.2.2.7 Storage operators

The warehouse operators constitute an important resource, since warehouse performance largely depends on their skills and availability. Different operator characters and attitudes are usually devoted to specific jobs, and the best practice is to specialized operators with a confined set of activities. The proper management and scheduling of truck loaders and un-loaders, storage operators, restockers, pickers and sorters allow the system to achieve high throughput performances and reduce time and costs.

2.2.3 Warehouses decisions

The warehouse organization involves all the set of decisions regarding with the strategic design, the tactical planning and the operative management and control of warehouse infrastructure and operations. Resources, such as space, labor time, equipments need to be configured and allocated among the different warehouse functions, and coordinated in order to achieve system requirements in terms of capacity, throughput, and service at minimum resource costs (Gu et al. 2007). The most important decisions entail the setting and definition of the process flow. Therefore, a wide set of concerns have to be taken into account to model and configure each process and aspect of the warehousing system.

The remainder of this section is arranged through a detailed description of the concerns mostly regarding with the warehousing processes presented in Chapter 2.2.1.

2.2.3.1 Receiving and shipping

Traditional warehouses receive goods put away products into storage until it is required, and later pick and ship through the shipping docks. For cross-docking warehouses, received goods are sent directly from the receiving docks to the shipping docks. The receiving and shipping are managed in accordance with the storage and order picking functions. Indeed, the scheduling of shipping trucks depends on how orders are batched and retrieved. The basic decisions in receiving and shipping operations mostly depend on the collection and gathering of information and data about incoming shipments, such as their scheduled arrival and contents, about customers demands, such as orders list and due date, and about warehouse dock layout and available material handling resources.

The availability of such information critically affects the assignment of inbound and outbound operators to docks and trucks, the scheduling of loading and unloading activities at each dock, and the dispatching of material handling resources, both operators and equipments. Generally the number of devoted resources, the level of service, the total cycle time, the docks layout and the shipping policies constraints the processes management.

Most of research on receiving and shipping focuses on the mathematical methods and models dealing with the carrier-to-dock assignment problem for cross-docking warehouses. Such systems receive inbound truck in the yard to be assigned to receiving doors for unloading. Therefore, the unloaded goods are sorted according to destination, and then loaded at shipping dock for delivery. The shipping doors can be devoted to a particular destination or shared. The decisions to be taken regard thus the assignment of either receiving or shipping docks in order to minimize the total operational costs (Gu et al. 2007). Many contributions are proposed by literature to address this concern. Gue (1999) proposes an optimization model for the truck-to-door assignment based on the local search to find an efficient door layout. Bartholdi and Gue (2000) consider the cross-docking warehouse doors layout problem aiming to minimize the total travel time and delay time due to congestions and operations. They adopt the queuing approaches and methods that embed the cost model in a simulated annealing algorithm to find an efficient door layout. In summary, few contributions refer to the management of loading/unloading activities, whilst most literature addresses shipping and receiving scheduling and assignment strategies in cross-docking systems.

2.2.3.2 Storage

The storage process regard with one of the most relevant operations of the warehouse. This section focuses on the most crucial storage questions such as the storage quantity (i.e. inventory level) and storage location to assign to each SKU. The former issue belongs to the traditional inventory control area, not particularly discusses and treated in this and further sections. Gallego et al. (1996) and Hariga and Jackson (1996) give a comprehensive summary of the wide set of models and techniques often debated to define the proper inventory of products throughout the supply chain in accordance with order policies, uncertainty and service level. Whilst the inventory management establishes the SKUs stock over a macro perspective within logistic stages and throughout the chain, the so-called storage allocation issue involves the micro decision of the quantity to allocate to each SKU in storage forward or picking area (see Section 2.2.1.2). A storage allocation strategy is a set of policies used to define the proper inventory level per each SKU in forward area.

Conversely, the latter issue regards with the decision of assigning SKUs to various storage zones, of scheduling and arranging SKUs transfer among zones, and of storage location assignment within a zone. A storage assignment method is a set of rules which can be use to assign products to storage locations (De Koster et al. 2007).

2.2.3.2.1 Forward-reserve storage allocation

The interdependency of storage allocation and storage assignment concerns is not handled in detail by literature. Research uses to face such aspects as independent, lacking to propose joint solutions and approaches. Nevertheless, the impacts and effects of both decisions is evident in particular and complex systems based on forward-reserve allocation. As previously introduced in Section 2.2.1.2, it is common and best practice in warehousing to separate the bulk stock (reserve area) from the picking stock (forward area), devoted to high-demand and fast-moving products. This policy reduces order picking costs but increase labor due to material handling to replenish the forward locations. Therefore, since the size of the forward area is limited, it is crucial to decide which SKUs should be stored in forward, in which quantity and finally where it has to be located within this area.

Bozer (1985) first introduces the problem of splitting a pallet rack into an upper reserve area and a lower forward picking area. Hackman and Rosenblatt (1990) respond to the question of choosing SKUs to store in forward and how to allocate volume to each SKU by presenting some analytical models. They propose a knapsack base heuristic to reduce the total material handling costs for both picking and replenishment. Frazelle et al. (1994) extend this approach by considering the size of the overall forward area as a decision variable. These models assume the replenishment of a SKU as performed by a single trip, whilst Van den Berg and Zijm (1998) consider the problem of unit-load replenishment. Literature includes a bright discussion on forward-reserve problem presented by Bartholdi and Hackman (2011).

2.2.3.2.2 Storage assignment

The storage assignment problem consists on the assignment of incoming products to storage locations in properly defined storage zones in order to reduce material handling cost and improve space saturation (Gu et al. 2007). The decision maker may select different storage assignment policies per warehouse zone in order to match the different characteristics and demand profiles of SKUs belonging to each zone. A set of information are exploited to define the most performing assignment strategy, such as the configuration of zone layout, the size and shape of rack and storage locations, the size, the shape and features of the SKUs to be stored, the storage and picking efficiency. Obviously, the availability of such information affects the set of suitable storage assignment policies. In particular, three main chances can be implemented whether or not products data are available.

In the *assignment policies based on item data*, the arrival and departure of each SKU is known within a selected period. Thus, the storage locations are assigned in a particular batch to a SKU or a set of SKUs and then, in another time batch, to another or another set of SKUs. The expected duration-of-stay (DOS), the replenishment lot size and the demand rate of an item determines its temporary location. The items of all different products having the shortest DOS are assigned to the closest locations (Goetschalckx and Ratliff 1990).

In the *assignment policies based on product data*, the available information on products refers to the demand profile, the shape and size of items but does not give any other detail on the operative scheduled flow of products within the system. The most significant opportunity by having details on products profiles is to dedicate a location to a SKU or a set of SKUs in the so-called *dedicated storage*. Even though a wide as desired interval of time is taken into account to assess the behavior and profile of each product, the assignment of products to the locations is static. The main disadvantage of such policy is that a location is reserved even for out of stock products, thus the space efficiency is low. On the other hand, a relevant advantage consists on the knowledge of pickers about where products are within the system. Typically, dedicated storage is applied in the forward areas, with a common reserve area randomly arranged in order to ensure both time efficiency in picking and space efficiency in storage.

Different criteria are usually adopted to assign product to storage locations according to the dedicated storage policy. A list of such criteria is reported as follows (Gu et al. 2007, Frazelle et al. 2002):

- Popularity. This metric is defined as the number of storage/retrieval operations per unit of time. For popularity policy, product classes are ranked by decreasing popularity and the products with highest value are assigned to the most favorite locations.
- Maximum inventory. This metric is defined as the maximum warehouse inventory allocated per product. This rule consists on devoting the most favorite locations to the lowest maximum inventory SKUs, so that higher pick-density and SKU-density are achieved in the easy-to-access storage zone.
- Cube-per-Order-Index (COI). This metric is first introduced by Heskett (1963, 1964), is defined as the ratio of the maximum allocated storage space to the number of storage/retrieval operations per unit of time. The COI policy considers both the SKU popularity and its inventory. According to COI policy products are ranked by increasing COI and those with lowest value are stored in the most favorite locations. Among the others, COI is the most debated policy in literature. Kallina and Lynn (1976) discussed the adoption of this rule in real case studies and instances. Even though, a rigorous proof of the optimality is not given, COI is the best performing assignment strategy in reducing material handling costs when some assumption are satisfied: (1) the object is to minimize the long-term average order picking cost; (2) the travel cost depends only on locations (Malette and Francis 1972); (3) when there is not dependence among SKUs in the same picking tour; (4) when traversal routing policy is adopted (Jarvin and McDowell 1991).
- Turnover. This policy distributes products according to their turnover. The SKUs with highest value are located to the most favorite locations. Slow moving SKUs are assigned to the back of warehouse.
- Weight-to-volume rate. This policy requires to store heavy or high weight-to-volume rate products at begin of picking tour so that heavy products are dropped into the bottom of the pallet and lighter on top. Therefore, a good stacking sequence is obtained without additional effort.

Products may be classified into classes based of shape, size, or demand rate, etc. In the so-called *class-based storage assignment* each SKU is assigned to a class depending on product characteristics and then the class is devoted to a particular zone of the warehousing system. The class-based storage assignment previously assesses and computes the previously introduces criteria per class of products and not per single product. Class-based storage provides an alternative that is between and has the benefits of both dedicated and random 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 relevant impact on the required storage space and the material handling costs. Such technique is mostly utilized in automated storage system, as AS/RS, where products are classified per class, but randomly stored within each class. Literature (e.g. Hausman et al. 1976, Kouvelis and Papanicolau 1995, Eynan and Rosenblatt 1994, Petersen 1999, 2002, Petersen et al. 2004 and recently Gamberi et al. 2010, 2011) widely focuses on the consequence of the application of class-based storage in AS/RS but this topic is no further debated in this manuscript.

Finally, in the *assignment policies based on no data*, no information is available on the profiles of incoming SKUs, neither SKU master file, nor shipment and picking list. In this case, there are some methods and rules supporting the decision maker in storage assignment listed in following:

- Random storage (RAN). This rule consists on assigning every incoming pallet to a location randomly chosen from all candidate empty location in the warehouse with equal probability (Petersen 1997). This policy results in a high space utilization at the cost of increased travel time for retrieving (Choe and Sharp 1991). Such rule works only in a computer-controlled environment able to record and track the location filled by a SKU.
- Closest-open-location storage (COL). This rule entails to assign each incoming SKU to the first empty location encountered by put-away operator. This rule leads to extreme SKU density for areas close to the depot, and gradually more empted areas towards the back. Hausman et al. (1976) argue that COL storage performs as RAN storage when products are moved by full pallet.
- Fartherst-open-location storage (FOL). This rule aims to reduce the congestions in the forward area by storing products in the farthest empty locations.
- Longest-open-location storage (LOL). This policy stores the incoming SKU into the location that has been empty for the longest time in order to increase the locations turnover.

No reported assignment strategies consider the interdependency among SKUs. Indeed, customers might be used to order a group of products together, and these product likely should be stored together. Thus, such relationship among products in the order profiles may be handled through the adoption of *family-grouping storage assignment* or *correlated storage assignment*. Grouping of products can be combined with the previously introduced policies. In order to apply correlated storage policies, the historical and statistical correlation among items (i.e. frequency at which they appear together in an order) should be known or at least predictable. In literature, two types of correlated storage are discussed (Gu et al. 2007):

- Complementary-based method. This approach encompasses two steps. In the first, it groups items into groups based on a measure of strength of joint demand. In the second, it locates the items belonging to the same cluster as much closer as possible. For finding the proper position of clusters, researchers adopt many techniques based on the previously introduced storage assignment rules (Liu 1999, Lee 1992).
- Contact-based method. This approach is based on the concept of contact frequencies. For a given (optimal) routing solution, a contact frequency between two items is defined as the number of times that a picker retrieves either item *i* before item *j* or viceversa.

The adoption of joint optimal solution for both problems is not a realistic approach, at least not for problem instances of the size of real practical industry case. Thus, the development of heuristics is kindly recommended.

The storage assignment policies hereby discussed and reported assume that the inbound and outbound material flow patterns are stationary over the planning horizon. In reality, the material changes dynamically due to the factors such as seasonality and life cycle of products. Therefore, the storage assignment should be adjusted to reflect changing the material flow requirements. In this term, the adoption of these policies is fair whereas is it possible to relocate items over the varying demand profiles.

2.2.3.2.3 Storage layout

The storage assignment problem depends significantly by both the adopted strategy and the layout and infrastructure patterns, which influences the setting of the "most favorite locations". The layout design involves a set of decisions concerning where to locate warehouse zones and departments (i.e. receiving and shipping docks, picking, sorting, etc.) and, then, how to arrange and organize each zone. The first issue is addressed by setting control points, identifying each zone, and considering the flows and travel operations among the departments in order to minimize the overall handling and travel costs. Tompkins et al. (2003) present a comprehensive discussion of effective layout design approaches, Meller and Gau (1996) summarize and review the state of art on this topic, whilst

Heragu et al. (2005) propose a model and a related heuristic to assign SKUs to different warehouse zones.

The second issue regards with the intra-zone layout design, and concerns with the definition of the number of blocks, the number, the length and width of aisles, the number of bays and the proper aisles visiting strategy. The goal is pointing out the better zone configuration for travel distance minimization.

Literature does not propose many comprehensive discussions on storage layout design for low-level manual order-picking systems, since the particularity and variability in such instances and applications. Different businesses and system purposes compel for different layout and infrastructure arrangement. Rosenblatt and Roll (1984, 1988), using both analytical and simulation approaches and methods, enquire the effect of storage policy (i.e. how to assign products to locations) on layout and overall storage capacity. More recently, Roodbergen (2001) proposes a non-liner object function aimed to determine the aisle configuration in random assignment policy that minimizes the average picking tour length. With the same goal, Le-Duc and De Koster (2005), focus on warehouse layout in accordance with class-based storage assignment policy.

On the other side, for automated warehouse systems (e.g. AS/RS system) the problem of layout entails and is reduce to the design of picking face per each aisle. Therefore, most of manuscripts (Bozer and White 1984, Larson et al. 1997, De Koster and Le-Duc 2005) handle the problem of storage assignment as treated in previous section.

2.2.3.3 Picking

Order picking involves the process of clustering and scheduling the retrieval of customer orders, of carrying out orders to the floor, picking the SKUs from storage locations, of stacking load, and of traveling within aisles. Despite of the methodologies adopted to retrieve items (e.g. single-order picking, batch-order picking, zone-picking, etc) defined in Section 2.2.1.3, many different order-picking systems can be found into a warehouse. Moving from the original classification by Sharp (1992), recently De Koster et al. (2007) present some main categories:

- Picker-to-parts system. The majority of warehouses employ humans for order picking. In such systems pickers walk or drives along the aisle to pick items. In *low-level order-picking* system, the picking is fulfilled from storage racks or bins (bin-shelving storage) at low level, while traveling along the storage aisle. In *high-level order-picking* system, order pickers travel to pick locations on board of a lifting truck or crane. The crane manually or automatically stops in front of the proper location and waits for the manual retrieval of goods. This system is also named *man-aboard order-picking* system.

- Pick-to-box system. This system divides the picking area in zones, each of them devoted to pickers according to the previously defined zoning approach (see Section 2.2.1.3). A conveyor, responsible for leading the boxes that contain each order across the system, connects all the picking zones. The pickers wait for boxes coming and the fill the box in response to a specific order list. The costs and complexity of such system are related to workload balancing among the multiple picking zones.
- Parts-to-picker system. In such system, an automatic device brings unit loads (i.e. AS/RS) or bins (i.e. Mini-load) from the storage area to some picking stations, where the pickers select the required amount of each item. These systems are defined and discussed in Section 2.2.2.5 where storage equipments are classified per purpose, and are not further treated in this manuscript.
- Automated picking system. These systems completely perform without humans assistance and are managed and organized by WMS and other computer-based supports, so that optimizing strategies are already implemented.

The performance of a OPS are deeply affected by the proper mix of storage allocation and assignment strategies adopted. The most common objective of OPS is to maximize the service level subject to resource constraints such as labor, storage equipment and layout (De Koster et al. 2007) and obviously minimizing the order retrieval time, which does give no-added value to ordered products. For picker-to-part system, the travel time is an increasing function of the travel distance (Petersen 1999, Roodbergen and De Koster 2001, Petersen and Aase 2004). Consequently, the travel distance is often recognized as a primary objective in warehouse design and optimization. Other objectives regard with the minimization of throughout time and the maximization of space saturation and use of storage equipments and labor. The most relevant decisions to address such issues involve the assignment of orders to batches, the grouping of aisle into work zones, the routing of order pickers. The organization and operational policies include batching, zoning and routing as further discussed.

2.2.3.3.1 Zoning

Compared to other planning decisions, the zoning include the fact that each order picker only operates within a small area, reducing congestion, and being more and more familiar with the storage locations of the zone. The main disadvantages due to zoning consist on the need for sorting and consolidating of order before shipping. There is a set of approaches configured by the methodologies in sorting and retrieving items. The first approach consists on the progressive assembly of an order. When a picker completes the fraction of the order belonging to his zone, the tote and the picking list shift to the next zone, which continues assembling of the order. The order is completed whenever the tote passes through all the zones of interest in a typical pick-and-pass methodology. The second approach for zoning is parallel picking where a number of pickers start on the same order and the partial orders are merged just before shipping.

A discussion on zoning is treated by De Koster (1994) who provides a model of zone pick-and-pass system base on queuing approach allowing to figure out both order throughput time and WIP. This work aims to determine the number of zone and the system size. By using simulation, Petersen (2002) shows that the zone shape (i.e. given by the number of aisle per zone and aisle length), the number of items on the pick-list and the storage policy have a significant effect on the average travel distance within the zone. Using MILP, Le-Duc and De Koster (2005) determine the optimal number of zones in a synchronized zoning system such that the total order-picking and assembly time is minimized.

An alternative for progressive zoning with fixes zone sizes, is a more dynamic and significantly improving approach base on the bucket-brigades (Bartholdi 1993, Bartholdi et al. 1999, 2006, Bartholdi and Eisenstein 1996, Bartholdi and Hackman 2011). This technique coordinates pickers while they are progressively assembling products along a flow line. In such system, one picker start to retrieve from the rack and passes the tote or box containing the partially fulfilled order to the next picker when the latter is ready to process the order. The order is handled picker by picker and reaches the far right of the line where it is put on a conveyor or other sortation or transfer means.

2.2.3.3.2 Batching

Batching is a popular strategy for reducing the retrieval travel time per order. A batch is a set of orders picked in a single tour (Van den Berg 1999). The orders in a batch may not exceed the storage capacity of the picking vehicle. This approach is typicall exploited when orders are small and there is a significant benefit in grouping orders into a number of sub-sets. According to Choe and Sharp (1991), there two fundamental criteria for batching: proximity and time windows.

The *proximity batching* assigns each order to a batch based on proximity of its storage location of items belonging the orders. The major issue is measuring the proximity among orders, which is affected by the adopted routing and visiting strategies. Many researchers (Gademann et al. 2001, Chen and Wu 2005, Chen et al. 2005) demonstrate that order batching is an NP-hard problem, so that many studies develop heuristic method to solve it. For manual picker-to-part systems there are two main classes of algorithms: seed and savings algorithms.

The *seed algorithm* builds batches by following:

- Seed selection rules. These rules define a see order per each batch. Some examples of seed rules are random, high number of locations, long pick tour, far locations, high difference between right and left aisles to be visited.
- Order congruency rules. These rules determine which unassigned order should be added next into the current batch. In this term, an order is candidate to be included within a batch in accordance with the distance from the seed of the batch. Samples of these are: the number of additional aisles which have to be visited if an order is added, the difference between the gravity centre of the order and the gravity center of the batch, the sum of the travel distance between every location of item in the seed batch and so on.

On the other hand, the *saving algorithms* are based on the algorithm of Clarke and Wright (1964) for the vehicle routing problem: a saving on travel distance is obtained by combining a set of small tours into a smaller set of larger tours.
Central to both types of algorithms is an order-to-route closeness metric aimed to define the order addition rule in the seed algorithm and the combination rule in the saving algorithm. The seed and savings algorithm proposed in literature are similar in terms of their general procedure, but differ in the closeness metric used. As instance, some of the classic closeness metrics are the number of common locations between two orders, the sum of the distance between each location on one order and the closest location, the center of gravity, the number of additional aisles to travel when two orders are combined.
De Koster et al. (1999) perform a comparative study for the seed and the time savings heuristics mentioned above for multiple-aisle picker-to-parts systems. The performance of the algorithms is evaluated by using two common routing heuristics. They mainly summarize and conclude that: simple order batching methods significantly improve the first-come-first-serve batching approach. Furthermore, the seed algorithm are best in matching the S-shape visiting strategy with a large capacity of pick trucks, whilst the time saving algorithms perform best in conjunction with the largest gap routing method and a small pick truck capacity.

In the time windows batching, the orders arriving during the same time interval, named time batch, are accordingly grouped. This strategy refers and fit with the sort-while-picking pattern. De Koster

(2007) considers variable time window order batching with stochastic order arrivals for manual picking systems.

2.2.3.3.3 Routing

The routing decisions aim to define the proper sequence of items on the pick list to ensure a good route through the warehouse. This problem of order pickers routing in a warehouse is a particular Traveling Salesman Problem (TSP), where the picking/storing location of an item is given. In literature, this problem is defined by a salesman which has to visit a set of points of interest. He knows the distance between each pair of destinations and his purpose is setting the best order of visiting, so that the total travelled distance is minimized.

Some differences exist by considering the classical TSP formulation in warehousing systems. Literature handles routing problem in general multi-parallel-aisle OPS, man-on-board AS/RS systems, unit load AS/RS systems and carousel systems.

In particular, in widely common *multi-parallel-aisle OPS*, the aisles and racks constraint and limit the possible travel paths. The difficult in TSP is that in general is not solvable in polynomial time. In 1983, Ratliff and Rosenthal propose a dynamic programming algorithm able to solve the problem in running time linear in the number of aisle and of pick locations. This algorithm takes into account parallel and equal aisles, a single I/O point, a crossing aisle at the end of aisle and the given location of SKUs. Other (Roodbergen and De Koster 2001) authors relax such hypothesis by proponing further algorithms.

Although it is possible to build optimal routing algorithms efficiently, in warehouse pickers routing is mainly solved through heuristics. Indeed, an optimal algorithm is not available for every warehouse layout. Furthermore, optimal routes may appear irrational to human operators, so that they can deviate in daily operations (Gademann and Van de Velde, 2005).

In order to overcome these criticalities a list of the renowned (De Koster et al. 2007) heuristics for routing order pickers is reported as follows:

- S-Shape (or traversal) heuristic. This consists that pickers enter any aisle containing at least one pick which is traversed entirely. Aisles without picks are not entered.
- Return heuristic. This rule makes an order picker entering and leaving each aisle from the same end. Again, only aisles with picking locations are visited.
- Mid-point heuristic. This rule divides the every aisle in two parts and sides. Picks in the front half are accessed by bottom and picks in the back half are accessed by top of warehouse.

Pickers cross to the back half by either the last or the first aisle to be visited. Hall (1993) shows that such method performs better than S-Shape when the number of picks per aisle is small (i.e. one pick per aisle on average).

- Largest gap. This technique is similar to the midpoint strategy except that an order picker enters an aisle as far as the largest gap within an aisle. The gap represents the separation between any two adjacent picks, between the last pick and the back aisle. If the largest gap is between two adjacent picks, the order picker performs a return route from both ends of the aisle. Otherwise, a return route from either the front or back aisle is used. In other words, the largest gap is thus the portion of the aisle that the other pickers do not travel. The largest gap always overcomes the performance of mid-point, which is conversely simpler to implement (Hall 1993).
- Combined heuristics. This method consists in a combination of S-Shape and return heuristics.

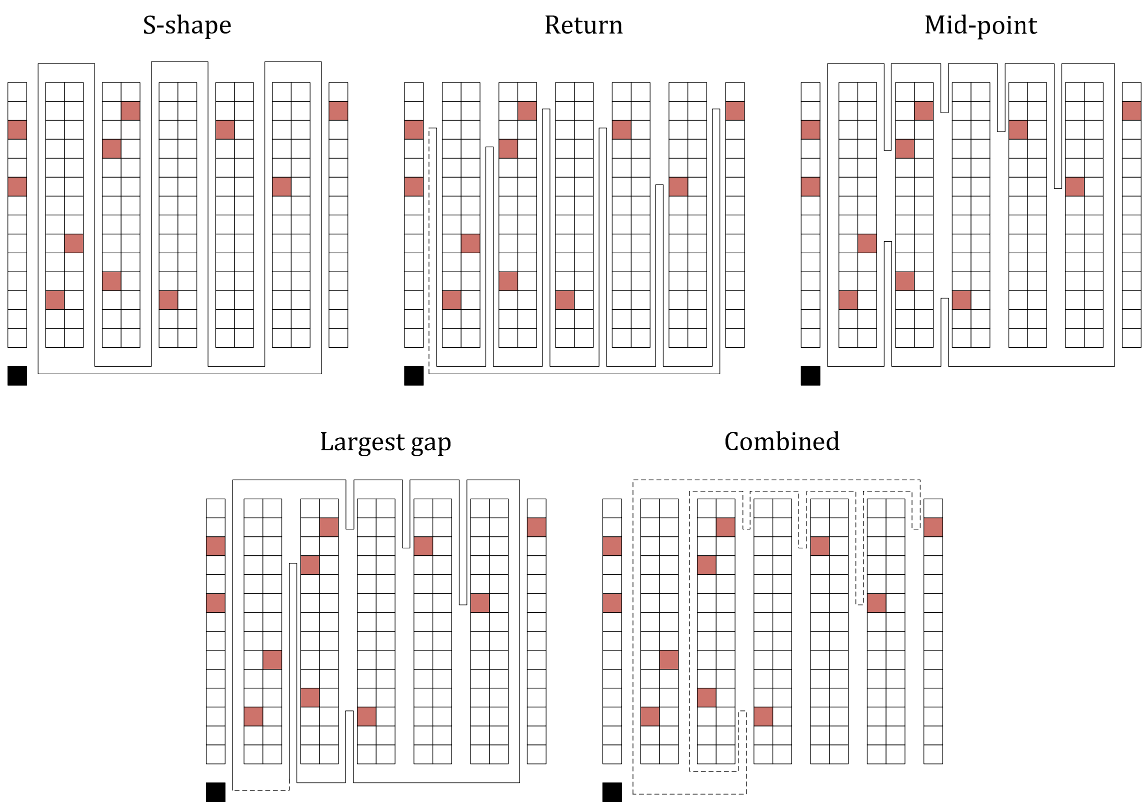


Figure 12. Routing heuristics (Roodbergen 2001)

Figure 12 illustrates the picking path according to the different reported heuristics (Roodbergen 2001). Petersen (1997) measures through a simulation analysis the performance of the previously introduced heuristics in lieu of the solving algorithm introduced by Ratliff and Rosenthal (1983). This work concludes that the best heuristics solution is on average 5% over the optimal solution.

In man-on-board AS/RS OPS the TSP is implemented by considering Tchebyshev distance metric. Gudehus (1973), firstly, proposes a band heuristics based on the division of the pick face in two equal eight horizontal bands: the points in the lower band are visited in the increasing x-coordinate direction, while the points in the upper band are visited in the opposite direction. Goetschalckx and Ratliff (1988) handle the problem by introducing a convex hull algorithm, whilst Bozer et al. (1990) proposes the combination of the previous heuristics. Other relevant heuristics include the center sweep (Bozer et al. 1990) and the space-filling curve based heuristics (Bartholdi and Platzman 1998).

The sequencing of storage/retrieval operations in unit-load is widely debated and faced by literature. Graves et al. (1977) demonstrates that the adoption of dual command cycles enables the travel time reduction of up to 30%. In general, the algorithms proposed by research consider either a fix sequence of storage/retrieving missions or a dynamic sequence of activities updated whenever new requests arrive. The static routing problem for random and class-based storage layout is NP-hard, so that most solving methods adopt nearest neighbor heuristic. Among these, most significant works include Han et al. (1987), Van den Berg and Gademann (1999). On the other hand, the dynamic approach is handled by iterating the static algorithms in order to re-sequence the incoming orders (Lee and Schaefer 1997, Ascheuer et al. 1999). Moreover, several works (Bozer and White 1984, Peters et al. 1996, Van den Berg 2002) deal with the definition of the optimal dwell point in a unit-load AS/RS, which is the position in the pick face where the crane stops when the system is idle.

Finally, the sequencing problem in carousel system is firstly considered by Bartholdi and Platzman (1986) and further handled by Van den Berg (1996). By assuming as negligible the time needed by picker to operate within the same shelf compared to the time required to rotate the carousel to the next shelf, the problem consists in finding the shortest Hamiltonian path on a circle. Linear time algorithms are proposed aimed to find the optimal solution.

As a comprehensive summary of the literature review reported in this chapter, Figure 13 illustrates the organized set of decisions and concerns involving the design and management of a warehousing system.

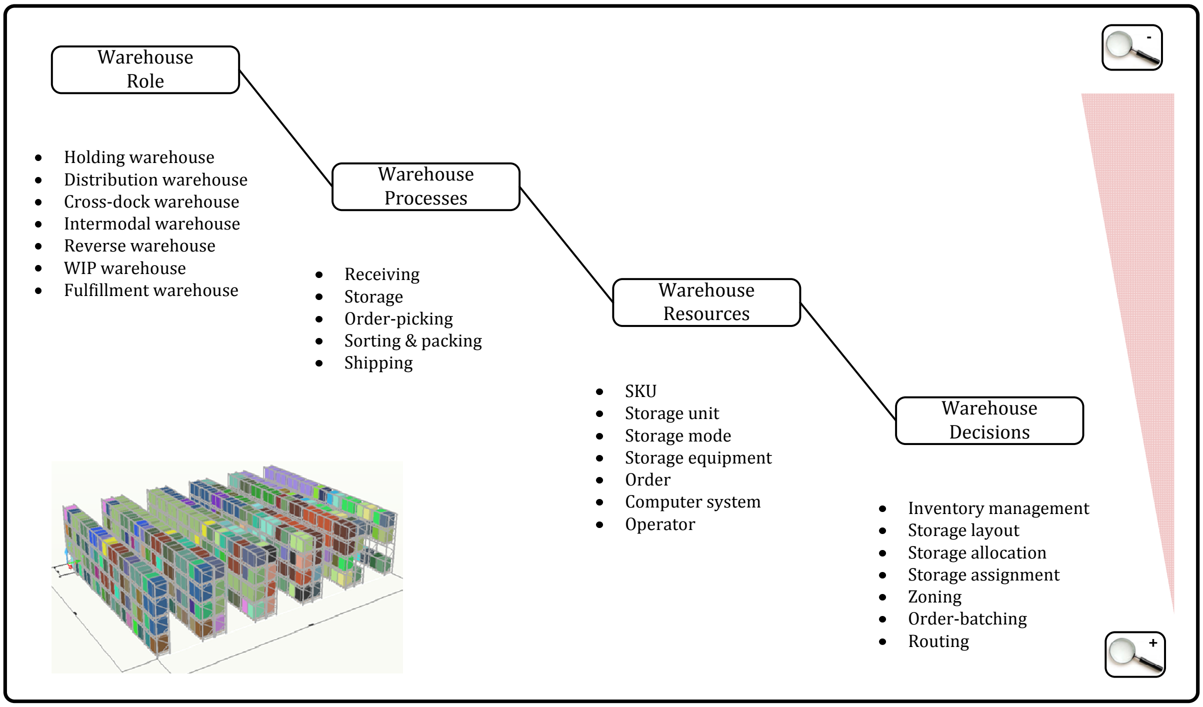


Figure 13. Literature review architecture

2.2.4 Warehouses types

In order to better approach to the variability of warehousing system environments it is useful to classify the distribution centers in categories depending mainly on goods they handle and customers the serve. As overview of the summary of warehouse roles reported in section 2.1, Bartholdi and Hackman (2011) present some important distinctions among the following businesses:

- Retail warehouse. These warehouses store products to supply to retailer or megastore (e.g. Walmart, Target, etc.). The demand is highly affected by seasonality in products type but not in the overall ordered volumes. Indeed, retailers receive daily scheduled shipments of full-loaded trucks and the shipped flow is huge. The variability in stored products compels retail warehouse to arrange and organize multiple storage zones, with different storage equipments and modes able to fit with different features and sizes of fresh products, dry stuffs, toys, home device, appliances, etc.
- Grocery warehouse. These warehouses are similar to retail warehouse expect for the exclusive perishability of handled products. All the operations regarding with fresh items are subjected to climate control and the multiple zones are necessary to store product belonging to different food classes (e.g. fishery, dairy, fruit, meat, etc.). The main issue is to operate according to FIFO method in order to comply outdate of products. Automated warehouses typically do not fit with this system due to food safety and sanitary conditions.
- Pharmaceutical warehouse. These warehouses are characterized by intensive high throughput of small pieces. The number of different SKUs accounts on average tens thousands of items. The perishability of products is not a constraint due to the high turnover of products that are shipped much earlier than outdate. The general homogeneity of items cartons and pieces matches with the high demand flow and the high value of each product, thereby supporting the application of automated systems and equipments. The flow is controlled, monitored and automatically processed from the receiving to the shipping, and human operators are responsible for statistical quality checking and other service and supporting activities.
- Spare parts warehouse. These systems hold spare parts and service parts devoted to expensive capital equipment, such as car, truck, train, airplanes, computer systems or medical equipments. Therefore, these warehouses hold a huge capital in inventory, accounting sometimes more than ten thousands of SKUs. Because of the large number of held parts, the management of the whole system is based on different storage zones distinguished by the unit load volume, the rate weight to volume and so on, and the adoption of different pickers and equipments. The complexity of such system depends also on the

velocity in responding to customers orders, because an important piece of capital equipment (e.g. machine) might be unavailable without the required parts. Furthermore, the spare parts life cycle represent a further criticality to address. Indeed, the failure rate tends to increase at the beginning and at the end of product life. This means that a part might experience an high popularity just before being discontinued, leaving the warehouse with excess inventory of useless parts.

- E-commerce warehouse. This catalog fulfillment receive small orders from final consumers by phone, fax, internet. The order, typically composed by 1-3 pick lines, is retrieved through zones and dropped down into cartons, which represents both picking and shipping packaging. The main purpose of such systems is quickly respond to the order and to ensure order accuracy, in order to reduce at minimum expensive returns.
- 3-Part Logistic (3PL) warehouse. This warehouse offers storage and distribution operations to companies. The 3PL provider serves multiple customers from one facility gaining economies of scale. They manage different businesses in the same facility and often they match some of the previously introduced warehouse types in the same building. The time and space efficiency are in this case fundamental metrics of the performances and the profitability of the system.

3. Warehousing Design. A Procedure

Warehouses are one of the most critical resources in production and distribution systems and networks, whose performance significantly depend on the availability of materials in the right location, in the right quantity and at the right time.

The literature summarized and illustrated in Chapter 2 shows that many contributions for the design and control of a storage system are proposed, but a few of them discuss the importance of an integrated approach based on the adoption of different supporting decisions models and tools, from MILP to visual interactive simulation (VIS), passing through heuristic procedures and cluster analysis (CA).

This chapter presents a conceptual and integrated framework for the design, management, control and optimization of both manual, i.e. man-on-board, picker-to-part and automated, i.e. part-to-picker, storage systems, less than unit-load order picking systems (OPS), by the development and application of different models, algorithms and tools. The proposed framework integrates the different steps and management decisions in order to point out not a system configuration as a result of local optimum, but the minimal overall cost warehousing configuration and layout. The illustrated top-down procedure takes into account subsequent concerns such as the infrastructure and layout aspects, the design of storage zones (e.g. forward area and bulk in a OPS), the storage allocation within each area, the storage locations assignment, the aisle visiting strategies, the routing policies, the batching procedures, and so on.

Advanced and integrated approaches to improve order-picking efficiency can significantly reduce customer response time in a supply chain system, decrease the overall logistic costs, and improve customer service level. The aim of this chapter is also to present an easy methodology for manager and practitioners in facing real instances problems of storage design and control, as a useful tool for the implementation of the renowned and original models. The further described systematic hierarchical top-down procedure allows combining sequential decision steps in particular focused to allocation and assignment issues, which are the most significant criticalities of an OPS. The proposed procedure is applied to a case study, and the results obtained from a what–if analysis are compared to assess its effectiveness and its applicability.

3.1 Tips from literature

Literature traditionally deals with storage allocation problem and storage assignment problem separately. The main reason of this distinction is that storage allocation typically entails space efficiency, rack slotting concerns and replenishment operations, whilst the storage assignment affects the time efficiency and the picking tour and activities. Table 3 summarizes and compares several meaningful and recent works dealing with the adoption of models and techniques to address storage allocation and/or storage assignment issues.

Author	*Year*	*Storage issue*		*Methodology*		*Methodology*					*Case study*
		Allocation	*Assignment*	*Models*	*Design procedure*	*MILP*	*Metaheuristi*	*Heuristic*	*Cluresting*	*Stochastic*	
Heragu et al.	2005	•	•	•	•	•		•			
Hassini	2006	•		•		•		•		•	
Hua and Zhou	2008		•	•		•			•		•
Xu et al.	2008		•	•		•		•			
Landa-Silva et al.	2009	•		•				•			
Zhou et al.	2010		•	•							
Gu et al.	2010	•		•		•		•		•	
Chiang et al.	2011		•	•	•	•			•		•
Wang et al.	2011		•	•			•				
Kutzelnigg	2011		•	•		•		•			

Table 3. Recent literature

This table is organized through three main categories/fields as follows:

- *Storage issue*. This field deals with the storage problem addressed in the manuscript: allocation and/or assignment. Table 3 illustrates as many different approaches are proposed for the storage allocation problem as well as for the storage assignment problem, but just one treats both problems within a jointly approach (Heragu et al. 2005).
- *Methodology*. This field explains the analysis approach proposed in the manuscript. The papers are classified in terms of: *Models* when innovative models and/or algorithms are presented; *Design Approaches* when complete, integrated and/or hierarchical approaches or procedures are proposed and discussed to support practitioners in warehouse design and control.
- *Solving Method*. This field summarizes different solving approaches typically adopted by literature.

The results presented in this recent literature overview are mainly computed and illustrated through the generation of random instances and numerical examples. Real case studies and industrial applications are unfortunately rarely illustrated.

Particularly interesting, Heragu et al. (2005) present a mathematical model for warehouse design and products allocation that jointly determines the product assignment to different zones within the warehouse as well as the size of each area. The originality of such work consists on the development of a MILP model and a solving heuristic procedure for a storage allocation/assignment problem. in two step. Firstly, it aims to assign the SKUs to different zones, thereby defining the overall size of each zone. Secondly, it chooses the optimal location per each SKU within the zones. However, this model consists of many different strictly hypotheses and constraints that might significantly affect the application to real industrial case studies.

Table 3 shows that no any other significant contributions join the allocation and the assignment issues. Furthermore, there are not contributions presenting and discussing significant case studies, which deal with both these crucial decisional problems.

The aim of the further sections can be summarized in three main objectives, named (1), (2) and (3). The first objective is to present and apply an original systematic and hierarchical procedure for the design and management a warehousing system (1). This top-down procedure is based on the joint application of storage allocation strategies, that define the proper inventory level and the filling volume per each SKU, and storage assignment rules, which assign a location to each SKU according to specific criteria. This framework points out that the best configuration to reduce the travelling for both picking and restocking in a specific warehouse, depends on interdependent choices about allocation and assignment issues (2). In particular, this chapter would demonstrate that the so-called optimal allocation strategy, named OPT (Bartholdi and Hackman 2011), enables the minimization of number of restocks in an OPS (3), but at the potential expense of affecting the adopted assignment policy, and increase the picking costs.

3.2 Warehousing design hierarchical procedure

The proposed original procedure for the design and management of warehousing OPS is arranged through the subsequent application of models and algorithm aimed to respond to different but integrated concerns. This methodology is based on four sets of decisions corresponding to four different levels and stages (illustrated in Figure 14):

[1] Layout.

[2] Allocation.

[3] Assignment.

[4] System operations configuration.

[5] Simulation analysis and performance assessment.

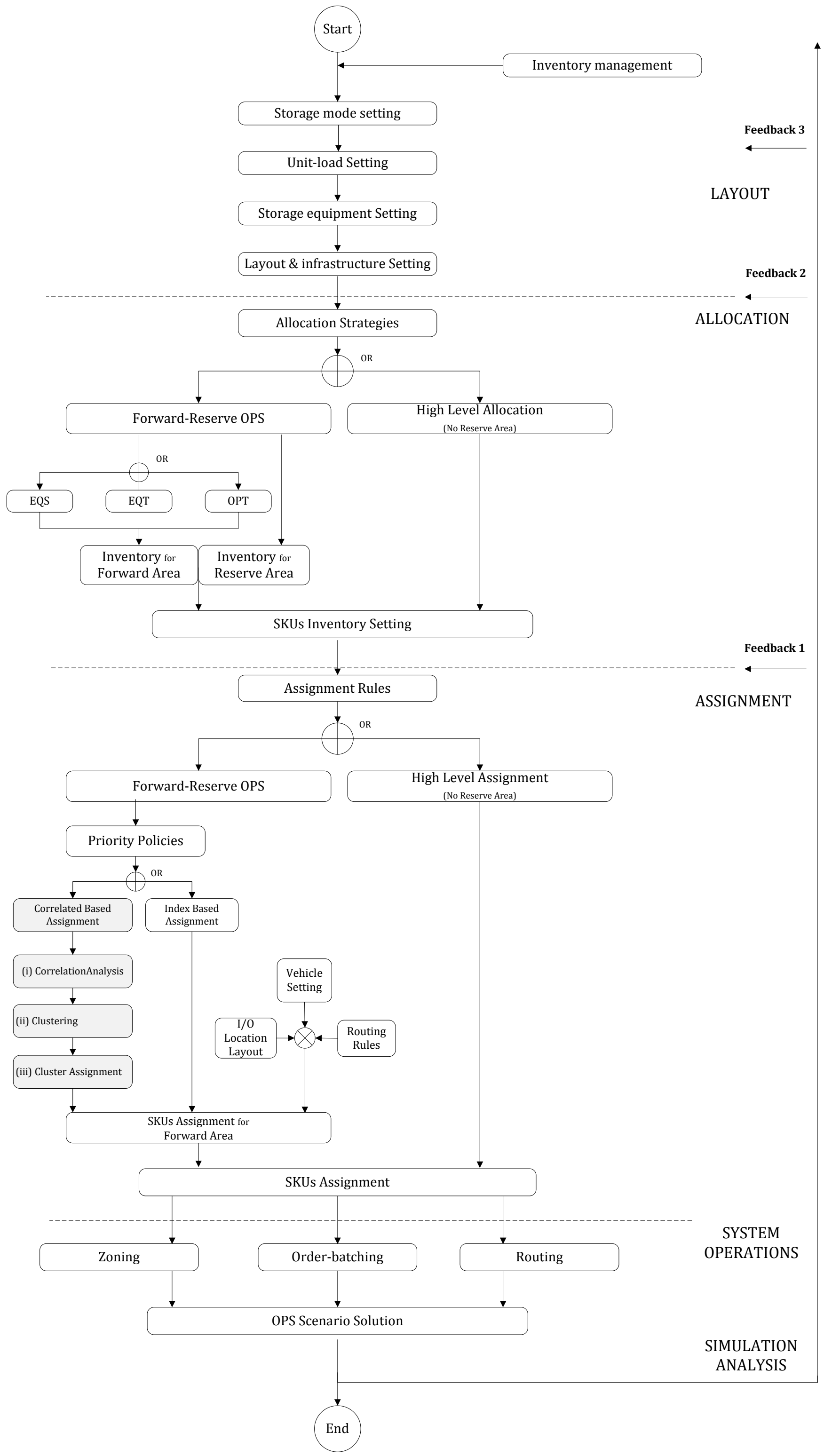


Figure 14. Hierarchical procedure

3.2.1 Layout issue

The first section in Figure 14, called layout, includes models and tools for the determination of the layout and configuration of the storage areas, including layout concerns (e.g. shape factor, receiving and shipping docks locations, etc.), unit load issues (e.g. load size and weight, storage capacity, etc.), vehicles issues (e.g. volume and weight load capacity, velocity and acceleration performance, lift performance, etc.), and structural system (e.g. forward-reserve, part-to-picker, picker-to-part, etc.). As previously treated in Chapter 2 the characteristics of order profiles and SKUs sensibly affects the decision on storage modes and storage equipments. The procedure considers a set of mindful design approaches and arguments to support the managers or practitioners in selecting the best fitting storage infrastructure for the real instance.

On one side, the size of storage unit load determines the rack type, the size of bay, whilst the weight of load fixes the maximum number of levels and the features of the rack components. On the other the order profiles, the number of pick lines, the shape and size of retrieved products influence the choice of the vehicle, thereby influencing even the aisle width. Finally, the overall layout of the system suggests the proper sites for receiving and shipping docks, attempted to reduce congestion and increase flow throughput.

3.2.2 Allocation issue

This section deals with the storage allocation issue. This aspect is handled by defining the proper storage volume of the generic SKU within forward and reserve areas in presence of forward-reserve OPSs (see the left output at allocation level of Figure 14) or within the whole available storage area in the so-called high-level storage OPSs (see the right output at the allocation level of Figure 14). The adopted storage allocation strategies, classified by Bartholdi and Hackman (2011), are reported in Table 4.

Allocation Strategies	Inventory level [%]	Description	
Equal Space (EQS)	$v_i = \frac{1}{n}$	Same storage volume per each SKU	(1)
Equal Time (EQT)	$v_i = \frac{f_i}{\sum_i^n f_i}$	Same number of restocks per each SKU	(2)
Optimal (OPT)	$v_i = \frac{\sqrt{f_i}}{\sum_i^n \sqrt{f_i}}$	Minimize the total number of restocks	(3)

v_i *average percentage inventory level for SKU i*
f_i *demand (volume) of SKU i in a period of time*
n *total number of SKUs*

Table 4. Allocation strategies (Bartholdi and Hackman 2011)

They propose and compare three different inventory levels for the fast pick area, named Equal Space Strategy (EQS), Equal Time Strategy (EQT) and Optimal Strategy (OPT). EQS assigns the same fraction of available volume in fast pick area to each SKU. EQT assigns the proper fraction of available volume to each SKU so that each is replenished in the forward area an equal number of times. Finally, OPT strategy assigns the proper fraction of available volume that minimizes the total number of replenishment of the forward area as argued by Hackman and Rosenblatt (1990).

The first two strategies represent what companies usually apply to manage their forward area. The principle benefit of EQS consists on using space efficiently, because the total available volume is uniformly assigned. On converse, EQT strategy makes the number of restocks be the same for each SKU, so that the labor time due to replenishment is the same over all SKUs population, the re-stocker work is much more balanced and stockout risk for the most popular items decreases.

The OPT strategy enables a useful tradeoff between space and labor time by minimizing the total number of restocks needed to maintain the forward area. Furthermore Bartholdi and Hackman (2011) prove that OPT balances the number of replenishments among SKUs, so that restocks are uniformly distributed across the forward pick face.

The preliminary limit of the proposed models is that the total available volume within the forward area is treated as a continuously divisible fluid. Therefore, it is important to choose carefully real case applications of the proposed procedure in order to test their effectiveness.

The allocation strategies previously presented fit better with small parts picking or pieces from case or carton picking than with cartons from pallet picking because of size and geometry issues.

Although the so-called optimal allocation (OPT) provides labor time saving due to efficient restocking operations, apparently it does not affect the picking activities and travelling within warehouse.

In brief, since allocation strategies describe how to assign the available volume among SKUs and to maintain the forward area efficiently, it would be necessary to figure out how allocation affects the traveling distance, and the total operative time including both retrieval activities and replenishments.

This is the main aspect of the research and one of the most relevant insights of this chapter. Indeed, the literature does not face this pattern and split the problem considering the allocation strategies as not affecting the travel distance for picking. Nevertheless, the aim of this is topic is even figure out the interdependency between the arrangement of space (i.e. warehousing layout), depending on the storage volume (i.e. inventory) devoted to the SKUs, and the arrangement of SKUs within the space. Given an overall available storage volume to hold a set of SKUs, the fraction of volume devoted to each SKU arranges the space allocation thereby influencing the location of each SKU within the space. Moving the location of SKUs means to affect the time spent to achieve and retrieve products, and to impact on travelling performance. The interdependency between space allocation and operative time for picking is strictly related to the assignment policies, but some clues might suggest that even allocation strategies play a relevant role. Such as in Physics even in Warehousing, space and time are dependently related each other and in order to design an efficient warehouse saving both time and space is absolutely necessary. On one side, each storage location represents a space that need to be used as efficiently as possible. The larger the space, the fewer the number of replenishment of each product is. On the other, each storage location asks for a number of picks depending on the assigned SKU. In order to point out this interdependent relationship, the assessment of allocation strategies combined with assignment policies might state their jointly effects on travelling performance including picking and restocking operations.

3.2.3 Assignment issue

This section deals with the assessment and application of different storage assignment policies based on available products data as described in Section 2.2.3.2.2. In an OPS SKUs are assigned to a specific location, or in some cases to multiple locations, and this determines the travel of the workers to retrieve or store that particular item. The preliminary decision step, concerned with inventory management issue, proceeds with a second phase that deals with the storage assignment problem, defined as the assignment of products to storage locations. This problem has been formalized by

Frazelle and Sharp (1989) and classified as a NP hard problem. Therefore, a set of heuristics can be implemented and applied to real case studies and real industrial data.

In particular, the patterns considered to manage the SKU assignment to the forward area are sets of heuristics dedicated storage rules based on criteria (i.e. index based or criteria based) and correlated based. These priority policies can be also adopted to assign products to the reserve area in presence of forward-reserve OPSs or also high-level OPSs.

3.2.3.1 Criteria based assignment

In industry an implicit agreement is often apply to address the locations to the SKUs population: the fastest-moving SKUs should be stored in the most convenient location (Bartholdi and Hackman 2011). This approach is widely treated and discussed in literature and lot of different metrics or criteria have been developed to fit each particular warehouse category.

The adopted criteria based policies carry out the evaluation of the metrics or criteria defined for the generic SKU, as previously introduced and reported in Chapter 2, and hereby described in Table 6 and in the following list:

- Popularity (P). This metric describes the total number of picks accounted by the SKU during a specific period.
- Cube per Order Index (COI). This metric describes the ratio of inventory to the popularity value for a generic SKU.
- Turn (T). This metric describes the ratio of the picked volume to the inventory volume per a generic SKU during a specific period.
- Order completion (OC). This metric describes the ability of a generic SKU of contributing to the completion of an order, made by multiple order lines of different SKUs. Based on Bartholdi and Hackman (2011) the OC index is the sum of the fractions of orders the generic item performs.

Orders	Order 1	Order 2	Order 3	Order 4	
SKUs	Value				**OC**
SKU 1	1/4	1/2	0	1	7/4
SKU 2	0	1/2	1/3	0	5/6
SKU 3	1/4	0	0	0	1/4
SKU 4	0	0	1/3	0	1/3
SKU 5	1/4	0	0	0	1/4
SKU 6	1/4	0	1/3	0	7/12

Table 5. Ordeder closing metric

Table 5 presents an example product-order incidence matrix for six different SKUs and four customer orders. As instance, the SKU 1 belongs to order 1 and at the same time three different items belong to the same order, so it is responsible for fraction ¼ of order 1, which is composed of four contributions.

In accordance with the OC definition for SKU 1 the obtained value is 7/4. Therefore, the OC value ranges from the lower bound of the ratio of 1 to the number of SKUs to the upper bound of the number of orders.

The proposed procedure selects and compares the warehousing configuration determined by the adoption of reported assignment policies within the forward. Table 6 illustrates the priority rules responsible to rank SKUs according to a set of criteria. In particular, the column named ranking represents the priority of ranking adopted per each metric. As instance, the down arrow indicates to sort SKUs by decreasing value of popularity.

Index	Value	Ranking	
Popularity (P) index	$P_i = \sum_j x_{ij}$	↓	(4)
Cube per Order Index (COI)	$COI_i = \frac{s_i}{P_i}$	↑	(5)
Turn Index (T)	$T_i = \frac{f_i}{s_i}$	↓	(6)
Order Closing (OC)	$OC_i = \sum_j O_{ij}$	↓	(7)

x_{ij} *product-order incidence matrix*
m_j *number of order lines for picking order ;*
s_i *inventory stock level of SKU i*
$O_{ij} = \frac{x_{ij}}{m_j}$
↑/↓ *increasing/decreasing ranking*

Table 6. SKU classification metrics

3.2.3.2 Correlated based assignment

In order to reduce the complexity of warehouse management issues, it is generally helpful to store SKUs in families or clusters that share the same behavior within the customer demand.

Correlated storage policies manage to store together SKUs with a high degree of correlation, which is usually based on the frequency of requests. Different metrics of correlation among SKUs can be estimated. Once the relationship between each couple of SKUs has been evaluated, the pairs with the highest value of correlation are immediately candidate to be stored beside. As evidence of the importance of this approach,

There are particular categories of warehousing system, e.g. retail distribution centers, where customers used to order complementary items together, e.g. pasta and tomato sauce. These SKUs might reasonably have high correlation between each other. Indeed, the closer the locations, the shorter travelled trips by pickers to respond to those orders, especially with few lines (2-3) per order.

In order to group products, the level of correlation between them should be predictable, as described by Frazelle and Sharp (1989), and by Brynzér and Johansson (1996). The correlated storage assignment policies adopted in the proposed procedure have been recently illustrated in Manzini et al. (2012) and consist on the assessment of the following three hierarchical steps of decisions (see Figure 14):

[1] Correlation analysis.

[2] Clustering.

[3] Cluster assingment.

3.2.3.2.1 Correlation analysis

Correlation analysis. This step evaluates the degree of correlation (also called similarity) between the SKUs on the picking list for a particular period. The level of similarity is usually measured by introducing an index of similarity. The literature presents several indices of similarity. One of them, the Jaccard index (McAuley, 1972), which is frequently used in statistics and in CM, can be adopted to assess the correlation between SKUs. In particular, the procedure implements two different classes of similarity metrics: general-purpose metrics and problem-oriented metrics. As instance, one index per every category is proposed as follows.

McAuley index (1972)

This is a general-purpose similarity index which means that the similarity between parts (e.g. SKUs in picking, machines in cellular manufacturing) is assessed and computed only in accordance with the operative behavior (e.g. request in customer orders in picking, presence in working cycle in cellular manufacturing). This index, as in general all the general-purpose, bases on the definition of the Incidence matrix, whose sample is briefly illustrated through Table 7.

	SKU *i*	SKU *j*
Order 1	0	1
Order 2	1	1
Order 3	1	0
Order 4	0	1
Order 5	1	0
Order 6	0	0
Order 7	1	1
Order 8	1	0
Order 9	0	0
Order 10	1	0

Table 7. Incidence matrix

The illustrated Incidence matrix describes the behavior of SKU *i* and SKU *j* within a set of customer orders. The matrix value per each column is equal to 1 if the SKU belong to a selected order and 0 otherwise. The evaluation of index value depends on the following four parameters, expressed in Table 8, computed from the Incidence matrix per each pair of SKUs:

			SKU j	
			Incidence matrix value	
			1	0
SKU *i*	*Incidence matrix value*	1	*a*	*b*
		0	*c*	*d*

Table 8. Incidence matrix parameters

The value of parameters consist on the following descriptions: (a) is the number of orders containing both SKUs, (b) and (c) are respectively the number of orders containing just SKU *i* rather than just SKU *j*, whilst (d) is the number of orders do not containing neither SKU *i* nor SKU *j*. By these parameters, McAuley (1972) is therefore defined by (8):

$$S_{ij} = \frac{a_{ij}}{a_{ij} + b_{ij} + c_{ij}} \qquad (8)$$

This similarity metric is defined in the range $0 \leq S_{ij} \leq 1$, whereas 1 value represents the maximum similarity and 0 the minimum.

Accorsi & Maranesi index (2012)

The principle lack of general-purpose similarity metrics, as among the others McAuley index, consists on the fact that the particularity of every context of application are not taken into account. Indeed, general-purpose metrics account the number of orders where SKUs are jointly requested, but do not consider the features of SKU, their turn over or the storage volume they require. Aimed to address these criticalities a picking-oriented index is hereby proposed by the author of this manuscript. There are some insights concerning with the picking activities and practices that lead to the definition of this metric, also named picking-oriented index (POI).

Generally, it is helpful to locate SKUs near one another if they tend to be requested together. Although the popularity is one of the most appreciated criteria that allow to analyze and to sort the items within the warehouse, sometimes it would not be enough to explain the demand routine and the related picking activity. Moreover, one of the most important issue to face on is when do some SKUs deserve to be grouped and stored together with the aim of time and space efficiency increasing.

Some mindful tips might answer the question of when a pair of SKUs deserves to be stored together:

- If SKUs occur often in same order.
- If SKUs are highly requested during a specific horizon of time, so that they have high values of popularity.
- If SKUs turn inventories at the same rate. Indeed the throughput of a SKU across the warehousing operations (i.e. receiving, put-away, picking, shipping) allow to define the suitable storage equipments to save space and labor time. Therefore SKUs with similar values of Turn index required often to be stored together in the same zone or storage mode (i.e. region of storage for which cost to pick or to storage from or to any locations are all approximately equal).
- If SKUs jointly tend to complete the order whose they take part.
- If SKUs with divergent popularity active SKUs is likely and the least active holds little space within the shelves than the other, probably it makes sense to store them together.

The first tip is clearly addressed by the general-purpose McAuley index. Nevertheless, in some cases SKUs with different behavior and characteristics belong to the same family or cluster even if they present divergent popularity. Let consider the previously introduced sample of tomato sauce and pasta as typical SKUs of a grocery distribution centre. Let be pasta as high demanded items, whilst let be tomato sauce a less requested products. Anyway, whenever one tomato sauce item is demand also at least one pasta pick line belong to the same order. Therefore, the number of orders where they are jointly requested is not the only aspect to considerer. As instance, the popularity of SKUs and other parameters, such as the level of inventory, the turn over, and the order completion should be enquired. The proposed index encompasses a set of variable assuming value in range from 0 to 1 and considers different arguments to cluster SKUs.

Order-based rule. This variable, named x^1_{ij}, accounts the ratio of number of orders of a specific period where a pair of SKUs *i* and *j* appears in the same order (see *a* parameter of (8)) to the total number of orders. The ratio is proposed as follows:

$$x_{ij}^1 = \frac{a_{ij}}{a_{ij}+b_{ij}+c_{ij}+d_{ij}} \quad (9)$$

Popularity-based rule. This variable, named x^2_{ij}, accounts the popularity values of SKUs *i* and *j* and evaluates their suitability to share closer locations in the system. The aim of this variable is to give more strength to highly requested SKUs, in lieu of considering as equal the correlation among less demanded and large demanded products.

$$x_{ij}^2 = \frac{(P_i + P_j)}{2 \cdot (a_{ij} + b_{ij} + c_{ij} + d_{ij})} \qquad (10)$$

Turn-based rule. This variable, named x^3_{ij}, accounts the turn values of SKUs *i* and *j* and evaluates their suitability to share closer locations in the system. The insights of this variable entail the best practice to store highly requested products together in the most convenient and accessible warehousing zones. Therefore, SKUs highly correlated in order list but with divergent values of turn are less suitable to be stored together. The proposed ratio aimed to implement this concept.

$$x_{ij}^3 = \frac{min\{T_i, T_j\}}{max\{T_i, T_j\}} \qquad (11)$$

Order-closing-based rule. This variable, named x^4_{ij}, accounts the order-closing values of SKUs *i* and *j* and evaluates their suitability to share closer locations in the system. As for the turn products that commonly close the order they belong to should be stored in the same warehousing zone, likely the most convenient and accessible zone. This approach leads to the configuration of multiple zones and gives some arguments to combine assignment policies and warehouse layout decisions. This variable is represented by the following ratio.

$$x_{ij}^{4} = \frac{min\{OC_i, OC_j\}}{max\{OC_i, OC_j\}} \qquad (12)$$

Compatibility-based rule. This variable, named x^5_{ij}, considers to chance to store in closer locations SKUs with divergent values of popularity whereas their inventory is complementary. In other words, highly correlated products with different value of popularity can be stored together if they hold different level of inventory. Otherwise, a pair of SKUs deserves to be stored together if both products are highly or poorly requested by costumers. Indeed, popular SKUs should be stored together within a quick and accessible zone of the system. Moreover, the most convenient locations are few and the management of space here is more critical than in order areas. Highly correlated SKUs but with divergent values of popularity should not be stored closer to each other. Therefore, the latter variable is defined as follows:

$$x_{ij}^{5} = max\left\{\frac{min\{v_i, v_j\}}{max\{v_i, v_j\}}\right\} \qquad (13)$$

The equation (13) allows combining the decisions on assignment and allocation by considering respectively the compatibility in popularity values and the compatibility in storage volume devoted to SKUs in forward. The insight of this variable is briefly illustrated in Figure 15, where some samples of the implication that allocation and assignment decision as on the picking travel path. Figure 15 shows a pick face, as appears to the pickers, with assignment of more popular and less popular SKUs to the locations. Mindfully, the fraction of storage volume (i.e. level of inventory in forward area) devoted to each SKUs impacts on the overall distance travelled by pickers. The darker SKUs are the most popular, and the correlated assignment policies arrange the pick face according to the level of correlation among SKUs instead of the popularity values. Also the storage volume, represented by the number of squares per each SKU affect the assignment policy.

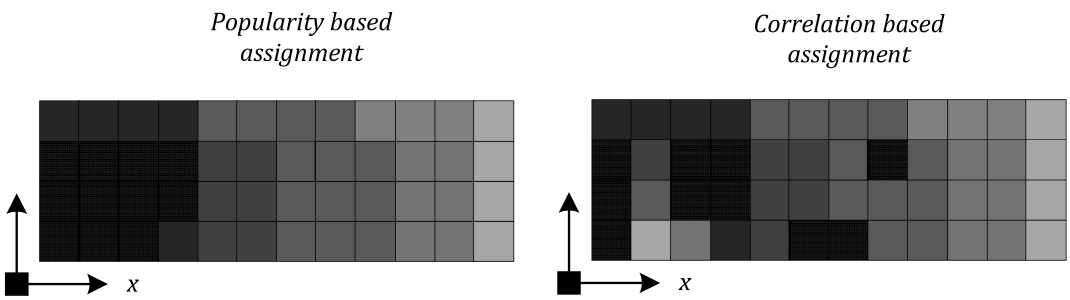


Figure 15. Pick face samples

The proposed similarity metric consists on the products of the previously introduced variable. The decision maker states the adoption of one, two or more variables in accordance with the particular warehouse environment. The procedure tests the effectiveness of each variable in correlating the SKUs. The similarity index is thereby presented:

$$S_{ij} = \prod_{z=1}^{Z} x_{ij}^{z} \qquad (14)$$

The opportunity to implement a set of multiple variables enables to capture which factor mostly influences the correlation of SKUs. Indeed, the procedure compares the grade of correlation obtained by the adoption of one variable a time. The variable able to minimize the overall travel distance for picking operations represents the factor that better matches the implicit correlation in demand profile and in SKUs characteristics.

3.2.3.2.2 Clustering

This second step concerns with the clustering techniques used to form groups of similar SKUs in order to ensure high levels of correlation among the items within the same group, and poor correlation with the others. In particular, three of the most popular hierarchical clustering algorithms are applied in this procedure, that are, the farthest neighbour (fn), also named complete linkage (Clink), the nearest neighbour (nn) also named single linkage (Slink) as proposed by (Aldenderfer and Blashfield 1984), and the unweighted pair-group method using arithmetic average (Upgma), also named average linkage.

These hierarchical algorithms consist on statistics based heuristics aimed to solve clustering problem where parts to be grouped are characterized by similarity metrics. In order to group a set of parts (e.g. machine or SKUs) the algorithm carries out four main steps. The algorithm boots from the similarity matrix which is a matrix composed by the value of similarity of each part (e.g. SKU) with all the others. Table 9 illustrates a sample of a similarity matrix computed among a set of SKUs.

By analyzing the similarity value of such a matrix, the algorithms establish a hierarchy of clusters that step by step include more and more SKUs (i.e. rows of the matrix). The adopted algorithms consider at the begin each SKU belonging to one cluster with population one (i.e. the only SKU) and a similarity value of the cluster equal to 1. Then, the clusters step by step encompass more SKUs experiencing a population rise at despite of a similarity decrease. The process iterates until one single cluster encompasses all the SKUs. In the proposed procedure, the clustering algorithms are based on four main steps:

[1] Similarity matrix creation. This step aims to the selection of a similarity metrics (e.g. general purpose or problem oriented) and the computation of the similarity among each pair of SKUs given an order list of interval of time.

[2] Pair choice. This step aims to the selection of the most similar couple of SKUs present within the similarity matrix. This pair is immediately candidate to be grouped into a unique cluster.

[3] Cluster similarity computation. This steps differs per each of the proposed algorithms. The computation of the value of similarity of the new cluster with the remaining SKUs is necessary to update the previous similarity matrix.

[4] Iterate. This step requires to iterate the step [2] in order to select the next candidates to be grouped. Then, it is necessary to iterate further the step [3], until one single cluster encompasses all the SKUs.

In follows, three different algorithms are applied as sample to the similarity matrix of Table 9. The difference among them is at step [3], where three different approaches in computing cluster similarity are implemented. All algorithms begins with the calculation of the similarity matrix, give a selected similarity index.

	SKU 1	SKU 2	SKU 3	SKU 4	SKU 5
SKU 1	1				
SKU 2	0.5714	1			
SKU 3	0.8889	0.75	1		
SKU 4	0	0.75	0.3333	1	
SKU 5	0.75	0.5714	0.5714	0.5714	1

Table 9. Similarity matrix sample

3.2.3.2.2.1 Clink algorithm

The value of similarity of a generic cluster with all the other parts of the similarity matrix is given by the minimum value of similarity that the parts belonging to the cluster have with the other parts. According to the clustering procedures at step [2] the first candidate for grouping are SKU 1 and SKU 3 since they have the maximum value of similarity.

	SKU 1-SKU 3	SKU 2	SKU 4	SKU 5
SKU 1-SKU 3	1			
SKU 2	0.5714	1		
SKU 4	0	0.75	1	
SKU 5	0.5714	0.5714	0.5714	1

Table 10. Clink iteration 1

Step [3] enters in the main process of clustering by computing the similarity value of the generated cluster with all the remaining products. The Clink algorithm computes these values as the minimum value of similarity that each cluster member has with the other SKUs. As instance, the give the cluster SKU 1-SKU 3 the similarity value of SKU 2 with the new cluster is given by the minor value between 0.5714 and 0.8889. The clustering procedure iterates step [2] and step [3] building more and more populate clusters as illustrated in Tables 10, 11, 12.

	SKU 1-SKU 3	SKU 2-SKU 4	SKU 5
SKU 1-SKU 3	1		
SKU 2-SKU 4	0	1	
SKU 5	0.5714	0.5714	1

Table 11. Clink iteration 2

Whenever there are two or more equal similarity values, the procedure chooses randomly which is the SKU to be included. The last procedure iteration leads to a two-rows, two-columns similarity matrix where the remaining clusters attempt to be grouped with a similarity value equal to zero.

	SKU 1-SKU 3-SKU 5	SKU 2-SKU 4
SKU 1-SKU 3-SKU 5	1	
SKU 2-SKU 4	0	1

Table 12. Clink iteration 3

3.2.3.2.2.2 Slink algorithm

The value of similarity of a generic cluster with all the other parts of the similarity matrix is given by the maximum value of similarity that the parts belonging to the cluster have with the other parts. This algorithm aims to promote the clustering process computing similarity values of clusters higher than the Clink. According to the clustering procedures at step [2] the first candidate for grouping are SKU 1 and SKU 3 since they have the maximum value of similarity, but hereby the similarity values change.

	SKU 1-SKU 3	SKU 2	SKU 4	SKU 5
SKU 1-SKU 3	1			
SKU 2	0.75	1		
SKU 4	0.3333	0.75	1	
SKU 5	0.75	0.5714	0.5714	1

Table 13. Slink iteration

3.2.3.2.2.3 Upgma algorithm

This algorithm represents the proper combination of the benefits of the previously proposed. The value of similarity of a generic cluster with all the other parts of the similarity matrix is given by the average value of similarity that the parts belonging to the cluster have with the other parts. Let consider R and S clusters of SKUs, then the similarity values between them is given by (15):

$$S_{RS} = \frac{1}{r \cdot s} \sum_{i=1}^{r} \sum_{j=1}^{s} S[x_i, x_j] \qquad (15)$$

where (r) and (s) are respectively the number of parts belonging to cluster R and S, and (x_i) and (x_j) are respectively the *i*-th and *j*-th elements of cluster R and S.

According to the clustering procedures at step [2] the first candidate for grouping are SKU 1 and SKU 3 since they have the maximum value of similarity, but hereby the similarity values change.

	SKU 1-SKU 3	SKU 2	SKU 4	SKU 5
SKU 1-SKU 3	1			
SKU 2	0.6607	1		
SKU 4	0.16665	0.75	1	
SKU 5	0.6607	0.5714	0.5714	1

Table 14. Upgma iteration

As instance, the value of similarity between the SKU 2 and the new generated cluster is given by 0.6607 = (0.75 + 0.5714) / 2.

3.2.3.2.2.3 Dendrogram

The dendrogram is a graphic representation of the clustering process. Figure 16 shows a brief sample of the characteristics of such graphs. On the *x* axis the similarity value decreases from a value of 1 to 0, whilst on the *y* axis all the SKUs appears. At the beginning, each SKU represents one cluster, until the clustering process groups two SKUs in one node (i.e. clustering node). The process iterates until the similarity achieves value of 0 and all SKUs belong to the same clusters.

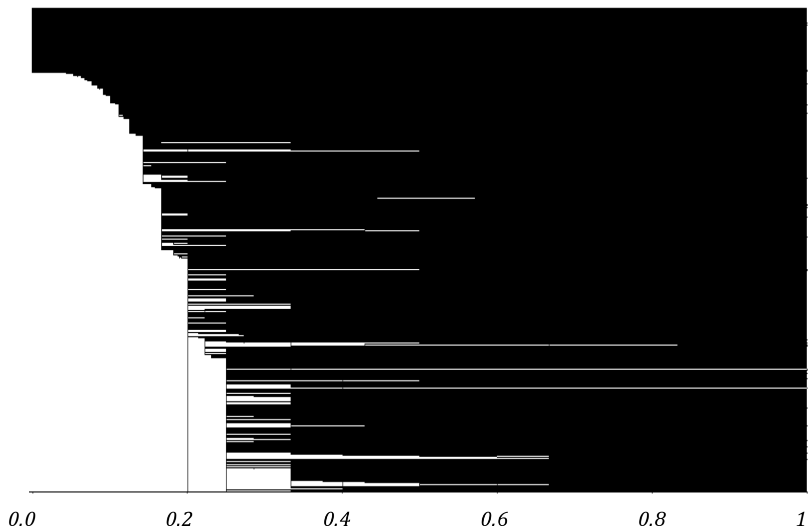


Figure 16. Dendrogram

At certain step, the continuous clustering process should be break up in order to configure which clustering nodes are considered to group products. The similarity threshold value is the similarity value that breaks the clustering process and allows forming the clusters, which have a similarity value at least equal to the selected cut-off threshold.

The results of the correlated assignment depend on the minimum admissible level of correlation adopted for the generic group of clustered items. Consequently, the choice of a threshold group of correlation measurement strongly influences the number and configuration of the clusters of products, that is, the partitioning of the whole set of items (product mix). In this paper a percentile-based threshold value of similarity, following named $T_{value\%}$, is adopted.

This value corresponds to a range of group similarity measurements and cuts the dendrogram at the percentile number of the aggregations (nodes of the dendrogram in Figure 16) identified by the adopted clustering rule, as follows:

$$T_{value\%} \in \left] L\{\lceil \%_p \cdot N \rceil\};\ L\{\lfloor \%_p \cdot N \rfloor\} \right] \qquad (16)$$

where (N) is the number of aggregations necessary to obtain one cluster starting from a number of clusters equal to the number of products, each cluster being composed of a single product. The term $(\%_p)$ is the percentile of aggregations, expressed as a percentage of the whole set of aggregations as generated by the process of grouping graphically visible in the dendrogram.

As instance, the value of percentile $\%_p$ = 100° percentile corresponds to the last admissible grouping which generates a single cluster with the worst, (i.e. the lowest, value of similarity). The term L{A} is the similarity value which corresponds to the A grouping/clustering (i.e. the A node given N nodes). Different values of $\%_p$ generate a different number and configuration of clusters.

The percentile-based similarity cut-off allows overcoming the criticalities of value-based similarity cut-off since the latter the arbitrary decision of the decision maker is affected by the type of adopted algorithms. Conversely, the percentile-based approach enables the comparison of the three proposed algorithms assessing their different performance in clustering SKUs, and thereby reducing the travel distance for picking operations.

3.2.3.2.3 Cluster assignment

Given the configuration and the population of generated clusters, the assignment of locations in forward area is determined by the adoption of appropriate criteria. At this step, the previously mentioned classifying metrics (i.e. P, T, COI and OC) are computed not for each SKU but for each cluster of SKUs according to the rules illustrated in Table 15.

Index	Value		Ranking
Cluster based (CB)	$CB_c = \sum_i x_{ic}$	(17)	↑
Cluster similarity based (CBS)	$CBS_c = L\{N_c\}$	(18)	↓
Cluster based & P (CB&P)	$CB\,\&\,P_c = \sum_i P_i \cdot x_{ic}$	(19)	↓
Cluster based & COI (CB&COI)	$CB\,\&\,COI_c = \sum_i \frac{s_i}{P_i} \cdot x_{ic}$	(20)	↑
Cluster based & T (CB&T)	$CB\,\&\,T_c = \sum_i \frac{f_i}{s_i} \cdot x_{ic}$	(21)	↓
Cluster based & OC (CB&OC)	$CB\,\&\,OC_c = \sum_i OC_i \cdot x_{ic}$	(22)	↓

x_{ic} *SKU-Cluster incidence matrix;*
↑/↓ *increasing/decreasing ranking*

Table 15. Correlated assignment rules

In particular, the adopted assignment rules combine the computation of metrics for the clusters, and then define the ranking of priority to be matched with the ranking of convenient locations, as follows:

- Cluster based assignment rule (CB). This rule arranges clusters by increasing number of SKUs contained and assigns the lowest of them to the most convenient locations.
- Cluster and similarity based assignment rule (CBS). This rule arranges cluster by decreasing value of similarity at which they are grouped by the clustering process. Then, the CBS rule assigns the most similar clusters to the most convenient locations. The argument for such method is that highly correlated clusters contains products which are always, at least often, requested together and the practice to store them in the favorite locations might reduce the total travel distance for picking.
- Cluster and popularity based assignment rule (CB&P). This method estimates the popularity of each group of items as the total number of picks addressed by the SKUs belonging to that specific cluster. This rule arranges clusters by decreasing popularity and assigns the most visited to the most convenient locations.
- Cluster and COI based assignment rule (CB&COI). This rule estimates the COI value of each group of items as the average COI of those SKUs belonging to that specific cluster. This rule plans to sort clusters by increasing value of COI and assigns the lowest of them to the most convenient locations.
- Cluster and order completion based assignment rule (CB&OC). This rule arranges clusters as for CB&P rule but uses OC instead of P values.
- Cluster and turn based assignment rule (CB&T). This method sorts clusters as for CB&OC rule but using the Turn index instead of OC values.

This section defines the proper location of each SKU within the fast pick area. Different sets of operations constraints, concerning with the side of shipping and receiving docks and the aisles visiting strategies (e.g. return or traversal), are considered in order to define a list of priority that ranks the available locations per grade of convenience. The proposed hierarchical procedure matches this list of locations with the lists of SKUs or clusters according to the ranking illustrated in Table 6 and Table 15.

3.2.4 Operations configuration issue

This section deals with the definition of the picking routines and best practices performed by pickers during the picking tours. Indeed there is an implicit agreement in industry according with the faster-moving SKUs are stored in the most convenient locations. Unfortunately, a more critical question arises: what is a convenient location?

The definition of the convenient locations depends of the positions of shipping and receiving docks and the method to visit aisles. At first, the distance travelled to pick a product from a location is determined by the travel from receiving dock to the location and, later, the travel from location to shipping dock. On the other hand, it is determined on the bases of the opportunity to visit aisle in one (i.e. traversal mode) or double directions (i.e. return mode). In the first way, the picker travels until the end of the aisle since it is not allowed to change routing direction. The return way enables to turn direction within the aisle since the aisle are wider. The average value of distance travelled by picker whenever the SKU associated to that particular location is requested and is a significant metric of the convenience.

In unit-load warehouses, the cost is independent of what is stored in other locations and so, if location *(x,y)* is visited P_i (i.e. popularity) of SKU_i in the horizon of time and the variable x_{xyi} is equal to 1 if SKU_i is assigned to location *(x,y)*, the total picking labor costs is proportional to:

$$\sum_{x=1}^{X}\sum_{y=1}^{Y} d_{xy} P_i \, x_{xyi} \qquad (23)$$

In less-than-unit-load warehouses, the picking tour if typically composed by a list of locations to be visited, therefore the cost accounted by each locations in terms of travelled distance is difficult to assess. The problem here entails concerns about both layout and routing decisions. Indeed, the decision on the proper location to assign to a SKU does not univocally affect the travelled distance, which is also significantly influenced by the routing strategies. Nevertheless, the value of distance d_l is a rough metric of the convenience of picking one item form that location also in a dedicated storage OPS.

The proposed top-down procedure at this step considers the sorting resulting from allocation and assignment phases and performs the following points:

- Rank all the available storage locations of the warehouse from the least cost dl (i.e. more convenient) to the greatest cost (i.e. less convenient).

- Rank all the SKUs according to the adopted criteria of allocation and assignment policies.
- Slide down the list, assigning the proper quantity of the next-in-list SKU, to the proper number of required storage locations.

As previously argued, the layout of the warehouse determines the cost associated with each storage location. As instance, when receiving and shipping docks are located at opposite sides of the warehouse, typical flow-through configuration, there are many locations of equal convenience since the path from the bottom to the top of the system is obliged. Conversely, should be enquired what would happen if the shipping and receiving doors are both moved to the right side of the system. The storage locations to the left would become less convenient than those in the right. Anyway, the convenience of the latter would not improve, while the quality of the very worst locations would become strictly worse.

WH	*Routing*	
	Return	*Traversal*
A	$d_{xy} = \left((MBlenght \cdot Y) + (MBwidth \cdot X)\right)$	$if\ (x\ mod\ 2 = 1) \begin{cases} then\ d_{xy} = (MBlength \cdot Y) + (MBwidth \cdot X) \\ else\ d_{xy} = (MBlength \cdot Y) \cdot 3 + (MBwidth \cdot X) \end{cases}$
B	$d_{xy} = \left((MBlenght \cdot y) + (MBwidth \cdot x)\right) \cdot 2$	$d_{xy} = \left((MBlenght \cdot Y) + (MBwidth \cdot x)\right) \cdot 2$
C	$d_{xy} = (MBlenght \cdot y) \cdot 2 + (MBwidth \cdot x) \cdot X$	$d_{xy} = (MBlength \cdot y) \cdot 2 + (MBwidth \cdot X)$
D	$d_{xy} = \left((MBlenght \cdot y) + (MBwidth \cdot x) \cdot \left\lvert\frac{X}{2} - x\right\rvert\right) \cdot 2$	$d_{xy} = \left((MBlength \cdot Y) + \left(MBwidth \cdot \left\lvert\frac{X}{2} - x\right\rvert\right)\right) \cdot 2$
E	$d_{xy} = MBlength \cdot Y$	$if\ (x\ mod\ 2 = 1) \begin{cases} then\ d_{xy} = (MBlength \cdot Y) \\ else\ d_{xy} = (MBlength \cdot Y) \cdot 3 \end{cases}$
F	$d_{xy} = \left((MBlenght \cdot Y) + (MBwidth \cdot x) \cdot \left\lvert\frac{X}{2} - x\right\rvert\right) \cdot 2$	$if\ (x\ mod\ 2 = 1) \begin{cases} then\ d_{xy} = (MBlength \cdot Y) + \left(MBwidth \cdot \left\lvert\frac{X}{2} - x\right\rvert\right) \cdot 2 \\ else\ d_{xy} = (MBlength \cdot Y) \cdot 3 + \left(MBwidth \cdot \left\lvert\frac{X}{2} - x\right\rvert\right) \cdot 2 \end{cases}$
G	$d_{xy} = \left((MBwidth \cdot x) + \left\lvert\frac{X}{2} - MBlength\right\rvert \cdot y\right) \cdot 2$	$d_{xy} = (MBwidth \cdot x) \cdot 2 + (MBlenght \cdot Y)$
H	$d_{xy} = \left(\left\lvert\frac{X}{2} - MBlength\right\rvert \cdot y\right) \cdot 2$	$d_{xy} = (MBlenght \cdot Y)$

Table 16. Single Command distances (see Figure 17 for WH configuration)

If both receiving and shipping are on the same side of the system, typical U-through configuration, there are fewer convenient locations, but with a high grade of convenience.

According to Bartholdi and Hackman (2011) the flow-through configuration makes many locations of equal convenience and is more appropriate for extremely high-volume systems, especially when building is long and narrow. Conversely, the U-through, making most convenient location more convenient is suitable for ABC skew product movements.

Table 16 reports the equations (i.e. from (24) to (39)) of the travelled distance addressed to each location of all system configurations and cases implemented in the top-down procedure. The x and y coordinates represent the progressive base modules accounted on both layout sides. The maximum number of base modules are respectively X and Y.

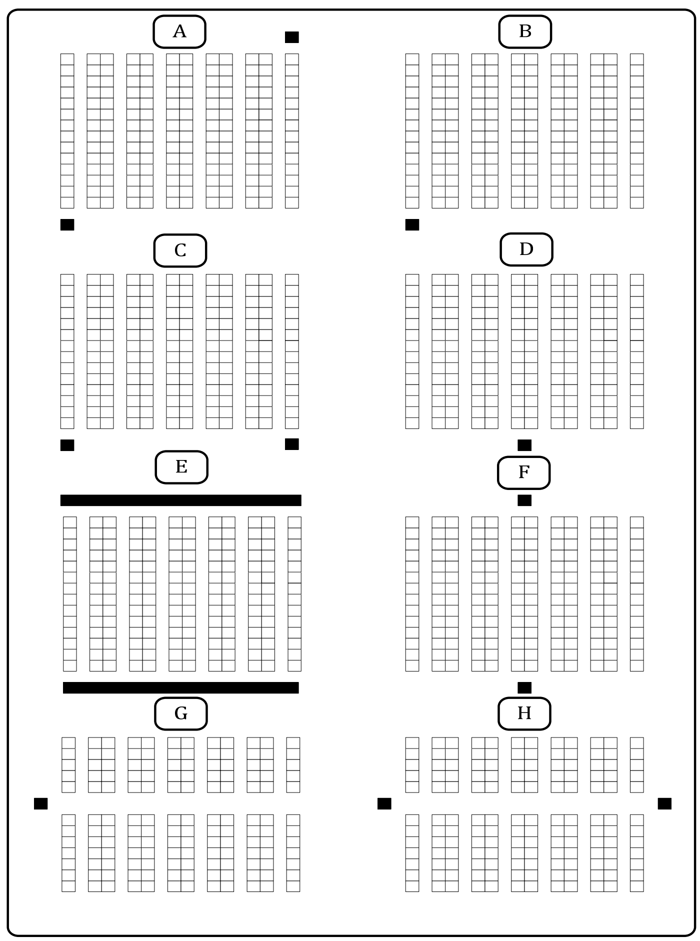


Figure 17. Layout configuration

In particular, the main distinction is between the aisle visiting strategy (i.e. return and traversal), then all possible shipping and receiving docks layout are taken into account. Figure 17 presents some birdviews of different configurations of the warehouse where shipping and receiving are represented by dark dots. Distance costs are computed as rectangular path (on x and y dimensions) from receiving to each location and then from the location to the shipping side. Let assume the warehouse as a scalar reproduction of a discrete number of modules (i.e. bay or base module) in both size (i.e. length and width) of the layout. Therefore, the computation of rectangular travel distance to achieve each bay or storage location is given by multiplying the length and width of the base module by the number of modules in both directions.

3.2.4.1 Zoning

The hierarchical top-down procedure implements the allocation strategies and the assignment policies of a set of SKUs in order to establish their behavior in the warehousing system. The definition of the proper storage quantity and the proper location per each SKU in a zone represent micro-warehousing concerns. Over a macro-warehousing perspective, the management, design and configuration of the warehouse zones play a crucial role on the definition of flows among zones, the arrangement of picking operations and the overall system performances.

In particular, in the proposed approach the main distinction among zones is recognized as the holding capacity and the characteristics of the rack and the storage mode. Different zones hold different classes of SKUs distinguished in particular for the size of unit load and the characteristics of the storage rack they require.

Therefore, different zones handle different subset of SKUs and manage their allocation and assignment within different storage rack. The characteristic and sizes of different racks configure the pick face in the different way. An high-density zone includes small items, stored in pieces and cartons, and a huge number of different SKUs is stored per bay. A low-density zone include big and heavy items, stored in pallet or in plastic, steel or wood container or cases, and little group of different SKUs can be stored per bay.

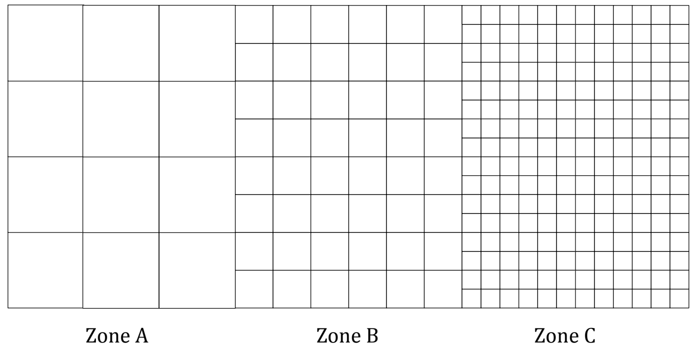


Figure 18. Different zoning configuration

Figure 18 briefly represents the concept over the zoning approach implemented in the proposed top-down design procedure. Three different zones are places next to each other assuming the shipping and receiving docks at the same side. Different squares indicate different sizes and dimensions of the storage racks zone by zone.

The aisle width, the number of locations per bay, the shelves level per bay, the rack level, the number of bays, the presence and width of a cross aisle are decisions to be taken per each zone at the layout issue step. The zoning involves the management of a multiple-zones system with inter material flows among them.

3.2.4.2 Routing

The problem of routing pickers through a set of locations as quickly as possible is a particular form of the TSP, in which travel is constrained by aisles and other layout concerns. Even though this problem in widely discussed by literature, and researchers propose many useful tools and algorithms to solve it, most warehouse management systems (WMSs) do not support pick-path optimization beyond simple sorting of locations. There are several reasonable reasons for this, but the most significant is that optimum-finding algorithm must know the geometry of the layout, including distance between every pair of locations, which is a information detail very hard to maintain (especially in manual OPS). Another problem is the cost of the communication tools or equipments allowing to support pickers during the picking tour.

The proposed top-down procedure does not enter in detail in this topic but provides one simple heuristic, given a proper aisle visiting strategy (i.e. return or traversal). This heuristic performs as follows:

- Step [1]. The picking list is sorted by increasing distance from the receiving docks, or any other tour starting point.
- Step [2]. Given the first location, the procedure enumerates the available destinations and picks the closer one, by adopting the nearest neighbor method.
- Step [3]. This step iterates the Step [2] until the last location of the order is achieved.

This simple heuristic approach provides good results in terms of traveling reduction and computation time, so that is potentially suitable for every real instances and applications. Other heuristics and useful algorithm are discussed in Ratliff and Rosenthal (1983) and Bartholdi and Hackman (2011).

3.2.4.3 Batching

In order to reduce the total traveling for picking mission the order-batching represents a good opportunity. The batch of order is handled in the proposed warehousing design and management procedure through the adoption or clustering techniques able to match and combine orders requiring for similar SKUs.

The steps, the clustering algorithms and the cut-off thresholds are the same presented in Chapter 3.2.3.2.2., but an original similarity problem-oriented metric adopted to assess the correlation among order is introduced as follows.

Accorsi & Maranesi (2012)

This problem-oriented similarity metric integrates the general-purpose McAuley index and includes a factor, which considers the costs of adding distance experienced by the picker during pick-path. Indeed, considering a couple of orders to be batched, this metric multiplies the McAuley index by the ratio of the permutations of SKUs not belonging to both orders but placed in the same aisle, to the permutations of SKUs not belonging to both orders. This roughly measures the cost payed by the picker in terms of travelling if the couple of selected orders is grouped in the same picking tour. Considering the parameters previously defined (see Chapter 3.2.3.2.2) the Accorsi & Maranesi batching similarity metric is proposed for orders *i* and *j* as follows. Let (a) be the number of items belonging to both orders, (b) and (c) the number of items belonging respectively just to order *i* and order *j*, *I(i)* the group of items *s* belonging to order *i* (i.e. $s \in I(i)$), l_s the location of items s and *A(l)* the group of generic locations within the same aisle A, and finally $p(I(i), I(j))$ the permutations of all the items s belonging to order i with those belonging to order j.

Therefore, the index is defined in equation (40):

$$S_{ij} = \begin{cases} \frac{a_{ij}}{a_{ij}+b_{ij}+c_{ij}} \cdot 1, & if\ p\big(I(i), I(j), \forall\ s \in I(i) \neq s \in I(j)\big) = 0 \\ \frac{a_{ij}}{a_{ij}+b_{ij}+c_{ij}} \cdot \left(1 - \frac{b_{ij}+c_{ij}}{a_{ij}+b_{ij}+c_{ij}}\right), & if\ p\big(I(i), I(j), \forall\ s \in I(i) \neq s \in I(j): l_{s\in I(i)}, l_{s\in I(j)} \in A(l)\big) = 0 \\ \frac{a_{ij}}{a_{ij}+b_{ij}+c_{ij}} \cdot \frac{p\left(I(i), I(j), \forall\ s\in I(i)\neq s\in I(j): l_{s\in I(i)}, l_{s\in I(j)} \in A(l)\right)}{p\left(I(i), I(j), \forall\ s\in I(i)\neq s\in I(j)\right)}, & Otherwise \end{cases} \quad (40)$$

The index consists of three different terms. The first is the McAuley index, as originally proposed, if the number of permutations of items not belonging to both orders is equal to zero. In other words, this metric is equal to McAuley index when the two orders are similar for every required SKU. The second term attempts to correct McAuley by reducing the similarity value when the number of SKUs (i.e. storage locations to be visited) belonging to just one of the order is high. The third term is the core of the index and upgrades the McAuley index with a ratio given by the number of permutations of items not belonging to both orders but placed in the same aisle, to the total number of permutations of the items not belonging to both orders. In other words, the value of similarity between two orders is reduced if the number of adding aisles to be visited to fulfill the batch order is high.

As instance, let consider the following numerical example, illustrated in Figure 19. The order i is composed by the group of items or storage locations$\{a, b, c, d\}$, whilst order j encompasses$\{a, b, e, f\}$.

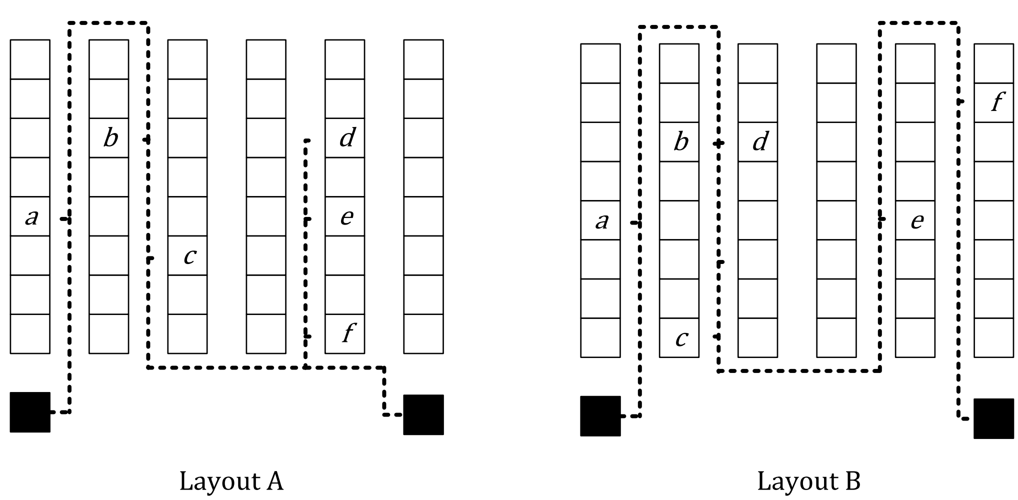


Figure 19. Routing samples

Given these two layout configurations (i.e. layout A and layout B) the parameters necessary to compute the Accorsi & Maranesi index (2012) assume the following values reported in Table 17.

Layout A	Layout B
$a_{ij} = 2$	$a_{ij} = 2$
$b_{ij} = 2$	$b_{ij} = 2$
$c_{ij} = 2$	$c_{ij} = 2$
$if\ p\big(I(i), I(j), \forall\ s \in I(i) \neq s \in I(j)\big) = 4$	$if\ p\big(I(i), I(j), \forall\ s \in I(i) \neq s \in I(j)\big) = 4$
$p\big(I(i), I(j), \forall\ s \in I(i) \neq s \in I(j): l_{s \in I(i)}, l_{s \in I(j)} \in A(l)\big) = 2$	$p\big(I(i), I(j), \forall\ s \in I(i) \neq s \in I(j): l_{s \in I(i)}, l_{s \in I(j)} \in A(l)\big) = 0$
$S_{ij} = \frac{2}{6} \cdot \frac{2}{4} = 0.16667$	$S_{ij} = \frac{2}{6} \cdot \left(1 - \frac{2}{3}\right) = 0.11111$

Table 17. Similarity value comparison

This sample briefly demonstrates the potential of the introduced metric compared with general purpose McAuley similarity metric, which would account $S_{ij} = 0.3333$. The purpose of the introduced similarity metrics is to consider the costs of order batching to comply changes in picking tour.

The warehousing top-down design procedure adopts this problem-oriented similarity metric, then implements a correlated orders batching day by day for a specific horizon of time.

The procedure is applied to a real case study in order to define the best design and management warehousing practices involving allocation, assignment, layout, routing and batching concerns and issues.

3.3 Warehousing design procedure. A Case study

The proposed hierarchical approach for the design and management of OPS is applied to a low level picker-to-part system for spare parts of heavy equipment and complex machinery in a popular manufacturing company operating worldwide (i.e. Caterpillar Inc.).

The total number of SKUs stored and handled is 185,000 but this is continuously growing. Consequently, the company is facing new problems in optimizing the warehousing system and reducing both logistic costs and time for picking activities.

The subject of the analysis is the picking activities concerning medium-sized parts weighing less than 50 pounds per piece. These parts are stored in light racks containing more than 3,000 different items.

The horizon time for the analysis embraces the order profile data during 4 months. The number of order picking lines is 37,000 that correspond to 6,760 different customer orders. The picking list presents an average of 86 orders fulfilled per day with the average depth varying around 6 items per order.

This section illustrates an experimental analysis for the identification of the most significant factors affecting travelling and logistic costs to retrieve OP lines. The adopted factors and levels subjected to a what-if multi-scenario simulation analysis are a sub-set of the proposed top-down hierarchical procedure. In particular:

- Three levels of storage quantity in the fast pick area in accordance with the previously illustrated strategies: EQS, EQT, and OPT.
- Nine different storage assignment rules: P, COI, OC, T, CB, CB&P, CB&COI, CB&OC, and CB&T.
- One similarity index: McAuley (1972).
- Two clustering algorithms: Slink and Clink.
- Three percentile threshold cut values of similarity: 40°, 60°, and 75°.

Therefore, the combination of the presented factors and levels enables the simulation of about two hundred different OPS design alternative scenarios, whose main performances are illustrated and compared as follows. The following sections present the results of the adoption of the proposed top-down procedure for the design and the performance assessment of real case warehouse system. The procedure builds a virtual warehouse, replacing the features, layout and characteristics of the original one, then adopts the combination of several allocation and assignment rules in order to enquire the role they play in enhancing picking performances.

3.3.1 Results

The result of the design of the OPS is a 58,400 square foot picking area. This virtual system holds the inventory of products stored in the original warehouse, replacing the proper number of bays, of aisles, the aisle with, the size of bay and rack, the level of rack.

Table 18 shows how OPT allocation strategy significantly reduces the number of restocks for the historical period of analysis. The reduction is about 55% compared to EQS, and about of 62% compared to EQT, thus confirming the effectiveness of OPT to minimize the total replenishments of the forward area. Nevertheless, the maximum reduction of restock costs does not supports necessary the maximum reduction of global travelling costs. This happens, in particular, in cartons picking by pallets OPS, where the forward area is represented by the low levels of storage racks, the storage locations are held by pallets and the fluid approach is not consistent.

	Allocation strategies					
	EQS		*EQT*		*OPT*	
	Restock	% Red.	Restock	% Red.	Restock	% Red.
	3,650	55.2%	4,269	61.7%	1,635	
Assignment rules	Travelled distance	Aisles crossed	Travelled distance	Aisles crossed	Travelled distance	Aisles crossed
CB&COI	6,733,114	33,709	6,883,564	34,337	7,182,665	34,635
CB&OC	7,905,437	34,288	8,473,296	35,645	8,301,692	35,158
CB&P	6,637,216	33,668	8,006,006	35,570	7,267,113	34,978
CB&T	9,131,562	35,671	8,888,392	35,507	9,249,124	35,749
CB	8,321,296	35,155	8,504,489	35,725	8,510,031	35,502
COI	**6,314,459**	**33,579**	6,425,585	33,659	6,706,537	34,482
OC	6,536,697	33,922	8,047,296	36,210	7,241,533	35,424
P	6,379,887	33,713	7,254,318	35,270	6,869,774	34,655
T	8,015,507	35,766	8,155,378	36,191	8,717,042	36,497

Table 18. Sample results

Furthermore, Table 18 reports the results in terms of travelled distance (in [feet]) and crossed aisles, as a metric of congestions within the forward area, for picking operations obtained by a simulation analysis on different settings of the warehousing system. The combination of allocation strategies and assignment rules is carried out at this step through a multi-scenario what-if analysis. This analysis takes into account the following factors and levels: three allocation strategies (EQS, EQT, and OPT) and nine assignment rules (COI, P, OC, T, CB, CB&COI, CB&P, CB&OC, and CB&T).

Table 18 shows that COI and P assignment rules aims to reduce total travelling due to picking. In particular, the best performance is obtained through a combination of COI assignment rule and the EQS allocation strategy. Obviously, this result complies just the proposed case study, but more in general highlight the fact that in a complex carton-picking OPS the adoption of different allocation strategy, to establish the storage quantity to devote low level to each SKU, also affect the traveling of pickers.

Indeed on one side, OPT minimizes the overall replenishment, but might not be the most performing strategy to reduce travelled distance and time due to picking operations at all. In Section 3.3.1.2, this effect is treated and discussed by considering the consequence of the proposed combined approach on the total overall travelling due to both picking and restocking operations.

3.3.1.1 Allocation strategies & correlated assignment

This section summarizes the most meaningful results obtained by adopting a set of allocation strategies in particular with the previously introduced correlated storage assignment policies. The reported graph (see Figure 20) is an interaction plot of the combined influence of scenario parameters on the travelled distance for picking missions.

Figure 20 shows, in the plot combining allocation and assignment policies, how given an assignment rule attempting to set the location off all SKUs, the traveling performance are even and significantly affected by the choice of the quantity to devote to each item (i.e. allocation decision). Indeed, the combination of space concerns (i.e. allocation) and time concerns (i.e. assignment) provides real and sensible effects on distance travelled by pickers. This concept is an unexpected result.

As instance, EQS performs significantly better than both OPT and EQT allocation strategies when combined with CB&P, CB&COI, or CB&OC assignment rules. Furthermore, EQT strategy provides the best performance in terms of picking travelling when combined with CB&T assignment rule. Finally, the three allocation strategies produce more or less the same travelling due to picking when the CB rule is applied, which demonstrates that such rule is not particularly suitable for the management of the analyzed system. The impact of interdependency between allocation and assignment, as well as between space and time efficiencies, is evident with CB&P assignment rule with huge difference of the travelling due to the adoption of the three allocation strategies.

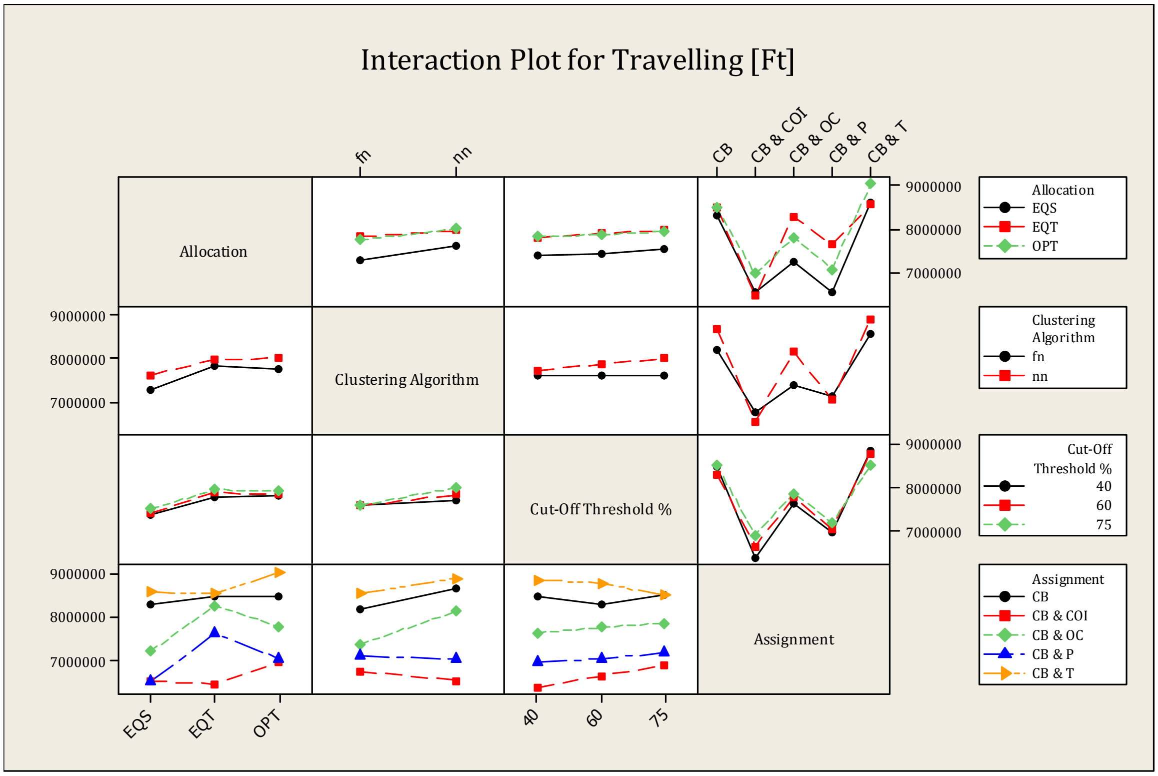


Figure 20. Results interaction plot

Others insights from this graph regard the behavior of clustering algorithm and similarity threshold percentile cut-off on the traveling performance. Figure 20 shows how Slink clustering algorithm (i.e. farthest neighbor) decreases the travelling for picking compared with Clink (i.e. nearest neighbor). A likely motivation for such result consists on the fact that Slink algorithm is more precautionary since assigns a little value of similarity to grouped clusters, and given percentile cut-off value ensures a more similar and homogeneous clusters. Further researches are expected to find general results. Furthermore, a percentile threshold similarity cut value of 40°, which only considers the first 40% of aggregations of items in the clustering agglomerative process, fits better the proposed case study (see Figure 20). All these results are strictly significant for the case study object of the what-if analysis, but represent some arguments to assess the effectiveness of the proposed top-down hierarchical procedure in managing real warehouse.

4.1.2 Allocation strategies & picking operations

This section mainly focuses on the effects due to the combination of allocation strategies and assignment rules in the same systematic approach, and their influence on the overall travelling due to both picking and restocking operations.

As previously illustrated, considering just picking travelling, the management of storage space set by OPT leads to poorer performances than the other allocation strategies (see Table 18). The OPT assigns the proper inventory level necessary to minimize the overall number of replenishments. The SKUs can be divided into two sets by comparing these optimal levels with those proposed by another strategy, e.g. the EQS strategy: the first set refers to the products whose inventory level increases when EQS is replaced by the OPT strategy; the second set groups the SKUs whose level decreases. Indeed, different allocation strategies differently arrange the SKUs population in filling the available storage volume. The management of storage space in forward area is strictly dependent by this choice.

As instance OPT strategy devotes major volume to the most retrieved SKUs and arranges their CGs (i.e. centers of gravity) within the rack further away from the shipping and receiving docks, so that, on average, operative costs and time for picking increase. Figure 21 presents a schematic illustration of the effects on the locations and distances generated by different allocation strategies.

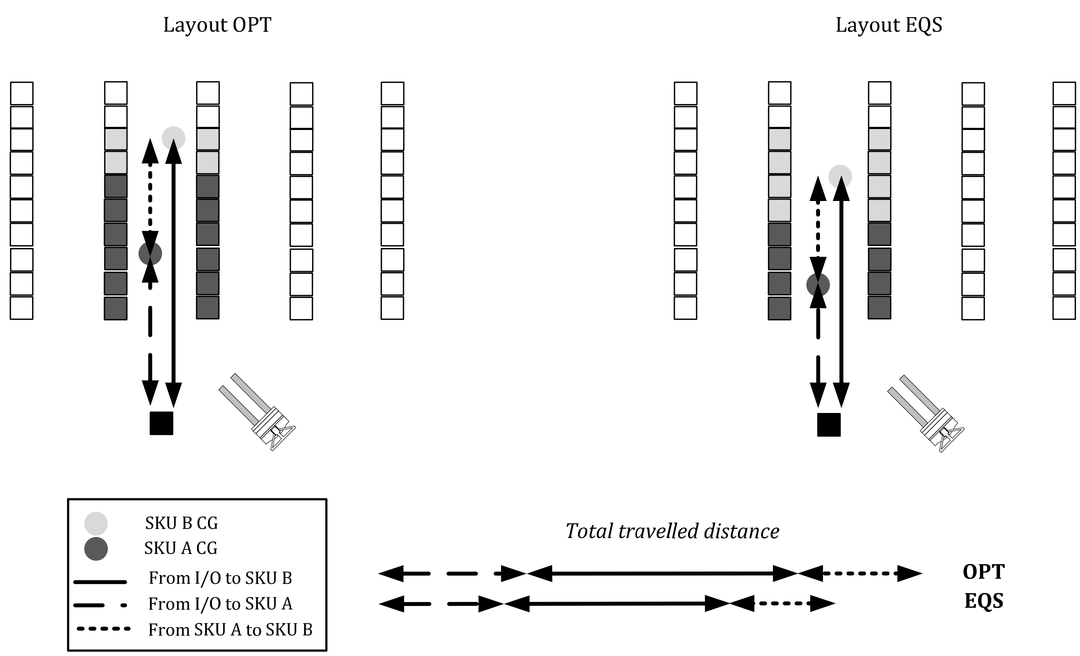
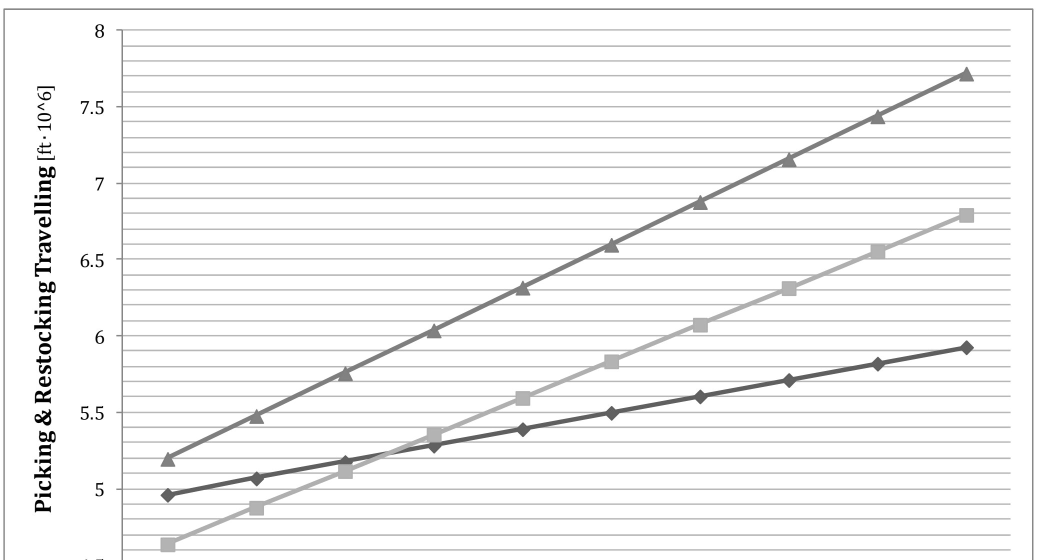


Figure 21. Allocatio influences on traveling

In order to quantify and control the overall travelling distance made for picking and restocking activities a new objective function has been introduced: it is made of two different but very closely related terms. These terms are: (1) the travelling costs due to restocking from bulk area to the forward area, and (2) the travelling costs due to picking within the forward area.

A what-if multi-scenario analysis for the evaluation of these combined contributions is carried out. Aimed to address this purpose, the parameter reported in Figure 22, named "AVG Cost of Restock", is introduced. It is the average cost in terms of travelled distance due to a restock complied by a worker, the so-called "re-stocker", within the warehousing system. We assume that this distance is closely related to the proportion of the shipping/receiving side of the pick area (i.e. the total distance in feet between the first and the last aisle of the forward area) that needs to be travelled, and we use this ratio as a rough metric of the weight of each restocking route. The larger the warehouse area, the higher the cost of travelling due to the restock of a location is.



	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
OPT	4.960881	5.068164	5.175448	5.282731	5.390015	5.497298	5.604582	5.711865	5.819149	5.926432
EQS	4.637132	4.876634	5.116135	5.355636	5.595138	5.834639	6.074141	6.313641	6.553143	6.792644
EQT	5.196079	5.476197	5.756315	6.036433	6.316551	6.596669	6.876788	7.156906	7.437024	7.717142

Figure 22. Overall performances

For example, let assume that the AVG Cost of Restock is 50%: it means that the average travelled distance to restock is a half part of the length of the shipping/receiving dock. Given the observed period, i.e. 4 months, the total cost of restocking is the overall number of restocks, evaluated in Table 18, multiplied by this average distance.

In this case study, Figure 22 shows that when the weight of restocking operations is little in travelled distance, i.e. under 30% in the graph, the EQS allocation strategy performs better than EQT and OPT and minimizes the total travelling costs due to both picking and restocking activities. Otherwise, given a more expensive average restock, the OPT allocation strategy performs better in reducing the overall travelling for operations (i.e. both picking and replenishment). These results are not general but highlights that allocation and assignment issues are significantly correlated and the design and management of a OPS should take them into account evaluating the combined effect on the system performance. Therefore, the proposed and illustrated hierarchical procedure effectively supports the decision making on storage allocation and assignment.

3.4 Conclusions

This chapter is focused on the definition and description of a top-down hierarchical procedure based on multi-decision steps for the design and management of less-than-unit-load OPS. These steps mainly concern with the problem of storage allocation and storage assignment but also include layout issue, routing of pickers, order-batching, etc.

A multi-scenarios what-if simulation analysis is conducted to assess which is the best performing configuration of a specific OPS, as the warehouse proposed in the case study, which is obtained by adopting alternative inventory level for each SKU within the forward area and by assigning those to different locations according to a panel of assignment policies. This analysis attempts to attest the effectiveness of the proposed top-down procedure to address two of the main issues in warehouse system design and optimization: how much of each SKU to store (1) and where are the most suitable locations to store each SKU (2). Furthermore, the procedure allows facing, through a design and simulative approach, the critical existing interdependency between the space allocation and the location assignment in an OPS.

The obtained performance values are not general because they refer to a single case study, but demonstrate that restocking performances might not fit with picking performances in term of travelled distance. Such decoupling of performances in warehouse operations (i.e. picking and restocking) represents a meaningful insight of the proposed analysis.

The proposed top-down procedure implements a set of easy and quick heuristics able to address different stages of operative activities. No optimal algorithms or models are considered since the real instance datasets, accounting hundreds thousands variables, do not fit with computational constraints.

Even though the set of heuristics proposed in the procedure can be implemented case by case with the support of Office Excel worksheets, for better support industry managers, practitioners, and research issues, an informative automatic tool implementing the top-down procedure is necessary. This consists on a computer-based interface able to import real data set, from industry case studies, to implement a list of decisions, to configure the resulting system and to measure the performance of the proposed layout in comparison with the real as-is performance. This is the topic and the goal of Chapter 4.

4. Order-Picking Warehousing. A Tool

Throughout the supply chain, warehousing systems and distribution centres allow to match vendors and demand, to respond to seasonality and change, to consolidate products and arrange shipments, playing a crucial role in reaching efficiency and customer satisfaction. Unfortunately, the warehouse design, in particular with less-than-unit-load OPS, entails a wide set of different decisions, involving layout constraints and operative issues, storage allocation, assignment, routing, order-batching, zoning seriously affecting the performances and the overall logistics costs. The top-down hierarchical procedure illustrated in Chapter 3 aims to organize the heuristic methods and algorithms able to address the overall steps and issue regarding with the design and management of and OPS.

With the purpose to support the application of the procedure to many practice real industry cases, the implementation of a computer-based interface able to collect data and apply methods and algorithms per each decision step is necessary.

This chapter presents an original decision-support tool for the design, management, and control of less-than-unit-load storage systems. In particular, this system implements the proposed top-down procedure in order to test the effectiveness of a joint analysis of warehouse design and warehouse operations concerns. The patterns illustrated in the procedure (e.g. layout, storage allocation, storage assignment, routing, etc.) slides through subsequent user interfaces to support the decision maker in all the system configurations. Indeed, the proposed computer-based platform implements support-decision models analytical methods and algorithms to comply most relevant warehouse issues. Resulting by the adoption of the this decision-support tool is a dashboard of key performance indicators (KPIs) of space and time efficiency allowing warehouse providers, practitioners, managers, as well as academics and educators to tackle real case studies and to pin down useful guidelines in keeping control of a storage system.

The remainder of the chapter is organized as follows. First section presents a brief literature review of decision-support tool for warehousing management. Then the developed DST is described through sub-sections dealing with the system architecture, the graphic user interfaces (GUIs) and the tool modules and the information and data flow. Final section discusses the conclusions and gives indications for further research.

4.1 Tips from literature

Nowadays the development of advanced and globalised market compels industry and practitioners to adopt new strategies and solutions to tackle variability and complexity of demand. As logistics nodes of the supply chain, warehousing systems represent the main source of inefficiency and costs. Therefore, literature considers issues of warehouse design and management aimed to minimize the operative costs and time and increase logistics performance. Recent comprehensive surveys on warehouse and industrial storage system topics are proposed by De Koster et al. (2007), Gu et al. (2007) and Dallari et al. (2009).

Inspired to Gu et al. (2007), Figure 23 presents a conceptual framework to classify warehouse design and operation issues considering the processes, activities and decisions related to storage systems. Two main aspects lead to enhance performance: the warehouse design and the operations control. First aspect refers to the layout constraints, the structural parameters, the definition of proper storage equipments as well as high-level strategic decisions on inventory management. The second concerns with the operative processes carried out within the warehouse (i.e. receiving, put-away, order picking, shipping) and focuses on techniques, approaches and methods to reduce travelling and operative time (i.e. zoning, storage allocation and assignment, batching, routing, etc.). Both leverages affect the warehouse performances and costs.

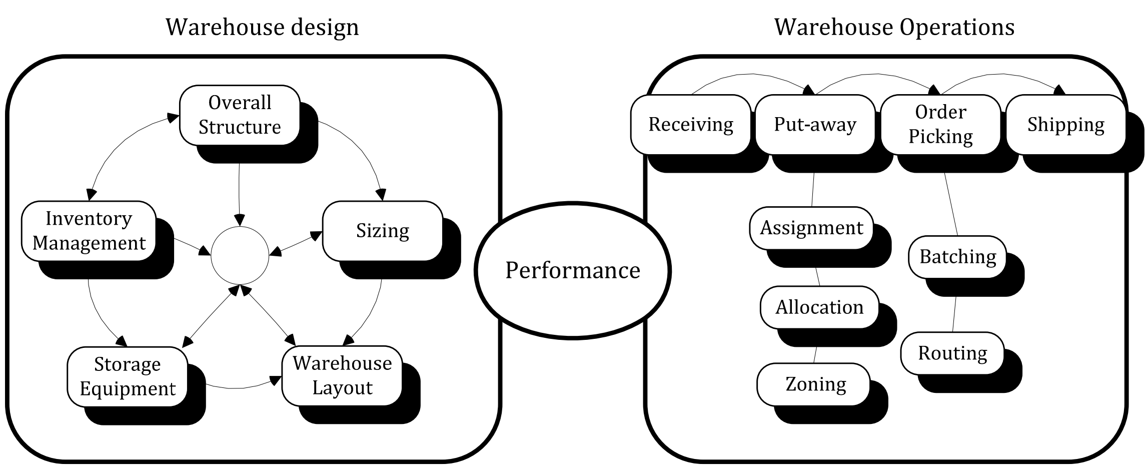


Figure 23. Warehousing conceptual approach

Many contributions aim to address a specific topic dealing specifically with warehouse design or operations. Gu et al. (2007) treats separately inbound/outbound processes (e.g. put-away, replenishment, picking) and presents a wide set of useful mathematical models subjected to constraints, which might not fit for real instances. The importance of space efficiency issues, typically regarding with the layout, the storage mode and equipments, and of time efficiency, recognized as the result of the management of operative process (e.g. picking, routing), arises within this conceptual framework. Indeed, it highlights the joint dependency of layout configuration and operations management aspects on the system performance. The awareness about the importance of considering both aspects to optimize the storage system, lead to criticalities due to the explosion of sensitive data and parameters to be taken into account. Indeed, often storage patterns concerns, on one side, with NP problems and, on the other, with a huge amount of real data to manage and process.

Therefore, a user-friendly and timeless solution for the most common storage issues is an ambitious aim for the research. To this purpose, the previously illustrated top-down design procedure consists on a collection of reasonable heuristics implemented in subsequent decision process through a user-friendly computer-based interface.

The principle insight of this chapter is to present a decision-support tool (DST) for warehouse design and operations management for less-than-unit-load and unit-load forward-reserve OP environment. Such system supports the design of complex multi-zones forward-reserve picker-to-part storage systems and provides a set of scenarios and configurations to fit SKUs and customer requirements of generic businesses. The proposed interactive computer platform implements a set of quantitative data-oriented analyses involving the most relevant criticalities of a storage system. The tool, considering a set of problems and decisions (e.g. layout planning, storage allocation, storage assignment, zoning, routing, order-batching and benchmarking), leads the decision-maker to handle real case studies, highlighting and interdependency among processes and related decisions and to pin down useful guide lines over storage issues.

Decision-support systems (DSS) are computer-based technologies adopted to support and aid complex decision making and problem solving (Arnott and Pervan 2008, Shin et al. 2002). Research in this area typically highlights the importance of information technology in improving efficiency adopted by user to make decisions, improving their effectiveness (Alter 2004, Pearson and Shim 1995).

Literature presents few contributions on computer-based tool to support warehouse analysis and design, due to the difficulty to manage real datasets and to encompass a wide set of models and algorithms for different purposes. Rouwenhorst et al. (1999) develops interactive decision support tools aimed at the conceptual design of dedicated storage system to store and retrieve pallet loads (i.e. unit loads). Other studies are conducted on tool for management of less-than-unit loads OPS supporting the analysis of operating data (SKU master file, order master file, inventory master file, etc.) to determine the requirements for OP operations and storage capacity (Govindaraj et al. 2000, McGinnis and Bittorf 2004). Currently, literature does not provide any contributions able to match and combine warehouse design and operations patterns into a unique analysis, as proposed by the present manuscript.

4.2 Order-picking design tool. A decision procedure

The lack of systematic approaches on this topic highlights the need to provide a DST able to gather data from real instance and systems and implement a set of effective models and algorithms to support automatically decision process on design and management. This chapter illustrates an innovative architecture of DST for the analysis of storage layout, structural features, storage equipments, storage allocation and storage assignment problems, adopting numerical simulation to assess results, statistics and performances. The expected results of the proposed computer aided system can be exploited by disseminating knowledge among logistic providers, practitioners, managers, by educating and improving industrial engineers expertise, by analyzing real data-oriented storage system case studies and point out useful guidelines.

The proposed tool is powered by a database management system able to gather, store and manage the dataset gathered from a real storage system case. The huge amount of data and information concerning with warehouse operations represents one of the most critical issues to tackle. As instance, a OPS usually collects tens or hundreds thousands SKUs, experiences a demand of millions order lines per year, managing inbound-outbound processes, quality checking, shipments scheduling etc. To this purpose, industry invests on the development of integrated information solutions, called WMS. These commercial systems provide real time view on material handling, often advising the efficient use of space, labor, and equipments (Helo and Szekely 2005). Nevertheless, WMS solutions consist on management system with no functionalities related to decision-making on warehouse design.

The proposed DST implements a top-down procedure for the design and management of warehouse and particularly less-than-unit-load OPS. This procedure arranges analytical methods, models, algorithms, in order to provide a wide set of design solutions and operative system configurations. In other words, adopting this procedure, the decision-maker carries through a sequence of analyses, generating a set of comparable configurations to be assessed in agreement with several KPIs. Considering the hierarchical top-down procedure presented in Chapter 3, subsequent decision steps are taken by the decision-maker attempting to configure the system and compare the design solution with a performance benchmark (i.e. as-is configuration).

Thus, the feedback flow allows the user to rearrange his/her decisions in order to achieve efficiency in both warehouse design and operations as illustrated in Figure 24, inspired to Lopes et al. (2008).

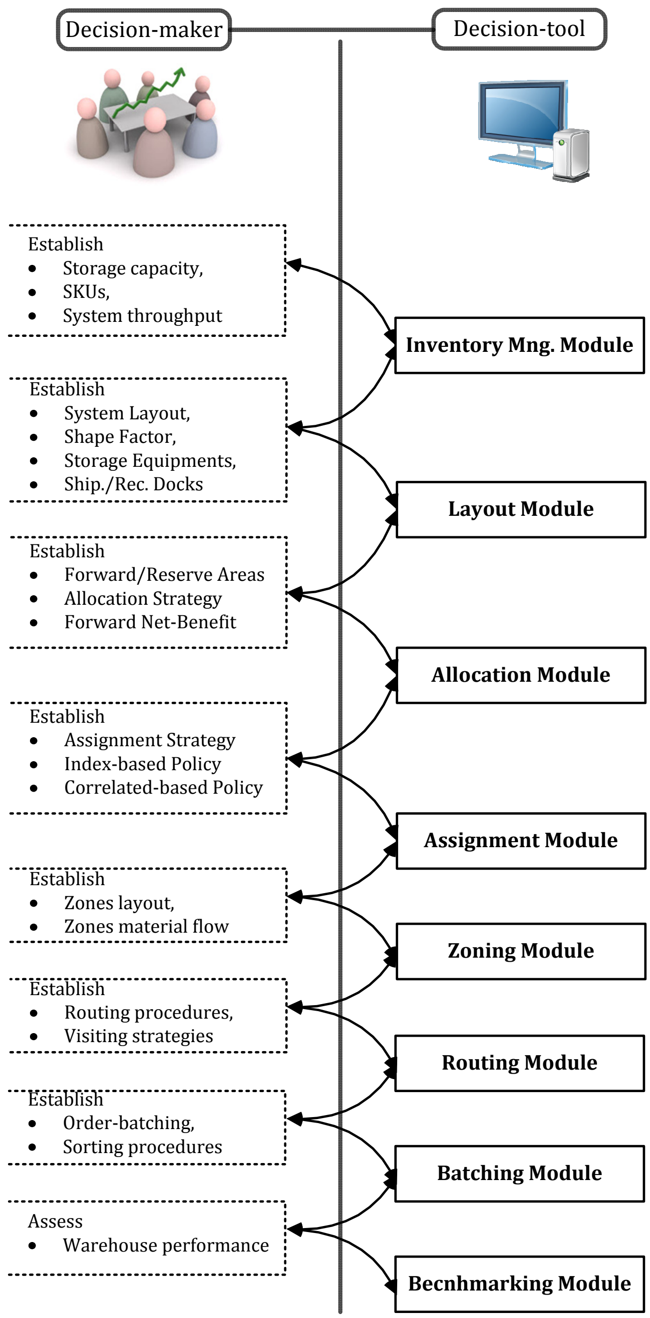


Figure 24. Decision-maker-tool interaction

This scheme shows the decision-process as an interaction between the decision-maker and the tool. To each set of questions and designing issues, the proposed tool responds with a dedicate software module and the related GUI. For each module it is possible to take decisions by configuring the virtual warehousing system to be assessed and compared with the as-is real configuration in the benchmarking module. Then, whether obtained performances are not satisfying, it is possible to go back to previous modules, change the settings of layout, allocation, assignment, batching and routing and then evaluate again the results of the new system configuration.

In the following sections, every module and related GUI is presented and illustrated, reporting the set of available functionalities to take a decision. Nevertheless, before entering a detailed description of the tool architecture with the main topics and functionalities is necessary.

4.3 Order-picking design tool. An architecture

The main purpose of this tool is to provide a useful and user-friendly tool for managers, decision-makers, having no background and expertise in programming and software developing, but frequently facing warehouse design and management issues.

In order to achieve this goal a critical study and overview of the most significant issues in designing warehousing systems is necessary. Due to the complexity of modern OPSs, the number of variables, parameters and data to be processed is huge and this represents the main criticality of the whole project. The warehouse operations involve a wide and complex set of entities, steps, procedures and activities to be considered, studied and analyzed. The monitoring, management and control of the whole system takes into account the complete set of processes carried out throughout the inbound and outbound steps. Literature retains the management of time and space efficiency the twofold crucial concerns to tackle in warehouse operations. These goals, which are the most significant and relevant for industry and practitioners due to its direct impact on logistics costs, represent just the tip of an iceberg. The higher the tip, the deeper the iceberg is. In other words, the higher is the increase in time efficiency and other operative performances the decision-maker attempt, the deeper the grade of analysis to develop, the wider the set of leverage, variables and factors to take into account.

Above the others, data to be necessarily considered involve the SKU master file (i.e. SKU anagrafy), containing all the details of size, shape, dimension and weight of the smaller handling unit of each SKU, and the historical inventory and order profile. The availability of such information enables to figure out how big the storage system should be, which kind of racks and storage modes adopt, the system goal throughput, and, also, to make some reasonable hypothesis about trends on customers demand, and on the interdependency among SKUs in picking and replenishment operations.

Although the knowledge of such aspects facilitates the analysis and the decision process on warehousing design, the management of such amount of data is hard to carry out.

Therefore, the proposed tool implements a classic DSS structure (Shim et al., 2002) entailing database management capabilities for data mining, powerful modeling functions and simple user interfaces enabling interactive queries, reporting and graphic visualization.

The proposed application, developed in Visual Studio© environment and C# language as further described in section on adopted languages and software, is based on object-oriented (OO) methodology and client-server architecture built through a database management system (DBMS). Results and input data regard with technical features, costs, operative performances, customer demand, and other parameters usually handled by practitioners in warehouse operations.

The DBMS allows the application of a SQL database architecture, which enables to gather, store and manage a huge amount of information quickly understandable by users, providing a fundamental support to lead the decision process trough dynamic queries.

The tool is organized over a main architecture schematically illustrated in Figure 25. Let enter in detail on the informative flows and the step of the tool architecture.

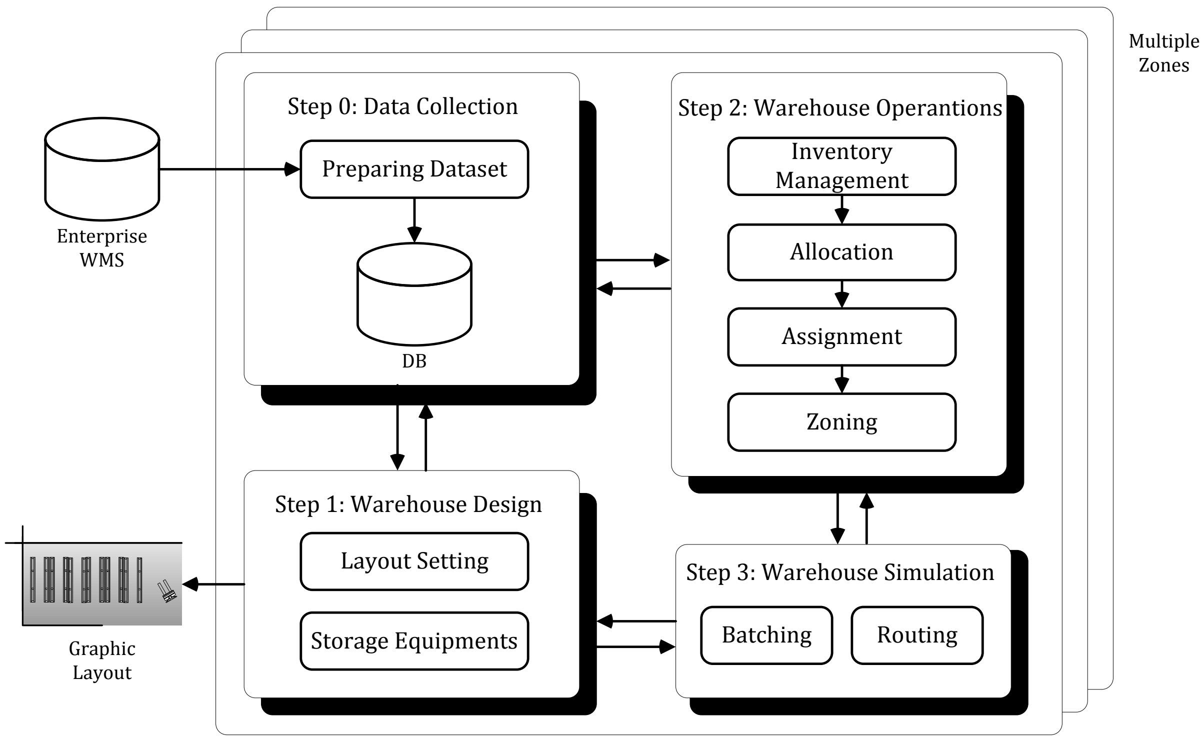


Figure 25. DST architecture

In real enterprise, the huge amount of available data represents an opportunity for data-oriented numerical analysis. Storage systems usually handle tens thousands of SKUs picked from thousands locations in order to fulfill thousands of order lines per day. In many cases, these activities (e.g. inbound, outbound processes) are registered and reported into proper WMS, offering opportunities to store data and collect process knowledge.

Therefore, in order to boot the decision process and the tool a preliminary process of data mining attempting to filter and organize this knowledge is required. The main purpose of this step ("Step 0" in Figure 25) is to assess available historical information (i.e. SKU master file, inventory, order list) and create a complete database structure according to a properly defined entity-relation diagram (ER), illustrated in follows. The table of the E-R diagram needs to be filled by the real enterprise data, taken and downloaded from the WMS.

Once dataset is prepared and database properly filled, the tool offers to the decision-maker the opportunities to focus on layout design ("Step 1" in Figure 25), or operations ("Step 2" in Figure 25), or both.

In particular, the first macro-decision to be taken is the purpose of the analysis. The decision-maker might be interested either in design a warehouse from a green-field or in re-configuring an existing warehouse by setting the operations. In both cases, the tool has to access the database to collect and gather the required information. The two main purposes are described:

- *New warehouse*. The proposed DST allows the decision-maker to design a new warehouse or a new zone starting from a green-field, by setting the storage mode, the layout features, and the rack components in the so-called *Layout module* (see Figure 24). The design of the layout take into account at this step also inventory management aspect, through the so-called *Inventory management module*. In particular, the overall storage capacity of the system might depend on the historical average inventory, the required pallet locations or the replenishment delay fixing the safety stock.

  The analysis proceeds with the decision on storage allocation (i.e. *Allocation module*), to set the quantity of each SKU devoted low-level, and the decision on storage assignment (i.e. *Assignment module*), to set the location of each SKU. At the end of these settings, carried out in "Step 1" and "Step 2" of Figure 25, the user can save the realized configuration of the warehouse or the warehouse zone on a proper table in the database.
- *Import warehouse*. The DST allows also the decision-maker to import from the database an already designed warehouse, statically defined in layout and storage mode, limiting the analysis to the allocation, assignment and so on. In this case, the analysis skips the "Step 1", and directly focus on "Step 2".

Regardless the purposes of the decision-maker (i.e. design a new warehouse or import an existing one), the tool in the "Step 3" (see Figure 25) supports the organization of a multi-zone warehouse (i.e. *Zoning module* in Figure 24), the management of order-batching (i.e. *Batching module*) and routing procedures (i.e. *Routing module*), and the assessment of the system performances through a what-if simulation approach.

Both functionalities require a connection with the database attempting either to import data or to save the results of the warehouse zone configuration.

The architecture illustrated in Figure 25 is implemented in the tool around a main window presenting all principle features and commands to open and import projects as well as load and save data. The toolbar is inspired to the common Windows® applications in order to propose a well-known interface for users. Not all functionalities are available at first sight, but properly activated after user decisions. At the beginning, if the user chooses to design a warehouse from green-field, the two available modules are those regarding with the inventory management, to set to overall storage capacity of the distribution centre, and with the layout design, to define the feature of racks, of storage mode, of aisles and bays, and of rack slotting. Otherwise, if an existing warehouse is imported from the database, these two modules are assumed as given, and thereby skipped. The analysis proceeds with the allocation module, enabling to define which SKUs are allocated in forward-area, and in what volume. The setting of storage volume per each SKUs leads to the definition of the proper location through the assignment module. This step definitely configures the warehouse zone, which can be saved into the database to be further imported.

This procedure can be iterate for a desired number of warehouse zones, selecting the set of SKUs to address to each zone, and then modeling independently the zone according to the allocation and assignment issues. At this point, the zoning module allows merging different zones (i.e. imported from the database) and to configure a whole system which encompasses all the selected zones and related SKUs. The benchmark of performances of such system is carried out through the simulation, based on the routing of pickers to fulfill a selected order list, and eventually a batch-order list.

Therefore, the user is leaded through the decision process by the gradually execution of the systematic top-down procedure, illustrated in Chapter 3. In summary, the tool requires at least the following data:

- SKU master file (handled unit volume available per each SKU).
- Inventory file (e.g. pallets, cartons, etc.).
- Order list (for a significant period).

Finally, the tool performs and points out the following analyses and results:

- Collection of input data into DBMS infrastructure.
- Design (or import) new (or existing) warehouse configuration.
- Analysis on layout, storage allocation, storage assignment per each storage zone.
- Space allocation adopting discrete and fluid approach.
- Management of multiple-zones warehouse system.
- Routing and batching of picking missions.
- Simulation and performance benchmarking (i.e. time and space efficiency metrics).

- Assess correlation among SKUs (Pro correlated-assignment).
- Assess correlation among orders (Pro order-batching).
- Export results (e.g. travel distance/time for picking and replenishment).
- Graphical 2D and 3D drawing of warehousing through an interface with AutoCAD®.
- System design based on commercial rack component.
- Flexible layout configuration (e.g. cross aisle, shape factor, shipping/receiving docks, etc.).
- User-friendly GUIs to support decision-maker.

In following sections, the detailed descriptions of the adopted software and applications, of the data management structure, and of the principle GUIs and tool modules are illustrated.

4.4 Order-picking design tool. Software & languages

In order to write and configure this tool for the design and management of warehousing systems, a wide set of other programs, software and application is considered. Due the complex context of analysis, the group of software adopted ranges from virtual machine compiler (i.e. Visual Studio©) to computer-aided drawing support (i.e. AutoCAD) or DBMS for the data collection and storage (i.e Access™). A brief description of the principle adopted software follows.

4.4.1 AutoCAD & AutoLISP

The wide set of computer-aided design (CAD) software present several robust solutions both commercial and open-source. The choice regards the opportunity to utilize a programmable environment, with a set of graphic using libraries for 2D and 3D modeling and with a diffused list of manuals, tutorials, documents and references.

Considering main features and skills the author retains AutoCAD® as a valid candidate to respond to these requirements. AutoCAD® is the first CAD software developed for PC in 1982. It works through proper Application Programming Interface (API) to facilitate insertion, manipulation and deleting of geometric figures and components. The development of AutoCAD® applications may involve different languages, as listed in follows:

- C/C++. This is the most worldwide diffused language, since it allows to develop high-performance graphic applications. The available API enable high velocity and flexibility in both drawing and management of OS functionalities. The main issue regarding this language is represented by a steep learning curve (especially for debugging), which makes difficult its application with small/medium private applications.
- Lisp. This is one of the first language, available since the first software versions. It is executed without any sort of preliminary process (i.e. compilation), typical for other structured languages. It is easy to learn and to use, and it is particularly flexible for small and medium applications (where no high-speed performance are required) due to an easy debugging. The program is based on AutoLISP language, which is a current and ready-to-use version of the wider Lisp.
- Visual Basic for Application (VBA). This language, a simplified version of Visual Basic (VB), represents an intermediary solution between C and Lisp, since it is more powerful than Lisp but easier than C. It allows developing high-performance and complex graphic interface, also supported by database. VBA is often supported by small AutoLISP procedures, devoted to the setting and definition of new commands.
- Microsoft .NET. Since 2005 AutoCAD allows to import and upload modules and procedures developed in .NET 2.2 languages. AutoCAD supports in particular two .NET-based languages: Visual Basic .NET and C#. In comparison with AutoLISP and VBA, these languages are extremely more flexible and powerful, but require a sensible amount of memory.
- ActiveX interface. This is not a proper programming language, but a Microsoft® technology enabling software to co-work. AutoCAD holds an ActiveX interface, which provides a set of objects and functionalities available for each language and software. Therefore, it is possible to access the CAD environment by another outside application, as it was integrated in the same environment. The fee payed to this functionality is the lower performance of the application.

The adopted language to write the AutoCAD interface is AutoLISP. Indeed, it enables to write small or complex procedures and routines to make the easy and iterative steps of automated drawing. This language considers a drawing as a list of entities and commands, thereby managing dynamic lists of objects (e.g. lines, curves, arches, etc.) which are easily modifiable and configurable.

Furthermore, in order to assist and support the writing of AutoLISP code, the useful open-source editor RsciTe is adopted. This tool is pre-set for AutoLISP language and automatically recognizes the language keywords.

4.4.2 Visual Studio & C#

Visual Studio is a development environment by Microsoft, which supports many different languages like C, C++, C#, F#, .NET, and executes the realized applications. The adopted language to write the proposed DST interface is the C#. This OO language allows to develop reality-oriented applications where entities exchange data (i.e. properties) and activities (i.e. methods) among each other. Furthermore, the benefit of such language consists on the easy code maintenance, even for huge project, the arrangement of code in modules (i.e. classes), and the adoption of GUI.

In order to understand better the discussion of the flowing sections a brief description of the principle code features follows. The class is a virtual representation of the real/physical entity to be modeled. The class, or the entity, is described and composed by its attributes and its methods. The attributes of a class represent the properties of the class while the methods represent the actions or procedures that the class executes and provides to the system. An object is an instance of the class and is generated at running time by the program. Therefore, the class defines the behavior of an object, instanced by the program, whilst the attributes represents the state of the object in running time.

During the design and conceptualization of the project, a preliminary phase of studying and problem modeling is necessary. Indeed, the main purpose before to begin writing is point out the most significant entities and related classes, and determines the right set of attributes and methods per each of them.

The design of the tool architecture and infrastructure is the core of the modeling of the tool. At this stage, many opportunities of implementation are evaluated but, finally, just one is considered ad adopted. A useful tool to pass from the conceptual scheme to the tool architecture, the so-called software engineering, is the class diagram in Unified Modeling Language (UML), which is a type of static structure diagram describing the structure of the tool by showing the system's classes, their attributes, operations (or methods), and the relationships among the classes. The class diagram is further described and illustrated in a dedicate section.

In follows, a list of graphic components, pre-set object and tools of C# language are reported, in order to make the reader aware about the adopted instruments to create this project:

- Form. The form represents the classic application window, and contains all the other controls or functionalities handled by the final user. In this project a particular form is applied, the so-called Multiple Document Interface or MDI Parent, which enables to create and contain multiple object form, named Form Child. Whenever a new project is opened and the application starts, a new Form Child is generated by the MDI Parent form object. This particular object allow to manage multiple warehouse zones independently, as well as in a common Microsoft Office® applications, the user can open and utilize multiple documents or worksheets in the same Word™ or Excel™ project.

- Tab Control & Tab Page. The Tab Control is a pre-set default class, containing sheets named Tab Page. In this project Tab Control are a fundamental tool to organize the different steps and modules of the tool and the designing procedure. Whenever a new project is opened and the application starts, each Tab Page represents a step (i.e. a module) of the tool.
- Combo Box. This a graphic component allowing the user to select an element (i.e. a choice) from a list contained into a window.
- Message Box. This is a graphic dialog window used to give warnings to the user.
- Data Grid View. This is a graphic object, which displays the data of table. It is composed by a grid of rows and columns as an Excel™ sheet. It offers several options for displaying and represents the principle tool adopted to show output data.
- Data Table. This is a pre-set default class consisting in a table of data stacked in memory. It is a sort of table in a database, but is generated in run time. This class provides methods to manipulate and handle data, and are particularly indicate to solve sorting problems, which are very common in the proposed tool. As for a database table is it possible to set and define data formats, and primary keys.
- Hash Table. This is a data structure, which matches a primary key of a table with an integer value and is useful for fast research, named hashing. This kind of research is based on the research into a list of integer values, in lieu of a comparison-based research. As instance, in the proposed tool, the string code of each SKU is a key matching with an integer value within an Hash Table.
- List <>. The class List is data structure, which contains a homogeneous collection of data (e.g. integer, string, objects, etc). It is adopted for the easy procedure of inserting, deleting, searching and sorting of elements.

4.4.3 Access & SQL

Microsoft Access™ is a DBMS, which originally integrates a Rapid Application Development (RAD) tool for the development of small/medium applications based on Open Database Connectivity

(ODBC). In computing, ODBC is a standard C programming language middleware API for accessing DBMS. Access™ reads data in Access/Jet, SQL Server, Oracle formats or any other format compatible with ODBC.

One of the most crucial aspects of whole DST is the efficient and effective management of huge amount of data. Such quantity does not fit with common datasheets (e.g. Excel™) and the adoption of DBMS is necessary.

A database is a structured collection of data, organized through a set of table linked by a proper E-R diagram. A general-purpose DBMS is typically a complex software system that meets many usage requirements to maintain properly the accuracy of its databases and tables. Table are composed by a number on records (i.e. rows or tuple) made by multiple columns (i.e. fields or attributes). A primary key, composed by one or multiple field, univocally identifies each row. The relationships among tables, illustrated through the E-R diagram, are defined by foreign keys, which link the rows of different tables. This link represents a constraint of integrity between two tables. The foreign key identifies a column or set of columns in a table that references a column or set of columns in another table (referenced). This implies that a record in the former table can not contain values that do not exist in the latter table, such as occurs in the reality of an industrial warehouse when a SKU is not allowed to be stored whether is not already handled and registered in the SKU master file.

Databases are applied to model relevant aspects of reality in any area where is required the management of large amounts of data. Thus, they are the basis of any management application. The proper sizing of warehousing systems compels the collection of details on SKUs, order profiles and inventories. Often this information is not always available, or is not easily gatherable. For this reason, the author retains mindful to base the database architecture of the tool as close as possible to reality known.

Data stored in the database are accessed and manipulated by the tool using SQL constructs queries. SQL is a special-purpose programming language designed for managing data in relational database management systems (RDBMS). Originally based upon relational algebra and tuple relational calculus, its scope includes data insert, query, update and delete, schema creation and modification, and data access control.

SQL supports a quick exploitation of data. Queries can be easily modified (e.g. table names, fields) to be compatible with any database. The power of this language consists on its portability, enabling to use the same constructs with different DBMS. The interaction between the tool and the database is further facilitated by .NET APIs, with their classes allowing quick access to database.

The principle .NET API applied for this purpose is named OleDB, which is data provider allowing the connection with any data formats and structures (e.g. text, worksheet, database). In particular, OleDB is a namespace (i.e. classes package) that encompasses several classes to access, enquire and modified database, independently by the type of adopted DBMS (e.g. Access, MySQL, Oracle, DB2, etc.). Over the others, most applied classes are:

- OleDBConnection. This class creates a connection to a data source, and requires the connection string to the specific DBMS. Some couples of keys/values comma-bounded compose this string, illustrated as sample.

```
@"Provider=Microsoft.ACE.OLEDB.12.0; Data Source=" + FileName + "; Persist Security Info=False;"
```

  FileName is the parameter representing the name of the database file to connect with.

- OleDBDataAdapter. This class provides a set of methods to use a connected database by filling, modifying or updating a data-structure object (e.g. Data Table, Data Set). The method .Fill loads data from the database to the Data Set, whilst the method .Update sends back to the database the data updating.
- OleDBCommand. This class consists on a SQL instruction to carry out on a data source. In particular, some useful methods are adopted such as .ExecuteNonQuery to implement INSERT, DELETE, SET commands.

Figure 26 illustrates the data and command flows between the tool and the data source. The classes package OleDB represents the interface between the data environment and the software environment, consisting in a properly defined set of C# classes.

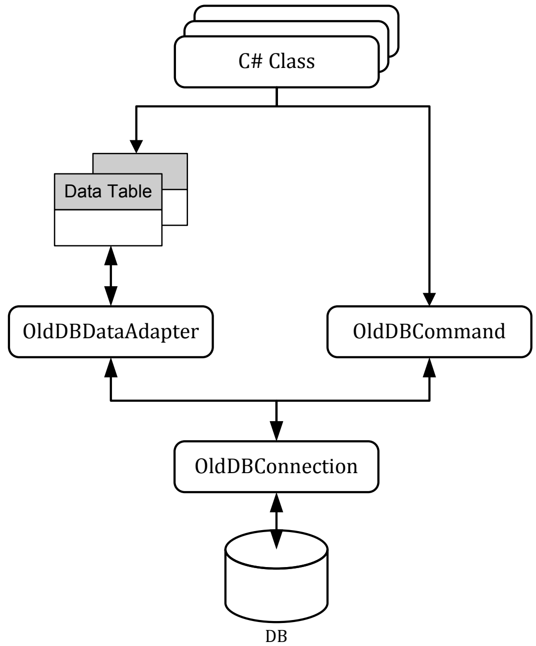


Figure 26. DBMS interface

4.5 Order-picking design tool. E-R diagram

The principle activity for the design and development of a tool for the management of warehouse is the conceptual definition of the E-R diagram. Indeed, all the common analysis by managers and practitioners on warehousing issues are based on database, since it is the priority candidate to handle the huge amount of data and available information, also offering knowledge synthesis device and procedures.

This study is inspired by the observation and analysis of many different enterprise realities, which daily face warehousing issues in different ways, approaching different data source and DMBS with different tables or spreadsheets. Nevertheless, the analyses of real case studies allow a synthesis process of knowledge that finds its concrete development within the proposed E-R diagram.

The purpose of proposed diagram is to collect all the available information from enterprises, to arrange them organically, to ensure data integrity, to storage the data required to begin the top-down design procedure illustrated in Chapter 3.

The decision-maker must be aware at least about the order list and the demand profile, the level of inventory of every SKU, the SKU master file. Therefore, the proposed E-R diagram, illustrated in Figure 28, is based on the contents of three main tables, which are named ORDERLIST, INVENTORY and SKU. These tables regards with the input data gathered and summarized by the enterprises WMS.

Then, there is a second set of tables, which are utilized to run the tool, since they store the data of layout design and allocation and assignment analyses. The adoption of a DMBS provider allows emptying the run-time memory and data object (i.e. Data Table), and store intermediate data into the database. These tables, specifically named WH, MB and LOC contain respectively the features and characteristics of the designed layout, the list of base modules, which is the storage area containing two opposite bays and the portion of aisle between them, and the list of storage locations contained within every base module. In Figure 27, a sample of base module composed by two unit loads per bay is give. In such case, three base module are drawn, one per each rack level.

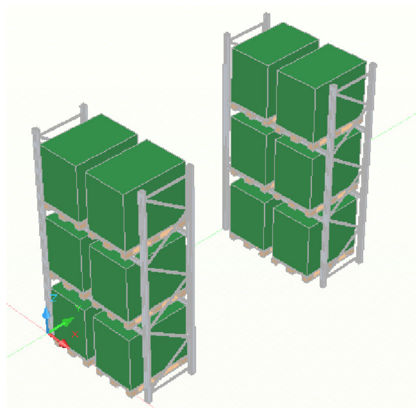


Figure 27. Base module sample

Table RACK and Table UL contains respectively all features and characteristics of the rack components imported by a commercial catalogue, and the type, size and weight of storage unit load to be filled by the SKU in the warehouse. The availability of multiple of unit-load allows to build and design different storage zones, specifically devoted to different-size SKUs.

Finally, the last set of tables concerns with the simulation and benchmarking module and steps. The table named SIMULATION and SCENARIO contain the details of the designed warehouse scenario, and the features and functionalities to test with the simulation. The table OUTPUT, which matches with the SIMULATION and SCENARIO ones, is filled by the results of the simulation of picking and replenishment activities over a defined warehouse scenario with a particular storage vehicle/equipment, selected in the proper table, named VEHICLE.

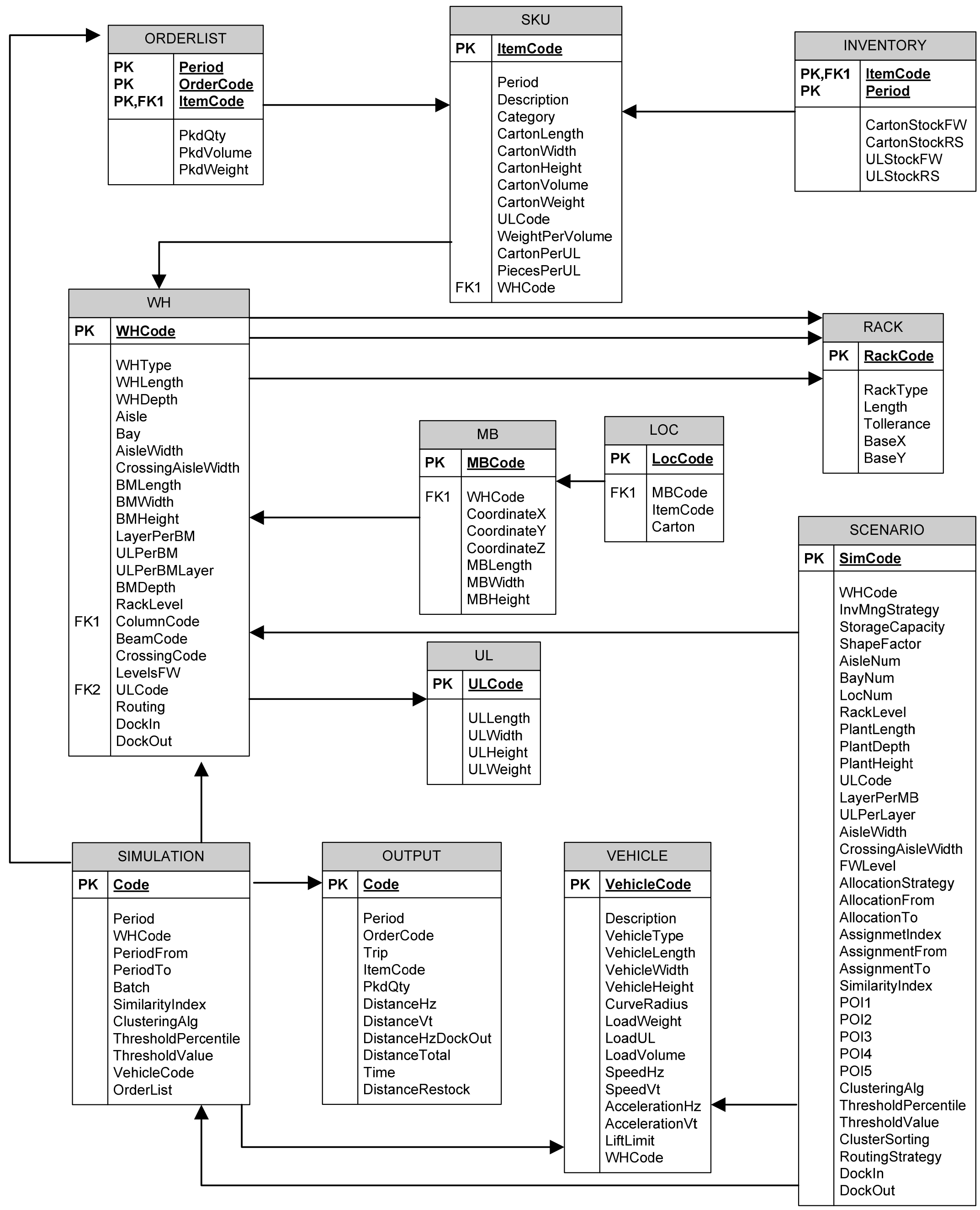


Figure 28. DST E-R diagram

In follows, a summary description of each table is given, with the detail of the principle data fields.

- *SKU*. This table represents the SKU master file, contains all available information regarding SKUs (e.g. code, carton volume, carton weight, description, pieces per carton, etc.) and usually counts ten thousands rows. The field description and category allow registering information of the name associated to the SKU code and the class or family of the product. The class of product might report the classification of the SKU turn over (i.e. A, B, C classes of Pareto curve) or the functional unit or manufacturing family of the item. Particularly interesting are the field CartonPerUL and PiecesPerCarton, which account the number of smaller unit (i.e. carton and piece) per handling unit (i.e. unit load and carton). Finally, the field WHCode pre-set the data source since it represents a crucial filter of the storage zone to be devoted to each SKU. The DST consider different-size-weight SKUs as categories of products that need to be store in different storage areas with particular storage racks or equipments. Hereby, the distinction appears in the SKU master file, which means that a pre-selection of which SKUs should be addressed to each zone is already made.

- *ORDERLIST*. This table represents the demand profile of a specific period of analysis (e.g. a year) and usually counts millions lines. Each tuple is composed by the due date of order, the order code, the SKU code and the picked quantity in terms of cartons. The field PkdWeight or PkdVolume replace the PkdQty column to fit a particular instance of demand profile (e.g. kilograms of potatoes in a grocery warehousing). The information held by this table allows computing the required metrics and indices for the allocation and assignment problems.
- *INVENTORY*. This table reports the inventory master file for SKUs in both forward and reserve area. The flexibility of proposed tool allows bypassing not available information, such as the number of unit loads stored in bulk area. To face the space allocation problem the overall quantity of pallets (expressed in term of required volume) present in this table is considered as the total storage capacity of the system. Then, the layout module sets and configures the racks of the storage zones, thereby constraining the storage volume to devote to forward area (i.e. low levels).
- *WH*. This is a fundamental table of the E-R diagram since it contains a tuple (i.e. a row) per each of the storage zone designed in the warehousing system object of analysis. Indeed, in each tuple it reports all features regarding the layout of a warehouse zone (e.g. shape factor, front size, number of aisles and bays, number of rack levels, base module size, location size, commercial rack components, side of inbound and outbound docks, level of forward area and bulk, the routing strategy, etc.). The DST carries out the design and AutoCAD drawing of each storage zone by properly importing all the details contained in the row. The table enables to import from the database an existing warehouse zone, or conversely to store in the database the tuple of a warehouse zone resulting by a decision-design procedure. The main criticality handled in defining such table is to establish the right set of parameters

managing to univocally identify a warehouse zone. The DST manage to consider both a one-zone warehouse, or a multiple-zone warehouse, based on merging of multiple WH rows into a unique layout solution through the zoning module.

- *MB*. This table reports the list of base modules per each storage level with the details of their storage locations. The base module is a unit function considered for the static design of a warehouse. The fraction of areas within two opposite bays and the faction of aisle between composes the base module. This table is filled by the results of the layout module, where a warehouse zone is designed as a tridimensional multiplication of a base module. This table holds even the geometry of the warehousing system, consisting on the spatial tridimensional coordinates of each base module. The awareness of such detail enable the routing and simulation approach for the performance assessment of each design scenario.
- *LOC*. This table reports the list of storage locations and their contents (i.e. SKU and number of cartons). The base module code, named MBCode, is a foreign key attempted to match the module base, in the proper table, which each location belongs. This efficient data infrastructure enables to associate the spatial coordinate of each base module, which might be thousands in a warehouse, with the spatial coordinate of each storage location, which might be hundreds of thousands. Whenever the DST executes the allocation and assignment modules, the LOC table is properly filled and the decision-maker knows where each SKU is stored within a completly-mapped environment and in which quantity.
- *UL*. This table indicates the type and size of unit load stored within racks. As previously discussed, each storage zone holds particular unit loads (e.g. pallet, plastic tote, steel container, etc.) and arrange the space in the rack accordingly. As instance the zone of car shields works with large unit load (i.e. cases or steel container) then the area of filter (i.e. typically handling cartons or pieces).
- *RACK*. This table is configured to base the design of a warehouse to real commercial components. It indicates the features, sizes, weight tolerance of real commercial rack, adopted to build the warehouse through graphical interface. The design of new storage modes (e.g. mezzanine or push-back rack) simply requires the uploading of the RACK table by the user. This table is mainly utilized during the layout module.
- *VEHICLE*. This table reports all the characteristics and features of a storage vehicle. The velocity and acceleration, as well as, the loading constraint (i.e. in terms of unit load, maximum weight or maximum volume) are defined to address the simulation and benchmarking modules. The fields and attributes of such table allows to concretely reproduce the real performance of a forklift or a walkie-stacker.

- *SIMULATION*. This table regards in particular the execution of the simulation and benchmarking modules. It contains the set of parameters, which completely describes the simulation process as set by the decision-maker. The simulation code is a progressive number accounting the simulation, also detailed by the period of the considered operations (i.e. picking and restocking missions), and the list of activities to be simulated (i.e. name of the table on which the simulation is based). There are also some attributes, which indicate the methodologies adopted to arrange the pickers operations. Batch is a binary attributes equal to one if an order-batching strategy match with the routing policy, or 0 if just routing is carried out. In the former case, Similarity, Clustering algorithm and Threshold attributes deal with the selected correlated-based batching approach.
- *SCENARIO*. This table reports the overall characteristics and parameters, which univocally represent a warehouse scenario. The scenario is a design solution or configuration resulting by one run of the top-down design procedure through the DST. All the aspects and stages of analysis, choices and decisions, are here reported as attributes of the scenario. As sample this table encompasses a set of parameters regarding with the layout the warehouse, another set devoted to the storage allocation problem, another dealing with the rules and policies of the storage assignment, both index or correlated based. The scenario, which is a tuple a this table, is a design solution to be tested with a simulation.
- *OUTPUT*. The results and KPIs of simulation run on a specific scenario are reported and summarized in this table. The table measures, per each tuple (i.e. the step or activity of retrieving one item), the travelled horizontal distance, the vertical distance for fork lifting, the time for both horizontal and vertical path (i.e. considering related accelerations) and the distance for replenishment, whenever the pick ends up the stock of a SKU and a restock is performed from the closest bulk location.

Once the E-R diagram is set, its implementation on a DBMS follows. As previously discussed in Section 4.4.3 the DST adopts as DBMS Access™ since it is highly compatible with other Office tool such as Excel, particularly useful to export graphs or other output. Although, this user-friendly DBMS does not implement any high-performance functionalities (i.e. client-server remote connection), like happens for MySQL or Oracle, Access™ is renowned and diffused among enterprises, thereby facilitating the preliminary step of data collection from WMS system to this database. Moreover, the data architecture, and in particular the adoption of OleDB APIs, allows the decision-maker to change the DBMS for the data storage (e.g. from Access™ to MySQL) whether the E-R diagram is respected.

The significant high-performance achieved through the adoption of such data architecture is due to the exploitation of SQL queries to manipulate, modify, and access data. Indeed, the computation of metrics, the sorting and key research of tables, are easily carried out through query at DB level in lieu of For-cycle at software level.

4.6 Order-picking design tool. Class diagram

The development of the software architecture is base on the class diagram, which reports the relationships and connections among the methods and attributes of the classes composing the project namespace. The proposed class diagram illustrated in Figure 29, also named UML diagram, reports the principle classes and the links among most utilized methods and significant attributes.

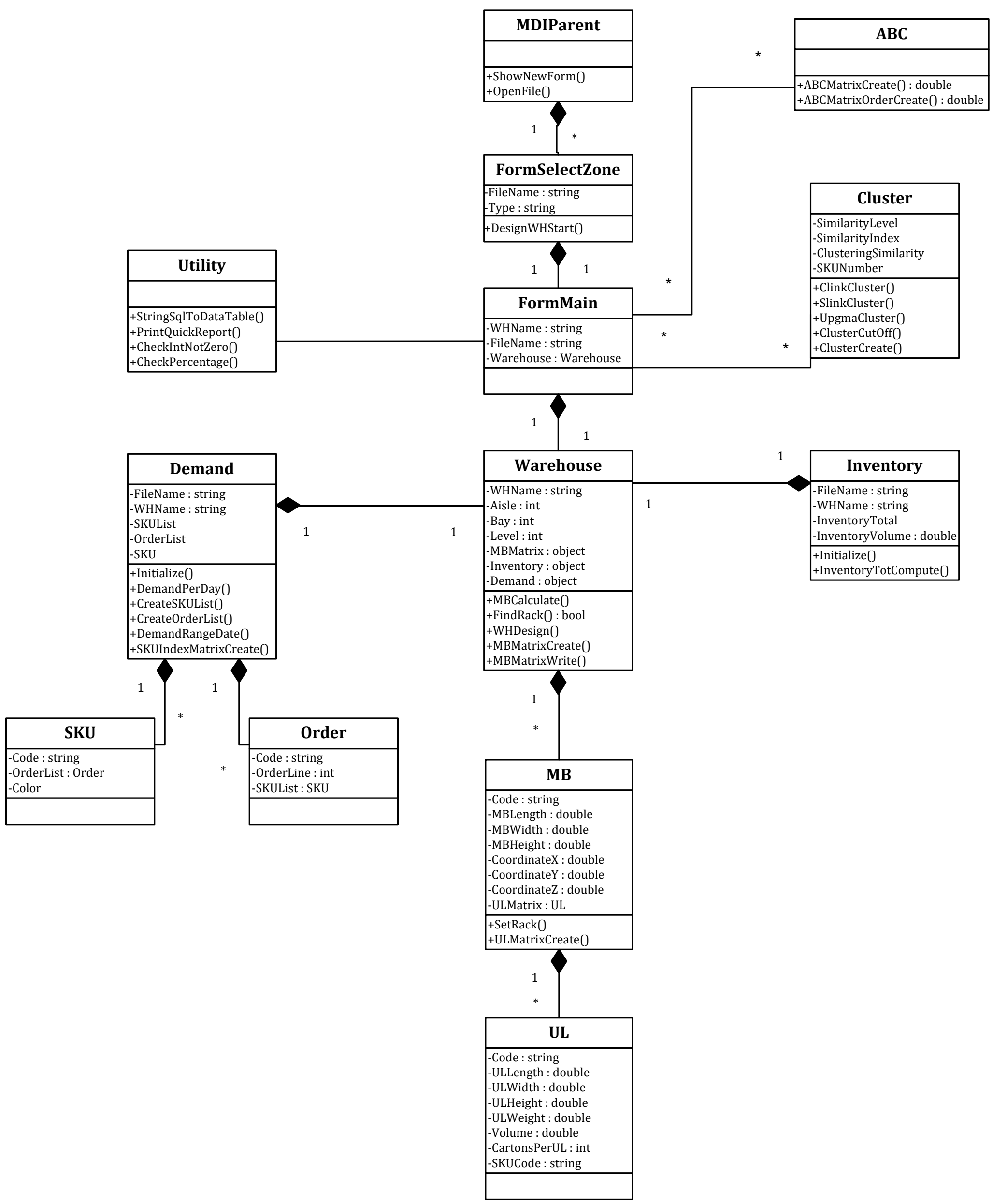


Figure 29. UML diagram

At first, the proposed DST creates an interface with the DBMS with the twofold purposes of designing a new warehouse from green-field or implementing an optimizing procedure on an existing imported warehouse. One of the most relevant insight of the DST is allowing to the decision-maker the chance to design a multiple-zones warehousing system. To this purpose, the class Warehouse, illustrated in Figure 29, represents the virtual entity of a storage zone, with its set of SKUs, its demand profile, its inventory, its layout and geometry. At the end of the design process, after establish layout, storage allocation and assignment, a zone is completely configured and the user decides to consider the zone as a one-zone warehouse, rather than merging multiple zones, independently configured, in multi-zone warehouse, into the zoning module, and then simulate the performance of such system.

The class Warehouse is configured as a set of attributes attempted to completely define a zone, and its virtual entity. These attributes are the same fields, or table attributes, which are defined for the table WH, which this class uses to import or export data. Each tuple of the WH table corresponds to a zone of the warehouse, or even a warehouse object of the class Warehouse. Each object of the class Warehouse matches with one object of the class Demand and one object of the class Inventory, required to the program to run the analysis. Moreover, the storage zone represented by a Warehouse object matches with one matrix of base modules, whose attribute is a matrix of storage locations.

Once the DST starts, the main Form, named MDIParent, is displayed offering the opportunity to choose the main run modality: new warehouse or import warehouse. In both cases, a so-called OpenFileDialog allows to select the database file to open. Another dialog window enables selecting the name of the storage zone object of analysis. Then, the tool proceeds with the analysis in accordance with the selected modality: if an existing warehouse is imported the layout module is skipped.

According to the Figure 29, the detailed description of the most relevant classes is proposed.

- *MDIParent class*. The Multiple Document Interface (MDI) class allows to generate and contain multiple Form object and consists on windows able to open multiple projects or documents. The MDIParent Form is the virtual container of many MainForms, and enables the application of multiple-project interface such as any other Office file. In the DST the MDIParent Form represents the user interface holding multiple Forms, one per each storage zone to analyze. The main decision at this step is the modality of the analysis to carry out: design a new zone from green-field or optimizing an existing warehouse. In both cases, a Form object of FormSelectZone class appears to let the decision-maker select the database file.

- *FormSelectZone class*. This class instances a Form object when the decision-maker selects the database file, object of the analysis. This form allows to select through a Combo Box the storage zone to focus. Once the storage zone is selected one object Form Main is open realted to the specific zone to analyze. The Form father MDIParent can contain multiple FormMain, one per each storage zone.
- *FormMain class*. This object represents the main interface of the tool and is instanced whenever a new or existing storage zone is open. This Form appears as main Tab Control, where each Tab Page consists on one-step of the analysis. The first Tab Page differently appears in accordance with the select modality: for new warehouse the first Tab Page, named Layout Design, encompasses all the commands and functionalities to set the layout parameters, whilst for an existing warehouse, the first Tab Page simply reports the layout parameters.

  Warehouse is the main attribute of this class, and represents the warehouse object to be analyzed. The start of such interface provides the initialization of all the variables, graphic functionalities and data structure required by the tools. This class contains the most important and complex methods of the whole project, which are responsible for the sizing and configuring of components (i.e. aisle, bay, base modules, storage locations, etc.)
- *Warehouse class*. This class provides the design of a storage zone and is composed by the set of attributes that univocally define a zone. Hereby, some of the most significant methods are listed and described:

  MBCalculate(). This method begins the design of the layout, once all the features and characteristics are set. In particular, this method receive the overall storage capacity of the zone, (in term of pallet locations or storage volume), and calculate the spatial coordinates of the base modules composing the storage system.

  bool FindRack(double Beam, double Column, double Crossing). This method receives some rough size of rack components, based on static design, and searches its relative commercial entity in the Table Rack of the database. The method returns on if the components are found, or zero otherwise. In such case, a Message Box warns the decision-maker.

  WHDesign(string Type, double Depth). This method designs the layout geometry of the storage zone on the base of the depth of the area and the shape factor.

MBMatrixCreate(). This method calculates and sets a tridimensional matrix of base modules, which compose the storage zone. The three dimensions consist on the number of rack levels, the number of aisles and the number of bays. Each base module of the matrix is recognized by a key code, or a label, and by its spatial coordinates, assuming the origin of axes as the down-left corner of the storage zone. By reading the label, the decision-maker figures out the effective location in the layout of every base module.

MBMatrixWrite(). This method writes on the Table MB of the database the list of base modules which compose the storage zone.

- *MB class.* This class models the base module entity and contains all required attributes. The Warehouse class contains as an attribute a tridimensional matrix of these objects. In order to go deeper in the analysis, this object contains as an attribute an array of object LOC, representing the list of storage location available per each base module. This class defines the attributes of the base module ID, its geometry and size, and its spatial coordinates.
- *UL class*. This class represents the handling and storage unit of the warehouse. Each zone adopts a particular UL object whose characteristics are imported by the related database UL Table. This object is also adopted to specify the label of each location within a base module. Two relevant attributes of the class are the SKUCode and CartonPerUL, which respectively represent the item code and the number of cartons per storage location.
- *Inventory class*. This class manages the historical inventory records of the SKUs within a storage zone. This class accesses to the database and gather all the required data, making them available through Data Table for the application. This class directly refers, as illustrated in Figure 29, to a specific storage zone. Therefore, there is an attribute, named WHName, responsible to address all the SQL queries to the specific WH zone.
- *Demand class*. This class manages the historical demand order records within a storage zone. As for the Inventory class, there is an attribute, named WHName, responsible to address all the SQL queries to the specific WH zone. Furthermore, this class is described through an attribute HashTableSKU which is an HashTable format. This table associates to each SKU object a progressive integer references to enabling fast hashing research in correlated approach. Hereby, some of the most significant methods are listed and described:

DataTable DemandPerDay(). This method returns the cumulative demanded picked volume per day captured from the ORDERLIST Table of the selected database.

CreateSKUList(). This method aims to populate a list of SKU objects. Each SKU filling such list has an attribute of a list of strings, which are the code of orders, which the SKU belong. The principle purpose of such method is to enquire the database to obtain a list of order per each SKU. This list is useful for computing the similarity matrix in correlated approaches.

CreateOrderList(). This method, as the previously described *CreateSKUList()*, aims to create a list of Order object as an attribute of the Inventory class. Each object order filling such list, defines a list or object SKU, which are the items requested in such order. This list is also useful to address the order-batching problem.

DemandRangeDate(). This method performs as the previously described *DemandPerDay()*, but here it is possible to select a specific period to focus the demand data collection.

DataTable SKUIndexMatrixCreate(DateTime Dmin, DateTime Dmax). This methods returns the popularity, COI, Turn and OC metrics per each SKU, referring to a specific period, within the parameters *Dmax* and *Dmin*.

- *SKU class*. Each object of this class represents a SKU described by its features and characteristics. It presents as an attribute a list of the order objects, which the SKU belongs. The Demand class has a method to create and set this list based on a SQL query to the database.
- *Order class*. Each object of this class represents an order described by its features and characteristics.. It presents as an attribute a list of the SKU objects belonging to each Order. The Demand class has a method to create and set this list based on a SQL query to the database.
- *Utility class*. This is a static class, since it does not require to be instanced, and contains the principle methods which are utilized in all the methods and classes of the project. Hereby, some of the most significant method is described:

DataTable StringSqlToDataTable(string FileName, string SQLString). This method returns a DataTable filled by the results of a SQL query to the database. The database is recognized by the *FileName* parameter, while the query is given by the *SQLString* parameter. The management of the connection to the databse is discussed in Section 4.4.3.

4.7 Order-picking design tool. GUIs

The management and control of the DST is allowed to the decision-maker, through a set of developed interfaces, named GUIs, which lead the user through the analysis and support the interaction between the illustrated tool and the proposed top-down hierarchical design procedure. GUIs enable the user to carry out analysis and decisions by utilizing the tool.

The main Form Window, (i.e. the previously illustrated MDIParent Form) presents a toolbar, inspired to the common Microsoft Office® applications, to select the main purpose of the analysis: the so-called modality new warehouse, represented by the button , or the so-called modality import warehouse, represented by the button , as reported in Figure 30.

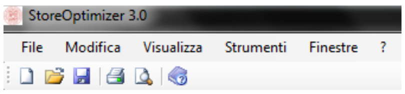


Figure 30. DST toolbar

Statistics and results of each decision, analysis and computation are summarized on a-part Form, named QuickReport, which is a dialog window to communicate to the decision-maker about the run-time processes. The selection of the analysis purpose in this main window, displays an instance of the FormSelectZone object, which mainly consist on a ComboBox to select the storage zone to focus.

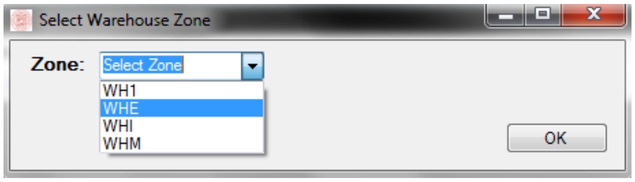


Figure 31. Selecting zone form

Such setting, as illustrated in Figure 31, begin the concrete analysis of a storage zone throughout the inventory management module, the layout module, the allocation module, the assignment module, the zoning, the batching, the routing and the benchmarking modules. In particular, Figure 31 shows how the decision-maker might choose among the list of available storage zone. These zones are added to the list on the bases of a database enquiring, by observing the attributes WHCode of the SKU Table. The GUI comprises a set of distinct modules further detailed in following sub-sections.

4.7.1 Inventory management module

This module supports the decision-maker in defining the overall storage capacity of a new warehouse zone. This step of analysis is skipped when an existing zone is imported, since, in such case, the layout of the zone is fixed and the overall storage capacity is given. This module is displayed on the left side of the Layout Design TabPage, which is the first preliminary TabPage of the main TabControl, as shown in Figure 32.

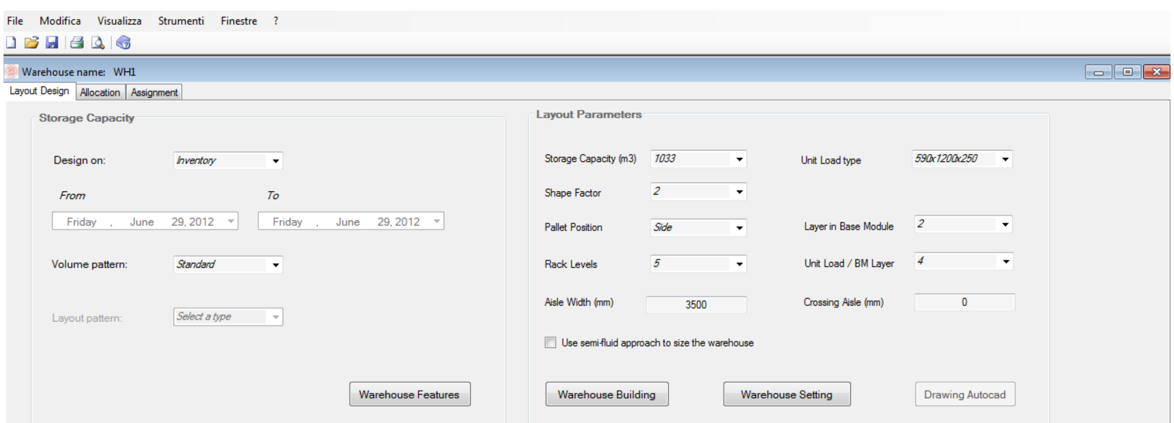


Figure 32. Inventory management GUI

The DST at this step implements a set of inventory management strategies in order to establish the overall available storage volume of a warehouse zone (e.g. WH1 in the sample of Figure 31). In particular, the ComboBox, labeled as *Design on*, allows the user to select three strategies, as follows:

- Inventory. This strategy accounts the overall inventory level (i.e. expressed in term of total volume of stocks), as the sum of the stocks of the SKUs present in the Inventory table of the database. The SQL query to import and elaborate data is carried out by the related method of Inventory Class.

- Demand. This strategy accounts the overall demand (i.e. expressed in term of total retrieved volume of products) of a specific period. This is the common policy based on the coverage period and on the inventory turn of the warehousing system. By increasing the range of the time batch, the decision-maker figures out how the total storage capacity alters. This also provides a useful tool to assess and address demand seasonality.
- Locations. This strategy attempts to configure a warehouse able to store a given number of unit loads, assuming one location per each unit load. The considered unit load might be different per each zone, depending on the details of the database.

The command named Volume pattern establish the rule to ceiling or truncate double values into integer values (i.e. the number of locations). The interface of Figure 33 represents a useful control board of the most relevant aspects of demand, inventory and system throughput. The TabPage SKU reports a record per each SKU of the selected zone, with the detail of the carton volume, the TabPage Inventory reports the stock of each SKU, while the TabPage Demand allows to plot the trend of demand, and also gives per each SKU the occurrence in customer orders.

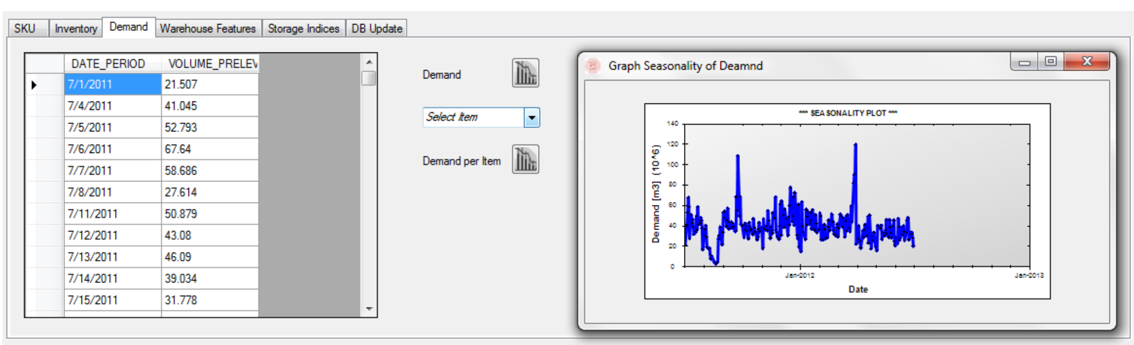


Figure 33. KPIs dashboard

Once the storage capacity is set, the user passes to the layout module, represented by the right side of Figure 32.

4.7.2 Layout module

This module defines the geometry, the layout, the storage mode and equipment, the spatial features and characteristics of specific new warehouse zone. The set of decision to be taken by the user regard the following points and commands, each of them displayed as a ComboBox with a list of alternative options:

- Storage capacity. This functionality reports the value of storage capacity (i.e. expressed in cubic meters) computed through the inventory management module. Although, the value of storage capacity is one, the list reports all the different solutions and choices resulting by the execution of different strategies.
- Shape factor. This functionality represents the ratio between length of the storage zone and its width. The list allows the user also to consider and configure storage area constrained in one or both dimensions (i.e. length and width).
- Unit load type. This ComboBox gives the opportunity to select the size of the handling nd storage unit per each new warehouse zone. This choice has a direct influence on the definition of the rack components and on the space allocation. Storage zone filled by huge SKUs (e.g. car shields) fits with high-volume unit load, whilst for small SKUs are more suitable smaller unit load (as the one chosen in sample of Figure 32).
- Unit load position. This choice regards with the position of unit loads within racks (i.e. side or head).
- Layer per base module. This functionality deals with the number of intermediate layers of rack within a base module.
- Unit load per layer. This choice regards with the number of unit load to be stored per each intermediate layer of the base module. Therefore, the number of unit load, or storage locations available per each base module is given by the multiplication of the layer per base module with the unit load per layer values. These two functionalities allow to address the problem of the slotting, since it is possible to configure very different storage zones able to hold very different SKUs (i.e. from selective rack to mezzanine).
- Rack level. Indicates the number of rack levels, thereby setting the heights of the warehousing system.
- Aisle width. Indicates the aisle width per each warehouse zone.
- Crossing aisle. Indicates the presence of a crossing aisle and its width per each warehouse zone.

By clicking the Warehouse design command, the DST roughly computes the size of the base module and searches through defined queries the best fitting commercial component into the RACK Table. If the proper required racks are found, in agreement with the weight tolerance check assuming to fill all rack levels with the heaviest SKU unit loads, then the zone is configured and the analysis proceeds. Otherwise, a dialog box warns the user to change his/her setting, or to upgrade the RACK Table.

The results and statistics of such design are summarized in the Warehouse features TabPage of Figure 34. A few examples of reported KPIs and statistics on warehouse layout follow: storage capacity, number and sizes of aisles and bays, storage saturation (i.e. the ratio of storage volume to the overall available volume), number of SKUs stored per each aisle, etc.

Figure 34. Warehouse layout features

The Inventory management and layout modules are skipped if an existing warehouse is imported by the database. Indeed, for such zone the layout features and the storage capacity are assumed as given. In this case, the layout module simply displays the zone geometry and spatial characteristics, as shown in Figure 35, without giving the opportunity to the user to change these settings. Then, the user might focus on the allocation problem, or bypass this analysis to face the assignment issue. In this case, the storage quantity per every SKU in both forward and reserve area is given, and imported by the database.

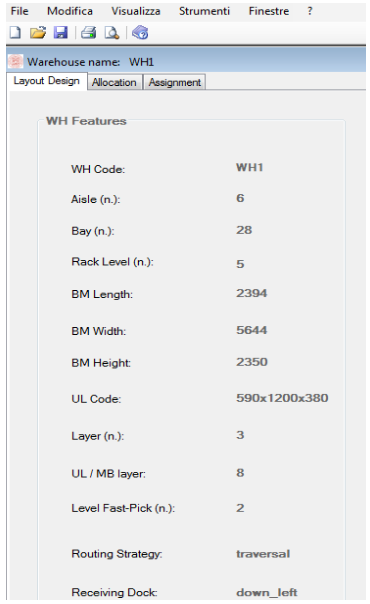


Figure 35. Imported warehouse GUI

Once the warehouse zone infrastructure is designed through the inventory management and the layout (or imported), the system allows the computation of 3D locations coordinates, stored into the database through the TabPage DBUpdate of Figure 35.

Finally, the DST develops an interface between Visual Studio® and AutoCAD® and draws the layout adopting real commercial racks and their graphical entities.

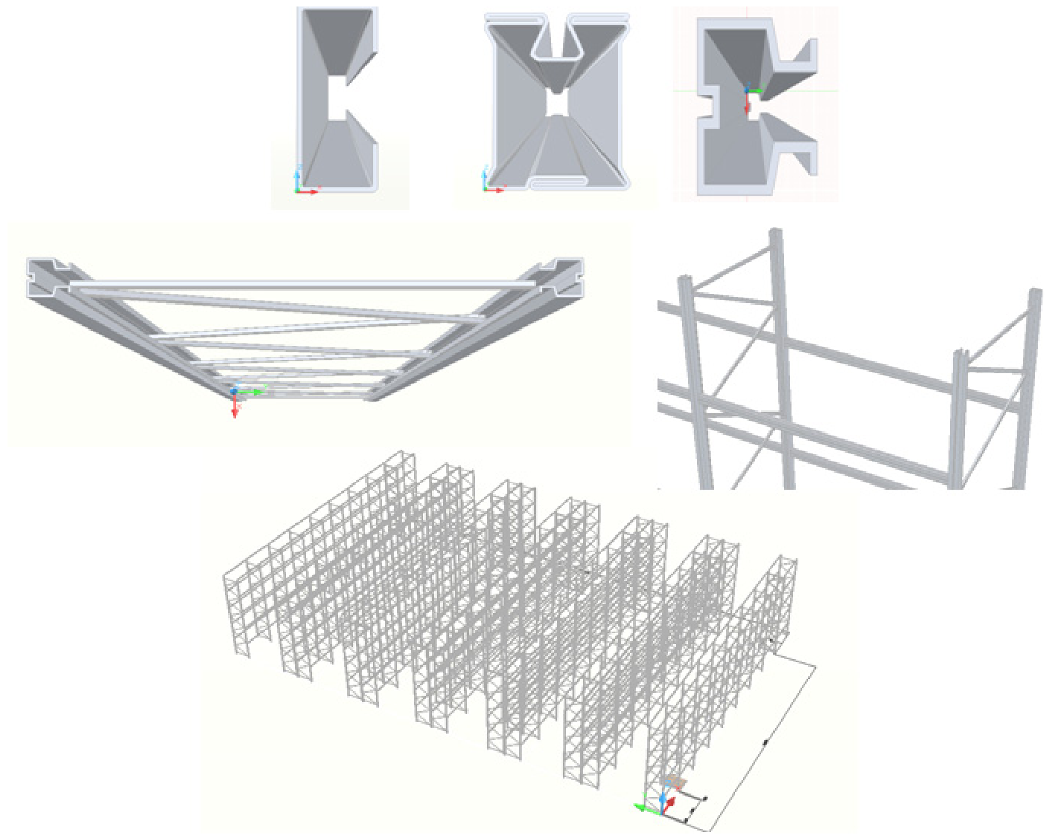


Figure 36. 3D racks representation

In particular, this application allows the user to import commercial rack components (e.g. beams, columns, crosses), taken from catalogues and libraries of rack manufactures, storing as database records and adopting these parts to configure a truthful and accurate warehouse. Figure 36 illustrates a few examples of 3D details of racks and shelves drawn through the graphical interface as results of the layout design modules. This module provides, as result, the final list of rack components detailed in terms of parts per code and the costs of raw material. A detailed description of the development of such interface is given by the following sub-section.

4.7.2.1 AutoCAD Graphic Interface

This interface allows the decision-maker exporting the warehouse scenario and drawing it on a 3D CAD platform. Such interface implements a procedure for the automatic drawing of a warehouse given by a proper combination of racks components and spatial features and parameters. The basic elements to create a rack are the beam, the column and the crossing or bolt and are illustrated in

Figure 37. The entire storage modes (e.g. select rack, double-deep rack, drive-in, etc.) are represented through the proper assembling of physical basic elements.

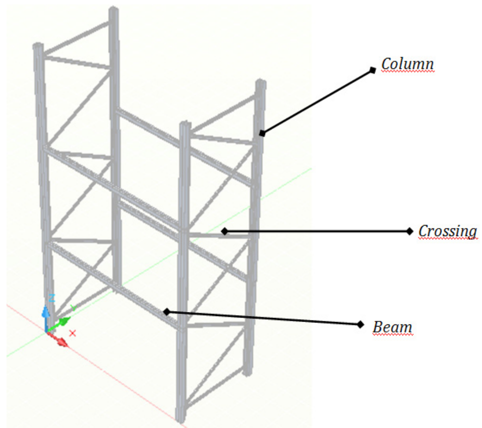


Figure 37. Rack components

In order to create a new project, the software AutoCAD enables the pre-loading of an application or a procedure written in AutoLISP language. This procedure works by typing on the command line the command string _*appload* and then selecting the file containing the application. To speed up and automate such activity, it might be suitable to insert the application name directly into the file ACAD.lsp. Consequently, when a new project begins AutoCAD imports and loads all the settings and commands and procedures contained in the ACAD.lsp file.

In particular, the ACAD.lsp file contains four main procedures (i.e. keywords), each referring to a specific drawing process:

- Initialize. This procedure reads and loads the variables and parameters from a txt file computed and exported by the DST, as result of the layout setting and design module.
- DrawSelectiveRack. This procedure draws the single deep base module as specified by the Initialize procedure and replicates such module over three dimension to drawn the warehouse.
- DrawDoubleDeepRack. This procedure draws the double deep base module as specified by the Initialize procedure and replicates such module over three dimension to drawn the warehouse.

- DrawSKU. This procedure fills the warehouse drawn by one of the previous two procedures with the SKU in the locations and quantities defined by the assignment module.

4.7.2.1.1 Initialize procedure

This procedure implements the following steps. At first, it reads the txt file saved by the DST, and imports the settings of variable and parameters. The second step of this procedure is loading the CAD libraries required to drawn the warehousing system. These libraries encompass the whole set of drawn objects, previously realized by the user or imported by a virtual catalogue. In particular, the rack components are the graphical representation of the records of commercial catalogue. Figure 38 gives a picture of some of the elements contained in the graphical libraries.

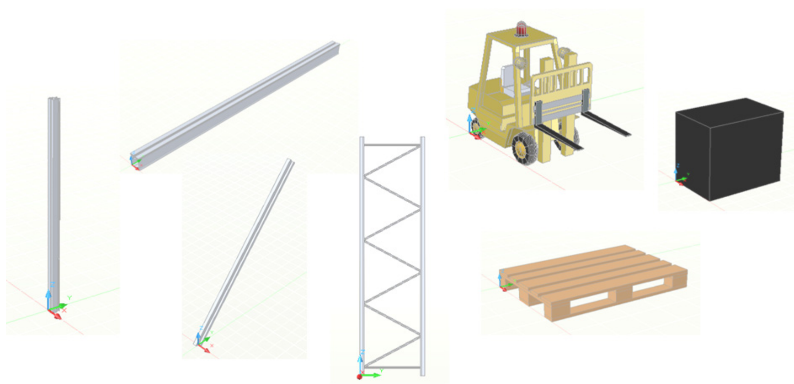


Figure 38. Graphic elements samples

The third purpose of this procedure is to prepare the work sheet, by drawing the area of the warehouse system, also reporting the dimensions of the system. The fourth and last step of the Initialize procedure is to create the dimension layer, the warehouse area layer and the aisle layer. The results of such procedure are illustrated on Figure 39.

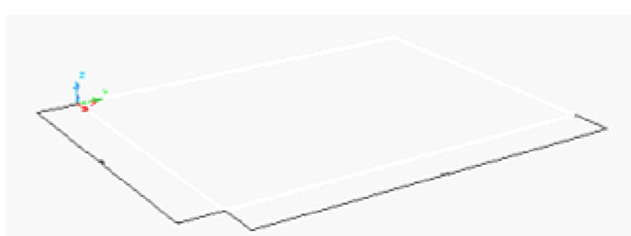


Figure 39. Green field layout

4.7.2.1.2 DrawSelectiveRack procedure

This procedure aims to draw the warehouse infrastructure considering selective racks. At first, it implements a properly defined function, named DrawBay, to draw a bay, then another function, named DrawAisle, to shift the cursor by the aisle width and again the DrawBay function to complete the base module. Then shift the cursor of the bay width and iterate the procedure to complete the aisle. Finally, iterate the overall procedure for a number of aisles specified by the DST.

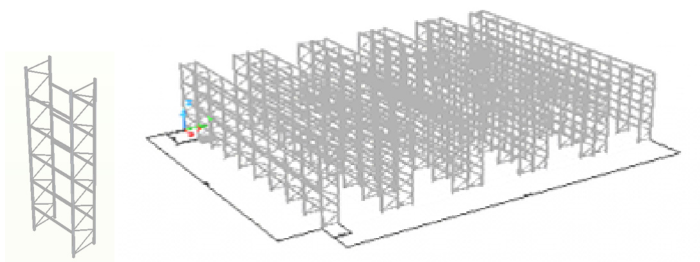


Figure 40. Warehouse infrastructure

As previously discussed, the DST allows configuring a warehouse zone with a crossing aisle in order to avoid too constrained picking tours. In order to achieve this goal, the function *DrawBay* is repeated until the half of the warehouse depth, then a second function, named *DrawBay2*, considers the width of the crossing aisle and scales the cursors accordingly. Figure 41 shows the result of the execution of this procedure in presence of a crossing aisle.

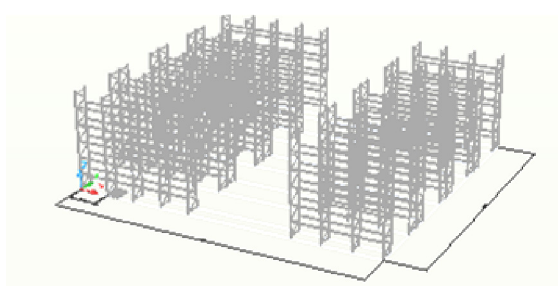


Figure 41. Warehouse infrastructure with crossing aisle

4.7.2.1.3 DrawDoubleDeepRack procedure

This procedure aims to draw the warehouse infrastructure considering double deep racks. The procedure replaces the step of the previously illustrated one and consists on an alternative design opportunity. The results of such procedure are shown in Figure 42.

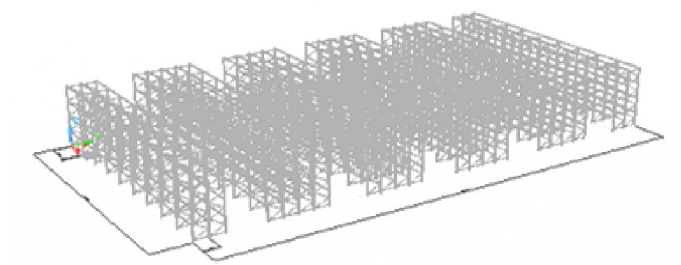


Figure 42. 2-deep warehouse infrastructure

4.7.2.1.4 DrawSKU procedure

This procedure aims to insert the SKUs in the rack as defined by the allocation and assignment modules. Each block, is differently colored SKU by SKU and represents one storage unit load. This procedure reads a txt file saved by the assignment module and imports the settings of variable and parameters. It iterates the function *RackFilling* per each SKU of the txt file. The results of such procedure are shown in Figure 43.

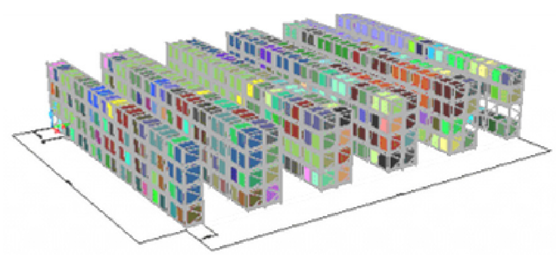


Figure 43. Filled warehouse

Finally, the AutoCAD interface permits also to represent a multi-zones warehouse in the same work sheet as illustrated in Figure 44.

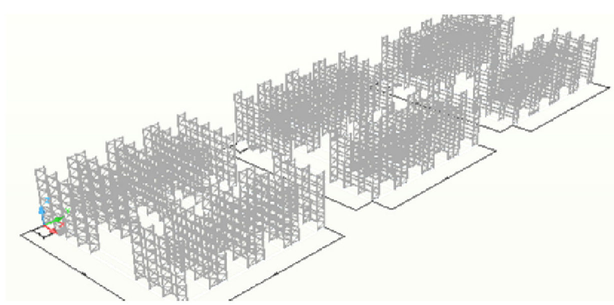


Figure 44. Multiple-zones warehouse

4.7.3 Allocation module

This module enables the decision-maker to compare different allocation strategies attempted to allocate the proper storage volume to a generic SKU within the forward area for a typical forward-reserve picker-to-part OPS. At this step, the DST implements three main allocation strategies (i.e. EQS, EQT, OPT) according to the previously illustrated top-down design procedure. This module maintains an open architecture allowing, eventually, a quick implementation of other allocation strategies.

Figure 45 illustrates the GUI such as is proposed to the decision-maker. On the up-left side of the interface, two input ComboBox, respectively named *Rack Level* and *Allocation Strategy*, define the number of rack level devoted to the forward area and select the allocation strategies to adopt for the forward configuration. Thus, the flexibility of the DST gives to the user the opportunity to design a low-level or a high-level OPS through the *Rack Level* command, thereby assigning the last levels to the reserve storage area. Obviously, the maximum number of rack level is an upper bound of the levels devoted to the forward area.

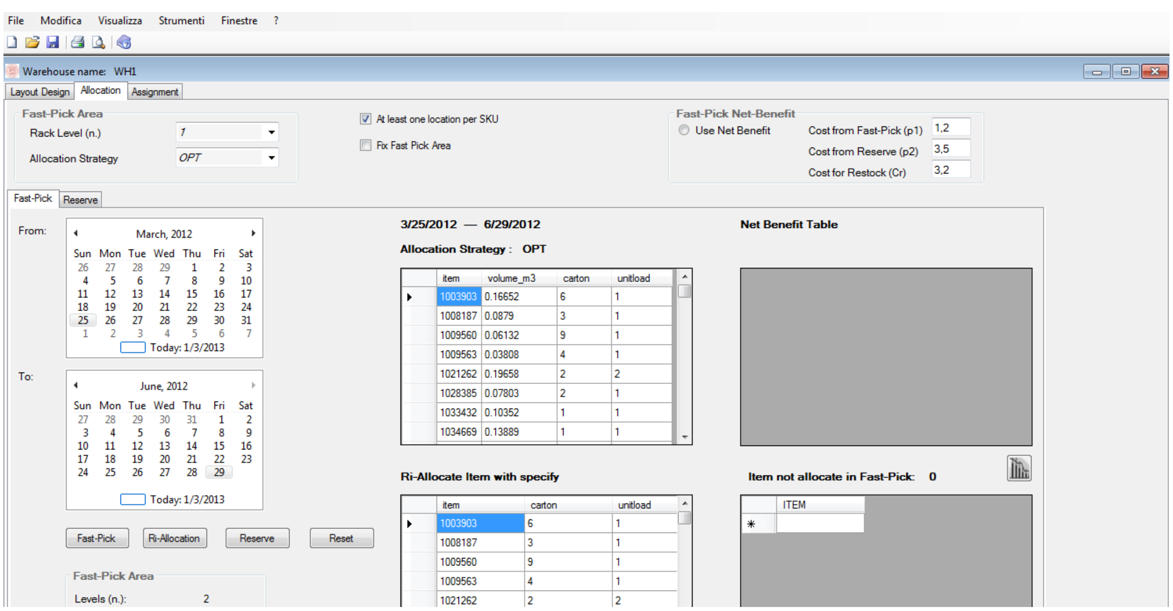


Figure 45. Allocation GUI

The calendar panels, displayed on the left of the interface, select the horizon of analysis, by filtering the dataset through dynamic SQL queries. Different time batches may be adopted to compute the fraction of storage volume devoted to each SKU according to historical demand and inventory data. As instance, given a temporal batch (i.e. from March 25th to June 29th, 2012 in the proposed sample) the selected allocation strategy (i.e. OPT) devotes to the SKU 1003903 0.16652 cubic meters of forward space, which correspond to 6 cartons and 1 unit load (see tables in the middle of the GUI).

Storage space is often a precious resource to be handled in order to reach efficiency and reduce operative costs. At this step, the decision-maker may compute the net-benefit of the forward area (see panel on the right side) according to the Bartholdi and Hackman (2011) pattern. This model establishes the set of SKUs responsible to maximize the net-benefit of the forward area, considering both time saving per pick (i.e. pick from forward vs. pick from reserve) and time for replenishment. The maximum value of cumulate net-benefit highlights the set of SKU to allocate within the forward area.

At this step, the decision-maker matches allocation results with layout features and eventually considers the opportunity to come back at previous analysis and fix layout or storage equipments. The quantity per each SKU to store in bulk area is given by the difference between the average historical inventory, known by the Table Inventory, and the quantity allocated in forward. Such stock is reported per each SKU in the TabPage *Reserve*.

If an existing warehouse zone is imported and loaded, the AS-IS inventory per each SKU (i.e. number of cartons and unit loads in both forward-reserve areas) is given and related data are stored into the database. Thus, the user may skip the allocation module, not considered as leverage of the analysis, leaping from layout design module directly to assignment module, thanks to the flexibility of proposed DST.

4.7.4 Assignment module

This GUI leads the decision-maker towards the assignment issue by the definition of the appropriate location to assign to a generic SKU in the forward area. Considered the horizon of analysis (e.g. the same chosen for allocation analysis or different as for the sample of Figure 45), the user classifies SKUs according to a set of proposed criteria or metrics (i.e. index based policies) rather than assessing the correlation among SKUs (i.e. correlated based policies) through a clustering approach.

Both opportunities compute a ranked list of SKUs (eventually of clusters of SKUs) responding to particular criteria (e.g. popularity, turn, order closing), to be properly matched with a list of locations, according to the procedure presented in Chapter 3.

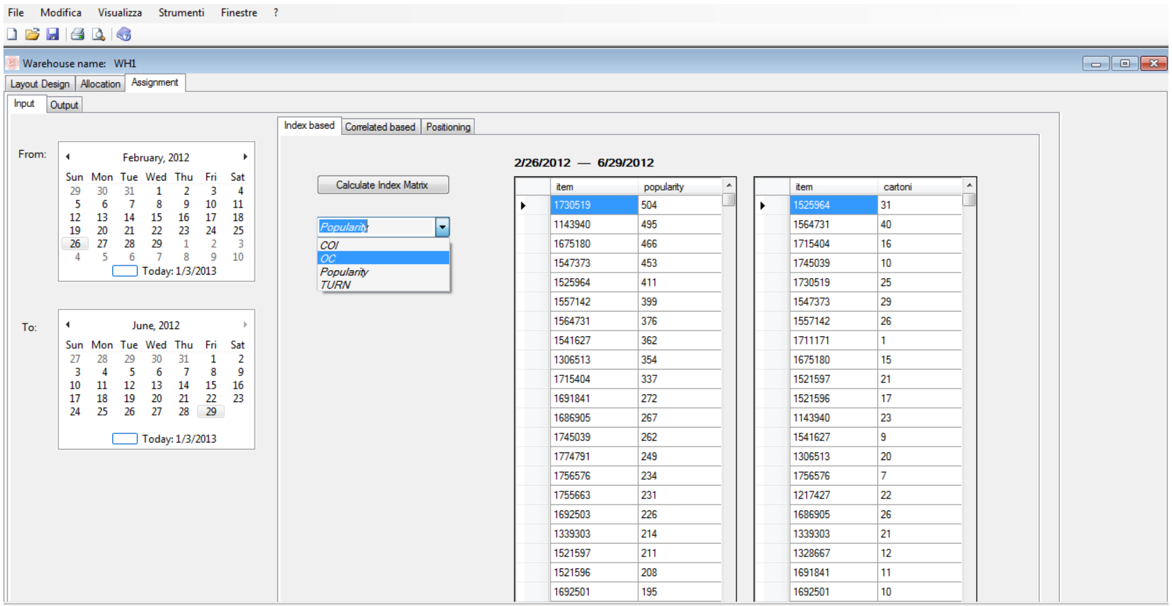


Figure 46. Assignment GUI

Figure 46 shows the Assigment module as appears to the decision-maker. On the left side two calendar panels allow to establish the interval of analysis, whilst the right side of the interface is composed by a TabControl with three subsequent TabPages. The first TabPage refers to the Index based assignment policies. The command named Calculate Index Matrix implements the previously described method *SKUIndexMatrixCreate()* belonging to Demand class. Once the metric is selected a list of SKUs is given sorted in accordance with the ranking rule illustrated in Section 3.2.3.1. In the proposed sample of Figure xxx the index adopted is Popularity and the SKUs are accordingly ranked from the highest requested SKU to the least.

The second TabPage is devoted to the correlated assignment policies based on clustering approach. The GUI illustrated in Figure 47 presents all the commands and functionalities for the implementation of the clustering techniques. At first, the user select the period of analysis as for the index based assignment rules. Then, define the similarity index (i.e. chosen between McAuley and Accorsi & Maranesi) to adopt and the clustering algorithm (i.e. chosen among Slink, Clink and Upgma) through the related Combo Boxes. The five factors composing the Accorsi & Maranesi metric, also named Picking Oriented Index (POI) are configurable through proper check box, labeled x_1, x_2, x_3, x_4 and x_5. The DST realizes the clustering and actuates the similarity cut-off based on the threshold percentile (i.e. 20 in the sample) or threshold value methods. Finally in the third step of the process, the decision maker decides the rules for the sorting of created clusters.

The graph in Figure 47, reports the value of similarity of the progressive SKUs, which enter into a cluster. Obviously, the trend of such curve is descendent, but its shape bright an important insight about the effectiveness of clustering in fitting the demand profile.

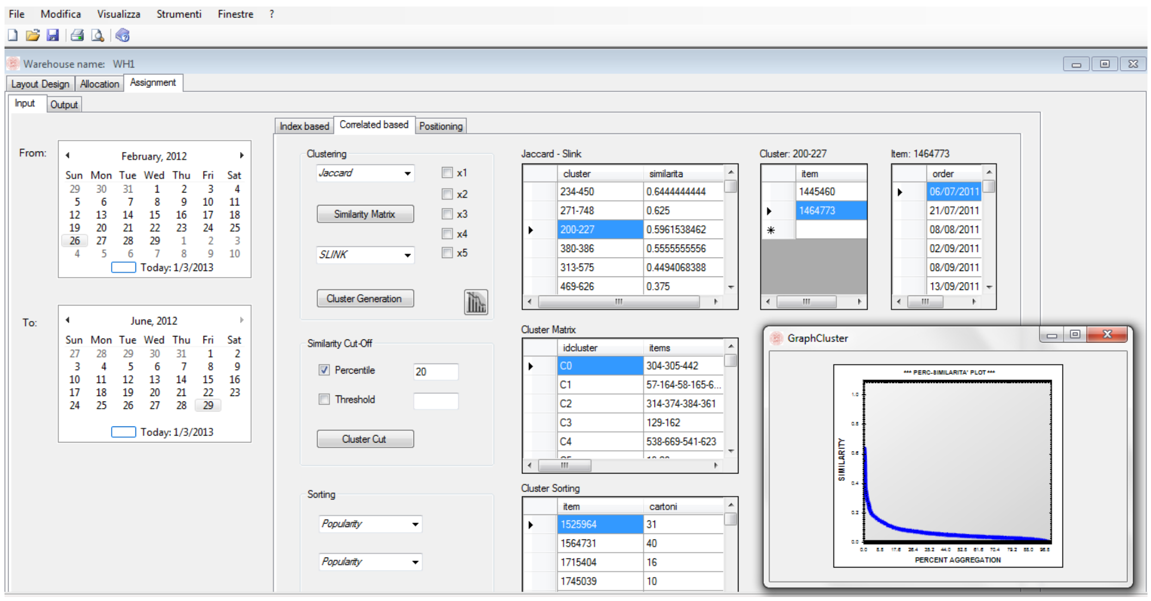


Figure 47. Correlated assignment GUI

The third input TabPage of the assignment module gives the opportunity to the user to define the most convenient storage locations within the zone are. This setting depends on the routing strategies (i.e. return or traversal) and on the site of receiving and shipping docks, assuming the former as the point where the picking tour begins, and the latter as the point where the tour ends. Figure 48 shows such more than twenty combinations for site of receiving and shipping docks (e.g. corner, middle, bottom-up, distributed), affects the single-command distance to access to a generic location. This distance (i.e. measured in millimeters) reports the path travelled by the picker starting form the receiving dock, achieving each base module, and then going to the shipping dock. This is assumed as the metric to rank the storage locations according to the grade of convenience.

In the Output TabPage the DST assign the sorted SKUs to the most convenient locations in the forward area, in a sort of greedy matching. Each SKU holds the number of location required to store the quantity set with the allocation step. Once the appropriate location in forward area is assigned to a specific SKU, the bulk area is accordingly arranged by the adoption of greedy heuristics to reduce the distance between an item and its reserve.

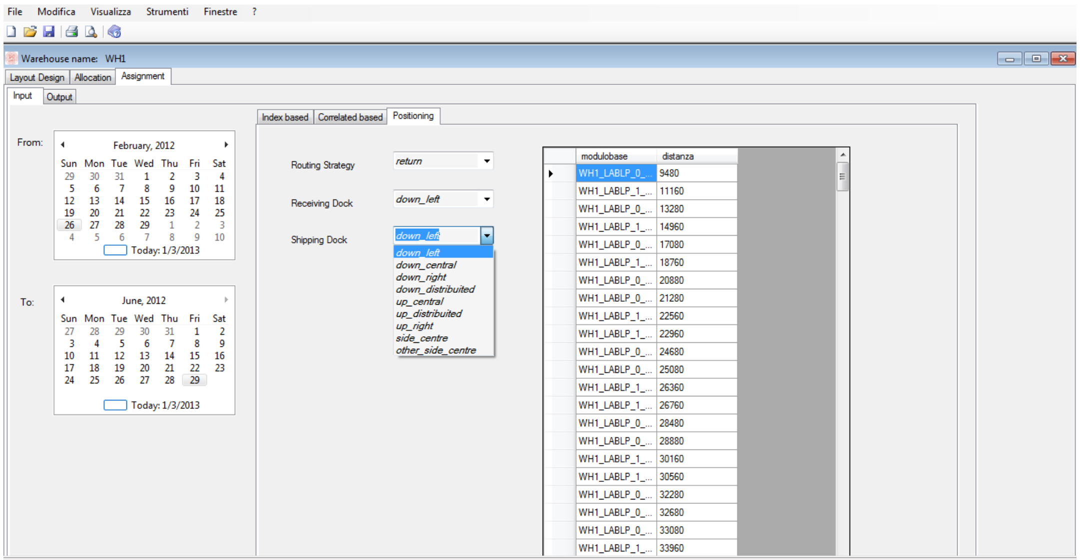


Figure 48. Assignment layout GUI

Results of the assignment module are store into the database, through the button Add WH Zone, and detailed illustrated as bird view of the designed warehouse zone. Once the assignment module ends, the zone is completely configured and its characteristics are stored in the database available for zoning, routing, batching and benchmarking modules. The bird view, proposed in Figure 49, is a frame shot of SKUs locations, where each SKU is differently coloured and storage details (e.g. location code, item code, number of cartons per item) are summarized on the right panel by a simple click.

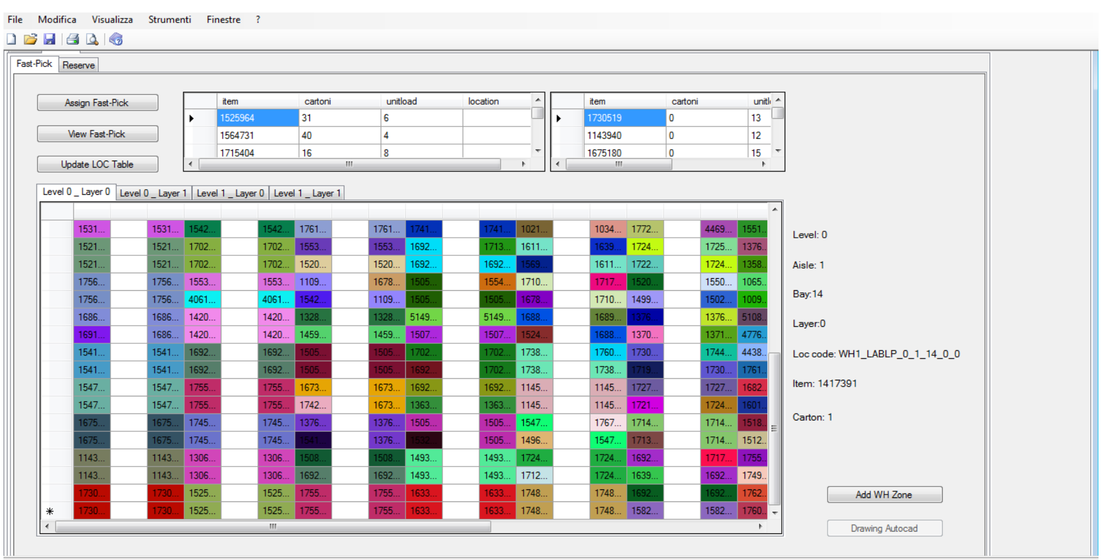


Figure 49. Assignment results GUI

The DST proposes this virtual 2D layout representation through a TabControl where each TabPage is a level of storage for both forward and reserve area.

At this step, the decision-maker might also realize a comprehensive 3D CAD layout of the configured scenario through the previously illustrated interface. The results of this interface is reported as sample in Figure 50, which shows how the rack infrastructure is fill by SKUs in the defined quantities and locations. By considering real commercial racks, the decision-maker obtains a ready-to-print version of the designed warehouse useful for warehouse builders as well as warehouse operators responsible for put away and picking activities.

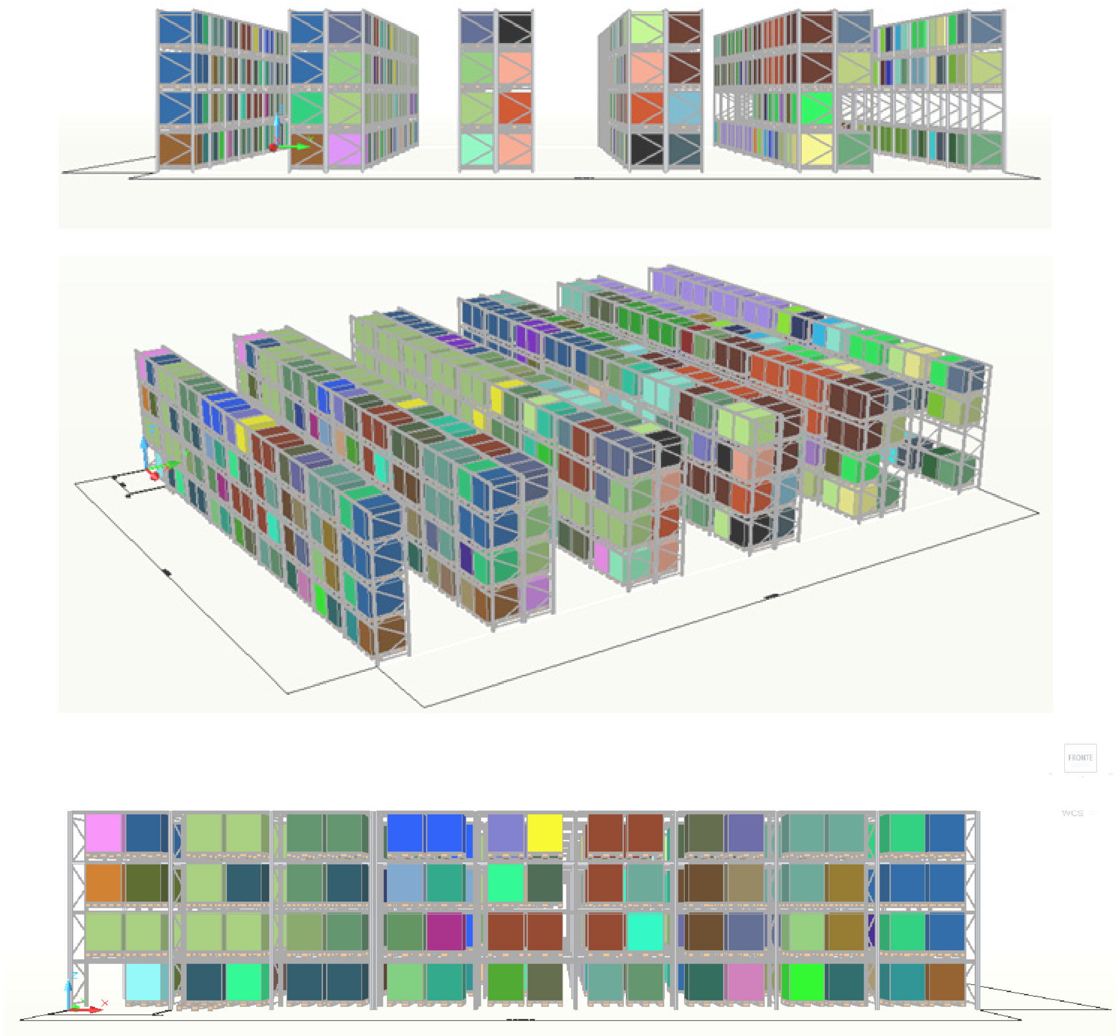


Figure 50. 3D warehouse scenario

4.7.5 Zoning module

The developed DST enables the design of a warehouse as composed of multiple zones analyzed and configured individually. This GUI allows the user to merge different zones configured through the modules illustrated, and move toward the simulation and performance benchmarking. Here the user has two opportunities: selecting a zone and set a one-zone warehouse, rather than selecting multiple-zones and set a multi-zones warehouse. The zoning module consists of one TabPages, named Build Zone, of a TabControl, which leads the decision-maker from the system configuration toward the performance benchmarking.

At the end of the assignment module, when the zone is completely configured and designed, the button Add WH Zone add an object of Warehouse class to a list of Warehouse object hold by the class MDIParent Form. Therefore, the MDIParent Form keeps track of all the storage zone (i.e. Warehouse object) designed during the session, which are all the Form analysis opened during the session.

The zoning GUI presents a ComboBox, illustrated in Figure 51, which reports all the storage zones added to the Warehouse list of MDIParent Form. Within this window, the user can select from such list the zones to create a unique warehouse, named Global Warehouse 1 in the sample.

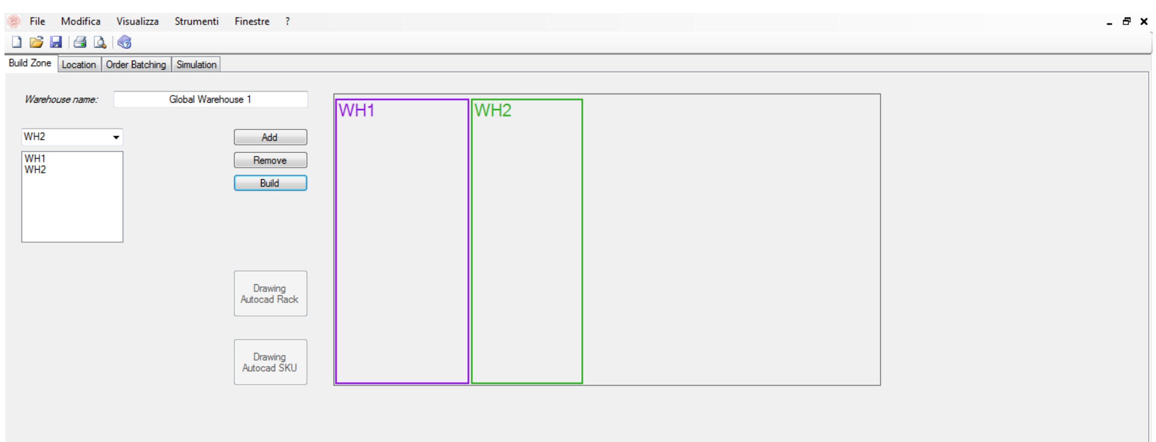


Figure 51. Zoning GUI

In the sample of Figure 51, two warehouse zones, named WH1 and WH2, are configured within the session and merged in a multi-zones warehousing system. The Add button Add allows adding a zone to the global warehouse, the Remove button Remove to delete it and the Build button Build to set the system. The realized AutoCAD interface allows, also at this stage, to drawn the layout of a multi-zone system as proposed for three zones in Figure xxx.

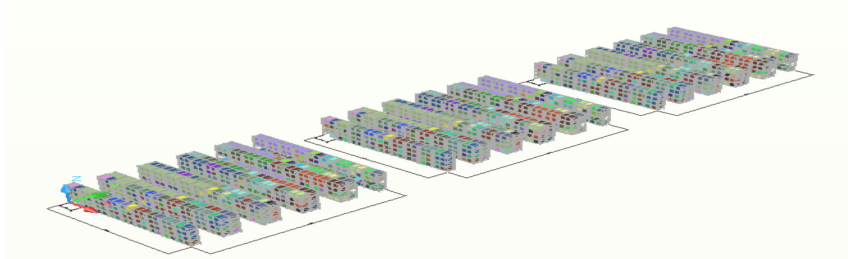


Figure 52. Multiple-zones 3D warehouse scenario

4.7.6 Routing module

The routing module consists of one TabPages, named Location, of the TabControl that leads the decision-maker from the system configuration toward the performance benchmarking.

This simple GUI hides a more complex data flows through the software. Indeed, at this step the spatial coordinates of the base module composing each zone are recovered and accordingly scaled to form a unique base module matrix. The results of this process is a From/To chart, as proposed in Figure 53, which reports the distance between each base module to all the others base module of the warehousing system. Thus, the geometry of the whole system is known and the routing procedure can be carried out.

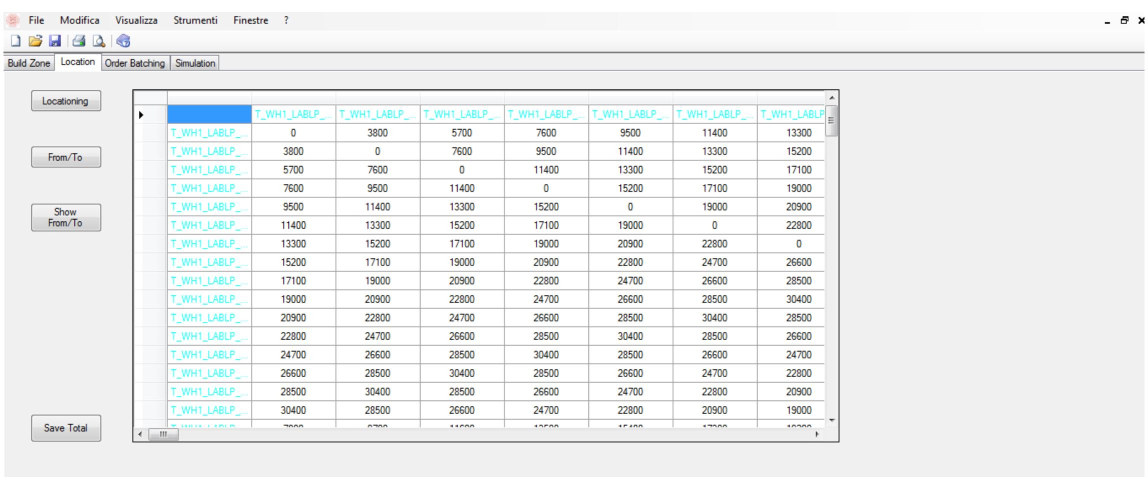


Figure 53. From/to warehouse locations chart

The distance within the From/To chart matrix take into account the selected routing strategy when the storage zone are configured (i.e. routing or traversal). Then, according to the nearest neighbor heuristic described in Chapter 3, the order list is sorted so that the order picker avoids back traveling. The From/To chart distance matrix is an HashTable which assigns a progressive integer key to each base module code on both rows and columns. The results of the routing module are compared and assessed in the final benchmark module.

4.7.7 Batching module

The batching module consists of the third TabPages, named Order Batching, of the TabControl that leads the decision-maker from the system configuration toward the performance benchmarking.

This GUI, illustrated in Figure 54, presents the commands and functionalities required to implement an order-batch analysis as proposed in the procedure of Chapter 3. In particular, the calendar panels of the left side of the GUI allow the user to select to horizon of analysis. The batching is thereby performed considering a group of orders day by day. The selected similarity index (i.e. McAuley or Accorsi & Maranesi) and the clustering algorithm assess the similarity among orders and create clusters or orders to be fulfilled day by day.

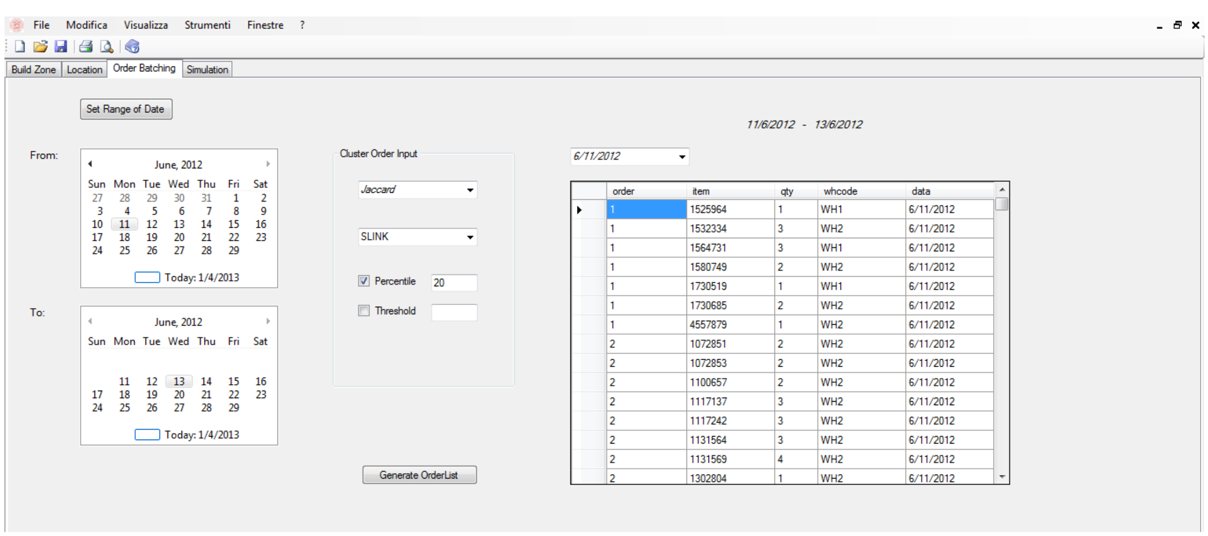
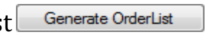


Figure 54. Batching GUI

In the illustrated sample, the *McAuley* similarity index is selected implemented through the *Slink* algorithm and with a threshold percentile of *20*. The button Generate Order List 

implements a method to upgrade the order list, by assigning a new code to the clusterized orders and by cumulating the ordered quantities line by line, as shown in the Gridview on the right.

4.7.8 Benchmarking module

The benchmarking module consists of the fourth and last TabPages, named Simulation, of the TabControl that leads the decision-maker from the system configuration toward the performance benchmarking.

The final GUI represents the benchmarking module, which allows the user setting and configuring the simulation and the collection of the scenario performance. A scenario is a warehouse completely configured with the DST, adopting different leverage at inventory management, layout, allocation, assignment, zoning and batching steps. In such interface, illustrated in Figure 55, the decision-maker selects the vehicle from a ComboBox, which links to the vehicle table of the database, then decides to base the simulation of operative performances considering simply the routing (i.e. Standard modality), rather than even the order batching.

Once again, the calendar panels define the horizon of the simulation that accounts the travelled distance and time for both picking and replenishment operations, as the most relevant KPIs of the warehousing system.

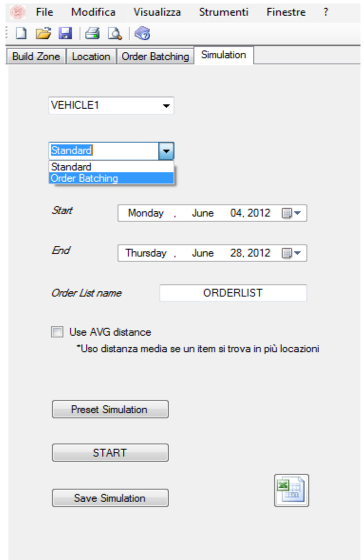


Figure 55. Benchmarking functionalities

As instance the principle detailed results and statistics concern with the travelled distance (horizontal and vertical) and time due to pick-path, travelled distance (horizontal and vertical) due to put away and replenishment, time waste due to stock-out, number of replenishment per each SKU, number of visited aisles, as a metric of congestions, etc.

4.8 Result sample

In this section, the proposed DST has been applied to a trial dataset of a real case storage system. The purpose is not to present a case study and describe the results of the application of the DST, but just to briefly illustrates the result of a quick configuration of real storage zone. The analyzed system system regards a storage zone of a regional distribution center (RDC) that totally counts about 27,000 SKUs, about 7,000 retrieval orders corresponding to an average number of order lines per month of about 180,000. The number of loads received in a month is about 6,000. The fulfilment system and related stock inventory levels are not object of the analysis because they are managed by the automotive company at the central distribution center (CDC) located in north of Europe. The low-level single order picker-to-part and forward-reserve OPS object of the analysis represents a significant but simple trial to assess the effectiveness of the proposed DST.

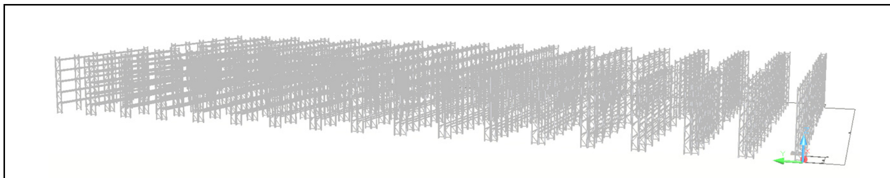
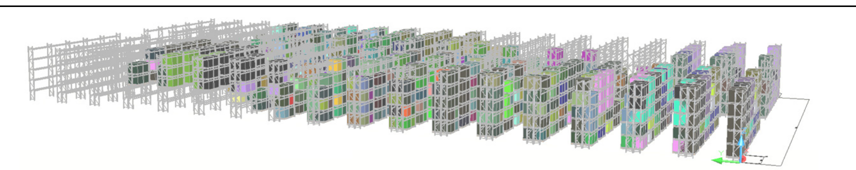
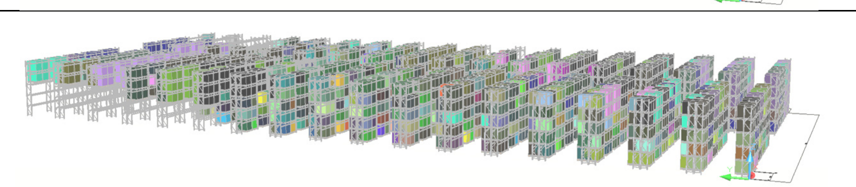
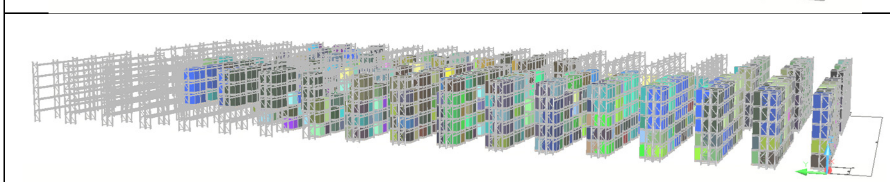
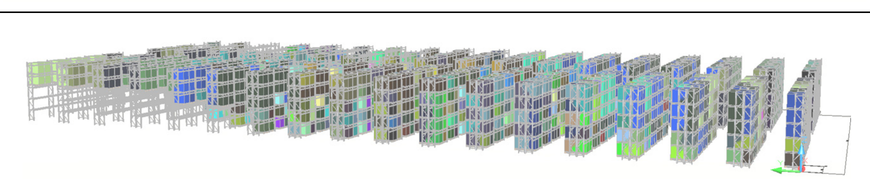
	Storage System Layout Shape factor: 2; Pallet Size: 1200x800x600 (mm); Rack level: 5; Unit load per bay: 2; Aisle width: 3000 (mm); Crossing aisle width: 5000 (mm).		
	Scenario 1		
	Allocation	Assignment	Picking Travelling [km/day]
	EQT strategy	Popularity rule	162.347
	Scenario 2		
	Allocation	Assignment	Picking Travelling [km/day]
	OPT strategy	Popularity rule	131.497
	Scenario 3		
	Allocation	Assignment	Picking Travelling [km/day]
	EQT strategy	Cluster & Popularity rule	163.152
	Scenario 4		
	Allocation	Assignment	Picking Travelling [km/day]
	OPT strategy	Cluster & Popularity rule	132.111

Table 19. Results of analysis.

Table 19 illustrates a comparison among four storage system scenarios interactively configured by the decision-maker according to a set of different decisions defined through the proposed top-down procedure. The alternative scenarios are assessed and compared by evaluating the total travelled distance for picking activities, obtained through a one-month simulation analysis over the real order dataset.

Table 19 shows the impacts of allocation and assignment patterns on both storage system design and operations performance (i.e. daily picking travelling). The graphical representation of the storage system allows the decision-maker quickly figuring out the influence of settled decisions over the SKUs locations in both fast-pick and reserve areas. The combination of OPT strategy and popularity rule mostly performs in reducing the daily travelled distance due to OP activities.

The illustrated results represent a brief exemplification of the potential multi-factors experimental analyses carried out through the DST. Many others parameters, decision-leverage, and KPIs might be handled and managed by the decision-maker to provide the optimal system configuration of different real case studies and to create knowledge over the most critical storage issues.

4.9 Conclusions

In this section, an original DST for picker-to-part storage system design and operations management is illustrated. The proposed interactive system consists on a user-friendly device to support practitioners, managers, decision-makers, logistics providers by addressing real case studies and experimental analysis over the design and operations control of storage systems. The tool enables to gather and store information from enterprises WMS, and to elaborate, through an efficient DBMS architecture, a set of data-oriented design solutions and configurations. The tool aims to design multi-zones storage systems and implements a wide panel of model and methods (algorithms) dealing with different stages of analysis (e.g. storage allocation, storage assignment, order-batching, zoning etc.). Results and statistics on performances and costs due to a generic warehouse scenario are computed through a what-if simulation analysis. An implemented graphic interface enables to draw a 2D or 3D of the designed storage system adopting real commercial racks components with the purpose to provide a ready-to-print release of the warehouse for operators and management.

Further develops are expected on the implementation of innovative methods, models and algorithms to comply warehouse layout, storage allocation and storage assignment issues in presence of automated storage solutions and equipments for part-to-picker systems (e.g. AS/RS, conveyor).

A useful module, integrating a cam interface for the barcode reading, may be implemented in order to support the introduction and registration of new SKUs and the updating of the enterprise SKU master file. This functionality might respond to the problem of periodical and partial storage rearrangement instead of overall warehouse redesigning.

The educational purpose of this work is to provide a set of dynamic and flexible interactive instruments to create and disseminate knowledge among logistic providers, practitioners, managers, and improve industrial engineers background and expertise over the most critical storage issues. Finally, the designed tool, as any other computer aided system, attempts to support, but not replace, the decision-maker asked to daily respond to strategic design and operations management within a storage system.

5. Order-Picking Warehousing. Case Studies

The top-down hierarchical procedure illustrated in Chapter 3 and the related DST illustrated and discussed in Chapter 4 provide a set of methods, procedures, algorithms and tools for the design and management of an OPS. In order to test the effectiveness and the efficiency of the proposed design and management solutions, the analysis of real case studies and real instances and application is required.

This chapter presents and illustrates in details some real less-than-unit load warehousing system cases faced by the adoption of top-down hierarchical procedures and the support-decision tool presented. In particular, the proposed case study deals with a spare parts management system for the automotive industry. A logistic firm operating worldwide provides the logistics services of transportation (inbound & outbound) and warehousing for an important automotive company in order to supply the demand of spare parts to hundreds of Italian customers and dealers.

Results in terms of operative performances in inbound and outbound warehouse operations are summarized to point out the interdependency of specific products and demand profiles in determining the best sets of operative strategies and policies to adopt.

The remainder of the chapter is organized as follows. First and unique section presents the principle insights of the adoption of the proposed hierarchical procedure and tool to a spare parts warehouse. Final section discusses the conclusions and gives indications for further research.

5.1 A spare parts warehouse

This case study deals with a spare parts warehousing system for the automotive industry. A logistic firm operating worldwide provides the logistics services of transportation (inbound & outbound) and warehousing for an important automotive company in order to supply the demand of spare parts to hundreds of Italian customers. This system is a regional distribution center (RDC) that counts about 27,000 SKUs, about 7,000 retrieval orders corresponding to an average number of order lines per month of about 180,000. The number of loads received in a month is about 6,000. The overall storage area is about 20,000 square meters.

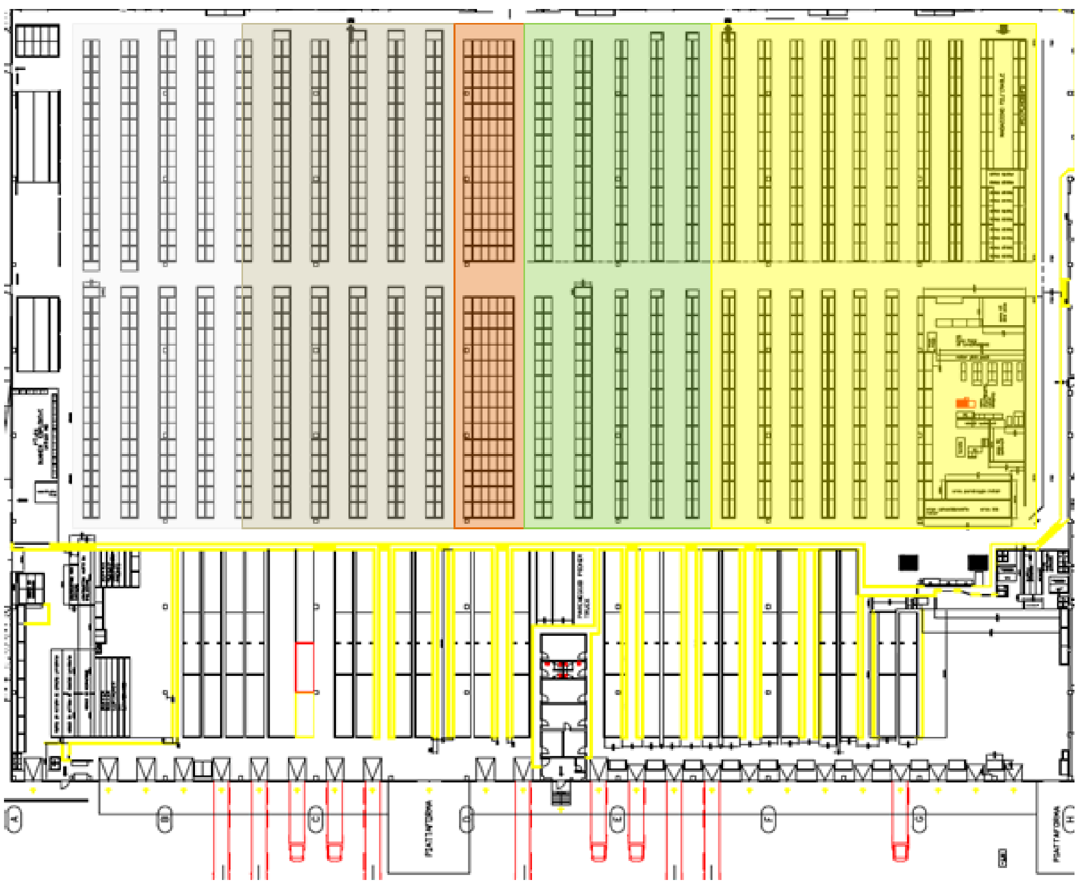


Figure 56. Case study warehouse layout

This warehousing system is a low-level single order picker-to-part and forward-reserve order picking system (OPS). The fulfilment system and related stock inventory levels are not object of the analysis because they are managed by the automotive company at the central distribution center (CDC) located in north of Europe. The huge number of SKUs and the significant available order profile dataset (i.e. more than one year) make this real case as meaningful candidate for the evaluation of the proposed DST.

The analyzed warehousing system is a multi-zones warehouse, which mainly consists of five different storage zones, differently colored, as illustrated in the layout of Figure 56.

The warehousing system is composed by twenty-four aisles, 30 bays per aisle and one wide crossing aisle along the whole area. The receiving and shipping activities are decoupled and limited respectively to the left and right side of the docks. Within each side, the receiving and shipping docks are distributed, and the area in front of the docks are typically held by stacks of unit load or containers to be stored and put-away in bulk area (or in forward area), or waiting to loaded in truck and shipped. Although the docks are distributed, the picking tour begins at the bottom left corner of the storage system and the ends at the right bottom corner of the system. These two control points represent respectively the parking of walkie-stackers and roll-containers and the checking and filming station for the fulfilled orders to be shipped.

The typical aisle visiting strategies (i.e. routing) is the traversal one, as previously described and defined in Chapter 2. Therefore, pickers are not allowed for back travelling within the aisle, which are crossed just in one-way.

The first storage zone, named *WH1*, colored in light grey, stands in the left side of the layout is composed by 4 aisles, and holds the bigger SKUs, with the highest values of rate of unit load weight to volume, and poorly requested such as car shield, bonnet, engine, bumper, seats, boot and so on. The particularity in size, weight and shape of such SKU requires the adoption of huge steel containers as unit-load.

The second storage zone, named *WH2*, colored in dark grey, stands next to the *WH1* and is composed by 5 aisles, and holds the large SKUs but more requested than the components store in *WH1*, such as windscreen.

The Third storage zone, named *WHFloor*, colored in light brown, stands in the middle of the system and consists on unit-load floor storage of steel containers received by the CDCs from Europe. These stacks and lanes aims for to operative purposes: some of them are the reserve of particular high-turnover SKUs and some others stand an easy-accessible storage mode waiting for cross docking. Since the top-down hierarchical procedure focuses on the design and management of less-than-unit-load OPS this zone is not taken into account for the analysis.

The fourth storage zone, named *WH3*, colored in green, stands in the right side of the system, is composed by 5 aisles, and holds the smaller and less requested SKUs, such as tyre, silencer, gear lever, steering wheel and so on.

The fifth and last zone, named *WH4-5*, colored in yellow, stands in the righter edge of the system, is the larger zone composed by 8 aisles, and holds the smaller and high requested SKUs, such as belt, handle, wing mirror, windscreen wiper, filter and so on.

Figure 57 proposes a brief illustration of the characteristics and behavior of the storage zones composing the warehouse layout, in terms of SKUs size and popularity.

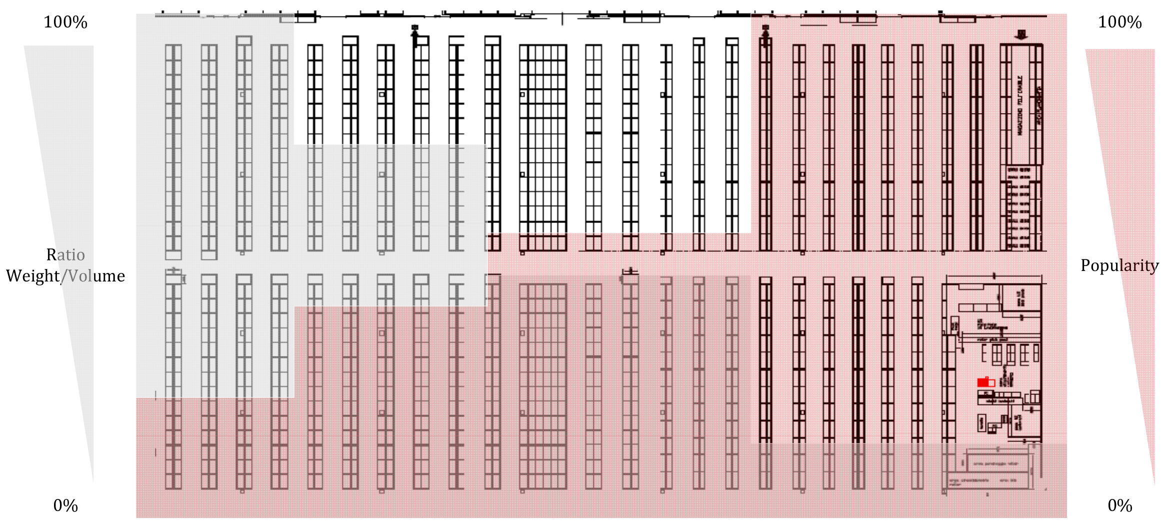


Figure 57. Warehouse behavior

The grey sheer area represents the decreasing value of the ratio weight to volume of the SKUs belonging to each zone, while the red sheer area represent the increasing value of popularity of SKUs belonging to each storage zone.

The adoption of the hierarchical procedure to enhance the performance of this warehousing system entails a preliminary analysis of the AS-IS system, as a benchmark to compare the set of TO-BE scenarios and configurations proposed by the DST. The following sub-sections reports the principle insights of the AS-IS analysis conducted on both inbound and outbound operations. This step attempts to point out the criticalities and points of interest to be addressed through to DST.

5.1.1 Inbound operations

The inbound operations regard all the activities and procedures of truck unloading, goods check-in and goods put-away. In particular, the analyzed warehousing system performs two different procedures of put-away process: the so-called "unit load" put away and a manual "less-than-unit-load" put away. The first is the typical way to receive loads in OPSs.

Conversely, the second process, the so-called reverse picking, is a sort of picking activity, where inbound operators progressively disassemble put-away orders and store the received quantities of SKUs into forward storage locations. Indeed, in such case study, the CDC located in north of Europe supplies the RDC with large wood cases or steel containers composed by the order lines complied at the previous supply node. These SKUs have to be stored in the forward locations and eventually in the corresponding reserve whenever the available volume in forward is not compatible. In order to realize such procedure, the inbound operators performs put-away tours, in lieu of picking tours. These containers are leaded with walkie-stackers throughout the aisles with the purpose to be disassembled and emptied.

This step has been supported by several analyses, whose a few exemplifying results are now reported. The largest part of these analyses is not trivial and the most critical problem is the availability of a set of historical data. Industrial companies do not usually use to collect data on flows and warehousing systems with the necessary level of detail, so they have to be deducted with a very labour intensive activity by analysts and managers of logistics. In particular, some critical aspects to observe are the logistic lead times and by the analysis of the popularity of accesses to the storage locations (i.e. Popularity analysis).

5.1.1.1 Lead time analysis

The lead-time analysis conducted on the put-away operations points out the lead time experienced by the loads from the unloading process until the instant they are stored in the rack. A load represents in case of unit load put way the handling unit of a SKU, which is the unit load to be stored in bulk area, whilst in case of less-than-unit load put away consists on the container of heterogeneous SKUs to be disassembled and emptied. In other words, this lead-time for both cases represents a rough metric of the delay and the efficiency of put-away processes.

In particular, Figures 58 and 59 report a few examples of the frequency analysis of the processing time of inbound put-away activities.

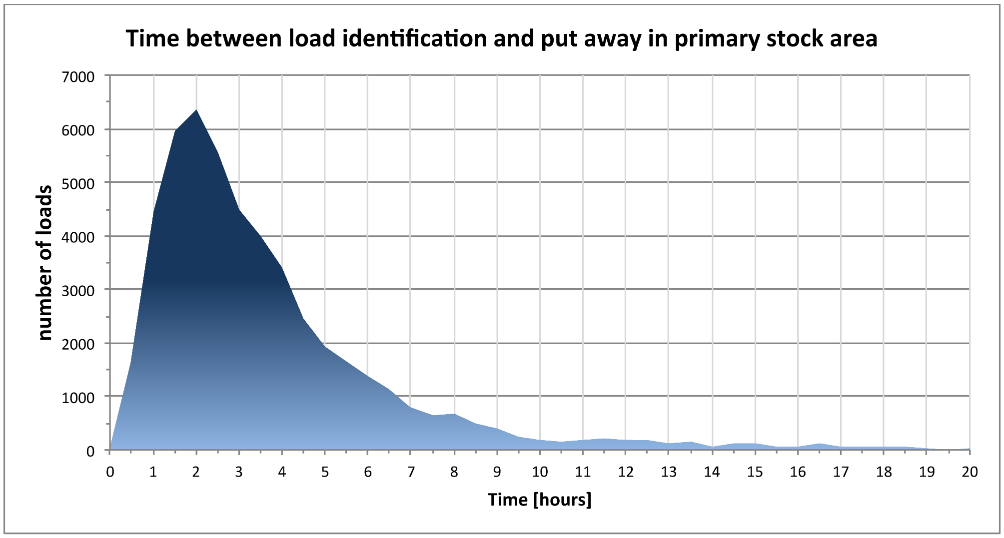


Figure 58. Unit-load put away frequency analysis

The first graph represents the time between the check-in of the homogeneous unit loads of SKUs and the time such loads are stored within the storage system (i.e. put away activity in the bulk or reserve area). The number of received loads is about 50,000 and they refer to an observed working time of 10 months. Figure 58 shows how, in the observed interval, the 25% of received loads needs a lead-time not greater than 1 hour and half, and another 25% of loads require a time greater than 4 hours and 20 minutes.

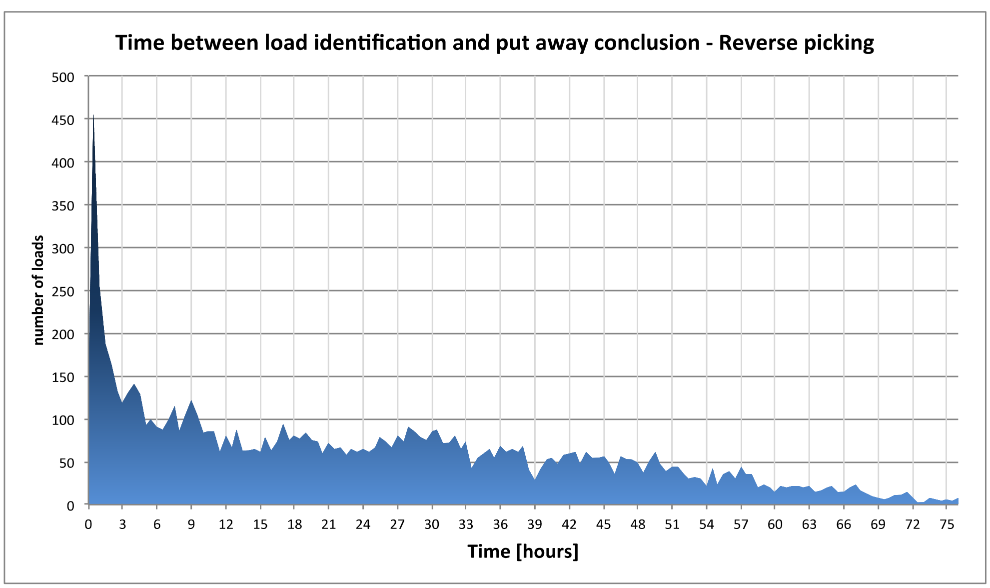


Figure 59. Less-than-unit-load put away frequency analysis

Similarly, Figure 59 refers to the products received as heterogeneous loads of SKUs requiring to be processed by the so-called reverse picking. The time requested for the inbound process is not greater than 7 hours for about 25% of the loads received within the observed period month (i.e. about 9,400 loads in ten months) and about 25% of the heterogeneous loads has a lead time greater than 40 hours.

This huge delay of inbound activities highlights the importance of focusing on the management of put-away processes, particularly of reverse picking procedures. The delay is due to the low efficiency of process of load disassembling since the order list (i.e. the receiving list) is not arranged to reduce the operators travelling. An improvement opportunity might be the rearrangement of the forward storage area to consider the access to the locations due to both the inbound (i.e. put away) and outbound (i.e. picking and restocking) operations. The following subsection deals with the popularity analysis of the inbound activities.

5.1.1.2 Popularity analysis

The popularity analysis measures the number of accesses to the SKUs and/or slots given an historical observed period. This analysis can be conducted for both the fast pick area and the reserve area. A graphical representation of the SKU and/or slot popularity can be conducted by drawing a so-called sphere/ball-graph. Figure 60 exemplify this analysis distinguishing inbound activities according to the process of unit load put-away or less-than-unit load put away. The illustrated figures present a 2D plant layout and the generic sphere dimension is proportional to the number of accesses (i.e. the popularity).

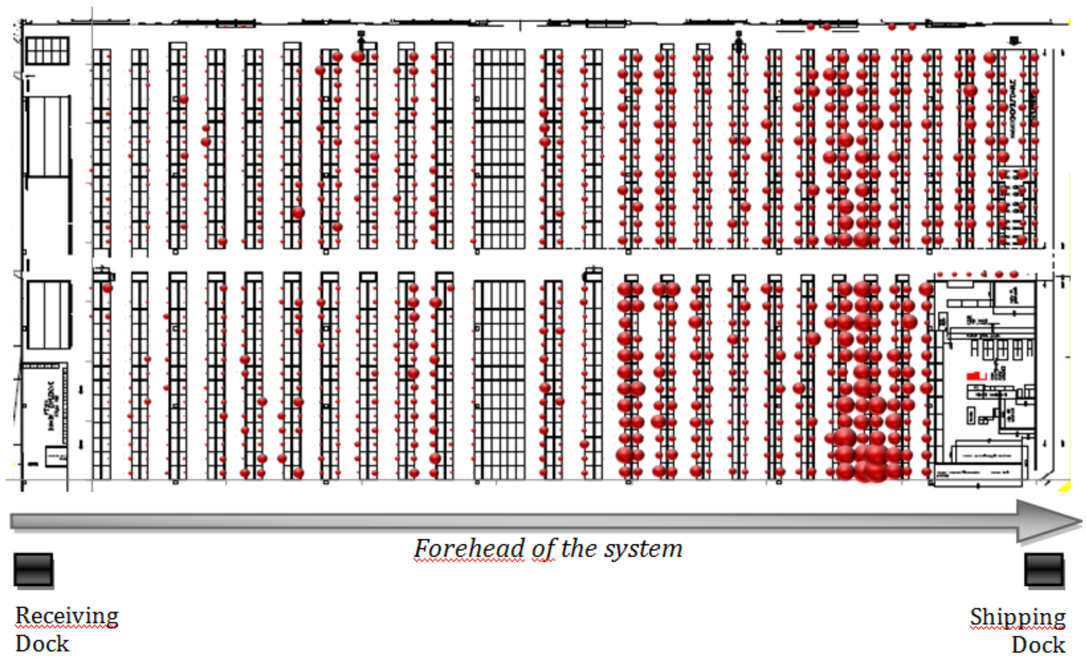


Figure 60. Overall operations popularity analysis

In particular, Figure 60 refers to total number of accesses, including inbound (unit load and less than unit load) and picking outbound accesses: the total number is about 110,000 and refers to a month. An ABC Pareto analysis demonstrates that 39 slots of 1,255 make 20% of accesses. The highest number of accesses is 1,126 in a month.

Similarly, Figure 61 presents the popularity analysis of less-than-unit load put away in a month. The same analysis for unit load put away is negligible, since the locations of forward and bulk are different and the comparison between the accesses to the two storage areas is pointless. Over a total values of accesses of 4459 in a month, while the highest value is 121 accesses accounted by the virtual location utilized when the quantity to be put away is not compatible with the inventory level in forward and a new location in bulk needs to be opened.

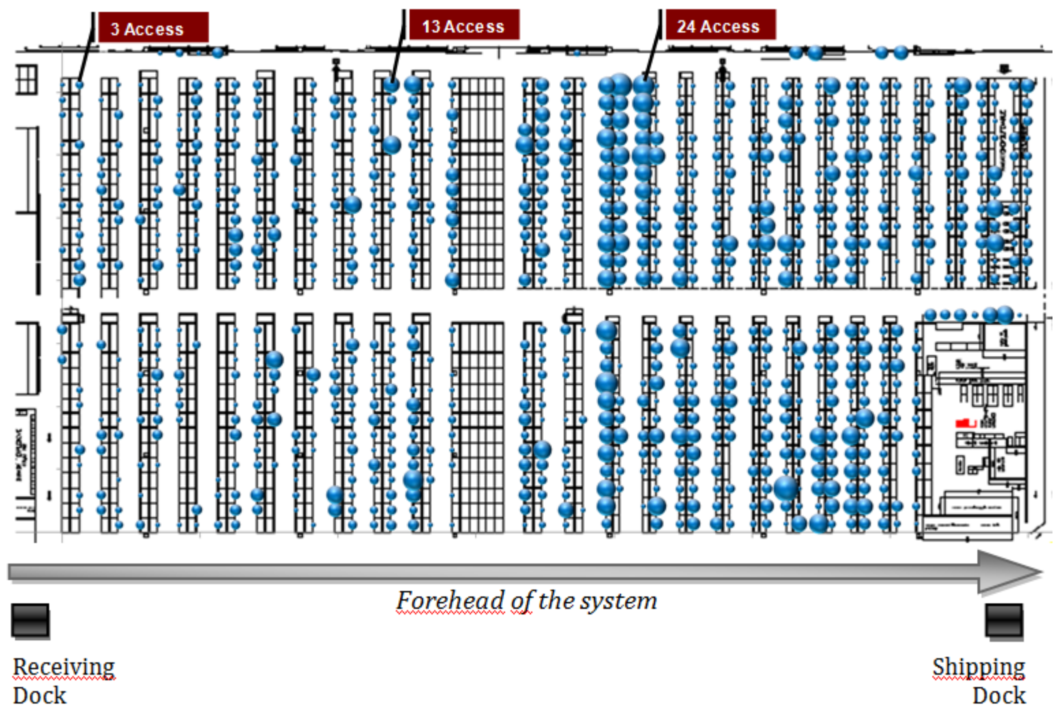


Figure 61. Less-than-unit load put away popularity analysis

The 20% of storage locations accounts for 57% of the overall accesses. These locations are assigned to the high-turn over SKUs, so that this percentage is a rough metrics of how the total inventory turns in the warehousing system.

The same analysis, base on the lead-time and popularity approaches, is handled in follows for the outbound operations with the purpose to assess the influence of such activities to the overall system performances.

5.1.2 Outbound operations

The outbound operations regard all the activities and procedures of picking, storage replenishment and goods checking, shipping. In particular, the most significant procedures analyzed refer to the management of picking and restocking missions. The performances of picking are renowned as the most relevant of an OPS accounting for more than 50% of the total warehousing costs. In particular, 55% of these costs are due to traveling, as previously discussed in the review of the literature of Chapter 2. In the lead-time analysis these percentage are enquired of the specific case study by considering the processes and procedures that affect the lead-time of picking missions.

5.1.2.1 Lead time analysis

The lead-time analysis conducted on the outbound operations refers to the detailed analysis of the activities, which contribute to the overall picking lead-time for the specific warehousing system object of the analysis.

The cake-graph illustrated in Figure 62 shows an example of the analysis of the duration of the tasks, which make the picking process. This is the result of the very important labor-intensive and on-field activity of mapping times and performance of forklifts, pickers and restockers moving within the storage area. The single order (i.e. the number and type of the orderlines), the picker, the scheduled time for picking, the congestions, etc significantly affect such activity. Consequently, it is very important to conduct this analysis mapping times and performance during multiple observations, (i.e. days, pickers job, times of observation during the working day, etc).

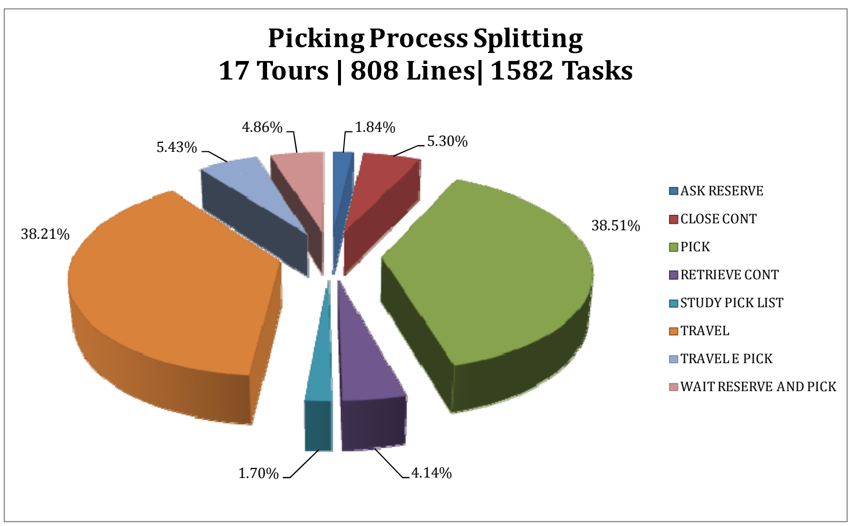


Figure 62. Cake graph of picking costs

The graph refers to a real sampling campaign carried out on field, by the monitoring and tracking of almost 20 relevant picking tours, accounting more than 800 pick lines and 1,582 operative tasks. In particular, the so-called *ask reserve* task is the time necessary to generate the call to restock products (a not automated activity in AS-IS configuration). The so-called *retrieve container* task is the time due to the initial retrieval of the shipping container (i.e. carton boxes, or roll-container) to be filled with the order. The so-called *close container* task is the time spent to re-arrange and close the shipping container of the full order. The so-called *wait reserve & pick* task is the time spent by the picker waiting for the replenishment of products necessary to the picker for his/her mission. The *picking* time is that necessary to pick products when the picker has already reached the right location. The *travel* time, about 38%, is the time spent for travelling. The latter task is the objective of the warehousing optimization analysis through the hierarchical top-down procedure and DST.

Unfortunately, the adoption of the proposed DST enables the study of the performance in travelled distance and time considering the re-arrangement of storage quantity and storage locations (i.e. allocation and assignment modules) and measures such metrics on the base of a static simulation accounting the path of picking and replenishment. Therefore, the subjective and arbitrary time spent by operators in checking the picking list, in sorting the order or waiting the replenishment is not taken into account by the simulation.

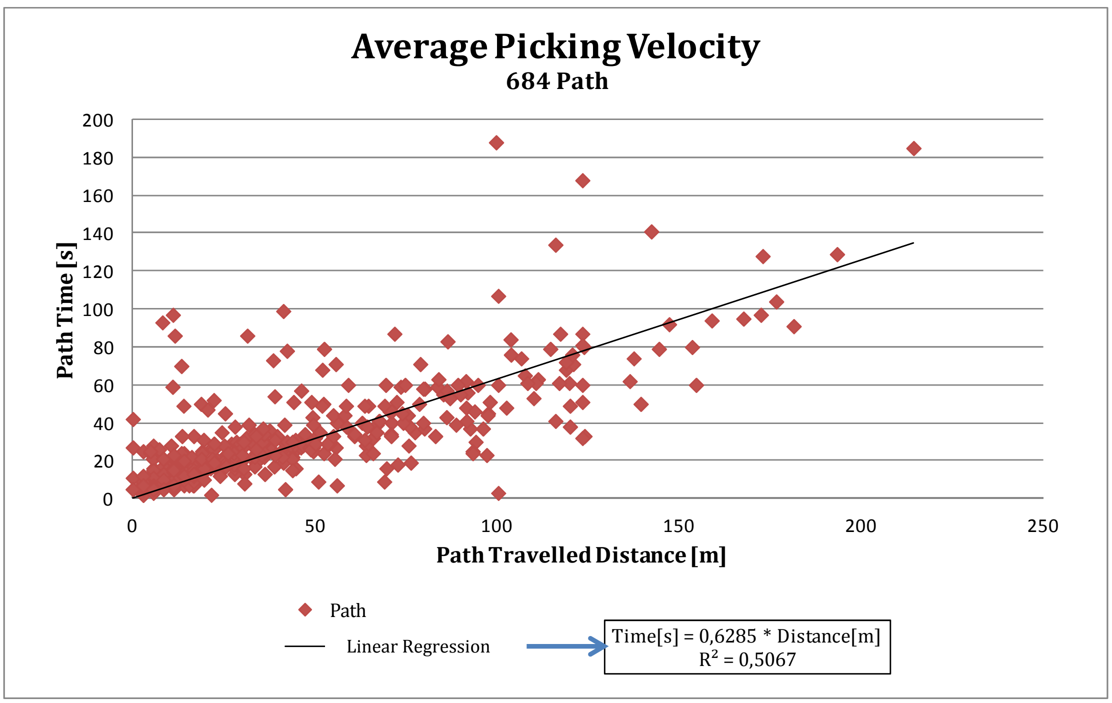


Figure 63. Linear regression analysis of picking traveling and time

In order to address this aspect, another sampling and tracking campaign is carried out with the purpose to point out the correlation between travelled distance and real operative time. Figure 63 present the Linear Regression analysis of the travelled distance for picking path to the related real tracked time. This represents a useful tool for the concrete evaluation of the results of the picking simulation.

5.1.2.2 Popularity analysis

Even for the outbound operations, the popularity analysis measures the number of accesses to the SKUs and/or slots given an historical observed period. In particular, the proposed ball-graphs of Figure 64 and Figure 65 illustrate respectively the popularity analysis of the storage replenishment and the less-than-unit load picking for the forward storage locations.

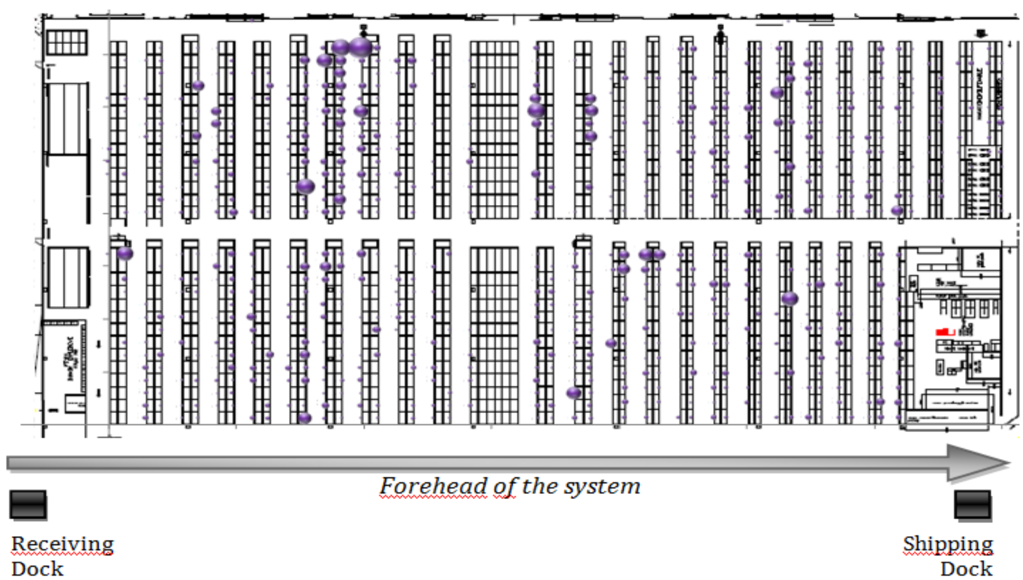


Figure 64. Replenishment popularity analysis

Figure 64 presents the popularity analysis of restocks in an observed month: the highest value is 102 accesses; the total number is 3,214 in a month; 16 of total number of slots make 20% of accesses due to restocking. Similarly, Figure 65 presents the popularity of locations due to picking in an observed period of a month. The total number of accesses is 90,145 and the highly visited location accounts for more than 1,062 accesses. The latter ball-graph highlights at first the higher influence of the picking to the overall storage locations accesses. Furthermore, the mostly-visited storage area is the definitely the WH4-5. The presence of large balls far from the shipping/receiving docks points out the opportunities for improvements. An ABC Pareto analysis demonstrates that the 20% of storage locations make more than 60% of the accesses, and the first 50% locations are responsible for the 90% of the overall accesses.

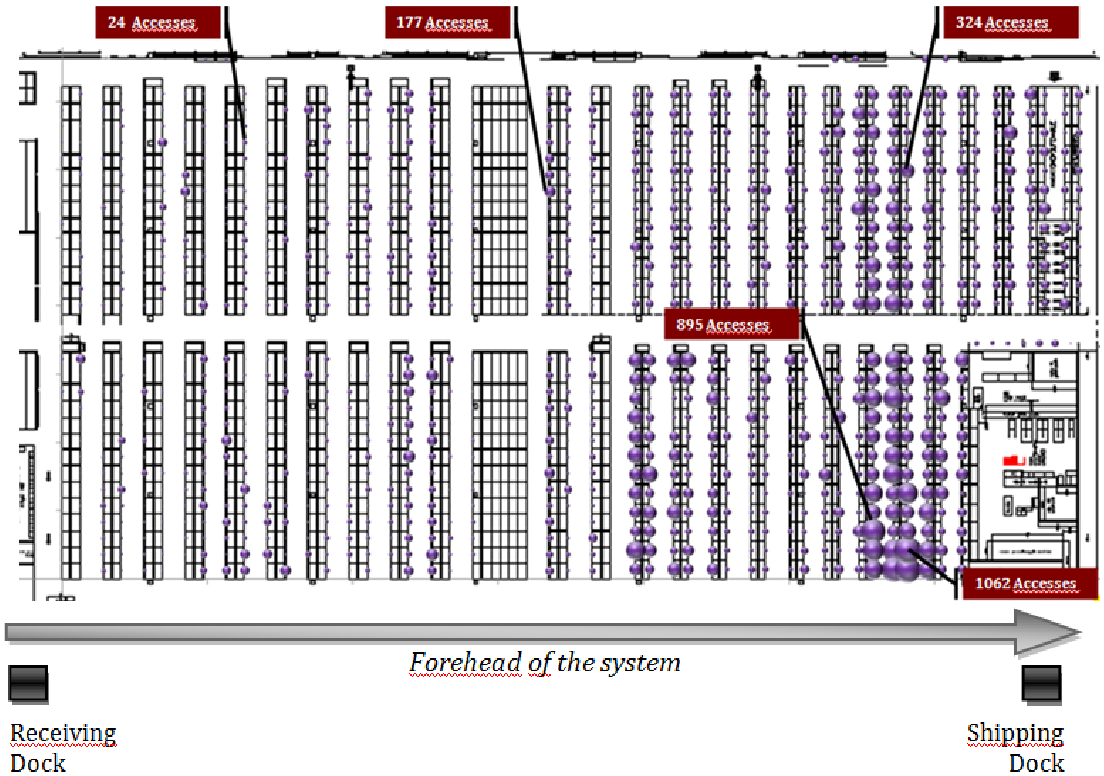


Figure 65. Picking popularity analysis

5.1.3 Results

The conducted popularity analyses demonstrate such the most expensive activity within the system is the less-than-unit-loads retrieving from the fast pick area according to a single order picking strategy. The proposed hierarchical DST is applied to assess the impact of the management of different allocation, assignment, routing and batching policies and strategies on the warehousing system performances.

The spare parts management suggests the implementation of a correlation analysis among products in order to assess the opportunity of the adoption of a correlated storage assignment strategy as discussed by Bindi et al. (2009) and Manzini et al. (2012). Other opportunities consist on the adoption of a zone picking strategies, eventually combined with batch picking strategies and rules. The storage area (i.e. the forward area) is very large and, given deep (made of many order lines) customer's order, the picker has to travel a lot to gather different products located in different locations sometimes far away one from the other. Furthermore, shape, weight and volume of each product significantly influence the determination of an admissible sequence of visit products to be retrieved. Finally, the analysis of logistic lead-times suggest the implementation of a scheduling system to best assign workload and logistic resources to the activities of inbound, inventory and outbound. This is a capacity constraints problem of scheduling to be properly modeled and supported by the development of quantitative models, methods and supporting decisions tools, such as the proposed ones.

This section deals with the procedure based adoption of the DST to import the characteristics of the storage zones object of analysis (i.e. storage zones named *WH1, WH2, WH3, WH4-5*) according to the functionality illustrated in Chapter 4. Each zone is independently imported and analyzed by the allocation, assignment modules. Once each zone is configured a unique warehouse system is configured and designed by merging the 4 different zones, as illustrated in Section 4.7.5. Therefore, the routing and batching modules allow simulating and assessing the traveling performance of the overall system due to replenishment and picking.

5.1.3.1 Allocation

The adoption of different strategies to allocate products within the forward area affects the requested number of restocks and the cost of restocking. This section deals with the comparison of the storage volume devoted to each SKU in forward area and related required number of replenishments.

Table 20 summarizes the obtained results in terms of number of monitored (on-field) and expected restocks adopting the following hypotheses: the whole storage capacity assigned to picking (the forward primary area) is the same in AS-IS and TO-BE scenarios; both AS-IS and TO-BE configurations assume the same number of products to be stocked in fast pick area. The so-called optimal (OPT) strategy, discussed by Bartholdi and Hackman (2011), results the best performing reducing significantly the number of restocks of about 16% within a corresponding period of 9 weeks.

9 Weeks Restocks 7,781	*Allocation strategies*					
	EQS		*EQT*		*OPT*	
	Restock	% Red.	Restock	% Red.	Restock	% Red.
	7,528	3.3%	7,721	0.8%	6,569	15.6

Table 20. Allocation strategies comparison

Figure 66 shows that the AS-IS allocated volumes in the forward area can significantly differ from that proposed by the OPT strategy. This analysis refers to the whole set of SKUs held by the selected storage zones. Some tips are illustrated as follows:

- about 47% of SKUs (at the right side of the graph in figure) asks for greater slot volumes;
- about 42% of SKUs (at the left side in figure) needs a reduction in the assigned volume in fast pick;
- the maximum increase and decrease are respectively +4043% and -95%.

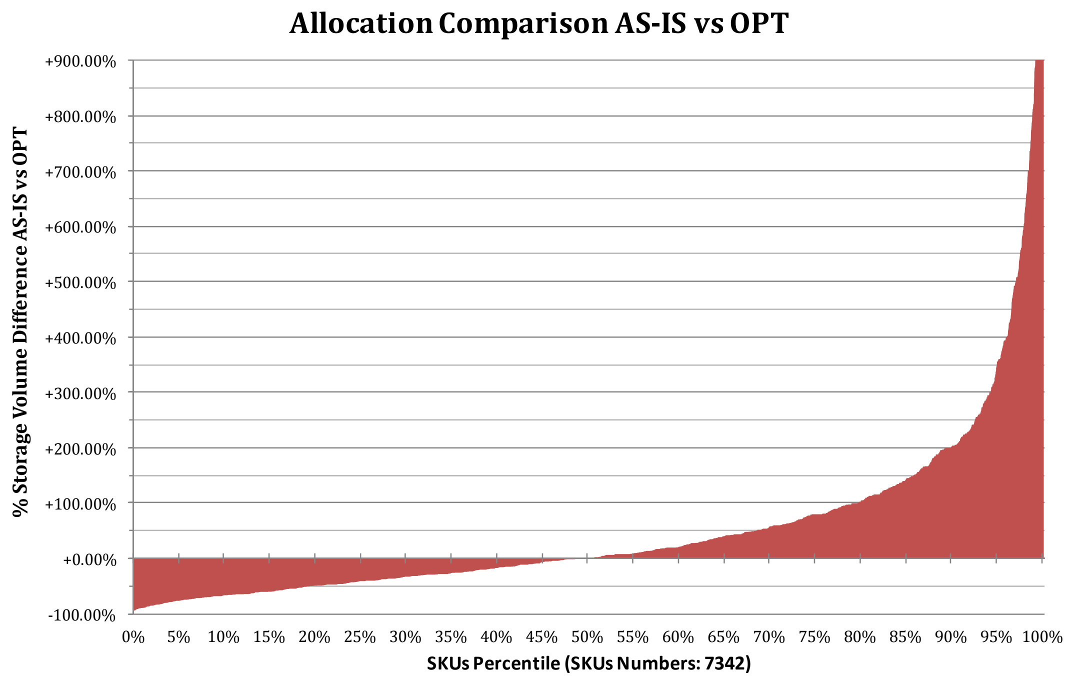


Figure 66. OPT v.s. AS-IS allocation

This graph highlights the influence of the adoption of different allocation strategies to the arrangement of storage volumes. There is a crucial impact of this behavior on the overall operative performance, comprising both replenishment and picking, as handled in the following section.

5.1.3.2 Allocation & Assignment

This section presents the results of a simulation analysis to compare the multiple scenarios of the warehousing system, resulting by the combination of allocation, assignment, routing and batching policies. The proposed analysis focuses on the assessment of the warehouse operative performances resulting by the adoption of top-down hierarchical procedure and DST. The horizon of analysis for the evaluation of a set of KPIs is wider than the corresponding intervals considered for the inbound and outbound as-is analysis. Multiple warehouse scenarios, each composed by multiple-zones, are set by the definition of the following parameters:

- Four allocation strategies (i.e. AS-IS, EQS, EQT, OPT).
- Five assignment strategies (i.e. AS-IS, Popularity, COI, Turn, OC).

- Three clustering algorithms (i.e. Slink, Clink, Upgma).
- Two similarity metrics (i.e. McAuley 1972, Accorsi & Maranesi 2012).
- Three percentile cut-off thresholds (i.e. 20, 40, 75).
- One routing heuristic strategies (i.e. nearest neighbor).

The results refers to an observed horizon of about 1 year, accounting 970,147 picking lines, 84589 picking orders, 44729 less-than-unit-load put away lines, involving respectively 828 SKUs in zone WH1, 1298 SKUs in zone WH2, 1783 SKUs in zone WH3 and 3477 SKUs in zone WH4-5, for an overall number of 7386 SKUs.

WH Settings		**WH Results**					
Allocation	**Assignment**	**Replenishment**	**Traveling**				
			Order Picking	**Less-than-unit-load Put Away**	**Replenishment**	**Order Picking & Put away**
AS-IS	**AS-IS**	27646	30162	4233	2765	34396
EQS	**Popularity**	26895	25748	4320	1670	30068
	Δ%	-2.72%	**-14.63%**	2.04%	-39.60%	**-12.58%**
	Turn	26895	30387	4363	917	34750
	Δ%	-2.72%	0.75%	3.06%	**-66.83%**	1.03%
	COI	26893	28708	4360	995	33068
	Δ%	-2.72%	-4.82%	2.99%	-64.00%	-3.86%
	OC	26893	25985	4309	1676	30294
	Δ%	-2.72%	-13.85%	**1.80%**	-39.39%	-11.92%
EQT	**Popularity**	20776	33199	4391	1664	37590
	Δ%	-24.85%	10.07%	3.72%	-39.80%	9.29%
	Turn	20776	33786	4341	1816	38127
	Δ%	-24.85%	12.01%	2.55%	-34.33%	10.85%
	COI	20776	32558	4421	1203	36979
	Δ%	-24.85%	7.94%	4.44%	-56.48%	7.51%
	OC	20776	33414	4412	1615	37826
	Δ%	-24.85%	10.78%	4.23%	-41.59%	9.97%
OPT	**Popularity**	12861	29084	4416	918	33499
	Δ%	**-53.48%**	-3.58%	4.31%	-66.80%	-2.61%
	Turn	12861	33731	4448	953	38179
	Δ%	**-53.48%**	11.83%	5.07%	-65.52%	11.00%
	COI	12861	29825	4386	951	34211
	Δ%	**-53.48%**	-1.12%	3.60%	-65.61%	-0.54%
	OC	12861	29317	4424	929	33741
	Δ%	**-53.48%**	-2.80%	4.50%	-66.39%	-1.90%

Table 21. WH configurations results (traveling in kilometers)

Table 21 highlights how the combination of allocation and assignment strategies has a different impact of the operative performances. The reported KPIs summarize the travelling (expressed in kilometers) for order picking, less-than-unit-load put away and replenishment. The combination of equal space allocation strategy with the popularity-based assignment minimizes the traveling for order picking, which is the most expensive activity among the warehousing processes. Even though the optimal allocation strategy halves the number of replenishment of forward area, the reduction in terms of traveling is negligible over the total warehouse performance.

WH Settings			**WH Results**				
	Assignment			**Traveling**			
Allocation	**Algorithm**	**Threshold**	**Replenishment**	**Order Picking**	**Less-than-unit-load Put Away**	**Replenishment**	**Order Picking & Put away**
AS-IS	AS-IS		27646	30162	4233	2765	34396
EQS	SLINK	75°	26893	28898	4397	1174	33296
		Δ%	-2.72%	-4.19%	3.87%	-57.52%	-3.20%
		40°	26893	26841	4352	1544	31193
		Δ%	-2.72%	-11.01%	2.81%	-44.15%	-9.31%
		20°	26893	26540	4332	1643	30872
		Δ%	-2.72%	-12.01%	2.34%	-40.58%	-10.24%
	CLINK	75°	26893	26563	4335	1801	30897
		Δ%	-2.72%	-11.93%	2.39%	-34.85%	-10.17%
		40°	26893	26033	4311	1747	30345
		Δ%	-2.72%	-13.69%	1.85%	-36.81%	-11.78%
		20°	26893	26180	4306	1644	30486
		Δ%	-2.72%	-13.20%	1.72%	-40.52%	-11.37%
	UPGMA	75°	26893	26110	4334	1609	30444
		Δ%	-2.72%	-13.44%	2.39%	-41.80%	-11.49%
		40°	26893	26256	4324	1755	30580
		Δ%	-2.72%	-12.95%	2.14%	-36.51%	-11.09%
		20°	26893	26097	4311	1766	30409
		Δ%	-2.72%	-13.48%	1.84%	-36.13%	-11.59%
EQT	SLINK	75°	20776	33579	4388	1623	37967
		Δ%	-24.85%	11.33%	3.65%	-41.28%	10.38%
		40°	20776	33815	4396	1468	38211
		Δ%	-24.85%	12.11%	3.84%	-46.90%	11.09%
		20°	20776	32808	4381	1660	37190
		Δ%	-24.85%	8.77%	3.50%	-39.95%	8.12%
	CLINK	75°	20776	32770	4381	1462	37151
		Δ%	-24.85%	8.64%	3.50%	-47.10%	8.01%
		40°	20776	32939	4385	1624	37323
		Δ%	-24.85%	9.20%	3.58%	-41.24%	8.51%
		20°	20776	32910	4396	1652	37306
		Δ%	-24.85%	9.11%	3.83%	-40.24%	8.46%
	UPGMA	75°	20776	33149	4388	1565	37537
		Δ%	-24.85%	9.90%	3.65%	-43.40%	9.13%
		40°	20776	33499	4391	1599	37890
		Δ%	-24.85%	11.06%	3.72%	-42.17%	10.16%
		20°	20776	33165	4394	1656	37559
		Δ%	-24.85%	9.95%	3.80%	-40.11%	9.20%
OPT	SLINK	75°	12861	31023	4433	948	35456
		Δ%	-53.48%	2.86%	4.71%	-65.70%	3.08%
		40°	12861	30091	4407	921	34497
		Δ%	-53.48%	-0.24%	4.10%	-66.68%	0.30%
		20°	12861	29676	4426	921	34102
		Δ%	-53.48%	-1.61%	4.56%	-66.70%	-0.85%
	CLINK	75°	12861	28803	4392	929	33195
		Δ%	-53.48%	-4.51%	3.76%	-66.39%	-3.49%
		40°	12861	29232	4403	933	33635
		Δ%	-53.48%	-3.08%	4.02%	-66.23%	-2.21%
		20°	12861	29253	4422	928	33675
		Δ%	-53.48%	-3.02%	4.46%	-66.44%	-2.10%
	UPGMA	75°	12861	29619	4406	942	34025
		Δ%	-53.48%	-1.80%	4.08%	-65.94%	-1.08%
		40°	12861	29143	4403	935	33546
		Δ%	-53.48%	-3.38%	4.01%	-66.18%	-2.47%
		20°	12861	29302	4437	936	33739
		Δ%	-53.48%	-2.85%	4.81%	-66.15%	-1.91%

Table 22. WH configuration results (traveling in kilometers)

Table 22 reports the same performances of the warehouse scenarios resulting by the combination of allocation strategies and correlated assignment strategies. This table points out the Clink clustering algorithm and the 40-percentile threshold as the best fitting strategies, especially if combined with equal space allocation. By adopting correlated policies, the highest reduction of traveling is -13.44%, which is almost equal to the adoption of the simple popularity-based assignment (i.e. -14.63%). The operative metrics computed in Table 22 are based on the grouping of SKUs in accordance with the McAuley similarity metrics. Table 23 illustrates a comparison among the general purpose McAuley and the problem oriented Accorsi & Maranesi similarity metric, by reporting the obtained performance given the best fitting clustering algorithm (i.e. Clink) and percentile threshold (i.e. 40).

WH Settings					WH Results				
		Assignment				Traveling			
Allocation	Zoning	Similarity metric	Algorithm	Threshold	Replenishment	Order Picking	Less-than-unit-load Put Away	Replenishment	Order Picking & Put away
EQS	WH1, WH2, WH3, WH4-5	McAuley	Clink	40^0	26893	26033	4311	1747	30345
				Δ%	-2.72%	-13.69%	1.85%	-36.81%	-11.78%
EQS	WH1, WH2, WH3, WH4-5	Accorsi & Maranesi x_1, x_2	Clink	40^0	26893	25762	4320	1672	30082
				Δ%	-2.72%	-14.59%	2.05%	-39.53%	-12.54%
EQS	WH1, WH2	Accorsi & Maranesi x_1, x_2	Clink	40^0	26893	25750	4318	1674	30068
				Δ%	-2.72%	-14.63%	2.00%	-39.45%	-12.58%
EQS	WH1	Accorsi & Maranesi x_1, x_2	Clink	40^0	26893	25750	4319	1670	30069
				Δ%	-2.72%	-14.63%	2.03%	-39.60%	-12.58%
EQS	WH3	Accorsi & Maranesi x_1, x_2	Clink	40^0	26893	25751	4319	1670	30069
				Δ%	-2.72%	-14.63%	2.02%	-39.58%	-12.58%
EQS	WH4-5	Accorsi & Maranesi x_1, x_2	Clink	40^0	26893	25757	4321	1667	30078
				Δ%	-2.72%	-14.61%	2.08%	-39.71%	-12.55%

Table 23. Similarity metrics comparison

The field allocation, algorithm and threshold indicate the best performing combination of WH setting for reducing travelling. Given such configurations, Table 23 illustrates the performance obtained through the adoption of the picked oriented index (POI) (i.e. Accorsi & Maranesi) based on first two factors. The setting named zoning allows pointing out the effects of the application of correlated assignment approaches just to the specified zone, considering a popularity-based assignment for the others.

Finally, Figure 67 illustrates and summarizes the most significant tips from the analysis through an interaction plot of the effective time (reported in seconds) computed by the operative traveling for picking and put away through a linear regression of the tracked real operative time and distances (see Figure 63).

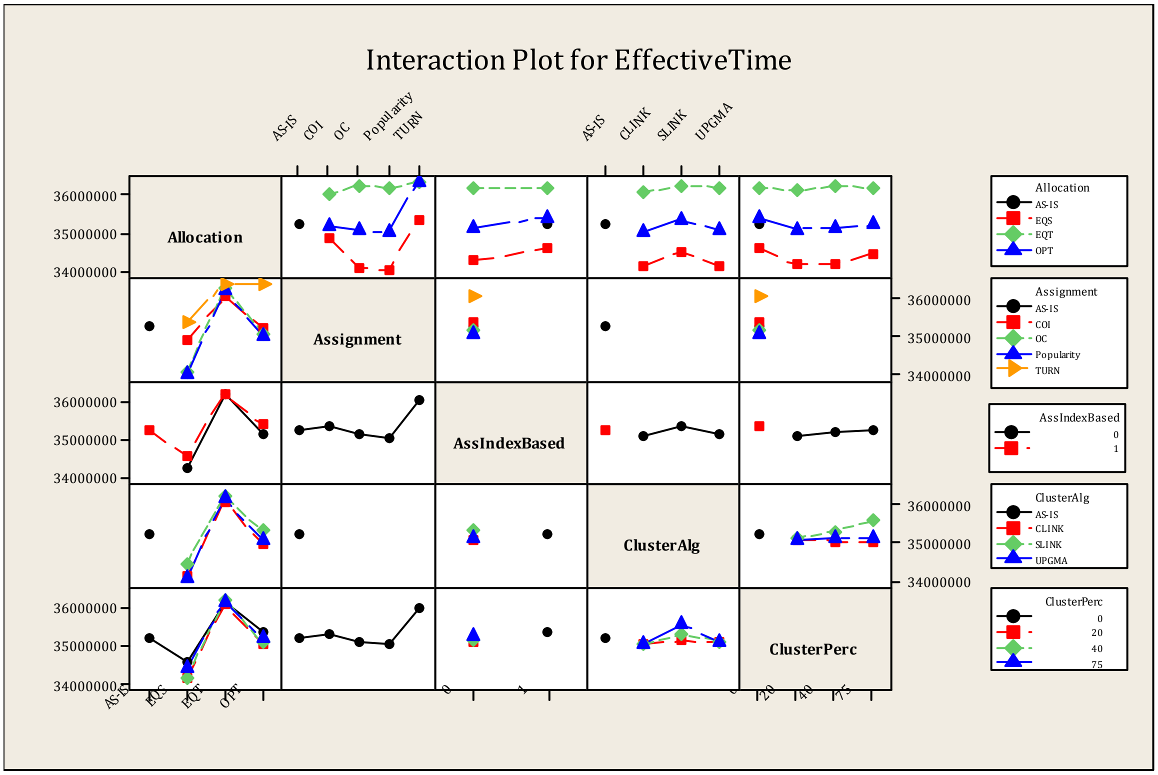


Figure 67. Interaction plot analysis main results

5.2 Conclusions

This chapter bases on the analyses by Manzini et al. (2012) and adopts the top-down hierarchical procedure and DST for the analysis and improvement of the performance of an industrial warehouse. The design and analysis procedure is applied to a very complex case study, which counts several SKUs, picking orders and picking lines. A few obtained results have been illustrated demonstrating the efficacy of the proposed procedure and adopted models and tools. Significant savings can be generated by a re-allocation and re-assignment of SKUs within the forward area of a multiple zones warehousing system.

Further research is expected on the application of the proposed procedure and related models and tools to new case studies and different sectors (e.g. food industry and distribution, tile industry, grocery, etc).

6. Unit-load Warehousing

This chapter focuses on the design and management of unit load warehouses, where pallets load are moved in, through and out the system (Van den Berg and Zijm 1999). These systems are the simplest to design and manage since layout and operation concerns are suitable to mathematical approach and modelization. Pallet-load storage systems typically handle commodities and other products characterized by large volume demand and high throughput. There are many enterprises and general industry sectors adopting these common and simple storage systems formats such as tissue, beverage, dry food, etc.

The goal of this section is to present an original hierarchical top-down procedure for the design and management of unit-load storage/retrieving system. The procedure gains traction by literature static mathematical models (Bartholdi and Hackman 2012) and aims to define the system layout implications in terms of storage mode to adopt and lanes depth. The lane is a common pallet placement strategy bases on homogeneous (i.e. holding the same SKU) queue (or line) of pallet facing the aisle by one or both sides. Aisles provide accessibility, but this empty space is not revenue-generating for the warehousing system. By storing SKUs in lanes, additional pallet positions can share the same space amortizing the cost.

The definition of layout entails a wide set of issues, but the most important one is the effective utilization of space. This is the principle goal of the proposed top-down hierarchical procedures.

A second section of this chapter presents and illustrates in detail a support-decision tool for the design, management and control of a unit-load warehousing system. As a computerized platform, it implements support-decision models, analytical methods and algorithms to comply most relevant layout issues concerning with lane depth optimization, space efficiency, put-away and retrieving operations. This section presents the data management architecture of the tool and a selection of graphic user interfaces (GUIs) to show the potential functionalities enabling the application of real data-oriented analysis.

The final section of this chapter illustrates in details some real unit-load warehousing case studies faced by the adoption of top-down hierarchical procedures and the support-decision tool. As for Chapter 5, this section reports the analyses conducted on real industry cases and applications in order to validate the effectiveness of the proposed methodologies and tools. Remarks from the analyses are the obtained improvements in terms of space and time efficiency of warehouse layout and operations in comparison with the AS-IS benchmark. Even though, the illustrated results only refer to the specific case study and are not generalized, the aim of the section is to gather a set of guidelines for industry managers, practitioners and researcher in facing real instances and applications. This section is a brief summary of the main contents handled in Accorsi and Manzini (2013).

6.1 Unit-load warehousing. A procedure

This research topic aims to the development of models, procedures and operative tools for the design and management of unit-load storage systems.

The main goal of the topic is the design and setting of the optimal depth of the lanes of a unit load warehousing. The lane is a common pallet placement strategy bases on homogeneous (i.e. holding the same SKU) queue (or line) of pallet facing the aisle by one or both sides. The lanes depth (i.e. storage channel) is the number of pallets of the lane and represents the principle leverage to affect the performance of the systems, in terms of space efficiency and time efficiency. The determination of the lane depth per each SKU and the proper number of lanes of each depth is crucial for the warehousing configuration and for the design of the storage layout.

Each lane, once available, is generally dedicated to a single SKU (eventually to a single and specific production batch of a SKU), until all pallets of such lane are shipped and the lane emptied. This general rule matches the need to avoid double handling.

Deep lanes fit with huge production batch of a generic SKU, but remain occupied until the last pallet of such SKU is retrieved and shipped. Within such period, the space efficiency the lane decreases proportionally to the demand rate. Conversely, short lanes are released earlier and the unoccupied space is lesser for an interval of time. On the other hand, to store huge production batch of a generic SKU requires more lanes, and longer aisles, representing a space waste.

The overall storage density of a system depends by the ratio of the unit-load location to the available square meters. Therefore, both space costs, respectively for the unoccupied locations within a lane and the unoccupied by aisles, significantly affect such metric.

The problem of lane depth design regards many different storage modes such as, floor storage, drive-in and drive-through rack, flow-rack and ASRV systems. The latter are sort of automated drive-in rack, adopting automatic shuttle able to travel within the rack instead of forklift. These devices assure the maximum space efficiency, making the storage position more selective and facility more productive. The shuttles are placed in the appropriate channel by means of automatic carriers, one per each level. The material flow among levels is allowed by proper lifts or elevators in order to maintain each level as independently accessible.

The purpose of this section is to present a top-down procedure for the design of the unit-load warehousing layout, through the setting of the lane depth, and the assessment of the space efficiency performances. This procedure boots by the adoption of patterns inspired to the literature (Bartholdi and Hackman 2011) and is arranged through sub sequential modules and steps regarding with the lane depth setting, the operations scheduling, the layout design, and finally, the performance assessment.

6.1.1 Lane depth setting

The first step deals with the determination of the optimal lane depth per each SKU considering a specific period. This step implements a static model to compute the optimal lane depth of SKUs, able to minimize the overall unoccupied space due to both costs drivers for empty storage locations, the so-called honey combing, and the aisles, the so-called accessibility.

Bartholdi and Hackman (2011) propose a pattern based on the following insights. In a unit-load warehousing system, aisles provide accessibility, not storage, and so this space for aisles is not directly revenue generating. Consequently, managers and practitioners prefer to reduce aisle space to the minimum necessary to provide adequate accessibility. For this, the aisles must be at least wide enough for a forklift to insert or extract a pallet.

On the other hand, by storing product in lanes, additional pallet positions can share the same aisle space and so amortize that cost. The most important issue to consider is the effective utilization of space. Indeed, deeper lanes produce more pallet storage locations per fixed available are, but they are of diminishing value since they are not accessible for reuse until the interior pallet location in the same lane becomes available.

The literature model at bases of the proposed procedure requires the univocal definition of the concept of pallet position or location. It is the floor space required to hold a pallet. This includes not only the footprint of the pallet but also any required gap between one pallet and an adjacent one. The floor space charged to a lane includes storage space, gap between lanes and one-half the aisle width in front of the lane.

In most warehouses, a lane is entirely dedicated to a single sku to avoid double handling. This save time but incurs a cost of space: when the first pallet is retrieved from a lane, that position is unoccupied but unavailable to other SKUs. The deeper the lane the greater the cost is. Figure 68 illustrated a bird-view of a lane, where the first pallet position in a k-deep lane that holds uniformly moving product will be unoccupied only *1/k* of the time, the second *2/k* of the time and so on. This waste is called honeycombing, whilst the waste due to the aisle is called accessibility.

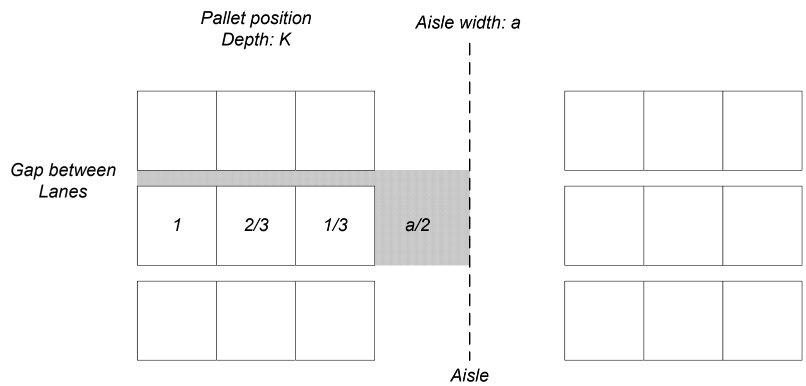


Figure 68. Lane space occupation

In order to describe the pattern, let the lanes be k pallet position deep, the space in front of the lane be of area a (measured in pallet position), while the total area charged to one lane be $k + \frac{a}{2}$. Furthermore, suppose that SKU *i* experiences constant demand of D_i pallets annually [pallet/year] with a reorder quantity of q_i pallets (and order cycle with a duration of $\frac{q_i}{D_i}$). Finally let the stackable column per SKU *i* be z_i and the total number of SKU be *n*. The pattern proposed by Bartholdi and Hackman (2011) defines the optimal lane depth able to minimize the honey combing and accessibility costs for a generic SKU *i* as:

$$k_i = \sqrt{\left(\frac{a}{2}\right)\left(\frac{q_i}{z_i}\right)} \qquad (41)$$

The first step of the procedure consists on the application of the model of equation (41) to define the optimal lane depth for the set of SKUs handled by the storage system within a selected period. Therefore, at this stage the decision-maker considers some layout characteristics, such as the aisle width and the rack levels (or the stack level in a floor storage), and returns a rough layout of the system obtained as the sum of lanes of different depth. The pattern is suitable to address different storage modes such as floor storage, drive-in and drive-through racks, flow-racks. The proposed procedure arranges the equation (25) in accordance with the selected storage mode as follows in Table 24:

Storage mode	Pattern		Rack level
Floor storage	$k_i = \sqrt{\left(\frac{a}{2}\right)\left(\frac{q_i}{z_i}\right)}$	(42)	Depends on stackability
Drive-In rack	$k_i = \sqrt{\left(\frac{a}{2}\right)\left(\frac{q_i}{z}\right)}$	(43)	Equal per all SKUs
Drive-Through rack	$k_i = \sqrt{a\left(\frac{q_i}{z}\right)}$	(44)	Equal per all SKUs
Flow-rack	$k_i = \sqrt{a \cdot q_i}$	(45)	1
ASRV system	$k_i = \sqrt{\left(\frac{a}{2}\right) q_i}$	(46)	1

Table 24. Pattern reviews

Furthermore, the settings of the lanes depth allow to establish the average number of lanes required to allocate the production batch of a generic SKU *i* as follows:

$$\#lane_i = \frac{q_i}{z_i \cdot k_i} \qquad (47)$$

Therefore, in order to match the production batches of a set of SKUs within a specific period, equation (41) aims to set the optimal lane depth per each SKU, while equation (47) fixes the number of lanes of such depth to allocate that SKU. The overall number of lanes of every depth required to store all the inbound batches for a set of SKUs represents a rough metric of the storage capacity of the warehousing system.

Unfortunately, the application of such pattern might not fit with the real instance if certain hypotheses are not assumed. The following sections attempt to address such criticalities and to make the pattern fitting with real applications.

6.1.2 Operations scheduling

The first step deals with the determination of the optimal lane depth per each SKU considering a specific period. The principle issues related to the application of the illustrated pattern consists on the fact that is bases on a constant demand rate. Therefore, the pallets of a generic SKU filling a lane are assumed to be shipped with a constant predictable rate. In real warehouse, the inventory differently turns for different SKUs and the honey combing and accessibility costs effectively depends on the inbound as well as outbound flows. As instance, the honey combing cost for slow moving SKUs, which hold the lane for longer, is higher than for fast-moving SKUs.

The second relevant issue consists on the fact that the adoption of the pattern of a period suggests the proper number of lane of the optimal depth to devote to each SKU, but consider all SKUs as stored at the same time. Finally, the allocation of lanes suggested by the pattern gives an instant picture of the best fitting layout, without taking into account the operative inbound and outbound flows.

Attempting to tackle these critical aspects, the procedure continues with the second step named dynamic scheduling. This step enables the dynamic scheduling of inbound and outbound operations by considering an interval of time for which a set of lanes is entirely devoted to a SKU. This time, also named release interval, is the period from the end of the put-away process (i.e. due to manufacturing or inbound receiving) until the retrieval of the last pallet stored in the lane. This is the interval allowing to assign a set of lanes, of the proper depth, to a batch of a generic SKU, and represents also the interval for which a lane is held and after then released. Therefore, the overall layout resulting by the sum of the lanes, of the proper depth, devoted to each SKU, for the whole population of SKUs, depends on the considered release interval. Furthermore, assuming such time batch as the average turn rate of each SKU, the decision-maker can address seasonality, demand rate of different SKUs, and obtain a more accurate metric of the whole storage capacity of the system.

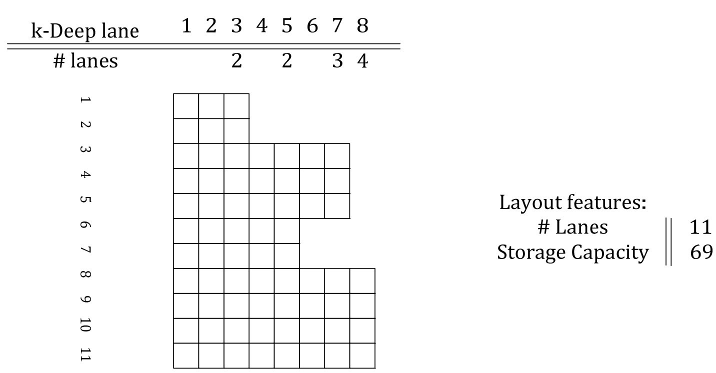


Figure 69. Layout configuration

This approach allows extending the static pattern proposed by Bartholdi and Hackman (2011), by considering also the interval of time after then a lane is emptied and released. By computing, day by day, the overall storage capacity (i.e. in terms of both locations and lanes) required to store the incoming lots of SKUs, the procedure provides also a useful tool to study and design the storage layout. Indeed, the warehousing system, treated as an incapacitated queue system, experiences day by day a ranging holding capacity, rolling accounted in accordance with the incoming lots of SKUs and the related lanes releases after the release interval.

Figure 69 gives a picture of the storage layout resulting by the adoption of the first two steps of the top-down procedure. The incoming of production lots (i.e. batches) of SKUs allow the setting of the optimal lane depth per each SKU, whilst the adoption of the dynamic scheduling module provides the ranging holding capacity of the storage system to fit day by day put-away and retrieval processes.

6.1.3 Simulation

The third step deals with the simulation and related assessment of the space efficiency performance of the unit-load warehousing system. Such performances regard with the ratio of occupied and unoccupied storage locations to the total capacity, the ratio of open (i.e. occupied) lanes to the overall number of lanes, and the saturation of every open lane.

In order to realize a benchmark of the storage system, it is necessary to establish and set a storage layout, composed by the sum of the number of lanes of each depth, and then simulate how the system matches the historical inventory or the historical inbound and outbound flows.

Once the layout is defined (through the first two phases of the procedure), the measurement of space saturation performances results by the process of filling the available lanes and storage locations with the historical inventory or inbound and outbound flows.

The assignment of incoming lots of SKUs to the lanes set through the first two steps is based on a greedy heuristics, consisting on both rankings of incoming lots of SKUs and available lanes of a generic depth. The first arriving lot of a generic SKU occupies the required lanes of the optimal depth, if available, decreasing the overall number of such lanes, until the last pallet of that lot is retrieved.

If the saturation metrics and the space efficiency performances do not satisfy the decision-maker (i.e. low values of space saturation), the procedures allows to iterate the step of dynamic scheduling in order to set other release interval and to rearrange the layout accordingly.

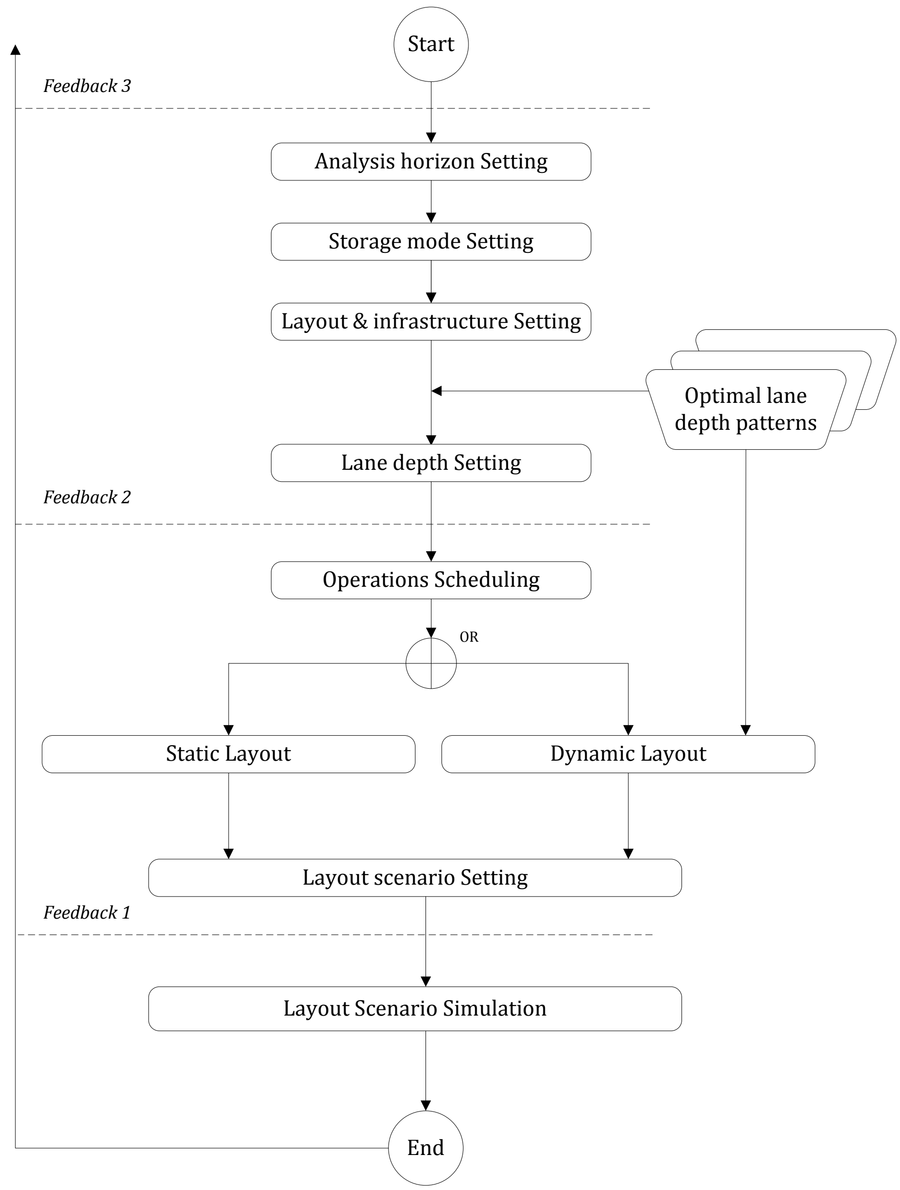


Figure 70. Design top-down procedure

Figure 70 represents the flow-chart of the main steps of the proposed procedure. The preliminary phase regards with enterprise data collection and is based on the gathering of the information on warehouse inventory and throughput to be store in properly defined database architecture. The first step regards with the settings of the horizon of analysis, the storage mode to study (i.e. floor storage, drive-in, drive-through, flow-rack, ASRVS) and the layout and infrastructure as input for the application of the lane depth patterns. The pattern adoption defines the optimal lane depth to allocate a set of SKUs, considering an interval of time. The pattern, if properly arranged, responds to multiple storage modes implemented in the procedure (i.e. floor storage, drive-in racks, drive through racks, flow-racks, ASRV systems).

The second step enables to extend to static pattern considering the delay between put-away and retrieval processes. This step considers the time for which a set of lanes is on average held by a SKU, and through a rolling approach, gives a picture of the overall storage capacity of system (i.e. in terms of locations and lanes) required to match inbound and outbound flows. Two main functionalities are available. The so-called static layout inherits the optimal lane depth computed for the average inbound lot of each SKU, and holds the proper number of lanes for the average storage time of a SKU. Conversely, the so-called dynamic layout computes different optimal depths for each different inbound lot of a generic SKU and then assigns the proper number of lanes for the average storage time of a SKU. The output of both functionalities consists on a set of layout configurations, rolling day by day, characterized by different value of storage capacity.

The third step sets the specific layout configuration, among the range of the configuration proposed by the dynamic scheduling module, and enables simulating and assessing the space efficiency performances over real inbound and outbound historical flows.

6.2 Unit-load warehousing. Data architecture

The design and management of a unit-load warehousing system, provided by the proposed procedure, are based on a set of real data instances able to describe the historical behavior of the storage system object of analysis.

This section aims defining a systemic data structure able to gather information from enterprises regarding with the production cycles, the inbound receiving processes, the demand and shipping rate, the historical inventory, and to store such information as input for the proposed design top-down procedure. The principle activity carried out at this step is the conceptual definition of the E-R diagram.

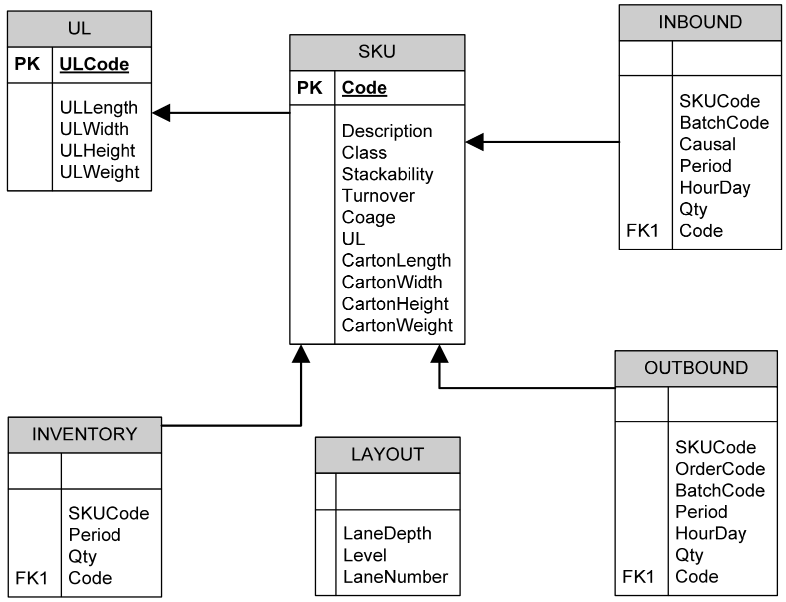


Figure 71. E-R diagram

As for the E-R diagram illustrated in Chapter 4, this study is inspired by the observation and analysis of many different enterprise realities, which often face common warehousing issues in different ways, approaching different data source and DMBS with different tables or spreadsheets. The main functionalities provided by DBMS solution ensure data integrity and accuracy, and the storage and management of huge amount of data, easy accessible through SQL queries.

The proposed E-R diagram, illustrated in Figure 71 bases on the contents of three main tables, which are named SKU, INVENTORY, INBOUND and OUTBOUND. These tables regard with the input data gathered and summarized by the enterprises WMS.

In follows, a summary description of each table is given, with the detail of the principle data fields.

- *SKU*. This table represents the SKU master file, contains all available information regarding SKUs (e.g. code, carton volume, carton weight, description, demand class etc.) and usually counts ten thousands rows. The field description allows registering information of the name associated to the SKU code. The class of product might report the classification of the SKU turn over (i.e. A, B, C classes of Pareto curve) or the functional unit or manufacturing family of the item. Indeed, the proposed procedure and DST consider class-of-demand SKUs as categories of products that need to be store in different storage areas with particular storage modes. As instance, there is an implicit agreement among practitioners operating in an automated systems (i.e. made by ASRS and AGVs), which sees high turn-over SKUs devoted to drive-in rack and slow-moving SKU, recognized by small inventory, devoted to ASRS, in order to guarantee an high space efficiency. Hereby, the distinction appears in the SKU master file, which means that a pre-selection of which SKUs should be addressed to each zone is already made.

- *OUTBOUND*. This table represents the demand profile of a specific period of analysis (e.g. a year) and usually counts millions lines. Each tuple is composed by the due date of order, the order code, the SKU code and the picked quantity in terms unit-load pallets. The field BatchCode is particularly interesting since allows to point out when the last pallet of a production lot of a generic SKU is retrieved and shipped, thereby releasing the related lane.
- *INBOUND*. This table reports the historical inbound profile composed by the incoming lots received by manufacturing lines or docks. Each record is made by the received date, the batch code and the SKU code, as well as the unit-load received quantities to be stored in the system. This table is fundamental for the implementation of the static pattern for the setting of the optimal lane depth for every SKU.
- *INVENTORY*. This table reports the inventory master file for SKUs. The historical stocks of the SKUs enable to assess the space efficiency and saturation performances of the designed unit-load warehousing system in the third step of the procedure.
- *LAYOUT*. This is a fundamental table of the E-R diagram since it contains a tuple (i.e. a row) per each depth of the lanes composing the storage system object of analysis. Indeed, in each tuple it reports the lane depth (i.e. the value called k in the pattern), the rack level (i.e. the value called z in the pattern) and the overall number of available lanes of each depth. This is a picture of the configuration of the storage system set at the second step of the procedure. Through this table the decision-maker may also import an AS-IS warehouse configuration, bypassing the first two steps, in order to measure the performance as a benchmark for furthr improvements.
- *UL*. This table indicates the type and size of unit load stored within racks. This table aims to define the aisle width in term of equivalent pallet locations, the so-called a parameters of the proposed pattern.

Once the E-R diagram is set, its implementation on a DBMS follows. As previously discussed in Chapter 4, here the proposed procedure is implemented through a DST. The application, developed in Visual Studio© environment and C# language as further described in Chapter 4, is based on object-oriented (OO) methodology and client-server architecture built through a database management system (DBMS). The adopted DBMS is Access™ since it is highly compatible with other Office tool such as Excel, particularly useful to export graphs or other output.

Without going in detail on the UML diagram and main software classes and entities, as for Chapter 4, the following section presents the principle GUIs of the platform in order to illustrate the functionalities and tools handled by the decision-maker.

6.3 Unit-load warehousing. GUIs

The management and control of the DST is allowed to the decision-maker, through a set of developed GUIs, which lead the user through the analysis and support the interaction between the illustrated tool and the proposed top-down procedure. GUIs enable the user to carry out analysis and decisions by utilizing the tool. In particular, the following sections deals with main DST modules, one per each of the previously discussed procedure steps.

6.3.1 Lane setting module

This module supports the decision-maker in defining the optimal lane depth for the considered SKU given a specific period. Such interval, defined by the calendar panels on the right of the interface, is assumed by the proposed DST as the filter to consider the inbound lots received by the either manufacturing lines or docks. The average value (in terms of pallet quantity) of incoming lots per a generic SKU i, the so-called q_i parameter of the pattern, contributes to the determination of the optimal lane depth.

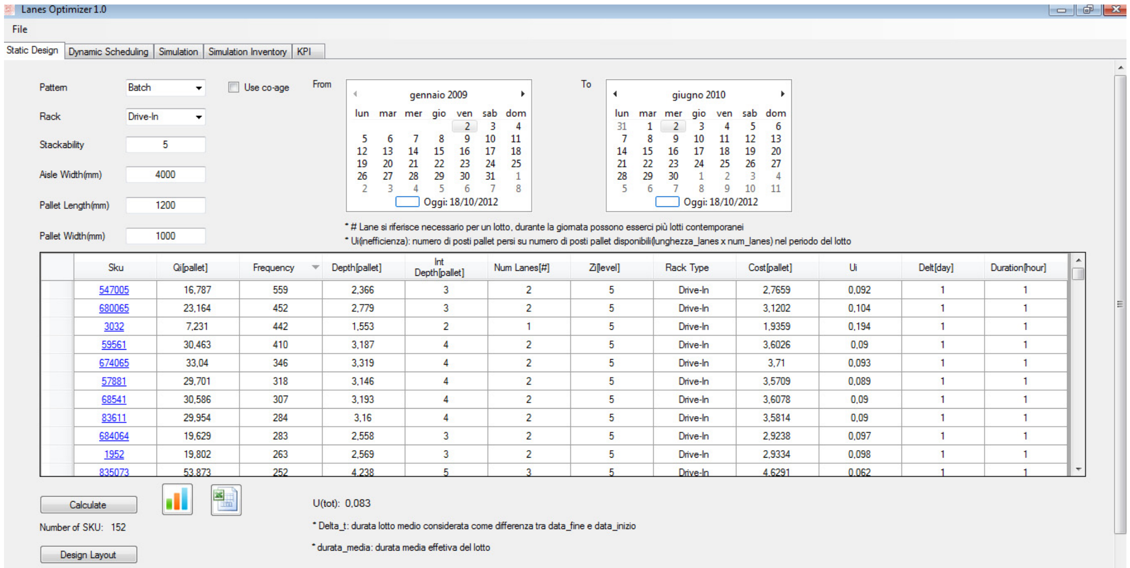


Figure 72. Lane setting GUI

The top interface of this GUI, illustrated in Figure 72, presents the forms for setting of the input parameters of the analysis. At first, through the interface toolbar and the button *File*, a database file structured according to the E-R diagram of section 6.2 is imported and loaded.

The ComboBox *Pattern* allows the user defining which table is selected for the computation of the average lot quantity value q per every SKU. The so-called Batch option, chosen in the proposed sample, bases this computation on the inbound table, and the average lot quantity is the average value of the incoming lots. Conversely, if the user gives more importance to the outbound flows, may decide to consider the average value of outbound shipping lots to compute the q parameter, through the option *Demand*.

The ComboBox *Rack* enables to set the static pattern according to the selected storage mode as illustrated in Table 24. Then, a set of other parameters, involving the layout constraints (i.e. ailse width), can be set by the user, whilst the size of unit load and the levels of rack are imported by the database, in case of floor storage, or directly define through the GUI.

Finally, the CheckBox *Co-Age*, allows the decision-maker to take into account the opportunity to store in the same lane pallets of the same SKUs, but belonging to different incoming batches (i.e. lots), if they are produced within the same Co-Age interval. Such period, recovered by the database per each SKU, is the interval that makes two subsequent production lots of that SKU as contemporary, an thereby equals, over a logistics and sales perspectives. This interval is typically 1 week for beverage supply chain, or 1 month for dry food supply chain, such as pasta.

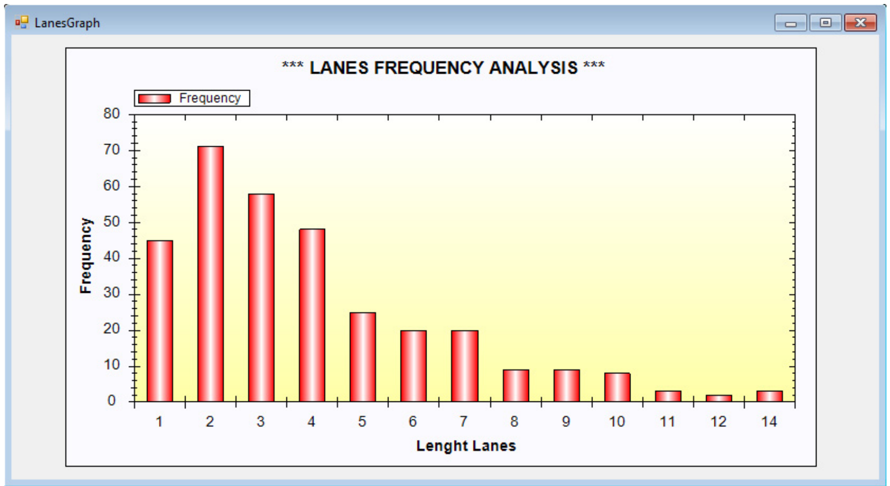


Figure 73. Lane depth frequency analysis

As illustrated in the reporting table of the GUI, there are multiple results by the application of this module. A significant dashboard of the main unit-load system metrics are reported to the decision-makers. This dashboard includes, per each SKU the numbers of incoming lots (i.e. from both manufacturing and docks) within the selected interval, the average pallets quantity for lot, the real optimal lane depth, the effective integer optimal lane depth, the rack level (or the stack height), the total number of lanes, the costs of honey combing and accessibility, and the average duration of put-away operations for a generic incoming lot.

Finally, the graph of Figure 73, shows the main insight of such analysis, which is the lane depth frequency analysis for the overall storage system. It counts per each depth, the total number of available lanes resulting by the sum of the required lanes to allocate the whole population of SKUs. Thus, it represents a rough picture of the layout, composed by the sum of the required lanes.

6.3.2 Operations scheduling

This module supports the decision-maker in extending the results of the previous module, by considering also the inventory turnover. Indeed, the roughly definition of the layout at previous step does not take into account the storage delay experienced by the pallets of SKU lot within the end of manufacturing or receiving and the end of the shipping processes.

Figure 74 shows the storage delay of each lot represented by a horizontal colored line. The longer the line, the wider the storage delay of a lot is. In particular, the lanes held by the lot 2153LA of the SKU 112200 remain occupied for 5 days, from the June 1st to June, 5th, and so on.

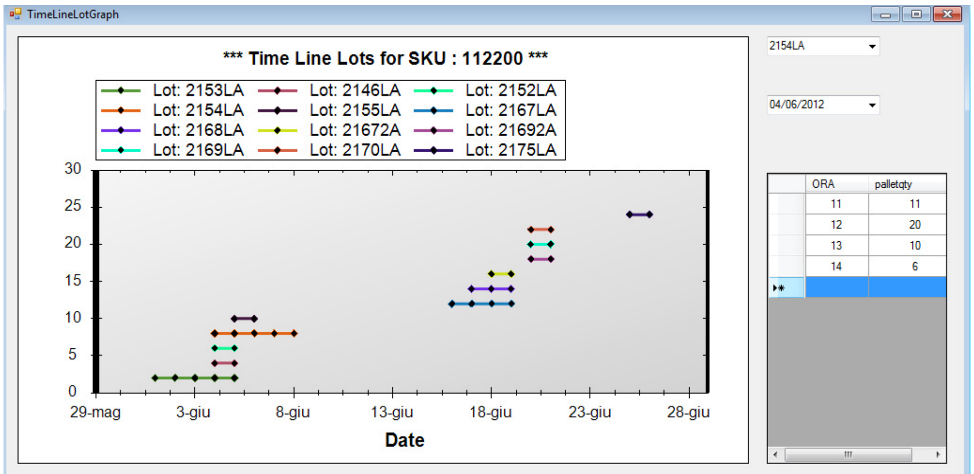


Figure 74. Storage delay for lots

The sum computed day by day of the required lanes of each depth, for the all the SKUs represents the storage capacity required by the system, ranging day by day according to the inbound and outbound flows.

This GUI, presented in Figure 75, aims to configure multiple-storage-layouts base on the inventory turn-over (i.e. inbound and outbound processes). This interface allows the user to set the release interval determining the period after that the lanes devoted to the received lot are emptied, thereby simulating the influence of the shipping process on the storage system.

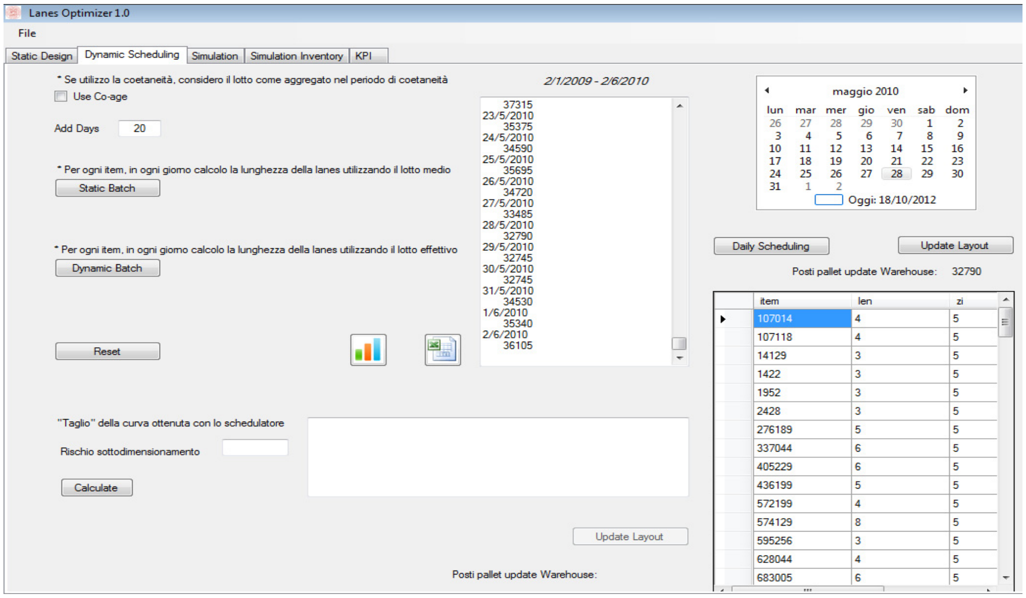


Figure 75. Operations scheduling GUI

In particular, the decision-maker decides to select the same release interval for the whole population of SKU, through the TextBox named *Add Days*, or to import a different interval per each SKU from the database. The former case is suitable for high-turnover SKUs (i.e. A class SKU in Pareto analysis), whilst the latter functionality matches more variable SKUs population.

Therefore, the DST offers two main analysis opportunities. The first analysis, named *Static Batch*, implements the computation of the overall storage system capacity, considering the optimal lane depth resulting by the average lot quantity computed at the first step.

The second analysis, more accurate, named *Dynamic Batch*, implements the computation of the overall storage system capacity, considering the optimal lane depth for each lot a generic SKU, to be stored. This functionality bases on the definition of multiple lane depth per each SKU, depending on the ranging quantity q of the incoming lots. Therefore, here the main purpose is not setting the optimal lane depth of SKUs, but providing a more accurate picture of the layout, in terms of overall storage capacity.

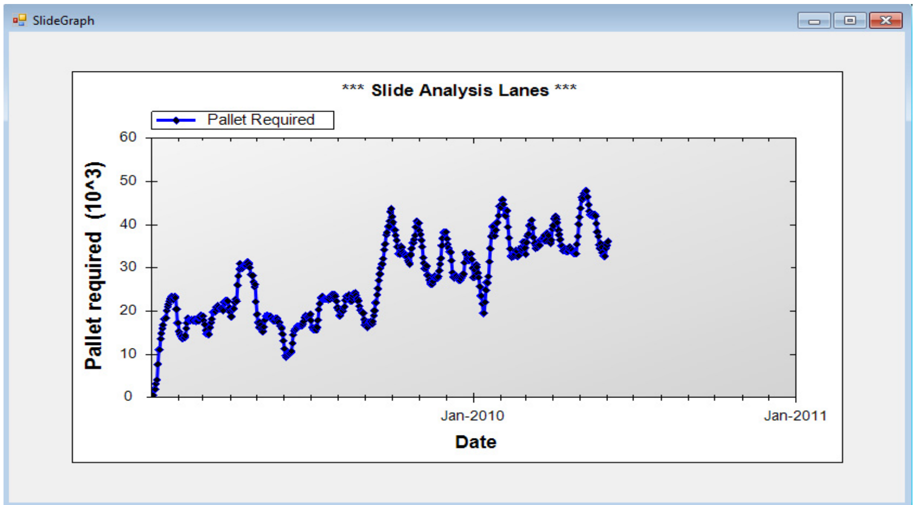


Figure 76. Ranging system storage capacity

Figure 76 represents the ranging storage capacity of the unit-load warehousing system treated as an un-capacitated queue system. Per each day of considered interval, the storage capacity (i.e. a point of the graph) might be split into a frequency analysis of the required lane depths, as illustrated in Figure 73.

Finally, the calendar panel on the right side of the interface enables to select the specific within the observed interval, which sets a specific storage system layout and configuration. Such configuration consists on a list of different lane depth, and the related number of available lanes (or storage channel). At this stage, the decision-maker may adopt the results of the second module to set the layout, or import an existing warehouse through the database table named *Layout*, described in section 6.2.

6.3.3 Simulation

This final module enables to assess the performance of space efficiency and saturation of a selected warehouse layout and configuration. The analyzed layout may be resulting by the application of the previously illustrated procedure modules and steps, or imported from the database to define the benchmark for further layout improvements.

Figure 77 presents the last GUI of the DST. The two calendar panels allow to define the interval object of the analysis. This setting represents a filter of the database historical inventory or inbound and outbound operations.

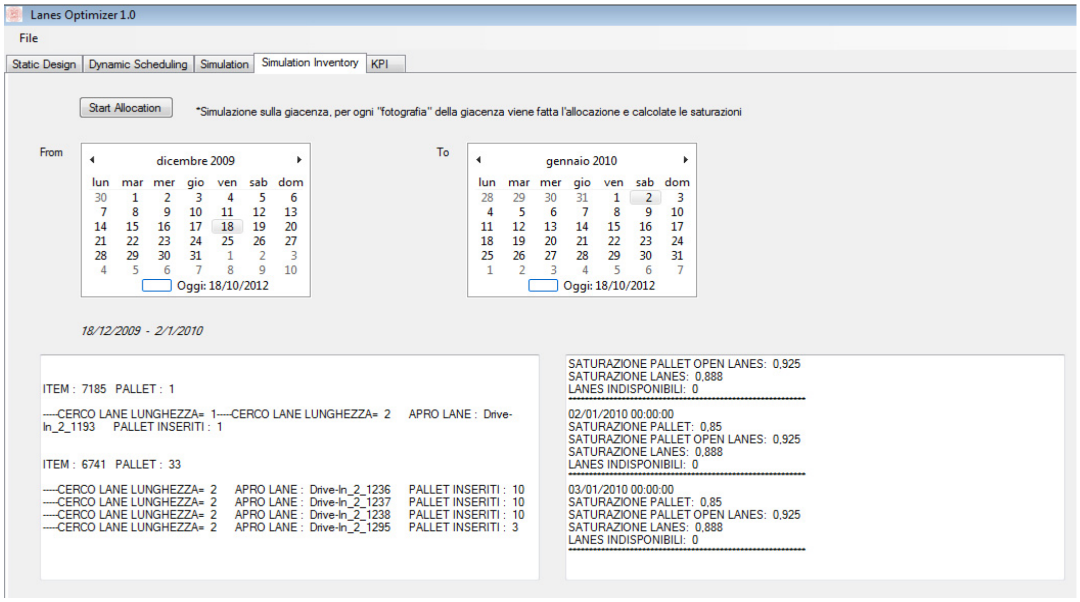


Figure 77. Simulation GUI

The DST gives at this stage to analysis opportunities. The first considers the historical snapshots of inventory and attempts to fit such levels of stocks per each SKU with the selected warehouse layout. Each SKU is assumed to fill the proper optimal lane (i.e. of the optimal depth) with a number of lanes determined by the quantity of pallets of the received lot. If such lane is not available, a greedy heuristics aims to match the available lanes with the generic SKU. The performances, in terms of occupied lanes, occupied storage locations and lane saturation, are computed per each inventory snapshot contained in the database. Figure 78 presents a brief sample of the obtained performances.

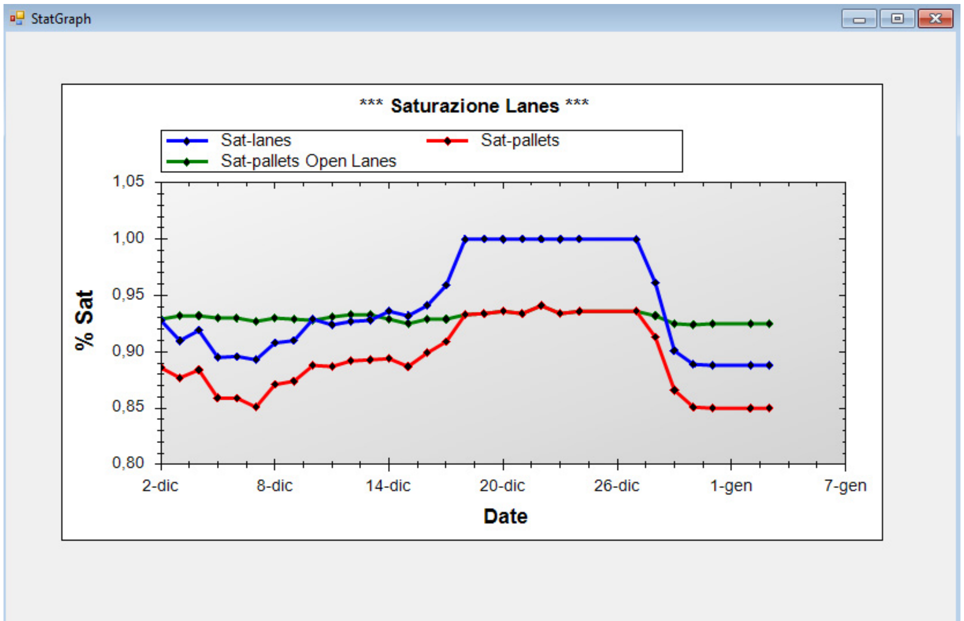


Figure 78. KPIs GUI

The second analysis is based on the simulation of receiving and shipping processes taken by the related database tables. In particular, the space efficiency metrics are computed day by day considering the occupation and release of the lanes.

Samples of the results obtained by the application of the proposed DST to a real case study are illustrated in the following section.

6.4 Unit-load warehousing. A case study

This section deals with the discussion of the results obtained by the application of the illustrated DST to the real instance data set related to the warehousing system of a worldwide renowned company of Italian pasta. The storage system is the Italian CDC of the enterprise and consists on a end-of-line buffer responsible to store the lots coming from the manufacturing lines and received by all the RDCs of the country.

The storage area is divided among three different zones, characterized by the different set of SKUs and adopted storage modes:

- AS/RS zone. This automated area holds the medium-slow moving SKUs, typically classified by the B and C classes of the Pareto analysis. The decision to store slow-moving SKUs within an automated system aims to guarantee of such SKU, characterized by a low inventory level, an high space saturation through the selective racks of an AS/RS system.
- Drive-In rack zone. This automated area is served by automatic laser guide vehicles (LGVs) and holds the high-inventory and high turn-over SKUs, typically classified by the A class of the Pareto Analysis.
- Selective rack OP zone. This storage zone is organized as a low level manual OPS, where higher levels are devoted to the bulk storage.

The aim of this analysis is focusing on the Drive-In rack zone and adopting the DST to study the optimal lane depth of the SKUs, and support the configuration of the best-fitting layout able to increase the system space efficiency. In such zone, 152 items compose the whole population of handled SKUs, and the observation period ranges from January 2009 to June 2010.

The application of the first module enables to implement the pattern for the optimal sizing of the SKUs lane depth. The results of the lane-depth frequency analysis for the overall storage system are proposed in Figure 79. The graph accounts per each depth, the total number of available lanes resulting by the sum of the required lanes to allocate the whole population of SKUs.

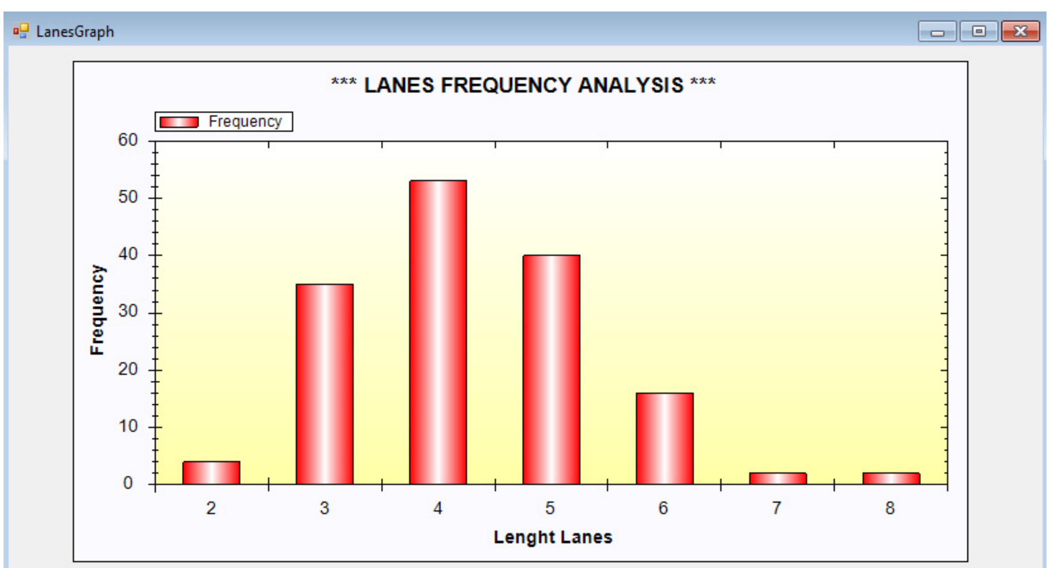
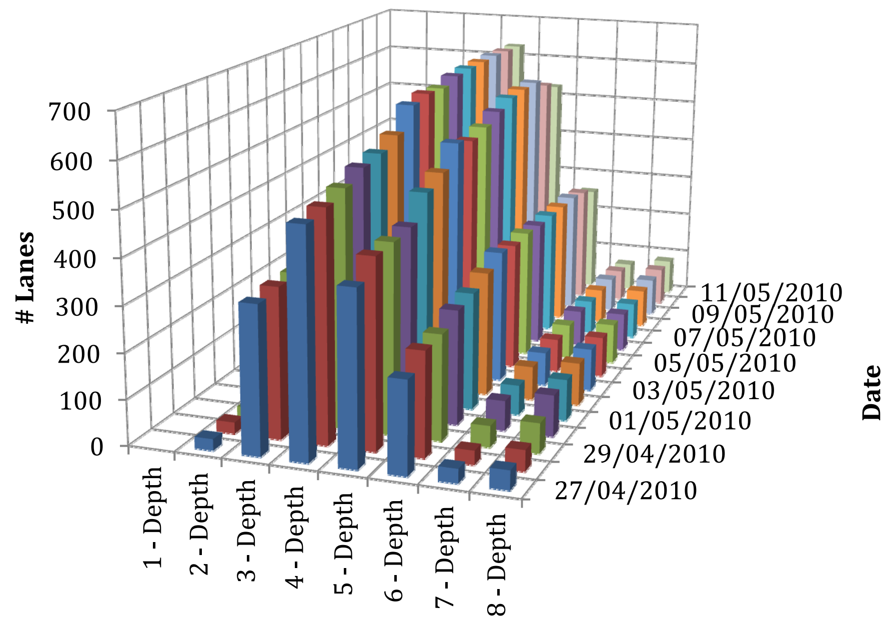


Figure 79. Case study lane depth frequency analysis

The mere application of the lane depth patterns guarantees the definition of the optimal lane depth per each SKU, but does not give any useful tool to configure the layout of the overall system. Indeed, the pattern computes the required number of lanes with equation (32), but this value does not consider the storage delay of pallets before being retrieved and shipped. As instance, the total storage capacity of the system computed as the sum of the lanes of Figure 79 is 8,775 storage locations.

Unfortunately, the average total inventory of the system ranges from 45,000 and 50,000 unit loads (i.e. pallets). Therefore, the adoption of the pattern does not provide a useful tool to address the configuration of the overall system layout.

In order to address such criticality, the analysis continues showing the results of the adoption of the dynamic scheduling module. The considered lane release interval is computed as the average interval within the end of receiving processes and the end of shipping of the lots of each SKU. Figure 80 represents the multi-dimensions lane-depth frequency analysis based on the range storage capacity of the system during a select horizon of time (i.e. from April 27th to May 10th 2010).



	1 - Depth	2 - Depth	3 - Depth	4 - Depth	5 - Depth	6 - Depth	7 - Depth	8 - Depth
27/04/2010		25	323	495	378	202	31	42
28/04/2010		25	330	505	414	229	31	46
29/04/2010		21	331	521	417	232	47	66
30/04/2010		21	331	542	423	253	66	91
01/05/2010		21	331	551	474	261	66	91
02/05/2010		21	333	571	495	278	75	95
03/05/2010		21	325	619	540	298	75	95
04/05/2010		22	338	627	525	288	75	91
05/05/2010		22	334	622	537	292	79	91
06/05/2010		26	361	634	555	286	83	87
07/05/2010		22	375	636	570	286	79	83
08/05/2010		22	387	636	573	284	79	87
09/05/2010		22	387	636	573	284	79	87
10/05/2010		22	369	632	549	274	74	87
11/05/2010		20	361	629	528	254	65	83

Figure 80. Multi-dimension frequency analysis

The selected scenario (i.e. the layour highlighted in the graph) corresponding to a storage capacity of 46,260 pallets aims to configure the storage system and to assess the space efficiency metrics and performances.

The third step consists on the simulation of the set of historical inventory snapshots related to the interval from April 15th to May 14th 2010 on the defined warehouse scenario. The graph of Figure 81 reports values of space saturation in terms of the ratio of occupied storage locations to the overall storage locations (i.e. red colored line), of the ratio of open lanes to the overall available lanes (i.e. blue colored line), and of the ratio of the occupied storage locations in the open lanes to the overall storage locations of the open lanes (i.e. green colored line).

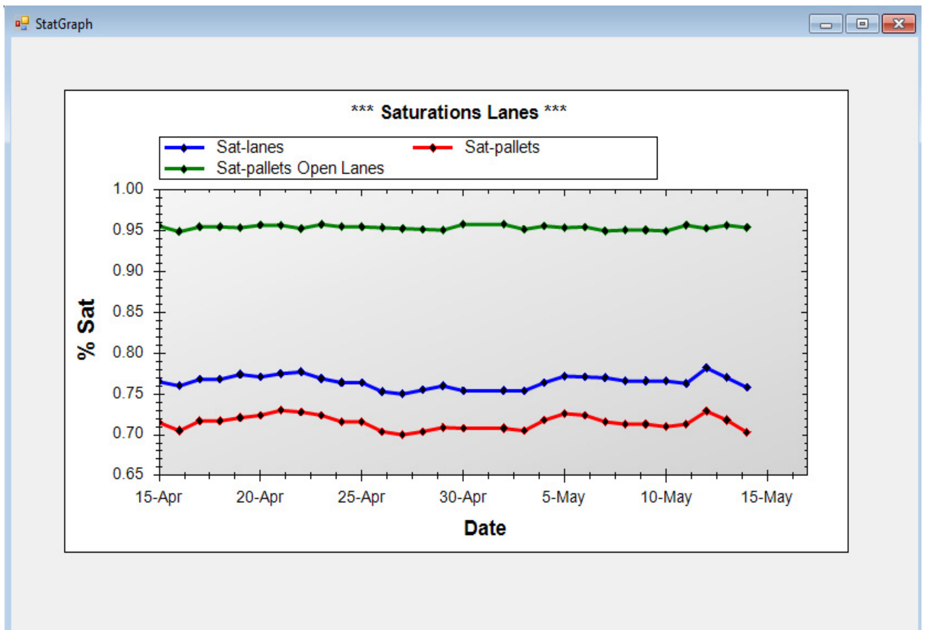


Figure 81. KPIs summary of the case study

If the obtained results do not satisfy the decision-maker, he/she can iterate the dynamic scheduling step in order to configure an alternative warehouse layout, to be simulated and assessed. Each scenario represents a benchmark to evaluate the space efficiency performance of the storage system.

6.5 Conclusions

This chapter focuses on models, procedures and tools for the design and management and control of unit-load warehousing systems.

The proposed top-down procedure gains traction by literature static mathematical models (Bartholdi and Hackman 2012) and aims to define the system layout implications in terms of storage mode to adopt and lanes depth. The definition of layout entails a wide set of issues, but the most important one is the effective utilization of space. The proposed procedure and DST aims to provide useful devices to managers and practitioners not only for the setting of the depth of the lanes, but also for the configuration and the assessment of the system layout.

Further research is expected to support the configuration of the optimal layout scenario through the adoption of optimization models based on maximization of the space efficiency.

7. Land Networking. An Integrated Perspective

As discussed in detail in previous chapters, throughout the modern global supply chains, warehousing systems and distribution centers allow to match vendors and demand, to respond to seasonality and change, to consolidate products and arrange shipments, playing a crucial role in reaching efficiency and customer satisfaction.

The definition of models, tools, procedures and patterns for the design and management of different type of warehousing systems, both unit-load and less-than-unit-load, is the purpose of the previous chapters. These sessions entail the study and discussion of the wide set of micro concerns and issues related to the material flow inside a distribution center. The optimization of the operative procedures and inbound/outbound activities aims to enhance the time and space efficiencies, thereby reducing the logistics costs of the warehouse. Such costs represent a relevant fraction of those experienced by the final consumers but not the only.

Indeed, by observing over a macro perspective the overall supply chain process, leading the products along the whole network through the warehouses to the final consumers, other significant costs and issues, regarded with the raw materials management and stowing, the manufacturing processes and the distribution network have to be handled at all.

The aim of this chapter, the last of the present manuscript, is to present an integrated macro-micro perspective for the overall study and analysis of the global supply chain. This perspective bases on the integration of macro and micro concerns related respectively to the material flows throughout the supply network and the material flow throughout the warehousing systems, which are the logistic nod of the distribution network.

Furthermore, this original perspective concerns also the entire product-life cycle. Indeed, the storage time (i.e. the horizon of time for which a SKU is held by a storage system) represents just a fraction of the overall lead-time occurring from the raw material collection, to the product use or consumption, until its final disposal.

Conversely, the proposed perspective aims to focus on the supply chain processes from the cradle to the crave of the product, involving also the land exploitation and collection of raw material, the manufacturing processes, the storage and distribution activities and end-of-life treatments, such as recycling, recovery or disposal.

Even though this perspective can be approached with any supply chain, the focus of this chapter deals with the design, planning and management of the food supply chain. Indeed, more than in other cases, the food supply chain entails a wide set of criticalities related to the logistic efficiency of processes, affecting the sale price, but also to the quality and safety of food products and the environmental sustainability of the system. Furthermore, the food supply chain encompasses the whole food products life-cycle, from the land seeding and farming, the stowing of food commodities, the manufacturing and transformation processes, the storage and distribution of finish goods, and the collection, recovery and recycling of related wastes. Therefore, so articulated chain is a valid candidate for the application of the proposed perspective.

This perspective entails the definition of original support-decision models for the management of an articulated close-loop food supply chain from farm to fork.

The remainder of the chapter is organized as follows. In the first section, some tips from the literature, related to the design and management of articulated food supply chain, are summarized in order to give a basic background to the reader. Then, the chapter continues with the problem statement and the definition of the hypothesis assumed to define a support-decision model for the design of close-loop food supply chain. A MILP model is presented and discussed in the third section of this chapter, and a brief application sample is presented and illustrated. This section is a brief summary of the main contents handled in Accorsi et al. (2013).

7.1 Tips from literature

Nowadays, due the development of more and more integrated and globalised markets and firms, some of the most critical issues involving supply chain management (SCM) are the analysis, design and control of efficient and integrated logistics and distribution network allowing both to convey products towards final consumer and to address economical and environmental sustainability.

The design and management of a global food supply chain involves two apparently separate issues and aspects of the reality, handled in the following two sections.

7.1.1 Distribution network

On one side, the decision-maker faces the problem of the strategic, tactical and operative design and planning of the distribution network. Therefore, supporting-decision methods and models are necessary in order to tackle strategic design issues, such as the decision on the intermediate logistic nodes or the operational planning and delivery scheduling, as well as the allocation of customers demand to particular facilities or warehouses and the inbound/outbound transportation activities.

Literature traditionally attempts to respond to these needs focusing on the following main issues and decisions: the facility location problem (FLP), the allocation problem, and the vehicle routing problem (VRP).

In FLP the selection of the sites where new facilities are to be established is restricted to a finite set of candidates. The simplest approach to solve such a problem consists on the so-called p-median problem, whereas some facilities, equivalent in opening-setup costs, are selected to minimize the overall weighted distances for supplying customer demands (Melo et. al. 2009). Many different mixed-integer linear programming (MILP) models have been proposed by the literature in order to suggest the best sites for the logistic nodes as plants, warehouses, depots etc., under different constraints and hypotheses. These models have been summarized in several meaningful surveys (Nagy et al. 2007, Melo et. al. 2009): uncapacitated (UFLP) or capacitated location problems (CFLP), or single and multi-period location problems, in which parameters, like customer demand, change over time in a predictable way, so that several time batches are considered.

In order to achieve an overall optimal and integrated solution, FL problem uses to be tackled combined with another critical aspect, i.e. the allocation of each supplier to a set of points of demand, within the so-called location-allocation problem (LAP). Unfortunately LAP represents an NP-hard decision problem, and consists on the simultaneous setting of the number of logistic nodes (e.g. manufacturing plants, DCs, etc.), their sites, and the assignment of customer demand (Nagy et al. 2007). Although a large set of MILP models have been developed to solve different formulations of LA problem (Nagy et al 2007, Manzini and Gebennini 2008, Melo et al. 2009) through branchand-bound or Lagrangian relaxations, the increasing number of discrete variables and constraints, accounted by case studies or real instances, forces the adoption of other solving techniques and methods, as heuristics approaches and metaheuristics (e.g. genetic, tabu search, simulated annealing etc.).

Finally operational scheduling and, particularly, fleet routing problem, i.e. the so-called vehicle routing problem (VRP), is approached through a wide set of methods and techniques considering single and multiple time windows, load capacity constraints with the attempt to minimize the total travelling and related costs due to delivery missions.

However in order to ensure the most efficient routing and the overall costs minimization throughout the distribution system, the above presented decision steps need to be jointly faced in unique problem, the so-called location-routing problem (LRP) (Zhang et al. 2007, Ye et al. 2008, Karaoglan et al. 2010, and more generally, Nagy et al. 2007). In fact, locating the facilities without considering vehicle routes may lead to suboptimal solutions (Salhi et al. 1989).

Table 25 summarizes several recent works dealing with the adoption of innovative models and techniques to address the distribution network design, management and/or control issues through an integrated and combined approach.

Author	Year	Topic			Stages (n. Levels)	Time Window	Products	Solving Method							Decision Steps			Application & Case Study			
		Models	*Benchmark*	*Tools*				*MILP*	*MINLP*	*Heuristic*	*Metaheuristic*		*Graph*	*Clustering*	*Str.*	*Tact.*	*Oper.*	*Plant*	*CDC*	*RDC*	*POD*
											Genetic	*Tabu Search*									
Ambrosino, D. Scutella, M.	2005	•			*MS (4)*	*MW*	*SP*	•							•	•	•	1	[2,5]	[5,23]	{25, 50, 75, 100, 104}
Liu, S. Lin, C.	2005		•		*SS (2)*	*SW*	*SP*			•					•		•		[2,20]		[4,200]
Zhang, C. et. al.	2007	•			*SS (2)*	*SW*	*SP*	•		•							•		[3,29]		[57,214]
Lopes, R.B. et. al.	2008			•	*SS (2)*	*SW*	*SP*	•		•				•	•		•		[2,14]		[12,150]
Manzini, R. et. al.	2008	•			*MS (3)*	*MW*	*MP*	•							•						
Manzini, R. Gebennini, E.	2008	•			*MS (4)*	*MW*	*SP*	•							•				1	5	1100
Wan, F. Zhang, Q.	2008	•			*MS (3)*	*SW*	*SP*	•		•					•		•				
Xu, L. et. al.	2008	•			*SS (2)*	*SW*	*SP*	•				•					•		5		25
Ye, W. Li, Q.	2008		•		*SS (2)*	*SW*	*SP*	•			•	•			•		•		{10,15,20}		{80, 100}
Dondo, R. et. al.	2009	•			*MS (3)*	*MW*	*MP*	•									•	1	{2,3,4}		{15, 17, 23}
Manzini, R. Bindi, F.	2009	•		•	*MS (4)*	*MW*	*MP*	•						•	•	•	•	2	[20,33]	[22,168]	464
Schittekat, P. Sörensen, K.	2009			•	*MS (3)*	*MW*	*SP*	•				•			•		•		[1,113]		800
Karaoglan, I. Altiparmak, F.	2010		•		*SS (2)*	*SW*	*SP*	•			•				•		•		{5, 10}		{20, 50, 100, 200}
Wan, F. Zhang, Q.	2010		•		*SS (2)*	*SW*	*SP*		•				•	•	•					[1,27]	
Bosona, T. Gebresenbet, G.	2011			•	*SS (2)*	*SW*	*SP*								•		•				
Sajjadi, S. R. Cheraghi, S.	2011	•			*SS (2)*	*SW*	*MP*	•			•				•		•				350

Table 25. Literature review

Table 25 focuses on the main goal of each single paper, classifying manuscripts according to three main categories:

- *Models*, i.e. if innovative models, techniques or algorithm are presented;
- *Benchmark*, whether a comparison among already proposed models and innovative presented heuristics is discussed;
- *Tools*, where innovative decision-support systems and methods are presented and illustrated.

The reported works concern with different problem formulation depending on the considered distribution network stages (single or multiple stages), the adoption of single or multiple time windows, and the number of products handled by the particular distribution system. Several different solving methods are applied and results of simulation analysis are illustrated through random instances or the application to real case studies.

Particularly interesting is the development of DSSs and software platforms managing the implementation of a capacitated location-routing problem (CLRP) and a capacitated and vehicle fleet routing solver (Lopes et al. 2008, Schittekat and Sörensen 2009). More in detail Lopes et al. (2008) realizes an integrated problem analysis through a four main decision steps approach: (i) construct clusters of customers in accordance with vehicle capacity constraints; (ii) determine the distribution in each customer group; (iii) improve the routes and finally; (iv) locate the depots and assign the routes to them.

Others relevant manuscripts on topic are organically summarized in several recent surveys and other publications (Nagy et al. 2007, Melo et al. 2009, Gebennini et al. 2009). Finally such aspects related to the design, development and management of a complex and distribution network need, nowadays, to be treated even in facing reverse logistics issues (Jayaraman and Luo 2007, Pokharel and Mutha 2009) in order to reach competitive advantage and sustainable development of the entire supply chain system. Innovative models and techniques, as well as integrated top-down DSS for reverse logistics have been recently proposed and illustrated (Gamberini et al. 2010, Manzini et al. 2011).

The design and planning of close-loop supply chain involves, in addition to those previously discussed, the management of both forward and reverse material flows. Therefore, the LA problem defines the placement of multiple logistics nodes for the manufacturing, warehousing, collection, recovery and recycling and allocates to such nodes the related material flows. This topic mainly regards with the management of waste and has relevant influence on the environmental impact of the whole supply chain. Therefore, this topic is widely debated in literature and the most significant contributions are summarized in recent survey (Beamon 1999, Srivastava 2007, Guide Jr. and Van Wassenhove 2009).

7.1.2 Land use

On the other side, the decision-maker attempting to plan and design a global food supply chain has to face the issue related to the strategic planning and sustainable management of the use of land. This section aims to focus on the application of LP and in general OR modeling to the problem of land use. As illustrated and discussed in Section 7.1.1, most of the strategic planning with which OR practitioners are involved concerns industrial or commercial strategic planning. This is perfectly understandable given the background history of the related concepts of strategy, tactics, and logistics. However, another relevant application of strategic LP approaches is in the field of land-use and development planning (Yewlett 2001).

In general, the adoption of OR models for the optimal allocation of land use is a mindful tool to address social (i.e. population growth), political (i.e. development plans and policies), economic (i.e. infrastructure building) and environmental (i.e. environmental care policies) concerns.

Van Diepen et al. (1991) described land use planning as the allocation of land to various categories of use according to criteria formulated during the land evaluation process.

The mathematical models most commonly applied in land use allocation systems correspond to multi-criteria evaluation techniques, mathematical programming applications or spatial simulation models (Riveira and Maseda 2006). In particular, mathematical programming, when applied to land use planning, seeks the combination of land uses that optimizes one or more objective functions subject to a series of constraints. Dealing with such approach, some recent contributions are given by Aerts et al. (2003), Janssen et al. (2008), Eldrandaly (2009). Furthermore, Witlox (2005) summarizes a state-of-the-art review of the use of expert systems in land-use planning. It focuses on the implementation and development of different types of computer-based systems (i.e. expert systems, decision support systems, integrated systems) and tries to assess the usefulness of each system for the strategic planning of land use. The close connection between this topic and the food supply chain is due to the application of these models, algorithms and support-decision tools to the problem of crop planning and crop yield maximization and rural management (Carsjens et al. 2002, Riveira et al. 2008, Sarker and Quaddus 2002).

Even though the previous two sections report many recent contributions, respectively dealing with the strategic planning of distribution networks and of the land use, an integrated approach to match these two aspects of reality lacks. The food supply chain is the concrete environment for the development of a new integrated perspective. Indeed, in order to combine the design and the strategic planning of lands for crops and farming processes and food distribution network, an original set of models, tools and algorithm to solve the so-called land-networking problem is required. Next sessions attempt to the definition of problem and related set of strategic MILP models.

7.2 Land networking. Problem statement

Global economy makes products travelling along the supply chain from the manufacturer to final customer at the other side of the world, being available almost in every place and at every time. The modern supply chains strive for sundering manufacturing district from consumption process.

Particularly, in food supply chains, consumers desire to be aware about product features, characteristics, and skills. They also want to be ensured about the level of quality, safety, and sustainability of processes driving the product from origination site to the place of consumption.

The food specialties harvested and manufactured in a typical area (e.g. Italian wine and cheese, Columbian chocolate, Brazilian coffee, Russian grain, etc.) are purchased and shipped all over the world for their particularity, their taste, and the safe environmental conditions where they grew. Unfortunately, the increasing food demand is altering the agriculture processes (i.e. seeding, harvesting, farming, etc.) and products manufacturing from traditional approaches and techniques towards intensive methodologies and patterns, aimed to boost the land and crop yield.

These innovative worldwide-diffused methods lead to the fulfilment of the food products demand exportation towards rich western countries, at the expense of the exploitation of land natural sources (i.e. land, water, energy, etc.) experienced by the producer countries, unsustainable in the long terms.

On one side, in order to comply food products demands, taking into account the land yield, the climatic condition, the soil features and characteristics, as well as the available natural energy sources (i.e. energy and water), the management and optimization of land use planning over economic and environmental perspectives is necessary.

On the other, the proper management of the complex supply chain that organizes the collection of raw material (i.e. food commodities), the manufacturing process, the distribution, and storage network, the delivery for final consumption and the end-of-life cycles, significantly improves the quality, the efficiency, and the sustainability of the overall systems.

The goal complied by the proposed new perspective is to join both sides of the coin, the agriculture and logistics aspects (i.e. manufacturing, and distribution) for the design and management of a sustainable food supply chain. The objective functions of design and optimization models and tools entail the minimization of carbon dioxide emissions, the reduction of land and water use, the minimization of logistics costs due to the collection of raw material, the manufacturing, distribution, and waste recovery.

In order to fulfil the products demand, the effective and efficient planning of flows from farm to fork depend on the selected lands and devoted crops, the climatic conditions of the land, the soil features, the location of manufacturing and distribution nodes, the production and storage capacity, and the location of final costumers and waste collection centres. These aspects are taken into account in set of LP models for the optimization of both economic and environmental cost drivers of both lands and distribution network.

7.3 Land networking. Strategic models

This section deals with the definition of parameters, decision variables, constraints and objective function for both presented strategic models. The first MILP model presents a simple tool to support the design and the allocation of land use in accordance with the minimization of the overall environmental costs. The second MILP model inherits the strategic allocation of land of the previous one, and attempts to configure the optimal close-loop supply network enabling the collection, manufacturing, storage, distribution, recovery, recycling of food products in accordance with the minimization of the overall costs.

The proposed land-networking design perspective is implemented through the top-down procedure based on the subsequent application of the proposed set of models.

7.3.1 Strategic land-use allocation model

The proposed strategic model for the land-use allocation takes into account environmental costs drivers due to the use of the land and the distribution flows among lands. For sake of brevity, a simpler and brief version of the model is proposed. The objective function is defined by (48) as follows.

$$\min \delta = \sum_{l=1}^{L}\sum_{u=1}^{U} gwp_{lu} \cdot y_{lu} + \sum_{l=1}^{L}\sum_{l_1=1}^{L}\sum_{c_a \in a}\sum_{a=1}^{A}\sum_{m \epsilon M^{l,l_1}} gwp_{c_a m} \cdot x_{ll_1 c_a m} \cdot d_{ll_1} \qquad (48)$$

The proposed objective function accounts the environmental impacts and costs due to the spatial land-use allocation of a generic territory object of the analysis. In particular, the first term represents the differential global warming potential (*gwp*) (i.e. carbon dioxide equivalent emissions) due to the use of the land. The second term accounts the *gwp* due to the transportation of product component (i.e. a resource) from an origin land to a destination land. In the presented perspective, a resource consists on any component utilized to manufacture a final product (i.e. raw material for package, food product, energy, water, etc.). There is a wide set of different land use to be studied and evaluated, but the most significant to address the goal of this project are listed in follows:

- Agricolture use. This land use provides food products in accordance with the combination of features and characteristics of land soil and land climate. Soil conditions are one of the most important elements in site evaluation and system design. Other restricting site parameters include the topography, separation distances, owner's preferences, existing water sources, depth to any limiting layer, and landscape position. Soil consists of four components in various proportions: mineral particles, organic particles, water, and air. The principle soil features are the depth of horizon, the thickness, the moisture content, the color, the percentage, size and type of rock, the texture, the presence of mottling, the structure, the size and distribution of roots, the presence of carbonates, the resistance to penetration. Matching soil features with climate condition (i.e. rainfall, minimum and maximum temperature, humidity, sun hours per day and sun days per year, solar radiation, wind, etc.) allows the decision-maker to make reasonable hypothesis about the crop yield (i.e. the production capacity) of the land, given a generic use (i.e. wheat, orange, grape, etc.). Nevertheless, the agriculture and farming activities generate carbon equivalent emissions, proportionally to the tones of output products, in contrast with the problem goal.

- Woodland use. This land use regards the allocation of wildwood and forestry to a land lot. In biology, carbon fixation is the reduction of inorganic carbon (i.e. carbon dioxide) to organic compounds by living organisms. The most prominent example is photosynthesis. Organisms that grow by fixing carbon are called autotrophs (e.g. plants). Heterotrophs (e.g. animals) are organisms that grow using the carbon fixed by autotrophs. Therefore, the allocation of woodland use to a territory attempts to reduce the overall *gwp* of the planned environment.
- Energy use. This land use provides renewable or not renewable energy to power agriculture, rural and industrial land uses. The climate conditions of a land (e.g. solar radiation, wind, marine currents, etc.) and the availability of waterways critically influence the opportunity to exploit renewable energy plant (e.g. photovoltaic plants, wind power plants), which reduce the overall *gwp* of the planned environment.
- Urban use. This land use provides the required homes to lodge the entire human population of the planned environment and territory. Nevertheless, the urban use generates carbon equivalent emissions, proportionally to the population density of every land lot, in contrast with the problem goal.
- Industrial use. This land use is devoted to location of manufacturing, logistics and distribution, collection and recycling nodes and district responsible to organize the forward and reverse flows of the food supply chain. The industrial use generates carbon equivalent emissions, proportionally to the output flows, in contrast with the problem goal.

The objective function aims to minimize the overall *gwp* of the observed environment in accordance with the fulfillment of the primary demands of food products and homes. Agriculture generate raw products that boot the supply processes, industry manufactures and distributes final products, woodland allows to contain the carbon dioxide equivalent emission of the system. Figure 82 illustrates a brief sample of the multi-site land-use allocation (MLUA) problem analyzed.

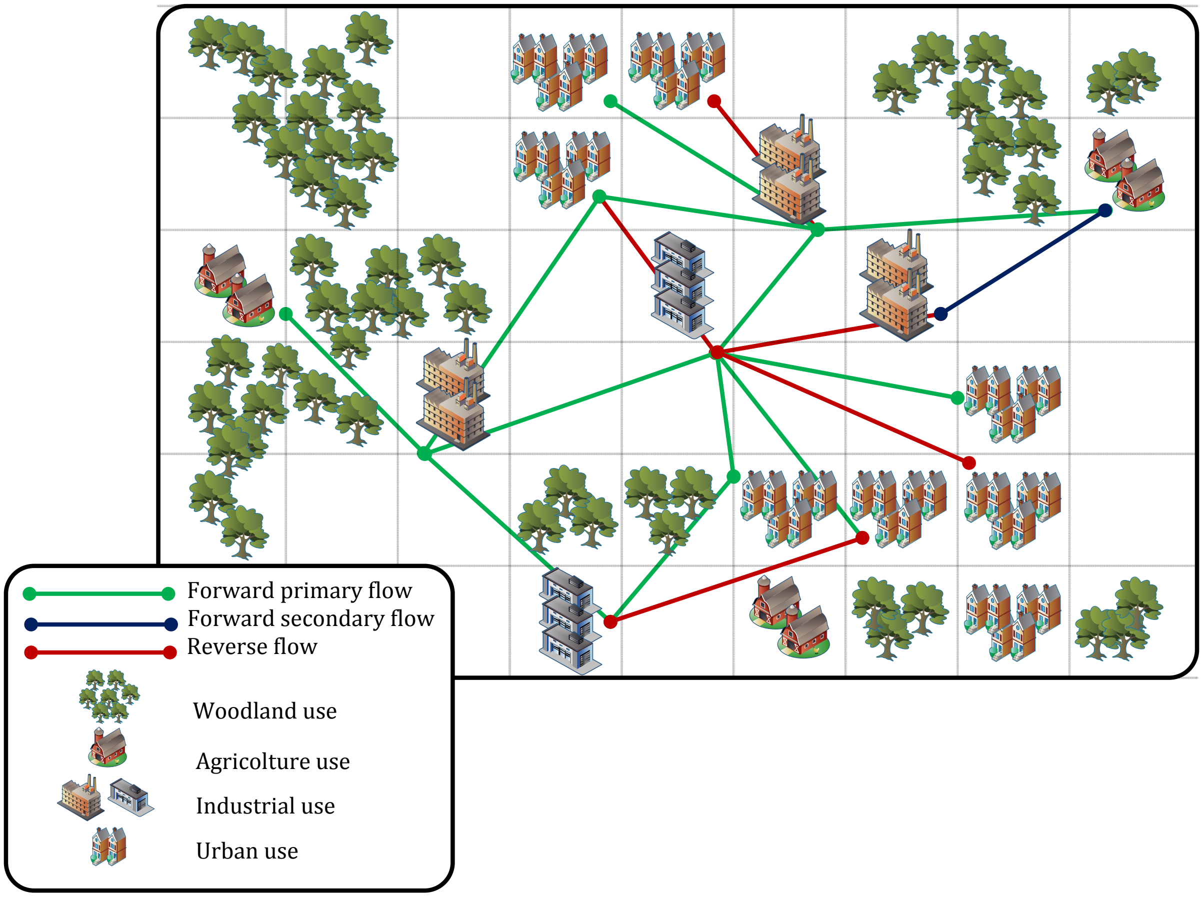


Figure 82. Land-use allocation sample

The in the simpler and brief proposed version of the model, the objective function (48) is subjected to the following set of constraints:

$$\sum_{u=1}^{U} y_{lu} = 1 \quad \forall\, l = 1, \dots, L \quad (49)$$

$$\sum_{l=1}^{L}\sum_{u=1}^{U}\sum_{m\in M^{l,l_1}} x_{ll_1c_am} = d_{c_al_1u} \cdot y_{l_1u} \quad \forall\, l_1 = 1, \dots, L\; u = 1, \dots, U\; \mathrm{a} = 1, \dots, \mathrm{A}\; \mathrm{c_a} \in \mathrm{a} \quad (50)$$

$$\sum_{l_1=1}^{L}\sum_{m\in M^{l,l_1}} x_{ll_1c_am} = p_{c_alu} \cdot y_{lu} \quad \forall\, l = 1, \dots, L\; u = 1, \dots, U\; \mathrm{a} = 1, \dots, \mathrm{A}\; \mathrm{c_a} \in \mathrm{a} \quad (51)$$

$$y_{lu} \in \{0,1\} \quad \forall\, l = 1, \dots, L\; u = 1, \dots, U \quad (52)$$

$$x_{ll_1c_am} \geq 0 \quad \forall\, l, l_1 = 1, \dots, L\;\; m \in M^{l,l_1}\; \mathrm{a} = 1, \dots, \mathrm{A}\; \mathrm{c_a} \in \mathrm{a} \quad (53)$$

where:

$l \in \{1 \dots L\}$ Lands.

$u \in \{1 \dots U\}$ Land uses.

$a \in \{1 \dots A\}$ Products.

$c_a \in a$ Raw components or raw resource of product *a.*

$m \in \{1 \dots M\}$ Transportation means.

gwp_{lu} = Fixed environmental costs to devoted a land l to the use u [tonnes eq. CO_2].

$gwp_{c_a m}$ = Variable distribution costs per product c_a by mean plant m [tonnes eq. CO_2/kg km].

d_{ll_1} = Distance from land l to land l_1 [km].

$x_{ll_1 c_a m}$ = Flow of component c_a by mean m from land l to land l_1.

$$y_{lu} = \begin{cases} 1 \; if \; land \; l \; devoted \; to \; use \; u \\ 0 \; Otherwise \end{cases}$$

The results of the strategic multi-site land use allocation planning are adopted as input for the application of the strategic design of food supply chain infrastructure according to the proposed top-down procedure and land networking illustrated approach.

7.3.2 Strategic close-loop network design model

The proposed strategic model for the design of a food close-loop distribution network takes into account costs drivers due to the activation of a generic logistic node (i.e. manufacturing node, distribution centre, collection node, recovery or recycling or transformation node), the inbound and outbound handling costs experienced by each node, the transportation costs among nodes. The objective function is defined by equation (54).

$$
\begin{aligned}
\min \delta = & \sum_{p=1}^{P} cf_p \cdot y_p + \sum_{s=1}^{S} cf_s \cdot y_s + \sum_{z=1}^{Z} cf_z \cdot y_z + \sum_{t=1}^{T} cf_t \cdot y_t + \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,s}} x_{psam} \cdot cvp_{pa} \\
& + \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,i}} x_{piam} \cdot cvp_{pa} + \sum_{s=1}^{S}\sum_{s_1=1}^{S}\sum_{a=1}^{A}\sum_{m\epsilon M^{s,s_1}} x_{ss_1am} \cdot w_a \cdot ch_s \\
& + \sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{a=1}^{A}\sum_{m\epsilon M^{s,i}} x_{siam} \cdot w_a \cdot ch_s \\
& + \sum_{z=1}^{Z}\sum_{z_1=1}^{Z}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{z,z_1}} x_{zz_1c_am} \cdot ch_z + \sum_{z=1}^{Z}\sum_{t=1}^{T}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{z,t}} x_{ztc_am} \cdot (ch_z + cvt_{c_a}) \\
& + \sum_{l=1}^{L}\sum_{p=1}^{P}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{l,p}} x_{lpc_am} \cdot d_{lp} \cdot ct_m \\
& + \sum_{p=1}^{P}\sum_{p_1=1}^{P}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,p_1}} x_{pp_1am} \cdot w_a \cdot d_{pp_1} \cdot ct_m + \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,s}} x_{psam} \cdot w_a \cdot d_{ps} \cdot ct_m \\
& + \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,i}} x_{piam} \cdot w_a \cdot d_{pi} \cdot ct_m \\
& + \sum_{p=1}^{P}\sum_{z=1}^{Z}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,z}} x_{pzc_am} \cdot d_{pz} \cdot ct_m + \sum_{s=1}^{S}\sum_{s_1=1}^{S}\sum_{a=1}^{A}\sum_{m\epsilon M^{s,s_1}} x_{ss_1am} \cdot w_a \cdot d_{ss_1} \cdot ct_m \\
& + \sum_{s=1}^{S}\sum_{i=1}^{I}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,s}} x_{siam} \cdot w_a \cdot d_{si} \cdot ct_m \\
& + \sum_{i=1}^{I}\sum_{z=1}^{Z}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{i,z}} x_{izc_am} \cdot d_{iz} \cdot ct_m + \sum_{z=1}^{Z}\sum_{t=1}^{T}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{z,t}} x_{ztc_am} \cdot d_{zt} \cdot ct_m \\
& + \sum_{z=1}^{Z}\sum_{l=1}^{L}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{z,l}} x_{zlc_am} \cdot d_{zl} \cdot ct_m
\end{aligned}
$$

Equation (54) represents the objective function for the strategic planning of the close-loop supply chain. The proposed objective aims to minimize the overall fixed costs of placing logistic nodes (i.e. production plants, forward and reverse warehousing systems, recycling or transformation nodes), the variable production and recycling costs per processed unit, the handling costs per weight of good crossing the warehousing systems, and the transportation costs per weight of good and transportation mean (i.e. train, truck, plane, ship). The forward chain handles units of products since the customer demand to fulfill is expressed in terms of discrete amount of a generic product *a*, whilst the reverse chain, as well as the supply of raw material from the generic land *l* to the production node *p*, handles flow expressed in terms of weight.

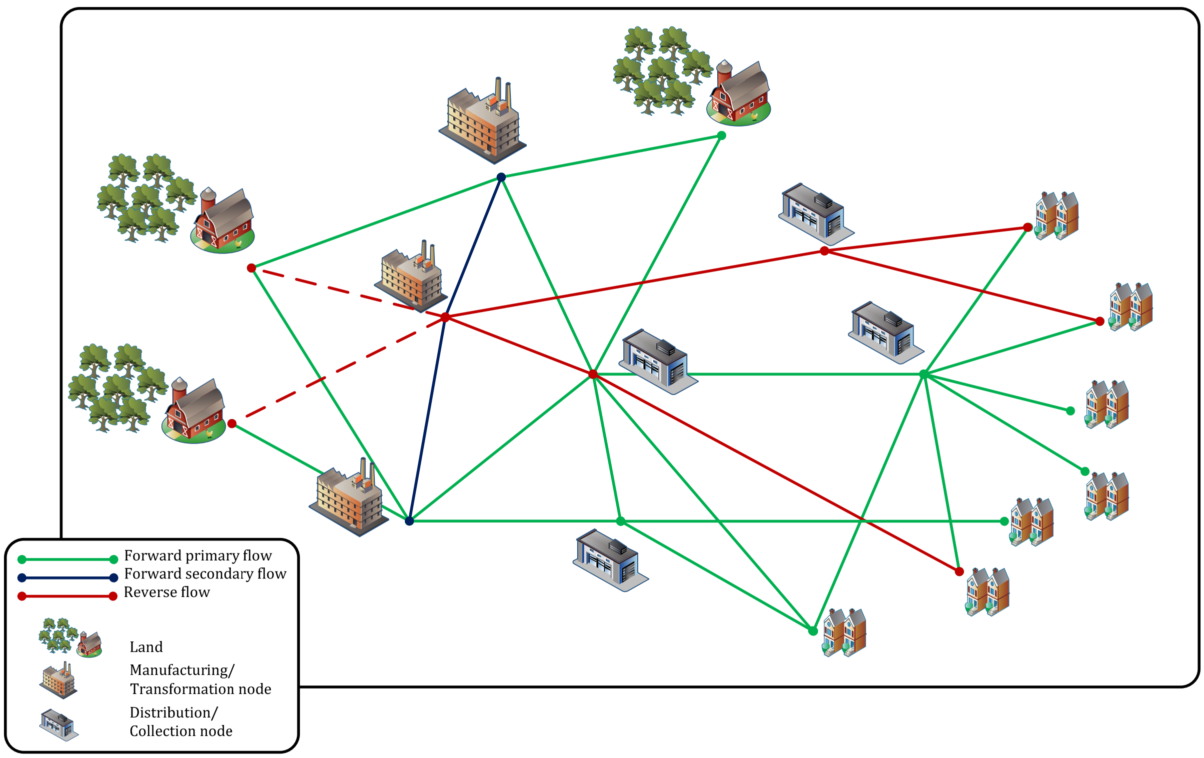


Figure 83. Close-loop supply chain planning.

Figure 83 illustrates a sample of the close-loop food chain object of analysis. Farmers and vendors supply the raw materials (i.e. food products and package components) to the manufacturing and processing nodes. The manufacturing plant is responsible to merge the raw components and to generate a products flow as output. Thus, the products travel throughout the chain crossing distribution node or directly achieving the final consumers. The reverse flow consists on the waste generated by the both manufacturing and final consumption processes. The collection nodes retrieve waste after a disassembling procedure carried out by consumers on a generic product. The final step is represented by the shipment of consolidated waste to transformation or recycling nodes or to the landfill according to the features and properties of the generic components. The proposed model aims to solve the LAP problem for a complex close-loop chain involving six stages and joining the products through their whole life cycle. The objective function (54) is subjected to the following set of constraints:

$$\sum_{p=1}^{P}\sum_{m\epsilon M^{p,i}} x_{piam} + \sum_{s=1}^{S}\sum_{m\epsilon M^{s,i}} x_{siam} = d_{ia} \;\; \forall\, i = 1, \dots, I \; a = 1, \dots, A \quad (55)$$

$$\sum_{s=1}^{S}\sum_{m\epsilon M^{p,s}} x_{psam} + \sum_{i=1}^{I}\sum_{m\epsilon M^{p,i}} x_{piam} \le pc_{pa} \cdot y_p \;\; \forall\, p = 1, \dots, P \; a = 1, \dots, A \quad (56)$$

$$\sum_{p_1=1}^{P}\sum_{a=1}^{A}\sum_{m\epsilon M^{p_1,p}} x_{p_1pam} \cdot v_a \le sc_p \cdot y_p \;\forall\, p = 1, \dots, P \quad (57)$$

$$\sum_{p=1}^{P}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,s}} x_{psam} \cdot v_a + \sum_{s_1=1}^{S}\sum_{a=1}^{A}\sum_{m\epsilon M^{s_1,s}} x_{s_1sam} \cdot v_a \le sc_s \cdot y_s \;\forall\, s = 1, \dots, S \quad (58)$$

$$\sum_{p=1}^{P}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{p,z}} x_{pzc_am} \cdot kv_{c_a} + \sum_{i=1}^{I}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{i,z}} x_{izc_am} \cdot kv_{c_a} + \sum_{z_1=1}^{Z}\sum_{c_a\in a}\sum_{a=1}^{A}\sum_{m\epsilon M^{i,z}} x_{z_1zc_am} \cdot kv_{c_a} \le sc_z \cdot y_z \;\forall\, z = 1, \dots, Z \quad (59)$$

$$\sum_{z=1}^{Z}\sum_{m\epsilon M^{z,t}} x_{ztc_am} \le tc_{tc_a} \cdot y_t \;\; \forall\, t = 1, \dots, T \; a = 1, \dots, A \;\; c_a \in a \; (60)$$

$$\sum_{l=1}^{L}\sum_{m\epsilon M^{p,s}} \frac{x_{lpc_am}}{w_{c_a}} \ge \sum_{s=1}^{S}\sum_{m\epsilon M^{p,s}} x_{psam} + \sum_{i=1}^{I}\sum_{m\epsilon M^{p,i}} x_{piam} \;\forall\, p = 1, \dots, P \; a = 1, \dots, A \; c_a \in a \; (61)$$

$$\left(\sum_{s=1}^{S}\sum_{m\epsilon M^{p,s}} x_{psam} + \sum_{i=1}^{I}\sum_{m\epsilon M^{p,i}} x_{piam}\right) \cdot w_{c_a} \cdot ks_{c_a}^{p} = \sum_{z=1}^{Z}\sum_{m\epsilon M^{p,z}} x_{pzam} \forall\;\, p = 1, \dots, P \; a = 1, \dots, A \; c_a \in a \; (62)$$

$$\sum_{p=1}^{P}\sum_{m\epsilon M^{p,s}} x_{psam} + \sum_{s_1=1}^{S}\sum_{m\epsilon M^{s_1,s}} x_{s_1sam} \ge \sum_{i=1}^{I}\sum_{m\epsilon M^{s,i}} x_{siam} + \sum_{s_1=1}^{S}\sum_{m\epsilon M^{s,s_1}} x_{ss_1am} \;\forall s = 1, \dots, S \; a = 1, \dots, A \; (63)$$

$$\left(\sum_{p=1}^{P}\sum_{m\epsilon M^{p,i}} x_{piam} + \sum_{s=1}^{S}\sum_{m\epsilon M^{s,i}} x_{siam}\right) \cdot w_{c_a} \cdot \left(1 - ks_{c_a}^{p}\right) = \sum_{z=1}^{Z}\sum_{m\epsilon M^{i,z}} x_{izc_am} \forall\;\, i = 1, \dots, I \; a = 1, \dots, A \; c_a \in a \; (64)$$

$$\left(\sum_{i=1}^{I}\sum_{m\epsilon M^{i,z}} x_{izc_am} + \sum_{p=1}^{P}\sum_{m\epsilon M^{p,z}} x_{pzc_am}\right) \cdot ks_{c_a}^{z} = \sum_{t=1}^{T}\sum_{m\epsilon M^{z,t}} x_{ztc_am} \;\; \forall\, z = 1, \dots, Z \; a = 1, \dots, A \; c_a \in a \; (65)$$

$$\left(\sum_{i=1}^{I}\sum_{m\epsilon M^{i,z}} x_{izc_am} + \sum_{p=1}^{P}\sum_{m\epsilon M^{p,z}} x_{pzc_am}\right) \cdot (1 - ks_{c_a}^{z}) = \sum_{l=1}^{L}\sum_{m\epsilon M^{z,t}} x_{zlc_am} \;\; \forall\, z = 1, \dots, Z \; a = 1, \dots, A \; c_a \in a \;\; (66)$$

$y_p, y_s, y_z, y_t \in \{0,1\} \ \forall p, s, z, t$ (67)

$x_{lpc_a m}, x_{pp_1 am}, x_{psam}, x_{piam}, x_{ss_1 am}, x_{siam}, x_{pzc_a m}, x_{izc_a m}, x_{ctc_a m} \geq 0 \ \forall l, p, s, i, z, t, a, c_a, m$ (68)

where:

$l \in \{1 \dots L\}$ Land with proper use (i.e. farm or landfill).

$p \in \{1 \dots P\}$ Manufacturing plant or nodes.

$s \in \{1 \dots S\}$ Distribution or warehousing nodes.

$i \in \{1 \dots I\}$ Final consumers.

$z \in \{1 \dots Z\}$ Reverse collection nodes.

$t \in \{1 \dots T\}$ Manufacturing plant or facilities.

$a \in \{1 \dots A\}$ Products.

$c_a \in a$ Raw components of product *a.*

$m \in \{1 \dots M\}$ Transportation means.

$cf_{p,s,z,t}$ = Fixed costs for opening a logistic node [€].

cvp_{pa} = Variable production costs per product *a* in plant *p* [€/unit].

cvt_{tc_a} = Variable transformation costs per component c_a in plant *t* [€/kg].

$ch_{s,z}$ = Variable handling costs in node *s, z* [€/kg]. This cost includes the average inbound/outbound costs and the mortgage for handling vehicles.

ct_m = Variable transportation costs per mean *m* [€/kg km].

d_{ia} = Demand of customer *i* for product *a* [unit].

d_{xx_1} = Distance from node *x* to node x_1 [km].

v_a = Volume of product *a* [m^3/unit].

w_a = Weight of product *a* [kg/unit].

w_{c_a} = Weight of component c_a per one unit of product *a* [kg].

pc_{pa} = Production capacity of product *a* in plant *p* [unit].

$sc_{s,z}$ = Storage capacity in node *s, z* [m^3].

tc_{tc_a} = Transformation capacity of component c_a in plant *t* [kg].

kv_{c_a} = Coefficient from component c_a weight to component c_a volume [m^3/kg].

$ks^p_{c_a}$ = Waste coefficient of component c_a at node p.

$ks^z_{c_a}$ = Waste coefficient of component c_a at node z.

$x_{xx_1c_am}$ = Flow of component c_a by mean m from node x to node x_1.

$$y_x = \begin{cases} 1 \; if \; node \; x \; opened \\ 0 \; Otherwise \end{cases}$$

The proposed set of equations is classified into four main categories of constraints:

- Equation (55) guarantees that the customer demands are completely satisfied by warehousing centers or directly by the manufacturing facilities.
- Equations (56), (57), (58), (59), (60) guarantee that the capacity constraints are respected for the generic manufacturing plant *p*, the generic warehousing distribution node *s*, the generic collection node *c*, and the generic recycling or transformation node *t*, respectively.
- Equations (61), (62), (63), (64), (65) and (66) guarantee the equilibrium of product flows at nodes (at manufacturing node for products flow, at manufacturing node for waste flow, at distribution node, and transformation node respectively).
- Equation (67) represents Boolean constraints, whilst Equation (68) the constraints for continuous variables defined for quantitative flows of materials.

7.4 Conclusions

The design and management of global food supply chains entails a wide set of issues and concerns related to the farming and agriculture processes, the manufacturing activities, the storage and distribution steps, the collection and recycling of packaging material, with a significant influence and impact on the society and the environment.

This chapter focuses on the definition of an original perspective to the study, the analysis and design of a global food supply chain. In particular, two aspects of the problem, separately addressed by literature, such as the land-use allocation and the strategic planning of a distribution network are combined and jointly handled. In particular, this perspective matches a set of MILP models based on the optimization of land-use allocation and food distribution network considering respectively environmental and non-environmental cost drivers.

This represents a very tough challenge for supply managers and practitioners worldwide operating. Indeed, on one side food specialties travel all over the world, despite of their origins. Unfortunately, on the other, the innovative intensive-farming techniques allows just the partial fulfillment of demand of food, mainly exported towards rich western countries, at the expense of the exploitation of locals natural sources (i.e. land, water, energy, etc.), in a way unsustainable in the long terms.

The illustrated perspective, through the top-down adoption of a set o strategic models, aims to balance the economical and environmental costs related to a complex and global food supply chain, considering the connection among the customers demand, the enterprises processes, and the strategic planning of the land.

Further research are expected on the design and development of support-decision Geographic Information System (GIS) tools able to collect, store and manage the whole spectrum of data related to the land climate and soil, the crop yield, the crop requirements (i.e. water and energy) the carbon footprint of manufacturing and transportation activities, the geographic coordinates of lands, logistics nodes and customers, the features and characteristics of vehicles, etc. Such GIS tools ought to collect real instance data sets (i.e. taken from supply chain enterprise and GIS database) in order to implement and test the proposed set of MILP models with real applications.

Furthermore, the integration of such models and tools for the strategic design of distribution networks with the previous illustrated models and tools for the design and management of warehousing systems and distribution center (i.e. storage nodes of the supply chain) is a crucial insight of this research topic.

8. Conclusions

In modern and global supply chain, the increasing trend toward product variety, level of service, short delivery delay and response time to consumers, highlight the importance to set and configure smooth and efficient logistic processes and operations.

In order to comply such purposes the supply chain management (SCM) theory entails a wide set of models, algorithms, procedure, tools and best practices for the design, the management and control of articulated supply chain networks and logistics nodes. Nowadays, warehouses represent the crucial operative nodes throughout the supply chain and distribution network.

The purpose of this manuscript is going in detail on the principle aspects and concerns of supply chain network and warehousing systems, by proposing and illustrating useful methods, procedure and support-decision tools for the design and management of real instance applications, such those currently face by enterprises.

In particular, after a comprehensive literature review and tutorial of the principal warehousing issues and entities, the manuscript focuses on design top-down procedure for both less-than-unit-load OPS and unit-load storage systems. The former systems involve a wide spectrum of manual and mechanical processes, and decisions to be taken regarding the storage allocation and assignment, the zoning, the batching and routing for the increasing of the system time efficiency. The latter systems (i.e. unit-load warehousing) mainly depends on the problem of layout, consisting on the definition of the optimal lane depth per each SKU, in order to match inbound and outbound flows and to increase the system space efficiency.

For both cases, decision-support software platforms are illustrated as useful tools to address the optimization of the warehousing performances and efficiency metrics. The development of such interfaces enables to test the effectiveness of the proposed hierarchical top-down procedure with huge real case studies, taken by industry applications.

Whether the large part of the manuscript deals with micro concerns of warehousing nodes, in the last chapter, macro issues and aspects related to the planning, design, and management of the whole supply chain are enquired.

The integration of macro criticalities, such as the design of the supply chain infrastructure and the placement of the logistic nodes, with micro concerns, such the design of warehousing nodes and the management of material handling, is addressed through the definition of integrated models and procedures, involving the overall supply chain. The main effort for the decision-maker is preliminary understanding the connections and interdependencies among the physical and virtual entities and flows throughout the supply chain. The long process leading products, from the origination site, through the process and collection of raw material, the manufacturing activities, the storage and distribution steps, the consumption and the final recycling and disposal of waste should be analyzed and studied as a whole. The current and more and more diffused integrating approaches based on the partnerships among actors and enterprises along the supply chain are virtuosos, but are not enough.

A new perspective should be applied in study and planning of a global (e.g. food) supply chain. The physical flow of products and materials is based on the interaction of actors (i.e. enterprises), and, mostly, on the exploitation of resources of any types and natures, such as land (i.e. space in warehousing system), energy, water, time (i.e. logistics working-time), air (i.e. carbon emissions), labor, per each step of the chain. Each product received by a customer accounts the whole spectrum of cost drivers experienced during the processes and activities carried out through the supply chain. Most of these costs are implicit, since are not measured by any supply actors, and only an integrated focus on the overall flows might point them out.

Therefore, another insight of this manuscript is to give a set of reasonable tools (i.e. procedures, methods, models) able to track and follow the products throughout the macro flows (i.e. flows inter-nodes) and micro flows (i.e. flows intra-node) of the whole supply chain and to measure the performances, the efficiency metrics, the resource saturation and use, supporting the study, analysis, planning and design of sustainable logistics chains.

"Some men see things as they are and say why?

I dream things that never were and say why not?"

Robert F. Kennedy quoting George Bernard Shaw, 8 June 1968

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