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INNOVATIVE METHODS AND MODELS FOR INTEGRATED WAREHOUSE PICKING SYSTEMS DESIGN

Ph.D. School Director: Ch.mo Prof. Alessandro Persona

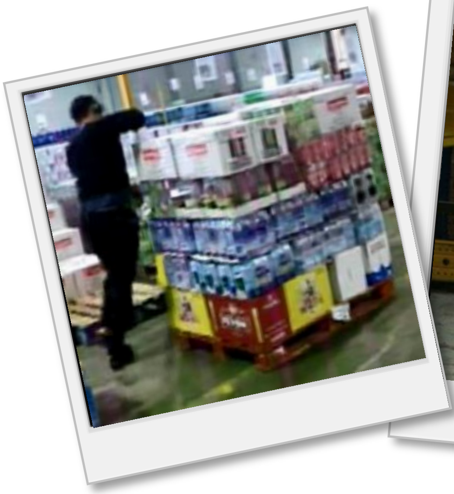
Supervisor: Ch.mo Prof. Alessandro Persona

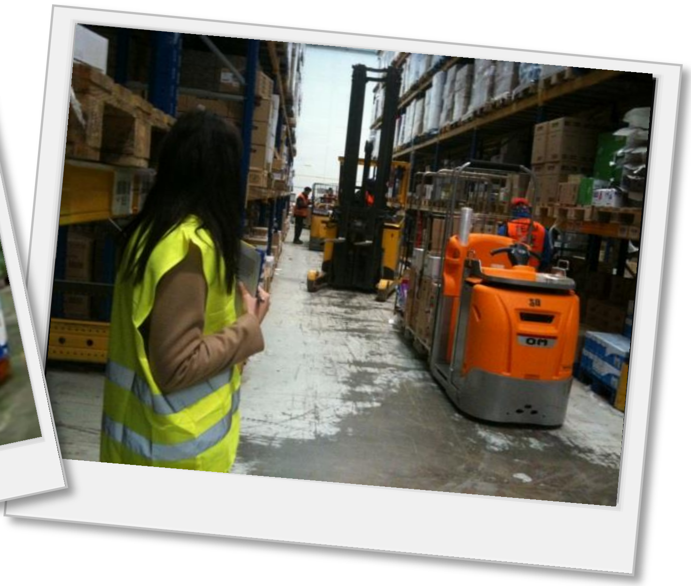
Ph.D. Candidate: Eng. Martina Calzavara

Innovative methods and models for integrated warehouse picking systems design

by

Martina Calzavara





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SOMMARIO

L’area di *picking* (o prelievo frazionato) all’interno di un magazzino è la zona in cui vengono create le unità di spedizione dei clienti, attraverso il prelievo dei prodotti richiesti dalle varie locazioni di stoccaggio. Se in questa area vi è la presenza di operatori umani, che camminano o viaggiano all’interno dei corridoi del magazzino per recuperare gli oggetti richiesti dai clienti, e riportati sulle loro liste di prelievo, il sistema di *picking* viene chiamato sistema di *picking* manuale operatore-verso-materiale. Nonostante nel tempo siano state inventate e sviluppate numerose soluzioni automatizzate, questo tipo di sistema è ancora il più diffuso, dato che la presenza degli operatori garantisce una grande flessibilità così come dei costi di investimento relativamente contenuti. A causa delle sue peculiarità, l’attività di *picking* di magazzino viene spesso indicata come l’attività che richiede maggiori sforzi in termini di costo e tempo, costituendo da sola il 50% di tutti i costi operativi di un magazzino. Inoltre, questo aspetto diventa ancora più critico se si considerano le ultime tendenze che caratterizzano l’attuale contesto logistico, nel quale i clienti richiedono che la merce venga consegnata rapidamente, in piccole quantità e con un elevato livello di servizio. Questa necessità di soddisfare gli ordini cliente in una finestra temporale molto ristretta si traduce in una conseguente necessità per i professionisti e i manager logistici di un miglioramento delle prestazioni delle attività di *picking*.

All’interno di questo contesto, la presente trattazione si pone come obiettivo quello di proporre un insieme di metodi e procedure innovativi utili alla progettazione di sistemi di *picking* manuale operatore-verso-materiale. In particolare, questa si basa sull’assunzione principale secondo la quale il miglioramento delle prestazioni di *picking* può essere raggiunto riducendo il tempo necessario all’evasione degli ordini di prelievo. Partendo dalla ricerca proposta da Tompkins et al. (2010), in cui vengono riportate quali sono le maggiori componenti di tempo che caratterizzano una missione di *picking*, questa tesi propone alcune azioni e, successivamente,

alcuni metodi che portano alla riduzione del tempo di percorrenza, del tempo di ricerca del prodotto da prelevare, del tempo di prelievo fisico del prodotto e, infine, del tempo complessivo.

La tesi si compone di 4 parti principali:

(1) Analisi dell'attuale contesto logistico al fine di definire le condizioni di funzionamento dei sistemi di *picking* di magazzino
(2) Proposta di azioni per la riduzione dei tempi di percorrenza degli operatori, giungendo allo sviluppo di procedure integrate per la riduzione delle distanze percorse dagli operatori
(3) Proposta di azioni per la riduzione del tempo di ricerca del codice da prelevare e del tempo di prelievo, definendo la necessità di adozione di sistemi di *paperless picking*
(4) Proposta di azioni per la riduzione del tempo globale, attraverso lo studio dell'impatto ergonomico delle attività di *picking*

Parte di tale ricerca è stata svolta presso il Dipartimento di Diritto ed Economia del TUD - Technische Universität Darmstadt, a Darmstadt, Germania, in collaborazione con il prof. Christoph Glock e il Dr. Eric Grosse.

Il lavoro di ricerca presentato in questa tesi ha portato anche alla formalizzazione di diversi contributi scientifici, sia in conferenze internazionali che in riviste scientifiche, sempre a carattere internazionale.

ABSTRACT

The warehouse picking area is the zone within a warehouse in which the shipping units for the customers are created, through the pick of the required products from the various stocking locations. When there is the presence of human operators, walking or travelling within the warehouse aisles to retrieve the items needed by the customers and reported on their picking lists, the picking system is called manual picker-to-parts picking system. Although several automated solutions have been developed so far, these kind of systems are still the most widespread ones, since the presence of human pickers warrants great flexibility as well as relatively low investment costs. Due to its peculiarities, warehouse picking is often referred to as the most cost- and time-consuming activity in a warehouse, accounting for about 50% of all operating costs. Furthermore, this aspect becomes even more critical considering the recent trends that characterise the current logistics context, in which the goods are expected to be delivered always in a faster way, in small quantities and with a high service level. This need of fulfilling the customer orders in a very small time window translates into a consequent deep necessity for practitioners and warehouse managers of improving the performances of the picking activities.

In such a background, the present dissertation aims at proposing a set of innovative methods and procedures useful for warehouse manual picker-to-parts picking systems design. In particular, it is based on the main assumption that the improvement of the picking performances can be achieved by reducing the time needed to process the picking orders. Following the research by Tompkins et al. (2010), reporting which time components are the most impacting ones during a picking tour, this thesis proposes some actions and, subsequently, some methods leading to travel time reduction, product search time reduction, item physical pick time reduction and, finally, overall time reduction.

The thesis is structured into 4 main parts:

(1) Analysis of the current logistics context to define the operating conditions of the warehouse picking systems
(2) Proposal of actions for travel time reduction, arriving to the development of integrated procedures for the reduction of the distances travelled by the operators
(3) Proposal of actions for search and pick time reduction, defining the need of paperless picking adoption
(4) Proposal of actions for overall time reduction, through the study of the ergonomic impact of the picking activities

Part of the research has been carried out as a visiting Ph.D. Student at the Department of Law and Economics of the TUD - Technische Universität Darmstadt in Darmstadt, Germany, in collaboration with prof. Christoph Glock and Dr. Eric Grosse.

The research work presented in this thesis has also led to several scientific contributions, both in international conferences and international journals.

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It seems like it was yesterday when I decided to leave the company where I used to work to start my new adventure as a Ph.D. student. Indeed, more than three years have already gone, and now I am here, writing my final Ph.D. thesis. I am so proud of my choice that I would like to share it with all the people who are not satisfied of their job, who complain with it, but that do not have the courage to change. Well, thanks to what happened to me, I have understood that if you are really sure of your decisions, you do not have to be scared of their consequences.

My Ph.D. experience has definitely turned out to be a great occasion to learn, to research and to put in practice something that I used to study only in theory. But, above all, it has been a big chance to meet interesting and inspiring people, to challenge myself and, finally, to grow.

Here, I want to use this page to remember and thank some of the people that contributed to this final goal. First of all, I would like to thank my supervisor prof. Alessandro Persona, an excellent teacher as well as a special person from the human point of view. He has been a fundamental milestone of my path, a guide for my research and a reference for my personal enrichment.

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I also thank prof. Christoph Glock and Dr. Eric Grosse, for having hosted me for one month in the Department of Law and Economics of the Technische Universität in Darmstadt, Germany; they have been so kind and hospitable. My staying in Germany has been a great opportunity to understand my strengths but also my weaknesses, both from an academic and a personal point of view.

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To my mum,
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1

INTRODUCTION

"Nowadays, warehouses have to face different requirements from different sales channels, from different production philosophies, different managerial perspectives, and the choice between old and new technologies. […] Picking is the most cost-driving activity in warehouses and needs to be explored. It is important to optimize this process to be smooth and cost-efficient."

Davarzani and Normann, 2015



1.1 Warehouse picking design

Warehouses are important elements of supply chains, having a large impact on performance figures such as product availability, delivery speed and customer satisfaction. Even though warehousing processes can be automated in general, most warehouses still heavily rely on manual material handling activities. This is due to the fact that the employment of human workers, instead of machines and automated systems, ensures a high level of flexibility with low investment costs. One of the most important manual activities in warehouses is order picking, which is responsible for retrieving items from storage locations to fulfill the customers' orders. Due to the low degrees of automation, order picking ranks among the most costly activities in warehouses, accounting for about 50% of all operating costs (Tompkins et al., 2010).

1.1.1 General overview

Warehouse areas

A warehouse is a fundamental logistic element which is present in almost all industries. In fact, although it often requires large investment and operating costs (it has been observed that a warehouse generally contributes to about 20% of the total logistics costs of a company; Pfohl and Mayer, 2004), it also warrants several benefits, which are crucial to pursue the main targets of a company. Among all its possible functions, Lambert et al. (1998) and De Koster et al. (2007) specify that a warehouse is mainly useful for:

- Achieving transportation economies (e.g. combine shipment, full-container load)
- Achieving production economies (e.g. make-to-stock production policy)
- Taking advantage of quality purchase discounts and forward buys
- Supporting the firm's customer service policies
- Meeting changing market conditions and uncertainties (e.g. seasonality, demand fluctuations, competition)
- Overcoming the time and space differences that exist between producers and customers
- Accomplishing least total cost logistics commensurate with a desired level of customer service
- Supporting the just-in-time programs of suppliers and customers

- Providing customers with a mix of products instead of a single product on each order (i.e. consolidation)
- Providing temporary storage of material to be disposed or recycled (i.e. reverse logistics)
- Providing a buffer location for trans-shipments (i.e. direct delivery, cross-docking).

Figure 1.1 reports a possible scheme of a general warehouse, in which the main functional areas and activities are highlighted.

Considering the normal flow of the goods within a warehouse, the first performed activity is the receiving of the products, which can come from suppliers but also from customers (because of wrong orders, non-compliant items etc.). in this first phase there is the unloading of the products from the transport carrier, their quality and quantity inspection and the updating of the inventory database.

From here, the goods can be transferred to three main directions. A first possibility is the moving of the products to the reserve storage area, in which the goods are stored and, eventually, picked in bulky units (usually full pallets). Alternatively, the full stock units of the products can be transferred directly to the forward area, for the performing of case picking. A last possibility is represented by the cross-docking, when the units are moved directly to the shipping area, without long stays and order picking activities.

In case the products have been moved to the reserve area, they can then be sent directly to the shipping area (in case of full pallets shipment) or, more commonly, to the case picking area, also called carton-pick-from-pallet area (Bartholdi and Hackman, 2011). Here it takes place the picking activity, that is, obtaining the right amount of the various products required for a certain set of customer orders. This retrieving activity is here performed directly from full pallets or from other kinds of big storage units. Furthermore, the picked cases can serve as a replenishment of the broken case picking area, also called piece-pick-from-carton area (Bartholdi and Hackman, 2011). In this last case, the cases are the units stored on the racks and the picking activity concerns the single items that are contained within.

Subsequently, the products picked both in the case picking area and in the broken case picking area are moved to the accumulation, sortation and packing area. Here, there could be the accumulation and the sortation of the picked orders, in order to divide by customer the products that were previously picked in batches. Once the customer unit is obtained, containing a set of different products required by a certain customer, this can finally be packed and then moved to the shipping area.

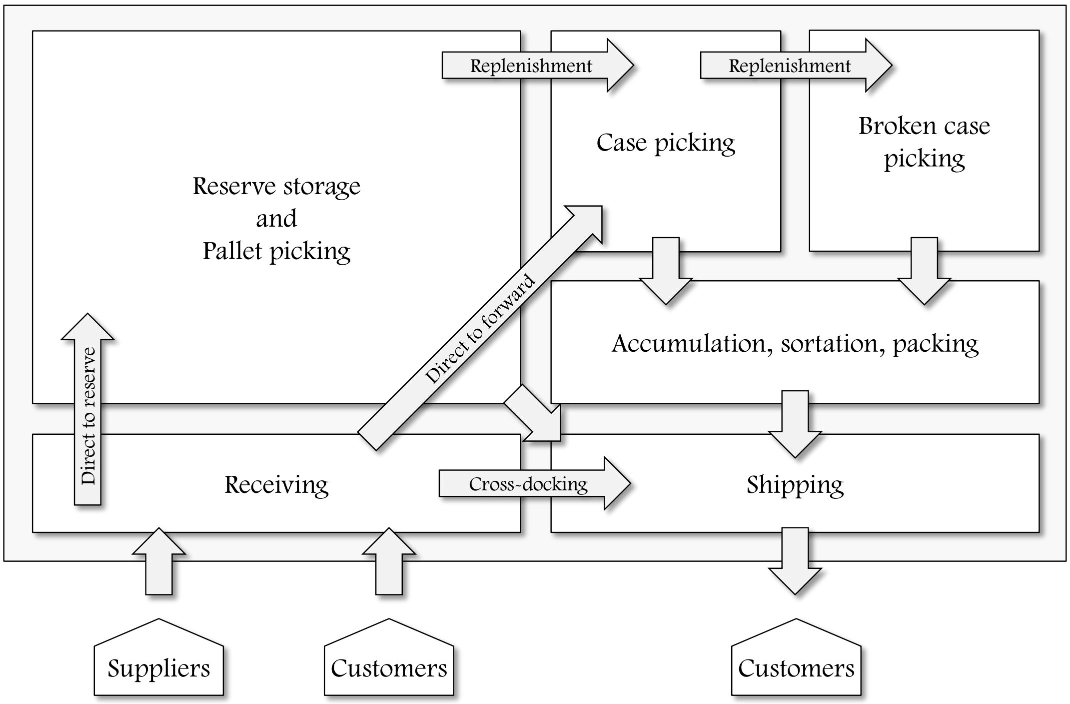

Figure 1.1. Warehouse functions and flows. (Adapted from Tompkins et al., 2010)

Order picking systems

Within a warehouse, order picking is the process of clustering and scheduling the customer orders, and of consequently picking the articles from the various storage locations to fulfil such customer orders. Customer orders usually consist of several order lines; all the order lines are then grouped in various picking lists, in which each line refers to a certain product code, that has to be picked in a certain quantity. An order picking system can be of different types, each type having peculiar characteristics which make it more or less suitable for the different fields of application. Figure 1.2 reports a proposal of classification for the picking systems: a first distinction can be done between the systems that employ humans and the ones that do not.

The systems that employ humans are the most widespread; as far as these systems are concerned, a further difference stands in their possible configuration. There are *picker-to-parts* systems, *parts-to-picker* systems and *put systems*. In picker-to-parts systems the human order picker walks or drives along the aisles to pick the items. Moreover, these can be *low level*, where the picker picks only the items that are located on the ground floor (in case of big storage units) or on a bin-shelving which the picker can easily reach while standing (in case of bins storage units) or *high level*, in which the picker moves on board of a lifting order-pick truck or crane in order to reach all the picking levels. On the other side, in parts-to-picker solutions the picker stands in a fixed position, while an automated system retrieves the storage units and brings them to the picking station, so that the picker can take the needed items. Once the picker has finished a pick, the automated system brings the storage unit back to its stock location. Existing parts-to-picker solutions are the automated storage and retrieval systems (AS/RS), where the products are stored in pallets, and the miniloads systems, which use smaller bins as storage units. Other interesting solutions, often used for small dimensions products, are the Vertical Lift Modules, the horizontal carousels and the vertical carousels (Choe and Sharp, 1991; Battini et al., 2015). Both in case of a picker-to-parts and a parts-to-picker retrieving, in some cases the picked items could be further handled in a put system. In this system, the already picked items are divided by a picker in different load units, for the different customers.

In case there is no human pickers, the picking system is *fully automated*. However, due to their high investment and operative costs, automated and robotized picking systems are rarely employed; they usually find some applications in special contexts, for example when the products are of high value, of small dimensions and that have to be handled with care.

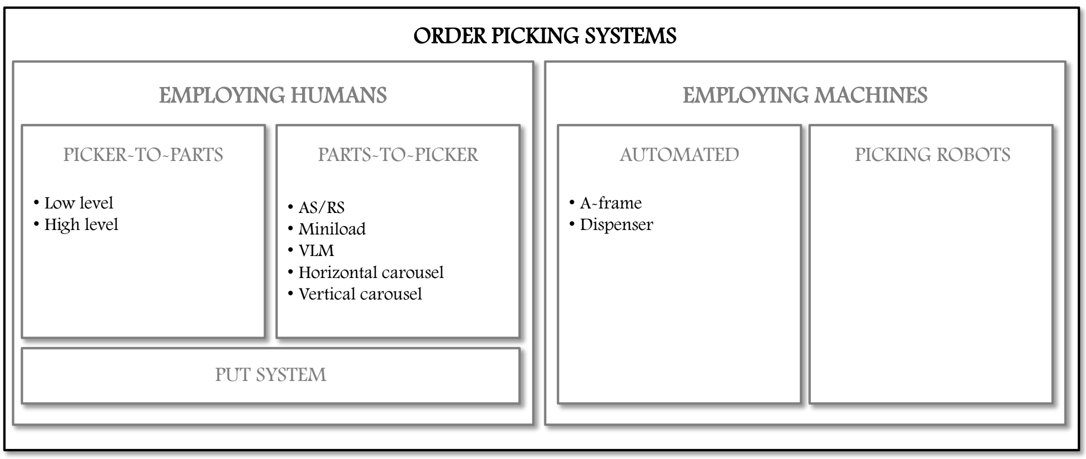

Figure 1.2. Picking systems classification. (Based on De Koster et al., 2007 and Choe and Sharp, 1991)

1.1.2 Manual picker-to-parts picking system design

The present Ph.D. thesis focuses on *manual*, *low level*, *picker-to-parts* picking systems. Such systems have been confirmed to be the most widely employed in warehouses worldwide, since they warrant high flexibility with relatively low investment costs, especially if compared to automated solutions (De Koster et al., 2007; Davarzani and Norrman, 2015).

The design of a manual picker-to-parts picking system represent an interesting challenge that has been pointed out by several contributions in literature. In particular, it requires to take into account several different external and internal factors, that are often interrelated, and that could also lead to important trade-off choices. Some external factors are: marketing channels, customer demand pattern, supplier replenishment pattern and inventory levels, overall demand of a product, state of the economy. Internal factors, instead, include the system characteristics (i.e. mechanization level, information availability, warehouse dimensionality), that are determined at the early design stage, at a strategic level, as well as the organization and the operational policies of the picking system, which typically concern more tactical and operative decisions, such as the ones dealing with layout configurations, routing policies, storage allocation and storage assignment strategies, batching, zoning and order release modes (Goetschalckx and Ashayeri, 1989).

In the following, the dissertation continues with the description of the main decisions (and of the corresponding possible alternatives) that have to be faced for the design of a warehouse manual picker-to-parts picking system.

Layout design

The layout design basically consists of two consecutive sub-problems: the *facility layout problem* and the *internal layout* (or *aisle configuration*) *problem*. The facility problem deals with the decision on where to position the various warehouse areas (shown in Figure 1.1), taking into account the mutual relationships that exist among them. Once the location of the picking area has been defined, the design can focus on its inner components, hence, with decisions on the number of storage blocks, which is also related to the decision on the presence of cross aisles, on the position of the depot, and, then, on the number, length and width of the aisles of each block.

Forward and reserve allocation

As already introduced in Paragraph 1.1.1, in a warehouse the bulk storage area is usually separated from the picking area (Figure 1.1). This distinction between the reserve area and the forward area is mainly due to the need of improving storage and picking efficiency. In fact, the forward area is a sub-region of the warehouse dedicated to the pick and order activities, in which there are only the stock keeping units (SKUs) that are reserved for the picking activity. Since the forward area is often concentrated in a small physical space, its presence warrants more processing efficiency, with a consequent reduction of the time needed to perform the picking tours. In fact, the picker, on average, travels shorter distances and needs less time to find the right stock location. On the other side, the reserve area is for full pallets storage, which are also used for the replenishment of the units in the forward area (De Koster et al., 2007; Bartholdi and Hackman, 2011).

Most of the existing contributions concerning the so called *forward-reserve problem* (Frazelle et al., 1994; Van Den Berg et al., 1998; Bartholdi and Hackman, 2008) underline that during the design of such zones a fundamental trade-off has to be considered. This deals with the fact that by enlarging the forward area through the introduction of more products and, therefore, of more stock keeping units, there is a saving due to a faster picking and to a reduction of the number of restocks; however, such benefits are inevitably accompanied by an increase of the distances travelled to process the picking orders, leading to a reduction (and in some cases also to a nullification) of the first possible saving. Hence, it follows that the design of the forward area has to consider both these conflicting aspects: some authors propose models useful to assess the most suitable dimensions, while others are focused on the choice of which SKUs should be stored within (Kong and Masel, 2008; Bartholdi and Hackman, 2011; Walter et al., 2013).

Storage assignment

A storage assignment method consists in a set of rules that are used to assign the products to the various storage locations. There exist several different ways for products storage assignment, the ones that are found more frequently are: *random storage*, *closest open location storage*, *dedicated storage*, *full-turnover storage* and *class-based storage* (De Koster et al., 2007; Accorsi et al., 2012).

As suggested by its name, in case of random storage the SKUs are stored on the racks without any specific criteria: a pallet can be stored in all the empty locations of the warehouse with the same probability. This leads to a high space utilisation but, at the same time, a possible increase of the distances travelled by the picker to find the required product. Characterized by similar performances of the random storage is the closest open location one, in which the incoming pallets are stored in the empty stock locations that are closer to the depot.

On the contrary, in case of dedicated storage each product is assigned to a fixed stock location. All the stock locations remain always reserved for the same products, even when these are out of stock. This inevitably leads to a low space utilization, but with the advantage of finding the product location in an easier and faster way. Moreover, this assignment strategy can be useful when there are particular needs, that require specific positions for certain products (for example storage in order of weight, or according to the positions of the items in the final stores).

The full-turnover storage strategy proposes to store the products according to their turnover: products with a high turnover are stored on easily accessible locations located near the depot. One of the possible criteria to evaluate the turnover of the items is based on the calculation of their cube-per-order index (COI). This parameter is the ratio between the total required space of an item and the number of trips that are needed to satisfy its demand. This storage policy can warrant, on average, good picking performances; however, it also requires great management and control efforts, due to the changes that usually can occur in the demand of the products, with implications on the stock positions.

The class-based storage is based on the application of the Pareto principle, according to which, for many events, roughly 80% of the effects come from 20% of the causes. In a warehouse context, this is translated into a grouping of the products in classes (for example A, B and C) according to their demand frequency (for example measured with COI, or the pick volume), so that the fastest moving class A contains only about the 20% of the products but that contribute to about the 80% of the turnover. Of course, the percentages can vary, according to the warehouse context, the kind of products stored, and so on. Then, each identified class is assigned to a specific area of the warehouse, so that the A-class products are dedicated to the area that is closer to the I/O point, the B-class products in an intermediate zone and the slow moving C-class products are in the farthest area. Generally, within each area the products are stored randomly.

All the just described storage assignment methods do not consider the presence of any possible relation between products. However, in some cases there could happen that some products are often picked together, with a consequent potential convenience in storing them close to each other. This kind of storage assignment approach is called *correlated assignment* or *family grouping* (Frazelle and Sharp, 1989; De Koster et al., 2007).

Picking strategy

The pick of the products required by the customers can be performed in various ways. The main alternative policies are *pick by order* (or *discrete picking*) and *pick by article* (or *batch picking*); both of them can also be accompanied by *zoning* (Figure 1.3).

In case of pick by order, a single customer order is assigned to a picker, so that each picking tour corresponds to the creation of the single customer picking load unit, which then is immediately ready for shipping. On the contrary, with the pick by article method different customer orders are picked simultaneously by a single picker, with a consequent need of sorting all the picked items, dividing them by customer. The sortation activity can be done during the picking activity or in a second moment. Finally, there is also the possibility of dividing the picking areas into different zones, and applying the so-called zoning strategy. In this case, every identified storage area is assigned to a specific group of pickers, who are dedicated only to the pick of the items that are stored within their area. The picked orders are then passed to another picking zone to continue the creation of the picking load unit in case of a pick-and-pass system (progressive zoning), or to the accumulation area for their proper consolidation in case of a synchronised (parallel) approach.

Figure 1.3. Picking strategies: products assigned to a single picker.

Routing policy

Another important factor impacting on the design of a warehouse picking system is the routing policy. A routing policy has the important aim of sequencing the pick of the items reported on the picking lists in order to warrant the best possible routes within the warehouse aisles. There exist different routing policies; the most widespread are: *traversal*, *return*, *mid-point* and *largest gap* (Figure 1.4).

According to the traversal policy, once the pickers have entered an aisle containing at least one product to pick, they always have to travel it completely. Different is the case of the return policy: all the aisles are always entered and left from the same side; therefore, the pickers can change their direction of travel inside an aisle. The mid-point strategy divides the warehouse in two parts, the front area and the back area. The stock locations that have to be visited and that are in the front area are accessed from the front cross aisle, while the stock locations that are in the back area are visited from the back cross aisle. The first and the last aisles, instead, are traversed entirely. Similar to the mid-point policy is the largest gap one: in this case the criterion for choosing the cross aisle to use to reach the stock locations to visit is based on the determination of the 'largest gap'. In an aisle, this gap can be between two adjacent products to pick, between the first product to pick and the front cross aisle or between the last product and the back cross aisle.

Further to these basic strategies, sometimes in practice it is used a combination of different routing policies. Moreover, the efficiency and effectiveness of a route can be influenced by some external factors, that could lead to a forced choice of the routing policy. For example, there could be some restrictions due to the layout of the warehouse (configuration of blocks and aisles, width of the aisles etc.), to the means of transport used by the pickers (need of a certain operating space to perform the change of direction) or to the adopted storage assignment (problems of congestion if the items with a high turnover are stored all in the same aisles).

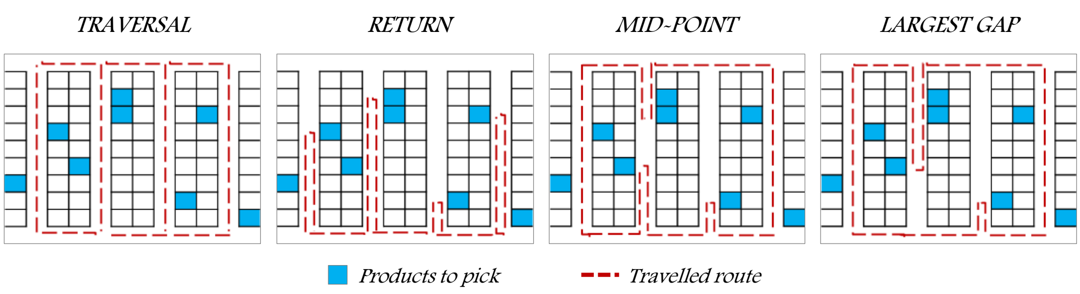

Figure 1.4. Routing policies.

1.1.3 Recent trends and impact on picking system design

Nowadays, the general logistic context of operation of a warehouse is characterized by the critical need of satisfying several different requirements. In fact, a warehouse faces the coexistence of various needs coming from different sales channels, from different production philosophies and from several managerial perspective which sometimes can also be in contrast to each other. In fact, always more often the goods are expected to be received in a faster way, in small quantities and with a high service level. In manufacturing, there is a move to smaller lot-sizes, point-of-use delivery, order and product customisation, and cycle time reductions. In distribution logistics, in order to serve customers, companies tend to accept late orders while providing rapid and timely delivery within tight time windows (thus the time available for order picking becomes shorter). Moreover, e-commerce is rapidly gaining importance for many companies, which are then facing the processing of customer orders that are different from the traditional ones, requiring the pick of very few cartons for few products codes (De Koster et al., 2007; Thomas and Meller, 2015; Davarzani and Norrman, 2015). Further to these critical aspects, there is the recent trend that sees many smaller warehouses being replaced by fewer large warehouses in order to realize economies of scale, with a consequent larger daily pick volume that has anyway to be processed in a short time window. Finally, the current technological development allows the availability of interesting advanced solutions, that, if from one side they represent a possible competitive advantage, from the other side they imply higher investment and management costs, as well as the presence in the company of specific competences.

In such a context, warehouse picking turns out to be one of the most critical issues in a warehouse, with a consequent felt and widespread need of improving its performances. In fact, it has already been widely demonstrated that warehouse picking is the most labour and cost intensive operation in manual warehouses, constituting about the 50% of the overall warehousing costs (De Koster et al., 2007; Tompkins et al., 2010; Gu et al., 2010). Moreover, warehouse picking represents a really time consuming activity, which heavily contributes to the overall time needed for the processing of a customer order. Therefore, in order to improve the performances of a warehouse, in terms of orders processing throughput, it is recommended to act on picking performances enhancement.

As already suggested by some recent researches (De Koster et al., 2007; Tompkins et al., 2010, Grosse et al., 2015), a possible improvement of the throughput of a picking system is obtainable through the reduction of the orders processing time. Figure 1.5 shows the typical time components of a general picking activity (Tompkins et al., 2010). In particular, it can be seen that half of the time needed to process a picking order (and, then, of performing a picking tour) is for the travel activity, that is the time the picker spends to walk or drive from a certain stock location to another one. The 20% of the total time, instead, is for the search activity: the picker looks for the right stock location from which he has to pick the items that are reported in his picking list. The actual physical pick of the items contributes to the 15% of the overall time, and another 15% is for other minor activities, like picking tour set up, paper picking list printing, pick confirmation, or any other action related to the use of specific devices. Then, considering this composition of the picking time, it derives that the most effective actions that can aim at reducing the picking time should primarily focus on the development of strategies concerning travelling, searching and picking time reduction.

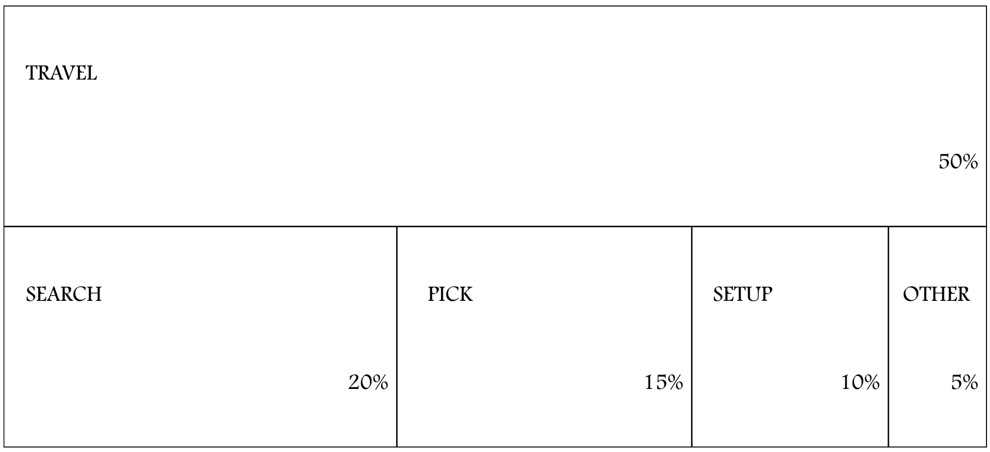

Figure 1.5. Picking time components. (Based on Tompkins et al., 2010)

Although in literature there are several researches facing the topic of warehouse picking time reduction, very few propose practical approaches to solve this issue (Thomas and Meller, 2015). Moreover, many contributions are mainly focused only on travel time reduction, due to the fact that this is the most impacting time component (De Koster and Van der Poort, 1998; Chew and Tang, 1999; Caron et al., 2000; Hwang et al., 2004; Manzini et al., 2007). However, a proper design of a warehouse picking system should consider also other aspects and other targets, also taking into account the expressions of interest that come directly from the industry. For example, a recent survey conducted by Davarzani and Norrman (2015) confirms the primary necessity for managers and practitioners of having available some innovative management instruments capable to drive their strategic and operative decisions, which cannot be anymore related only to a simple costs minimization. Moreover, during their interviews they often complaint about the presence of a dangerous distance between what the academic literature proposes with respect to the industry real needs, also considering the effective application possibility of some mathematical models that sometimes seem to be too far from the actual warehouse contingencies. The recent work by Thomas and Meller (2015) reports the same lack in literature of adequate instruments first for the design and, then, for the management of warehouse picking systems. Hence, it follows that it would be interesting the proposal of new methods aiming at facing this research and practice gap, for example through the development of an integrated procedure useful to support warehouse managers and practitioners during their work, able to consider simultaneously different factors and scopes. In particular, the design of a picking system should aim to different aspects, such as the minimization of the throughput time of an order and, then, of the overall throughput time. Moreover, it should tend to the maximization of the use of the warehouse space, of the use of the equipment and of the manpower, as well as to the maximization of the accessibility to all the stored items.

In the next paragraph the general framework of the Ph.D. thesis is introduced, reporting the structure of the approaches and of the design methods that have been developed during the three years of Ph.D.

1.2

Research framework

The present Ph.D. thesis comes from the acknowledged need of developing integrated methods and procedures for the design of warehouse manual picker-to-parts picking systems. The basic idea is to propose simple mathematical models and analyses that have to warrant an easy and fast application, above all by practitioners, directly in industrial contexts. The research framework introduced in this paragraph describes the approach that has been employed to reach such an important goal, which has started from the observation of the picking time main components and that has then continued with the derivation of some actions useful to improve picking performances, in terms of customer orders processing. These actions can be classified into 3 main macro-topics: travel time reduction, search and pick time reduction, overall time reduction, corresponding to the three main chapters of the thesis.

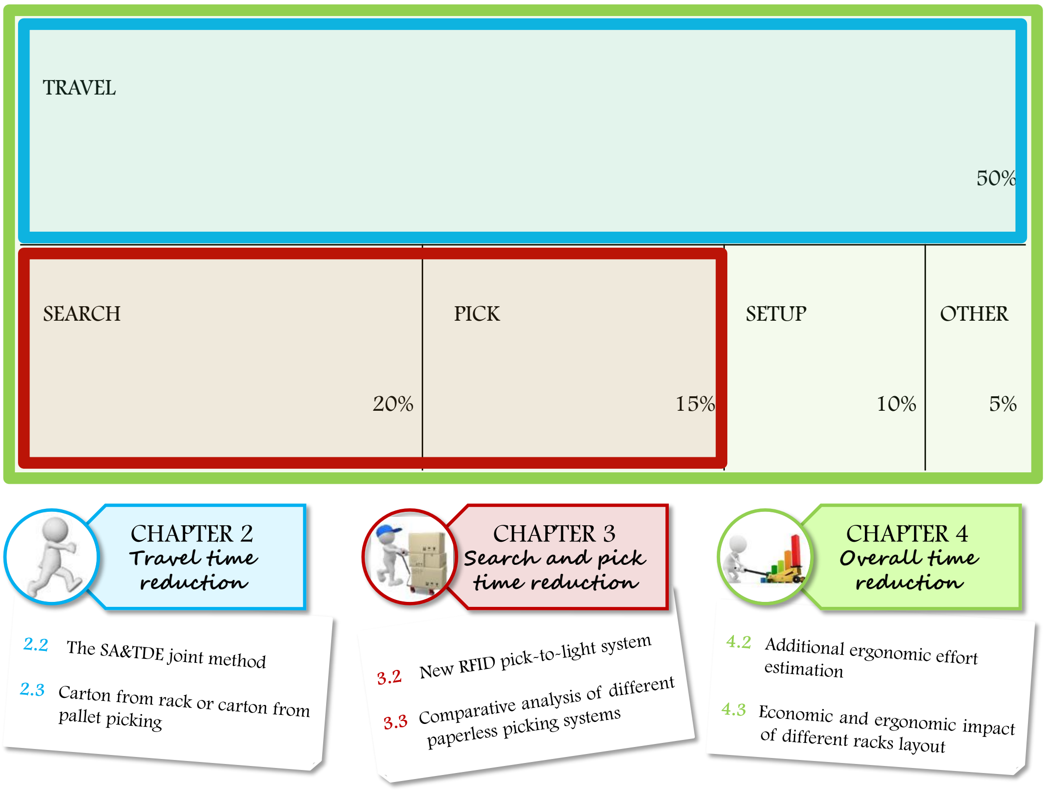

Figure 1.6. Research framework and thesis structure

1.2.1 Structure of the thesis

The present thesis introduces a research framework concerning warehouse manual picker-to-parts picking systems design, consisting of different possible approaches. The starting point has been the simultaneous consideration both of the current logistics context and of the needs shown by the practitioners (as also described in Paragraph 1.1.3), with a consequent focus on proposing a set of design procedures able to decrease the time needed to process a picking order.

In particular, the study of the reduction of the picking time starts from the classification by Tompkins et al. (2010), already shown in Figure 1.5, and leads to the proposal of some useful actions that can promote a faster picking. The resulting framework, together with the consequent structure of the present thesis, are reported in Figure 1.6.

First of all, the present research proposes to act on the reduction of the major time component, hence, of the travel time. In manual picker-to-parts systems, the travel time can decrease by reducing the distances travelled by the warehouse operators (De Koster et al., 2007). Therefore, it is recommended to develop methods that aim at this scope. Chapter 2 faces the issue of travel time and travel distance reduction. There are reported two contributions. The first one proposes a design procedure which is based on a storage assignment strategy that warrants the storing of the most frequently picked products as near as possible to the I/O point and, in case some products are often picked together, also one as close as possible to the others. The second one, instead, addresses the forward-reserve problem in an original way, proposing a method that allows the evaluation of different storing layouts, comparing the storage of small products on racks and on pallets, with a further benefit of reducing the occupied space.

The second action proposed by the present framework concerns the reduction of the search time and of the time needed to perform the physical pick of the items. Some researches (Iben et al., 2009; Guo et al., 2014; Grosse et al., 2015) have proved that to obtain some benefits in this sense it can be useful to consider the adoption of paperless picking systems. In fact, the recent technology evolution is making available some very attractive solutions that could find some smart applications also in an industrial context, with interesting potential benefits. For example, the search time could be decreased through the employment of *poka-yoke* solutions, like the pick-to-light ones; then, the pick time could be improved by avoiding some useless actions and reducing the picking errors. Chapter 3 addresses the problem of search and pick time reduction. In the first paragraph, the description and characterization of a new paperless picking system, called "RFID pick-to-light system", is reported. Subsequently, Paragraph 3.3 introduces a procedure to evaluate and compare different paperless picking solutions, taking into account their main characteristics, their different error probabilities as well as their economic convenience.

Finally, a further action to reduce the picking time can derive from actions that have an impact from a general perspective, with an overall time reduction. In particular, since the most widespread warehouse picking systems are manual, hence, involving human operators, it can be interesting the study of the so called *human factor*, in order to gain a general time reduction and, as a consequence, an overall long-term system improvement (Grosse et al., 2015). Chapter 4 reports two studies concerning the human factor in warehouse manual picking systems. First of all, a method to evaluate and quantify the additional ergonomic effort of the various picking activities is reported. Then, it is presented an in-depth analysis regarding the comparison of different storage layouts, both from an economic and an ergonomic point of view.

Research questions

Based on the context overview characterisation introduced in this chapter, the study that has led to the present dissertation, and the dissertation itself, aims at answering the following six research questions:

RQ.1 - *How is the current logistics context of warehouse order picking?*

RQ.2 - *How can manual picker-to-parts picking systems be improved?*

RQ.3 - *Which aspects should be taken into account during the design of a picking system?*

RQ.4 - *How can travel time reduction be achieved?*

RQ.5 - *How can search and pick time reduction be achieved?*

RQ.6 - *How can the human factor in picking activities be considered?*

RQ.1, RQ.2 and RQ.3 have already been faced in this chapter. RQ.4 is discussed in Chapter 2, while RQ.5 and RQ.6 are the base of Chapter 3 and Chapter 4, respectively.

1.2.2 Strengths and limitations of the research

The present Ph.D. thesis aims at constituting a research contribution to warehouse manual picker-to-parts picking systems design. As also acknowledged in literature (De Koster et al., 2007; Bartholdi and Hackman, 2011; Thomas and Meller, 2015), the design of a warehouse picking system represents a complex activity, in which several interrelated as well as contrasting factors can come into play. Therefore, it is fundamental the development of instruments that can facilitate both its design and its management. Moreover, in their recent survey, Davarzani and Norrman (2015) pointed out the need for practitioners of having available methods and procedures useful for this scope.

Therefore, the main purpose of the thesis is the proposal of methodologies that have to foster a better evaluation of the typical context of a picking warehouse, its criticalities, and the possible actions for its improvement. The strengths of this dissertation can be summarized into three main aspects. First of all, the research has been supported also by a field work, that has allowed me to visit existing picking warehouses and to observe directly their practical operation as well as their weaknesses. Subsequently, this thesis proposes approaches that are easily applicable in practice, and with an acceptable computational effort. Finally, all the reported research works have always been validated with numerical examples and real industrial case studies, that further confirm the concrete approach of the whole research.

However, this thesis presents also some important limitations. First of all, due to the complexity of the problem and to the time that was available to study it, the research had to focus only on manual picker-to-parts low level picking systems, and only on some specific aspects for warehouse picking system performance improvement. In fact, I decided to propose a research framework in which picking performances are improved by reducing the picking orders processing time, although, of course, this is not the only possible approach. Moreover, it would be interesting a further study of the proposed methods, in order to get some other results that can support their validity and help their extension to other warehouse picking contexts.

1.3 List of publications

The research activity of my Ph.D. has lead to the writing of some papers concerning different aspects of warehouse picking and the proposal of new approaches to warehouse picking system design. All of them have contributed, some ones more deeply and some others just marginally, to the composition of this thesis. They are both international conference papers and journal papers.

1.3.1 Papers for Chapter 2

Battini, D., Calzavara, M., Persona, A., and Sgarbossa, F. (2014). A model for warehouse picking forward area allocation and dimensioning. *Proceedings of the XIX Summer School "Francesco Turco"*, 9-12 September, Senigallia (AN), Italy.

Battini, D., Calzavara, M., Persona, A. and Sgarbossa, F. (2015). Order picking system design: the storage assignment and travel distance estimation (SA&TDE) joint method. *International Journal of Production Research*, *53*(4), 1077-1093.

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Battini, D., Calzavara, M., Persona, A., and Sgarbossa, F. Carton from rack picking or carton from pallet picking: a selection procedure. Under review to the *European Journal of Operational Research*.

1.3.2 Papers for Chapter 3

Andriolo, A., Battini, D., Calzavara, M., Gamberi, M., Peretti, U., Persona, A., Pilati, F., and Sgarbossa, F. (2013). New pick-to-light system configuration: a feasibility study. *Proceedings of the XVIII Summer School "Francesco Turco"*, 11-13 September, Senigallia (AN), Italy.

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Battini, D., Calzavara, M., Persona, A., and Sgarbossa, F. Dual-tray vertical lift modules for fast order picking. Submitted to the *International Material Handling Research Colloquium (IMHRC)*, 12-16 June 2016, Karlsruhe, Germany.

1.3.3 Papers for Chapter 4

Battini, D., Calzavara, M., Persona, A., and Sgarbossa, F. (2015). Linking human availability and ergonomics parameters in order-picking systems. *IFAC-PapersOnLine*, *48*(3), 345-350.

Calzavara, M., Glock, C., Grosse, E., Persona, A., and Sgarbossa, F. (2015). The impact of alternative rack layouts on economic and ergonomic performance measures in order picking. *20th ISL International Symposium on Logistics*, 5-8 July, Bologna, Italy.

Calzavara M., Glock C. H., Grosse E., Persona A., Sgarbossa F. Models for ergonomics evaluation of picking from different rack layouts. Submitted to the *8th IFAC Conference on Manufacturing, Modelling, Management and Control*, 28-30 June 2016, Troyes, France.

Battini, D., Calzavara, M., Persona, A. and Sgarbossa, F. Additional effort estimation due to ergonomics conditions in order picking systems. Under review to the *International Journal of Production Research*.

Calzavara M., Glock C. H., Grosse E., Persona A., Sgarbossa F. Analysis of economic and ergonomic performance measures of different rack layouts in an order picking warehouse. Submitted to the *Computers & Industrial Engineering International Journal*.

1.4 Chapter references

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2

TRAVEL TIME REDUCTION

"For manual-pick order-picking systems, the travel time is an increasing function of the travel distance."

De Koster et al., 2007

2.1
Highlights and Problem outline

A traditional approach to the design of a picking system seeks to determine the right warehouse overall configuration to ensure the best performances in terms of travelled distances and, therefore, processing time. However, full procedures on such process are still not readily available at the moment (De Koster et al., 2007).

In this chapter, two possible design methodologies are proposed. In Paragraph 2.2 the *Storage Assignment and Travel Distance Estimation (SA&TDE) joint method* is presented, a decision-making process that can guide through the design of a picking warehouse considering at the same time both problems, storage allocation and travelled distances, allowing the simultaneous examination of the causes and effects of several factors on different possible solutions. Then, Paragraph 2.3 reports the *Carton from rack or carton from pallet picking selection procedure*, a method that can be useful to understand whether a certain product, according to its characteristics, is more suitable to be stored and picked in pallets or racks.

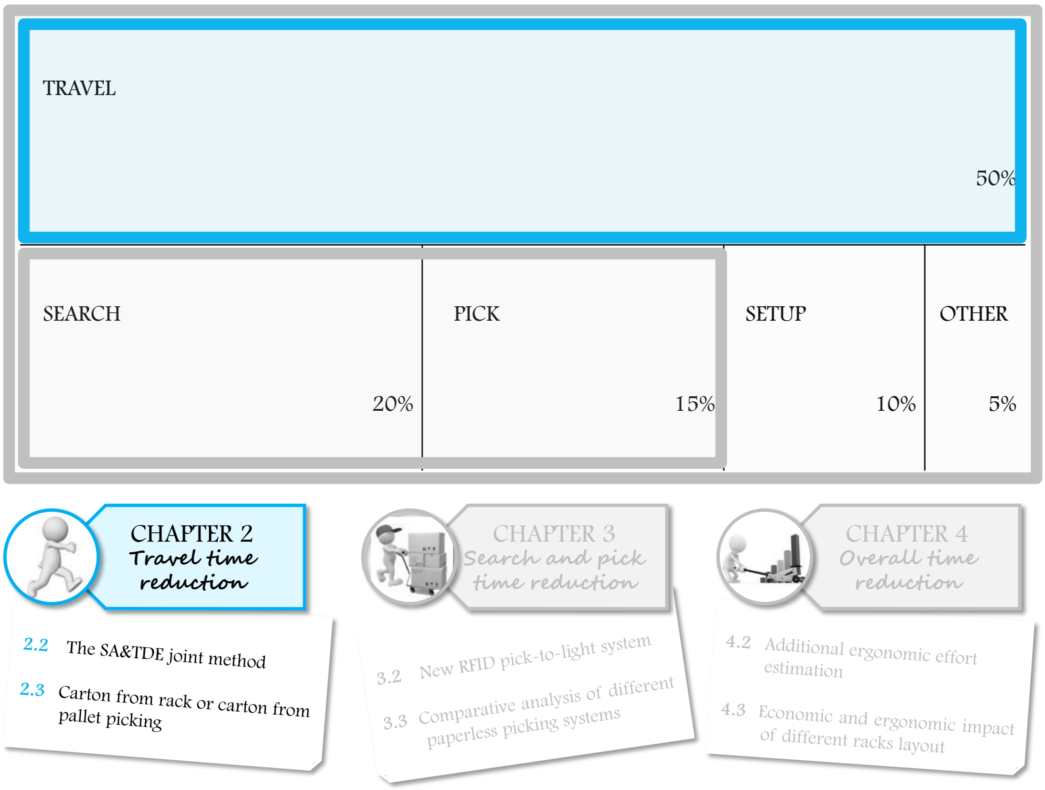


Figure 2.1. Research framework: Travel time.

2.1.1 Actions for travel time reduction

Warehouse picking represents a crucial aspect in warehouse management, and it has been faced by many authors, who considered different approaches and solutions to improve warehouse picking systems design (Jarvis and McDowell 1991; Caron et al., 2000a; Caron et al., 2000b; Manzini et al. 2007). Of all the topics relative to this issue, the one that is addressed most often concerns picking performances improvement, that can be achieved focusing on picking costs and time reduction, by optimizing warehouse layout and decreasing the distances travelled by the pickers to go from one stock location to another (Goetschalckx and Ratliff 1988; Tompkins et al., 2010; Gu et al., 2010; Staudt et al. 2015).

Most of the existing methods that aim to solve the question of distance and time estimation for manual picking systems present some important limitations as far as their application is concerned. The most crucial one is the deep dependence on the warehouse structure, in terms of layout (number and configuration of the aisles, position of the I/O point), storage allocation, and routing policy. The models offered are either suitable only for particular cases, or they propose an approach so general, that requires an overall average estimation of the distances, without focusing on the particular assignment of the various product codes to the different storage locations (De Koster et al., 2007; Bartholdi and Hackman 2011). Many of the models proposed so far could turn out to be too complicated to be applied, and do not present relevant evidence of layout optimization at the warehouse areas level. Finally, many authors highlight the lack of simple methods able to simultaneously address and solve different correlated problems concerning manual picker-to-parts picking systems, like travel distance estimation and storage assignment (Rouwenhorst et al. 2000; De Koster et al., 2007; Gu et al., 2010).

Linked to the question of performance increase and distance reduction is the problem of the dimensioning and allocation of the forward and reserve areas. The picking forward area is generally a sub-region of the warehouse dedicated to the pick and the order activities; such activities are often concentrated in a small physical space, in order to warrant more processing efficiency. On the other hand, the reserve area is the part of the warehouse designed for storage of bulk pallets, which are also used for the replenishment of the forward area (Rouwenhorst et al., 2000; De Koster et al., 2007; Bartholdi and Hackman, 2011). An interesting question concerning the forward and reserve problem, that until now has received very little attention, concerns the decision on how to store a certain item in the forward area (Kong and Masel, 2008). This problem is typically not often addressed, either in the literature or in industrial contexts, since in many cases the products stocking mode is defined *a priori*, referring only to people's experience or common sense and considering only a limited number of the aspects that can, in fact, come into play. For example, a warehouse manager could decide to store all the products in a pallet in order to warrant easier warehouse management and maintenance; alternatively, he could establish that small dimension items have to be stored in cartons and picked directly from racks, without considering how frequently they are ordered. However, an in-depth study in this field, leading to an understanding of the possible convenience of storing a certain item in a certain way with respect to another can bring relevant benefits. Among others, establishing that some product codes are more conveniently picked from racks than from a pallet implies a potential reduction of the space needed for storing such items, with a subsequent decrease of the distances travelled to process the picking orders and of the overall picking time (Tompkins et al., 2010).

Considering all these aspects, the present Chapter proposes two design methodologies for travel time and distances reduction. In Paragraph 2.2 the Storage Assignment and Travel Distance Estimation (SA&TDE) joint method is reported. Based on the data from the picking lists within a certain period of time, this model, to quantify the recurrence of the product codes in the orders, both alone and together with other codes, it defines all the product codes combinations and the values of probability to estimate the objective function *L*, which represents the total travelled distance. Such value is then used as a synthetic evaluation factor of the specific warehouse configuration and can be used to compare different warehouse picking strategies. In particular, it can be used to assign certain stocking locations to certain items according to the picking probability of certain codes and combination of codes. If the most recurring product codes, considered alone or in combination with other codes, are assigned to locations close to each other and close to the I/O point, the distance travelled to retrieve those items is lower, which reduces the performance time. The SA&TDE joint method has also the great strength of being easily applicable at different levels of detail. It can be applied to organize the warehouse macro areas, to decide the location of the aisles within a specific macro area or to assign the products to the storage locations, considering also the adopted routing policy. It is a simple and intuitive method, as also shown in the reported case study.

Then, Paragraph 2.3 focuses on describing a new approaching to the forward-reserve problem, through the introduction of a design and selection procedure that can be used to understand the best way of storing goods in a warehouse picking forward area. Starting from simple information referring to the single stored item, including also the characteristics of the carton and pallet employed, together with some typical warehouse times, it allows to establish, for every single product, whether it is more suitable for picking a carton from a rack or from a pallet. Also in this case, the method has been applied to a real industrial study, in which it has interestingly turned out that for several products that were usually stored on pallets it was more suitable a storage on racks, in order to reduce the occupied space and, hence, the distances travelled by the picking operators.

2.1.2 Literature background

The topic of travel time estimation and travel distance estimation for manual picker-to-parts picking systems has been discussed from several points of view in literature, typically relying on statistics and operational research methods. Chew and Tang (1999), Kunder and Gudehus (1975), Caron et al. (1998) propose different models relying on various kind of statistical probability, and including a multinomial probability distribution variable. On the other side, De Koster and Van der Poort (1998), Goetschalckx and Ratliff (1988), Ratliff and Rosenthal (1983) propose to estimate the distances by taking advantage of the graphs theory, which refers to the well-known traveling salesman problem. In other cases, the procedure can be composed of an analytical dissertation, as exposed by Hwang et al. (2004), Hall (1993), Parikh and Meller (2010). Moreover, some contributions aim at deriving decision support models, which can be divided into four main categories:

(1) *Layout design* models determine the configuration of racks, zones and aisles. The majority of works in this area focused on warehouses with rectangular shape consisting of a single or multiple blocks divided by cross aisles (Le-Duc and De Koster 2005; Roodbergen et al. 2008). Some researchers also studied different layouts for order picking warehouses, such as U-shaped order picking zones (Glock and Grosse 2012).

(2) *Forward-reserve problem* methods focus on the allocation and the dimensioning both of the forward picking area and of the reserve bulk area

(Frazelle, et al., 1994; Van den Berg, et al., 1998; Bartholdi and Hackman, 2008; Walter, et al., 2013).

(3) *Storage assignment* methods determine how items should be assigned to storage locations. A common storage assignment method is class-based storage, where items are categorized into a number of different classes, and where fast-moving items are usually assigned to locations close to the depot (Rao and Adil 2013; Chackelson et al. 2013). Another method that can help to reduce travel distances is to assign products that are often ordered together to locations that are close to each other (Glock and Grosse 2012).

(4) *Routing* methods define the way the order picker walks/drives through the warehouse and the sequence in which items are retrieved. The routing problem in one- and two-block warehouses can be solved optimally as a variant of the traveling salesman problem (Roodbergen and De Koster 2001). In practice, however, most warehouse managers use simple heuristics for routing order pickers, as heuristics are much easier to implement (Hwang et al. 2004; Rao and Adil 2013).

(5) *Order batching* methods either consolidate or split-up customer orders if the original orders are either too large or contain too few items. Research on order batching focused on developing optimal solution procedures for some special cases of the batching problem (Bozer and Kile 2008) or presented practical approaches to the problem with effective heuristic solution procedures (Won and Olafsson 2005; Xu et al. 2014). More recently, also meta-heuristic approaches were developed (Matusiak et al. 2014; Grosse et al. 2014). Another opportunity to reduce travel distance closely related to batching is zoning, where the pick area is divided into different zones and workers being responsible only for their own zone (De Koster et al. 2012; Choy et al. 2014).

The decisions deriving from the methods of all of these five categories are strictly interrelated to each other. For example, the problem of estimating the distances travelled by the operators during the processing of the picking orders is deeply interconnected with the storage assignment question (De Koster et al., 2007). In fact, the location of the items has inevitable consequences on the routes performed by the pickers and the times spent in transit, hence should be carefully thought out. Moreover, as already introduced in Section 1.1.2, storage assignment policies usually do not take into account possible relations between stored products, but rather dimensions and/or stock code, with the only exception of the correlated assignment strategy of Frazelle and Sharp (1989), who suggested a storage according to which SKUs or items that are frequently requested together (i.e. in the same order or in the same time window) should be stored together, in order to optimize picking tours and improve warehouse overall efficiency (Ballou 1992; Bartholdi and Hackman 2011). This kind of strategy, also referred to as *family grouping approach*, is primarily applicable when the statistical correlation between items is known or at least predictable. There are two main categories of family grouping: the *complementary-based* method (Lee 1992; Rosenwein 1994; Liu 1999; Wäscher 2004) and the *contact-based* method (Van Oudheusden et al., 1988; Van Oudheusden and Zhu 1992). One of the possible limitations of these location assignment methods is that they are focused on quantifying the correlation between products by considering them two at the time (Bartholdi and Hackman 2011), while, in some contexts it could be useful to understand whether a relationship between more than two products exists or not.

2.2 The Storage Assignment and Travel Distance Estimation (SA&TDE) joint method

Of all the warehouse activities, order picking is one of the most time consuming and expensive. In order to improve this task, several researches have pointed out the need to consider jointly the layout of the warehouse, the storage assignment strategy and the routing policy to reduce travelled distances and picking time.
In this paragraph the Storage Assignment and Travelled Distance Estimation (SA&TDE) joint method is presented, a new approach useful to design and evaluate a manual picker-to-parts picking system, focusing on goods allocation and distances estimation. Starting from a set of picking orders received in a certain time range, this approach allows to evaluate the combinations of product codes assigned to storage locations, aisles, sections or warehouse areas and to assess the most relevant ones, for the best location and warehouse layout, with the aim of ensuring optimal picking routes, through the application of the multinomial probability distribution. A case study is developed as well, in order to clarify the concept that underlies the SA&TDE joint method, and to show the validity and the flexibility of the approach, through the calculation of the saving at different levels of detail.

2.2.1 Notations

Notation	Description
i	Product codes index
i'	Maximum number of product codes
h	Orders index
h'	Maximum number of orders
m	Macro areas index
m'	Maximum number of macro areas
a	Aisles index
a'	Maximum number of aisles
z	Storage locations index
z'	Maximum number of storage locations
j	Groups of orders having the same value of M_h, A_h or Z_h index
j'	Maximum number of groups of orders having the same value of M_h, A_h or Z_h
k	Combinations of product codes index

k'	Maximum number of combinations of product codes
$M_{i,h}$	Incidence matrix value for product code *i* and order *h* at macro area level
$A_{i,h}$	Incidence matrix value for product code *i* and order *h* at aisle level
$Z_{i,h}$	Incidence matrix value for product code *i* and order *h* at storage location level
M_h	Number of order lines for order *h* grouped at macro area level
A_h	Number of order lines for order *h* grouped at aisle level
Z_h	Number of order lines for order *h* grouped at storage location level
M_{hj}	Number of order lines for order *h* of the *j*-th group of orders at macro area level
A_{hj}	Number of order lines for order *h* of the *j*-th group of orders at aisle level
Z_{hj}	Number of order lines for order *h* of the *j*-th group of orders at storage location level
M_{ij}	Number of order lines for product code *i* in the group *j* at macro area level
M'_{ij}	Number of order lines for product code *i* in the group *j* at macro area level, net of macro area surface
M''_{ij}	Number of order lines for product code *i* in the group *j* at macro area level, considering macro areas have all the same dimensions
A_{ij}	Number of order lines for product code *i* in the group *j* at aisle level
Z_{ij}	Number of order lines for product code *i* in the group *j* at storage location level
M_{totj}	Number of order lines for all product codes in the *j*-th group at macro area level
M'_{totj}	Number of order lines for all product codes in the *j*-th group at macro area level, redimensioned according to macro areas surfaces (sum of all M'_{ij})
A_{totj}	Number of order lines for all product codes in the *j*-th group at aisle level
Z_{totj}	Number of order lines for all product codes in the *j*-th group at storage location level
p_{ij}	Access probabilities for product code *i* in the *j*-th group of orders
p_{k_j}	Multinomial probability for the *k*-th combination of product codes in the *j*-th group of orders
$p_{k\,jn}$	Normalized multinomial probability for the *k*-th combination of product codes in the *j*-th group of orders
D_k	Distance travelled to pick the *k*-th product codes combination
L_j	Total travelled distance for the *j*-th group of orders
L_M	Total travelled distance at macro area level
L_{Am}	Total travelled distance at aisle level for macro area *m*
L_{Zam}	Total travelled distance at storage location level for aisle *a* in macro area *m*

Table 2.1. Notations.

2.2.2 The SA&TDE joint method

High level system

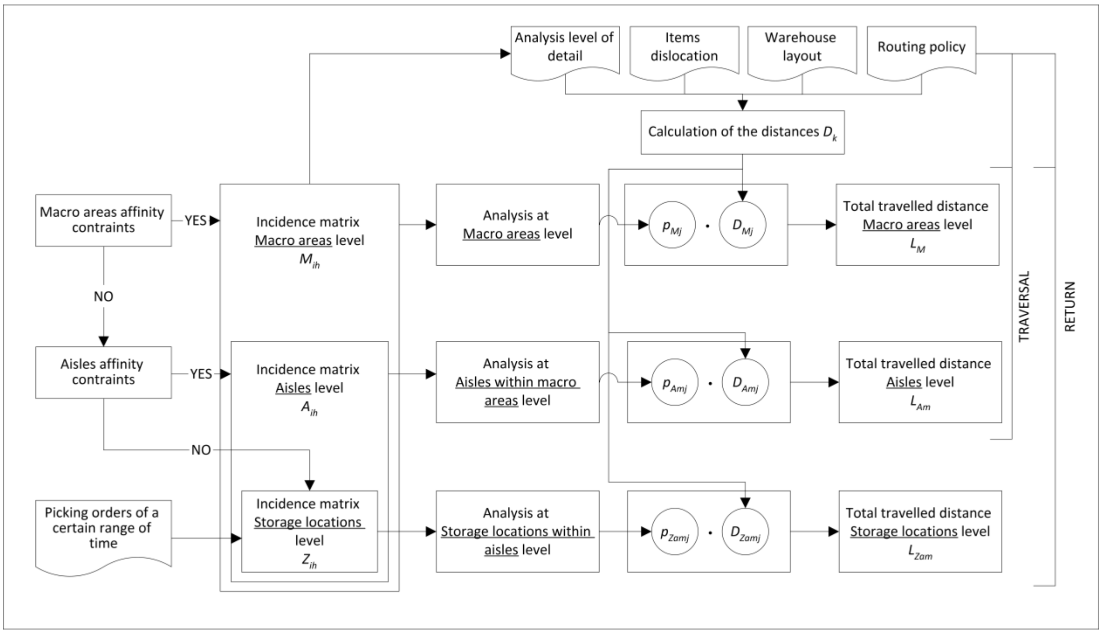


Figure 2.2. High level schema of the SA&TDE joint method.

The main objective of the Storage Assignment and Travel Distance Estimation (SA&TDE) joint method is the determination of a storage configuration that reduces the total distances travelled by the operators while processing the picking orders. These distances are composed of three main elements:

- the distances at macro area level, i.e. the route travelled to go through the different macro areas,
- the distances at aisles level, within every macro area, measuring the route travelled to go through the different aisles,
- the distances at storage location level, measuring the route travelled to pick each item from the corresponding storage location within every aisle.

Every single factor can be considered in the design of the warehouse configuration independently, or together with others, according to the needs and to the desired thoroughness.

The method starts considering a warehouse and a set of picking orders that have been processed in a given period of time, as shown in Figure 2.2. Each order is made up of a certain number of picking rows, e.g. 2, 3 or more, which can then be further analysed at different level of detail. It is derived that a picking order can refer to the visit of different warehouse areas or different aisles or yet different aisles sectors, so the system can be applied starting with the reorganization of the whole warehouse or of certain departments, or of certain aisles and all the way down to the study of the single locations, aisle by aisle.

Whatever the level of detail, the starting data and the steps to follow are exactly the same in every case; the only aspect that changes is the subject of the study, i.e. the level of detail at which data are processed and the space taken into account. This means that the same picking list, referring to the pick of some of the stored items, for example, can assume the three different structures reported in Figure 2.3.

PICKING LIST					
Code	Aisle #	Macro Area	Picking List at Storage location level	Picking List at Aisle level	Picking List at Macro area level
A	1	001	1	1	1
B	1	001	1		
C	2	001	1	1	
D	3	002	1	1	1
E	3	002	1		
F	4	003	1	1	1
G	5	003	1	1	

Figure 2.3. Example of a picking list and structure of the data for the three level of analysis.

One of the reasons for having these three levels of analysis lays in possible items affinity constraints to a macro area or to an aisle: the need for storing together items of the same product category in the same macro area could be determined by the kind of such products (for example, food and not food articles have to be stored in different areas, or frozen products have to be stored in a refrigerated dedicated zone) or from the type of routing the picker has to perform (for example, if the picker picks in order of weight, it is better to store all the heavier products at the beginning of the route and the lighter ones at the end). As far as aisles affinity constraints are concerned, the main limitations could derive from the type of shelving that could have different shelves heights or capacities, for example according to the product stored, or on the fact that the items have to be picked in order of weight.

The way the analysis is developed depends on the routing policy adopted, too (Caron et al., 1998). In particular, in case of traversal picking policy the analysis can only be implemented for the optimization of the arrangement in the macro areas and in the aisles. In fact, moving the various storage locations within a single aisle would not have any positive effect on the total travelled distance, as the picker, once he enters one aisle, he has to cross it completely anyway. In order to get relevant results, every storage location should be taken into consideration without the constraints of belonging to a particular aisle.

In case the routing policy is return, the analysis of the position of the single storage locations could become significant, and trying to assign the first storage locations of an aisle to the products with high value of multinomial probability of being picked can reduce picking times since the picker would have to cover with greater frequency a shorter distance. In this case, the intermediate analysis should be focused only on measuring the distances travelled to go from one aisle to another, while the travelled distances within the aisles should be estimated with the analysis at the lower level.

For the sake of ease, the following procedure deals only with picking orders entailing visits to warehouse single locations of a particular aisle in a specific department with return policy, while in the case study presented in Paragraph 2.2.3, there are reported some applications of the method at different levels of detail.

Detailed procedure

Figure 2.4 shows in detail the procedure to follow in order to apply the SA&TDE joint method.

First of all, an *incidence matrix* has to be set up, in which the different *h'* orders are in the rows and the *i'* product codes (referring to as many storage locations) are in the columns. In the intersection between rows and columns the values of $Z_{i,h}$ (Battini et al. 2009) are displayed, where

$$Z_{i,h} = \begin{cases} 1 & order\ h\ contains\ code\ i \\ 0 & order\ h\ does\ not\ contain\ code\ i \end{cases}$$

Once all the $Z_{i,h}$ are known, the Z_h factors can be calculated with the following formula:

$$Z_h = \sum_{i=1}^{i'} Z_{i,h} \tag{2.1}$$

since it represents the number of lines the order h is made up of, which correspond to a row of the *incidence matrix* (Battini et al. 2009).

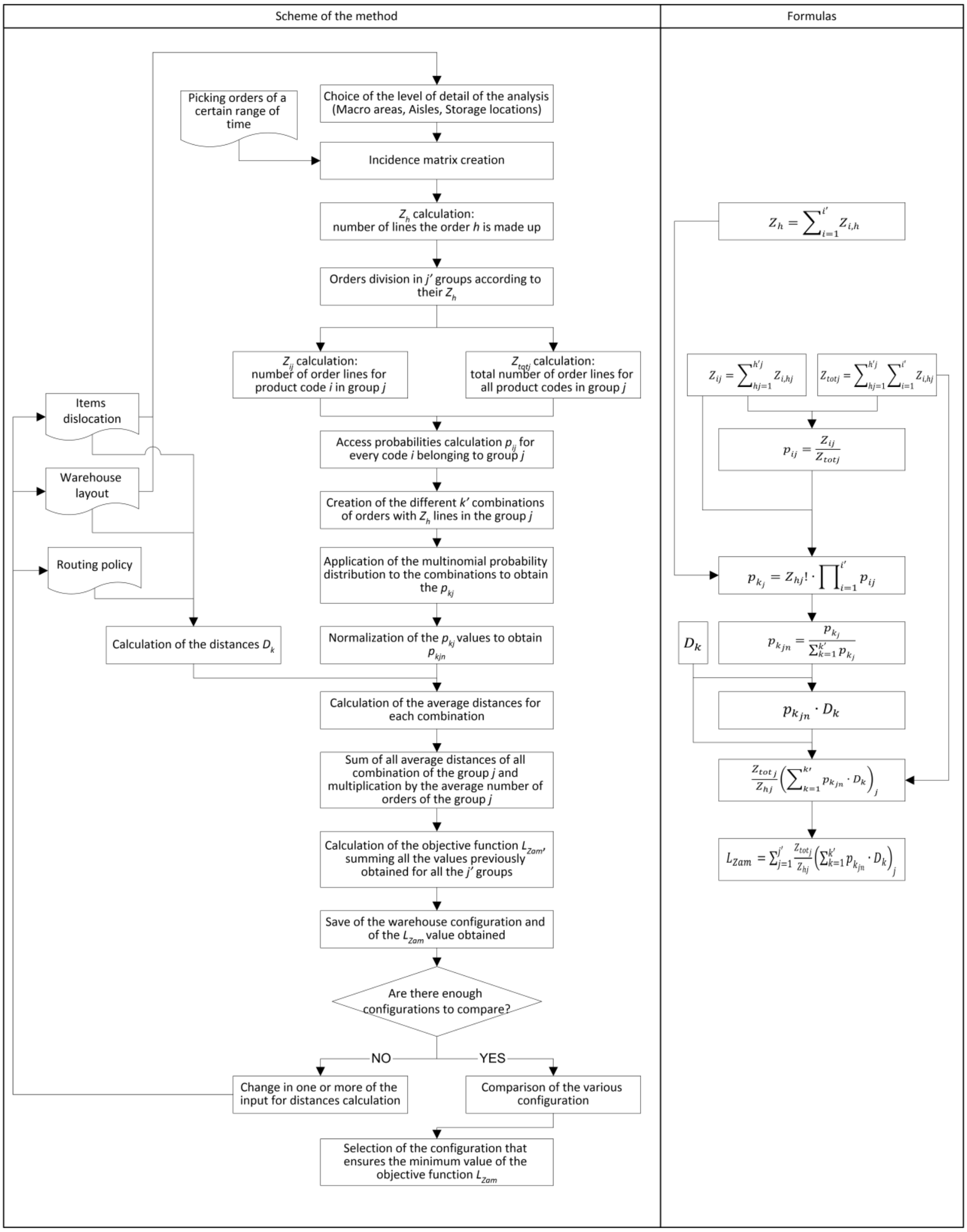


Figure 2.4. SA&TDE joint procedure with multinomial probability distribution flowchart.

Within each of the j groups, two further factors can be quantified: the number of lines in which the i-th item/part/component appears within a given time period, (which is the column of the *incidence matrix* regarding the group j)

$$Z_{ij} = \sum_{hj=1}^{h'j} Z_{i,hj} \quad (2.2)$$

and

$$Z_{totj} = \sum_{hj=1}^{h'j} \sum_{i=1}^{i'} Z_{i,hj} \quad (2.3)$$

where Z_{totj} is the number of order lines for all product codes in the group *j* in the considered time period.

At this point, with the data obtained so far, it is possible to calculate the *access probabilities* p_{ij} for every product code in every group of orders *j*, by dividing the number of order lines of each product code in the specific group Z_{ij} by the total number of order lines of the group Z_{totj}.

$$p_{ij} = \frac{Z_{ij}}{Z_{totj}} \quad (2.4)$$

These probabilities p_{ij} can be used to calculate the probabilities of the *k'* combinations of the various product codes, by relying on the multinomial distribution. In fact, it is possible to calculate the probability of any combination of numbers of successes for various categories, considering that each category has a given fixed success probability.

As explained in Appendix A.1, in the application of the SA&TDE joint method, the multinomial probability distribution concept (considering a replacement of the drawn items) can be used in place of the multivariate hypergeometric probability distribution (considering no replacement), because the number of items extracted from every category is much smaller than the overall category. In fact, in the case of the present paper the item extracted is the product code (this means just one draw) from a category including all the lines of such product code (that are, generally, much more than only one).

Considering the formula (A.1) reported in Appendix A.1, in this case *n* is Z_{hj}, the number of lines of one order belonging to the group *j* (always the same within the same group), k_i are the $Z_{i,hj}$ of the codes constituting the order (then, they can be equal to 1 or 0) and p_{ij} are the *access probabilities* calculated with (4):

$$p_{k_j} = P\left(Z_{1hj}, \ldots, Z_{rhj}\right) = \frac{Z_{hj}!}{\prod_{i=1}^{i'} Z_{ihj}!} \prod\nolimits_{i=1}^{i'} p_{ij}^{Z_{ihj}} \tag{2.5}$$

The multinomial probability has to be calculated for all the possible *k'* combinations of Z_{hj} product codes within the specific aisle.

It is important to notice that this formula can be further simplified for the purpose of this paper; in fact, since the $Z_{i,h}$ can be equal only to 1 or 0, according to the combination of the codes considered, it can be demonstrated that the formula (2.5) is equivalent to:

$$p_{k_j} = P(Z_{1h}, \ldots, Z_{rh}) = Z_{hj}! \cdot \prod\nolimits_{i=1}^{i'} p_{ij} \tag{2.6}$$

where Z_{hj} is the number of order lines of the *j*-th group of orders, while the p_{ij} that have to be multiplied are corresponding to the product codes of the combination considered. This simplification allows an easier management of the case $Z_{ij} = 0$, hence, $p_{ij} = 0$ for one or more product codes (in the orders group *j* such items have no picking lines). Subsequently, all the values obtained have to be normalized, dividing them by their overall sum:

$$p_{k_{jn}} = \frac{p_{k_j}}{\sum_{k=1}^{k'} p_{k_j}} \tag{2.7}$$

The normalized multinomial probabilities can be used to make important considerations about the location of the various products within the warehouse. In fact, if the combination of two or more product codes have a high value of $p_{k_{jn}}$, the corresponding products should be assigned to a warehouse location as close as possible to one another, in order to minimize picking routes. Furthermore, the combinations with the greater values of $p_{k_{jn}}$should be located near the I/O point.

In order to assess the most appropriate configuration of all product codes through the various storage locations, the set up of an objective function is needed, to represent the total distance travelled, and to consider the distances travelled to pick the various combinations of order lines. It is derived that the travelled distance can be obtained from the following formula:

$$L_{Zam} = \sum_{j=1}^{j'} \frac{Z_{tot\,j}}{Z_{hj}} \left(\sum_{k=1}^{k'} p_{k_{jn}} \cdot D_k \right)_j \tag{2.8}$$

according to which all the picking distances, obtained by multiplying the distances D_k travelled to pick every single combination of codes k by the corresponding normalized multinomial probability p_{kjn}, are summed together. The resulting factor is multiplied by the number of orders in the corresponding group, obtained dividing the total number of order lines in the j-th group $Z_{tot\,j}$ by the number of order lines of one order Z_{hj}, and eventually summed together for all the j' groups of orders.

To compute the various values of D_k specific software for distances calculation can be used, or a simple calculation algorithm that takes into account the configuration of the warehouse can be implemented. In either cases, it is obvious that the final distances depend on the chosen routing strategy (Manzini et al. 2007).

The total travelled distance L is a very useful parameter for the evaluation of goods allocation in a warehouse that changes according to the way products are assigned to the various warehouse locations. In particular, it is easily demonstrated that, if the product codes with a high value of $p_{k_{jn}}$ are stored as close as possible to each other, the value of L is lower than in other cases, in which for example products are assigned to specific locations without considering the correlation between the items to pick.

Once the value of L for a particular warehouse configuration has been determined, one or more parameters of the method can be modified, either the items allocation within the warehouse, the warehouse layout or the routing policy. Once these changes are applied, the method can be applied anew, in order to see how much the objective function changes accordingly. In particular, the change in products storage assignment and in macro areas or aisles arrangement has to take into consideration the value of $p_{k_{jn}}$. If the product codes (the macro areas or the aisles) with a high value of $p_{k_{jn}}$ are stored near each other, and near the I/O point, the value of L is lower than it is with other solutions. Both these concepts have already been defined as *complementarity* and *popularity* (Ballou 1992). When a sufficient number of configurations and values of L are available, the one that ensures the lower value of the objective function L can be selected.

Numerical example

In the following numerical example the picking orders are all made of two lines and the routing policy adopted is the return one.

8 products to pick, and a set of 20 picking orders are given; the corresponding *incidence matrix*, with the values of Z_h, Z_{ij} and p_{ij} is reported in Table 2.2. From the initial values of p_{ij}, p_{k_j} and, then, $p_{k_{jn}}$ are calculated; the distances D_k are obtained by measuring the routes travelled to pick every combination of two codes, assigned to two specific storage locations from the layout shown in Figure 2.5. These distances are multiplied by the $p_{k_{jn}}$ and then summed together. Such result is multiplied by 20, which is the number of orders considered, in order to obtain the total travelled distance *L*, which, in this case, is equal to 239 (Table 2.3).

	CODE A	CODE B	CODE C	CODE D	CODE E	CODE F	CODE G	CODE H	Z_h
ORDER 1	1					1			2
ORDER 2	1					1			2
ORDER 3	1					1			2
ORDER 4	1	1							2
ORDER 5	1		1						2
ORDER 6	1					1			2
ORDER 7	1					1			2
ORDER 8	1				1				2
ORDER 9	1				1				2
ORDER 10						1		1	2
ORDER 11						1	1		2
ORDER 12				1			1		2
ORDER 13					1		1		2
ORDER 14			1			1			2
ORDER 15		1		1					2
ORDER 16			1		1				2
ORDER 17				1		1			2
ORDER 18		1						1	2
ORDER 19		1	1						2
ORDER 20				1	1				2
Z_{i2}	9	4	4	4	5	9	3	2	40
p_{i2}	0.2250	0.1000	0.1000	0.1000	0.1250	0.2250	0.0750	0.0500	

Table 2.2. Numerical example incidence matrix.

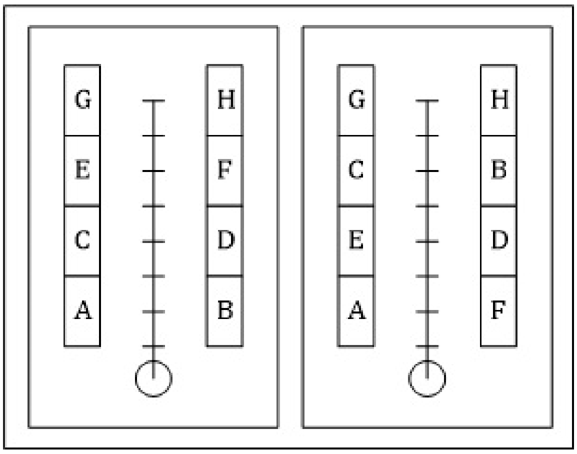


Figure 2.5. Initial assignment (left) and final assignment (right) for the single aisle numerical example.

Codes combination	CODES								Z_h	p_{k2}	p_{k2n}	D_k	$p_{k2n}\cdot D_k$
	A	B	C	D	E	F	G	H					
AB	1	1							2	0.0450	0.0533	4	0.2130
AC	1		1						2	0.0450	0.0533	8	0.4260
AD	1			1					2	0.0450	0.0533	8	0.4260
AE	1				1				2	0.0563	0.0666	12	0.7988
AF	1					1			2	0.1013	0.1198	12	1.4379
AG	1						1		2	0.0338	0.0399	16	0.6391
AH	1							1	2	0.0225	0.0266	16	0.4260
BC		1	1						2	0.0200	0.0237	8	0.1893
BD		1		1					2	0.0200	0.0237	8	0.1893
BE		1			1				2	0.0250	0.0296	12	0.3550
BF		1				1			2	0.0450	0.0533	12	0.6391
BG		1					1		2	0.0150	0.0178	16	0.2840
BH		1						1	2	0.0100	0.0118	16	0.1893
CD			1	1					2	0.0200	0.0237	8	0.1893
CE			1		1				2	0.0250	0.0296	12	0.3550
CF			1			1			2	0.0450	0.0533	12	0.6391
CG			1				1		2	0.0150	0.0178	16	0.2840
CH			1					1	2	0.0100	0.0118	16	0.1893
DE				1	1				2	0.0250	0.0296	12	0.3550
DF				1		1			2	0.0450	0.0533	12	0.6391
DG				1			1		2	0.0150	0.0178	16	0.2840
DH				1				1	2	0.0100	0.0118	16	0.1893
EF					1	1			2	0.0563	0.0666	12	0.7988
EG					1		1		2	0.0188	0.0222	16	0.3550
EH					1			1	2	0.0125	0.0148	16	0.2367
FG						1	1		2	0.0338	0.0399	16	0.6391
FH						1		1	2	0.0225	0.0266	16	0.4260
GH							1	1	2	0.0075	0.0089	16	0.1420
											$\sum_{k=1}^{k'}(p_{kjn}\cdot D_k)$		11.9349
												L	238.6982

Table 2.3. Results of the SA&TDE joint method for the numerical example initial configuration.

Using the value of L as a starting point, some iterations of the product codes assignment to the storage locations can be performed: the codes with the highest values of $p_{k_{jn}}$ will be assigned to the nearest locations in order to keep the value of L as low as possible In fact, the combinations with a high value of $p_{k_{jn}}$, i.e. AF, AE, AD, AC, AB, FE, FD, FC, FB, give a clear indication of the necessity to store item A and F near the I/O point.

Table 2.4 reports the better configuration of codes, with a value of L equal to 221, that is, 8% less than the initial configuration.

Codes combination	CODES								Z_h	p_{k2}	p_{k2n}	D_k	$p_{k2n} \cdot D_k$
	A	B	C	D	E	F	G	H					
AF	1	1							2	0.1013	0.1198	4	0.4793
AE	1		1						2	0.0563	0.0666	8	0.5325
AD	1			1					2	0.0450	0.0533	8	0.4260
AC	1				1				2	0.0450	0.0533	12	0.6391
AB	1					1			2	0.0450	0.0533	12	0.6391
AG	1						1		2	0.0338	0.0399	16	0.6391
AH	1							1	2	0.0225	0.0266	16	0.4260
FE		1	1						2	0.0563	0.0666	8	0.5325
FD		1		1					2	0.0450	0.0533	8	0.4260
FC		1			1				2	0.0450	0.0533	12	0.6391
FB		1				1			2	0.0450	0.0533	12	0.6391
FG		1					1		2	0.0338	0.0399	16	0.6391
FH		1						1	2	0.0225	0.0266	16	0.4260
ED			1	1					2	0.0250	0.0296	8	0.2367
EC			1		1				2	0.0250	0.0296	12	0.3550
EB			1			1			2	0.0250	0.0296	12	0.3550
EG			1				1		2	0.0188	0.0222	16	0.3550
EH			1					1	2	0.0125	0.0148	16	0.2367
DC				1	1				2	0.0200	0.0237	12	0.2840
DB				1		1			2	0.0200	0.0237	12	0.2840
DG				1			1		2	0.0150	0.0178	16	0.2840
DH				1				1	2	0.0100	0.0118	16	0.1893
CB					1	1			2	0.0200	0.0237	12	0.2840
CG					1		1		2	0.0150	0.0178	16	0.2840
CH					1			1	2	0.0100	0.0118	16	0.1893
BG						1	1		2	0.0150	0.0178	16	0.2840
BH						1		1	2	0.0100	0.0118	16	0.1893
GH							1	1	2	0.0075	0.0089	16	0.1420
											$\sum_{k=1}^{k'}(p_{kjn} \cdot D_k)$		11.0355
											L_{Zam}		220.7101

Table 2.4. Results of the SA&TDE joint method for the numerical example final configuration.

2.2.3 Application of the method: a case study

The case study presented in this section deals with a picking warehouse that mainly stores furniture, hardware items and household goods. Data of one full year of order picking have been collected, providing all the information necessary to apply the SA&TDE joint method shown in Paragraph 2.2.2.

SA&TDE joint method applied at macro area level

To begin, the overall warehouse layout is analysed and divided into 8 macro areas: Gratings, cast iron and flowerpots; Hardware and spare parts; Iron; Lamps and towels; Pillows, dishes and tablecloths; Polyurethane; Wood; Wood and iron furniture.

The data concerning the picking orders have been processed in order to obtain the appropriate *incidence matrix*, with $M_{i,h} = 1$ in case the order h requires the access to the macro area i. Once the *incidence matrix* is set up, the M_h of each order can be obtained, to divide the orders in eight groups according to the value of such factor, with orders with 1 to 8 picking lines, requiring the visit to only one macro in case of 1 line and all areas in case of 8 lines, respectively.

In the case of the macro areas, the setting of the right distances D_k needed to calculate the objective function L represents a crucial aspect. In fact, as every area inevitably has different shape and dimensions, generally proportional to the number of orders it will so-to-speak contain, it is important to find a way to generalize the analysis, so that it is not affected by the dimensions of every single macro area, since it would be impossible to estimate the distance travelled by the picker to pick an item in such wide areas without focusing on a particular storage location. It turns out that the most suitable action is to elaborate the picking data, considering that every macro area of the warehouse has the same dimensions, so that the choices concerning the disposition of the macro areas are not affected by the areas physical dimensions, nor are distorted by the possibility that a high number of orders for an area could derive from the dimension of the area itself. For feasibility purposes, the distances between areas are calculated considering each areas middle point as the unique picking point. Therefore, the M_{ij} obtained directly from the *incidence matrix*, as shown in Figure 2.6, have to be elaborated, assuming that every macro area has the same dimension.

In particular, the following steps have been performed:

(1) The dimensions of each macro area *m* have been estimated, obtaining an average area of 38.95 m^2

Macro Area name	Area [m^2]
Polyurethane	16.00
Iron	18.00
Gratings, cast iron and flowerpots	41.28
Pillows, dishes and tablecloths	46.08
Wood	29.88
Hardware and spare parts	20.00
Lamps and towels	37.84
Wood and iron furniture	102.48
Total	311.56

Table 2.5. Dimensions of the Macro areas.

$$Average\ area = \frac{Total\ area}{m'} = \frac{311.56}{8} = 38.95\ m^2 \tag{2.9}$$

(2) For each of the eight groups of orders the new values of M''_{ij} have been calculated, multiplying the starting M_{ij} by the area ratio

$$M'_{ij} = M_{ij} \cdot \frac{Average\ area}{Area_m} \tag{2.10}$$

and, then, multiplying the obtained M'_{ij} by the order ratio

$$M''_{ij} = M'_{ij} \cdot \frac{M_{totj}}{M'_{totj}} \tag{2.11}$$

where $\mathrm{M'_{totj}}$ is the sum of all the M'_{ij}.

Once that the M''_{ij} factors have been obtained, they have been divided by M_{totj} to calculate the p_{ij}. These probabilities have then been used to quantify the various combinations of product codes in different orders by applying the formula (2.5), obtaining the p_{k_j} and, then, the $p_{k_{jn}}$.

At this stage of the analysis the values of the distances D_k have been obtained considering a new configuration of the warehouse, in which every macro area has a square shape of 38.95 m^2, so that the distances travelled to visit the different areas are the same even if their disposition changes, and, as a consequence, the analysis turns out to be independent from the shape of every single area. The starting configuration of the warehouse has then been changed, as reported in Figure 2.6.

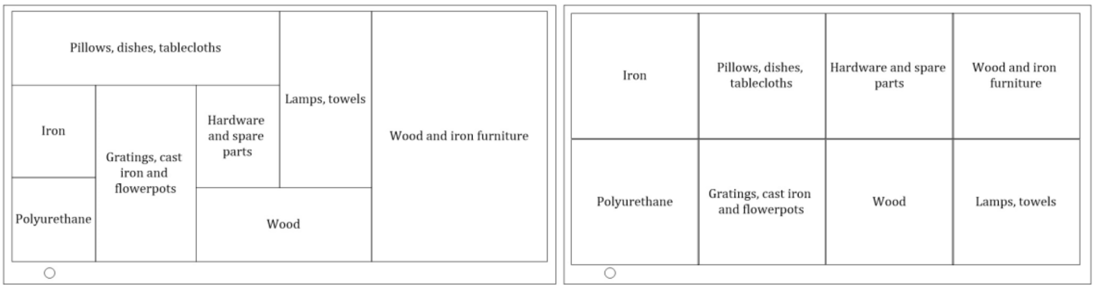


Figure 2.6. Initial configuration of the warehouse with real areas and average areas.

	INITIAL CONFIGURATION	NEW CONFIGURATION	
	L_j	L_j	Δ
1 LINE	181,182	89,500	-50.6%
2 LINES	132,890	78,020	-41.3%
3 LINES	63,371	49,630	-21.7%
4 LINES	45,466	38,407	-15.5%
5 LINES	46,236	40,828	-11.7%
6 LINES	45,719	42,759	-6.5%
7 LINES	41,200	38,893	-5.6%
8 LINES	19,220	19,220	0.0%
L_M	575,285	397,257	-30.9%

Table 2.6. Initial and new warehouse configuration evaluation in terms of total travelled distance.

An alternative approach to considering the middle point of every macro area as the only picking point could derive from the application of the graphs theory (Goetschalckx and Ratliff 1988; Tompkins et al., 2010; De Koster and Van Der Poort 1998), in which every macro area corresponds to nodes and the distances are reported in the arches connecting such nodes. After having multiplied every $p_{k_{jn}}$ by the corresponding distance D_k, all terms are summed together in order to obtain the average weighted distance, which is used as an input to calculate the total distance travelled to pick all the orders composed of M_h lines, represented by L_j, the distance travelled to pick the orders belonging to the group j. Finally, L is calculated as the sum of all the L_j, as shown in Table 2.6 which reports the evaluation of the starting warehouse configuration in terms of L_j and L_M.

The value L_M of the initial configuration can then be compared with the other values of the objective function obtained by changing the arrangement of the areas within the warehouse, and in particular, determining which have to be put closer to the I/O point, according to the value of the respective $p_{k_{jn}}$. In fact, if the macro areas that have a high value of $p_{k_{jn}}$ in the various combinations are assigned to the locations that are near the I/O point, the value of the total travelled distance L_M is typically lower than in a warehouse configuration that does not consider this aspect.

After some iterations, it has been found that the best configuration for the warehouse macro areas is the one shown in Figure 2.7. The result in terms of L_M is reported and compared with the one of the starting configuration in Table 2.6.

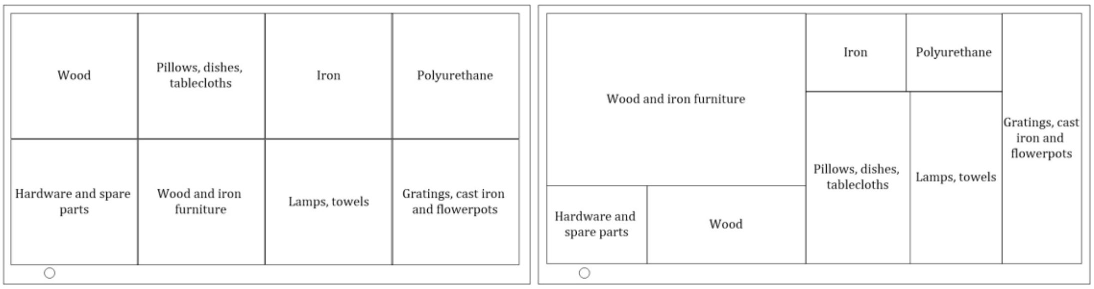


Figure 2.7. Final configuration of the warehouse with average areas and real areas.

After having made the decision on how to arrange the various macro areas within the warehouse, the dummy configuration has been translated into a real one, with the unavoidable constraints due to the actual dimensions of every macro area (Figure 2.7). The final layout can then be used to estimate the real distances travelled by the operators to pick the different orders.

SA&TDE joint method applied at aisles level

For the analysis at the level of aisles within a macro area, the following example concerns the Wood and iron furniture macro area, organized in 7 aisles and 14 shelves, with 35 different storage locations each. The main aisles affinity constraints are due to the type of product stored, its various weights and heights, and to the need of storing the wood furniture separated from the iron ones. The picking lists have been aggregated so that the *incidence matrix* has $A_{i,h} = 1$ if the picker has to enter a particular aisle, independently from the number of different items he has to pick within it. The adopted routing policy is traversal; this implies that the distance travelled to pick the products stored in the first aisle equals to the one travelled to pick products both in the first and in the second aisle. Furthermore, there is no need to focus on the storage assignment of the products to the various storage locations within the aisle, because once they have entered an aisle, the pickers have to travel it completely, and because they are able to pick from both sides of the aisle simultaneously.

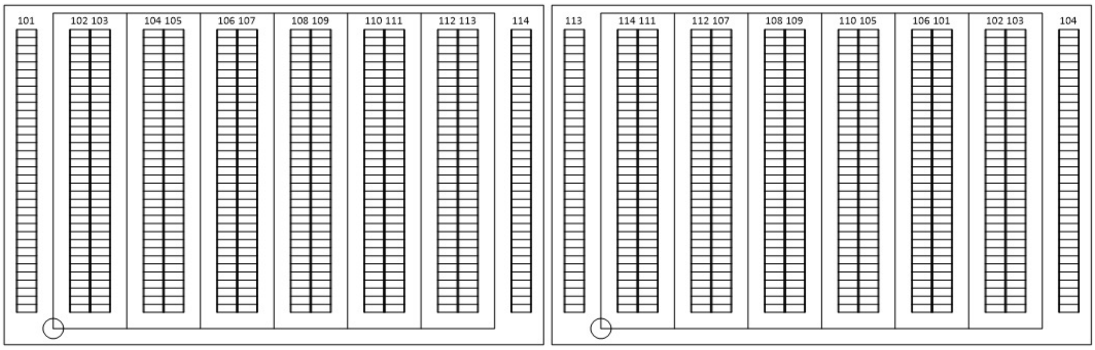


Figure 2.8. Initial and final configuration of Wood and iron furniture macro area.

	INITIAL CONFIGURATION	NEW CONFIGURATION	
	L_j	L_j	Δ
1 LINE	608,952	543,252	-10.8%
2 LINES	346,514	320,622	-7.5%
3 LINES	370,611	359,797	-2.9%
4 LINES	255,718	250,970	-1.9%
5 LINES	308,197	306,424	-0.6%
6 LINES	315,001	314,395	-0.2%
7 LINES	407,712	407,712	0.0%
L_{Am}	2,612,705	2,503,172	-4.2%

Table 2.7. Initial and new Wood and iron furniture macro area configuration evaluation in terms of total travelled distance.

Figure 2.8 shows the initial configuration of the Wood and iron furniture area and the new one obtained by applying the SA&TDE joint method. The position of some aisles, in terms of relative position and with respect to the I/O point, has been changed. The total travelled distance L_{Am} decreases of 4.2%, from 2,612,70 m to 2,503,172 m, as shown in Table 2.7.

SA&TDE joint method applied at storage locations level

In order to apply the method at single storage locations level, the Iron macro area has been considered, since it is a small area, with only one aisle and few storage locations that can be picked on both sides simultaneously. Due to the structure of the warehouse, the adopted routing policy in this area is the return one.

In this case the initial data have been processed so that the *incidence matrix* has $Z_{i,h} = 1$ if the picker has to pick a product stored in a particular storage location of the aisle.

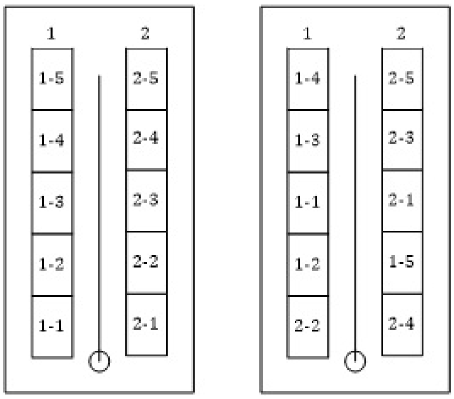


Figure 2.9. Initial and final configuration of Iron aisle.

	INITIAL CONFIGURATION	NEW CONFIGURATION	
	L_j	L_j	Δ
1 LINE	5,261	2,439	-53.6%
2 LINES	2,204	1,187	-46.2%
3 LINES	681	560	-17.8%
4 LINES	290	254	-12.5%
5 LINES	71	63	-10.1%
6 LINES	51	46	-10.5%
L_{Zam}	8,557	4,548	-46.9%

Table 2.8. Initial and new aisle configuration evaluation in terms of total travelled distance.

Figure 2.9 shows the initial configuration of the shelving 1 and 2 belonging to the analysed aisle, where each one of the 10 stored products has only one storage location.

After some iterations, that have taken into account the values of $p_{k_{jn}}$ of the various combinations, it has been found that the best storage assignment, which warrants a minimum travelled distance, is the one reported in Figure 2.9. The respective results in terms of total travelled distances L_{Zam} are shown in Table 2.8.

Since in the analysed case every storage location corresponds to only one product code, the SA&TDE joint method at storage locations level has been applied directly. However, when some product codes are assigned to more than one storage location, it is necessary to process the starting data by applying the procedure shown in case of the macro area level analysis (presented at the beginning of this paragraph), so that every product code would be assigned to the same average number of storage locations, with a number of picking rows that has been proportioned accordingly.

2.2.4 Results analysis

The case study presented in the previous paragraph shows that the application of the SA&TDE joint method allows an estimation of the picking frequency of every single code, family or product type and offers a way to evaluate the warehouse configuration with just one parameter, the total travelled distance L. The value of L can be used to compare various solutions that can differ in terms of layout, storage assignment or routing policy. After the application of the SA&TDE joint method, the new warehouse configuration in terms of macro areas disposition allows more efficient picking tours, with an overall relative reduction of L of 30.9%. As far as macro areas are concerned, the most critical aspect is the need of calculating an average area, so that the analysis is not affected by the different dimensions of the areas. Once the layout with the average areas has been created, the travelled distances for all the different combinations of picking orders have been calculated by considering the middle point of each area as the unique picking point. Another possible approach for distances estimation could derive from considering a proper application of the graphs theory.

The SA&TDE joint method has also been applied for the evaluation at aisles level of the Wood and iron furniture area, which presents aisles affinity constraints, concerning the two main categories of products stored and their own characteristics. Since in this area the adopted routing policy is traversal, the analysis can be focused only on the arrangement of the various aisles and shelving from the I/O point, without considering the assignment of different products to different storage locations of a particular aisle. This aspect should have been considered in case of return routing policy.

The case study for the application at storage locations level has been conducted in the Iron area, which is composed only of one aisle and 10 storage locations and where the adopted routing policy is return. In this case, the SA&TDE joint method has allowed a change in the assignment of the 10 product codes, reducing the total travelled distance *L* of 46.9%, from 8,557 m to 4,548 m.

2.2.5 Method discussion

At every level of application, the SA&TDE joint method has proved to lead to relevant results in terms of picking performances improvement in a simple and intuitive way. In fact, it allows the evaluation of a particular warehouse configuration, warehouse layout, storage assignment and routing policy, through a unique parameter *L*, representing the total travelled distance. Such parameter can be calculated for different configurations, in order to perform an effective comparison of the solutions and choose the one that ensures the lower value of *L*. The chosen warehouse configuration is, therefore, the best in terms of travelled distances and spent time for order picking processing.

A strength of the SA&TDE joint method is that it exploits the same procedure for the analysis at different levels of detail. According to the level of detail the only aspects that change are the level of aggregation of the input picking lists and the possible constraints that could emerge. Furthermore, it is applicable for different routing policies, e.g. traversal or return, which could be adopted at the same time in the same warehouse, as shown in Paragraph 2.2.3.

The crucial point in the application of the SA&TDE joint method is the perfect understanding of the problems, the different inputs and the actual constraints, in order to perform the best evaluation.

As explained in the previous section, the main inputs of the SA&TDE joint method are the picking lists that have been processed in a certain period of time, hence, it basically refers to historical business data. In order to obtain the most effective results from this procedure, data must not be handled in a sterile way, considering the possible factors and events that could eventually affect the structure of the analysed system in the future.

2.3 Carton from rack picking or carton from pallet picking: a selection procedure

Among all the available researches concerning warehouse picking, there is a specific thread dealing with the possibility of dedicating a specific area of the whole warehouse to picking activities, called the forward area or fast-pick area, which is separated from the bulk warehouse zone, named the reserve area. Related issues typically concern the convenience of realizing such a configuration, the choice of the items to store in both areas, their respective size, the way the items are stored and picked within these areas, i.e. carton-pick-from-pallet versus piece-pick-from-carton, with proposals for different evaluation methods and analytical dissertations. In particular, in the case of medium and small items, there is interest in the decision-making process that deals with the possibility of keeping a product directly in a pallet or storing it in racks, in which several factors, also conflicting, come into play. In the present paragraph a new procedure that can be used to assess the most suitable way of storing a product in the fast-pick area is provided. Starting from simple data, such as the picking characteristics of the items to pick and their physical dimensions, as well as the characteristics of the warehouse, the method supports the critical decision between storing the item directly in a pallet or putting it on a rack. The procedure is also applied in a case study, the results of which prove its effectiveness as well as its easy and full applicability, also in different warehouse contexts.

2.3.1 Notations

Notation	Description
Q_i	Number of picked cartons for item *i* in the considered time period
Z_i	Number of picking lines for item *i* in the considered time period
$T_{c,i}$	Total picking time for item *i* in the case of carton from rack picking
$T_{p,i}$	Total picking time for item *i* in the case of carton from pallet picking
$t_{REF\ c}$	Unitary pallet refill time, from reserve area to forward area, in the case of carton from rack picking
$t_{REF\ p}$	Unitary pallet refill time, from reserve area to forward area, in the case of carton from pallet picking
$t_{ref\ c}$	Unitary carton refill time, from pallet to rack
H_i	Number of cartons refilled simultaneously from pallet to rack for item *i*
$t_{PICK\ c}$	Unitary picking time in the case of carton from rack picking
$t_{PICK\ p}$	Unitary picking time in the case of carton from pallet picking

$t_{TRAV\ p}$	Single order line processing time in the case of carton from pallet picking
$L_{c,i}$	Carton frontal dimension
$L_{p,i}$	Pallet frontal dimension
$D_{c,i}$	Carton depth
$D_{p,i}$	Pallet depth
$H_{c,i}$	Carton height
$H_{p,i}$	Pallet height
$V_{c,i}$	Carton volume
$V_{p,i}$	Pallet volume
$W_{c,i}$	Carton weight
W_{ct}	Threshold for carton weight
$q_{c,i}$	Number of cartons available in the forward area for item *i* in the case of carton from rack picking
$q_{ct,i}$	Minimum number of cartons to put in the forward area for item *i* to make the carton from rack picking more convenient than the carton from pallet one
$q_{p,i}$	Number of cartons available in the forward area for item *i* in the case of carton from pallet picking

Table 2.9. Notations.

2.3.2 Mathematical modelling: carton picking time

As far as manual warehouse picking is concerned, there are several factors that can usually influence the outcomes of a picking tour. One of the most widespread and proven ways of describing and evaluating a warehouse picking system is to consider the time spent in processing a picking order, assuming that any action to reduce such time can lead to an improvement of the overall performance (Gu et al., 2010; Tompkins et al., 2010). For the study presented in this paper, the various time components involved in the picking process, in the case of cartons from both pallet picking and rack picking, have been considered and compared. Table 2.10 reports the different time elements that have been proposed for the analysis, together with some illustrations that can facilitate the comprehension of both picking scenarios. The considered activities are:

(1) Pallet refill from reserve area to forward area: the pallet is moved with a forklift from the bulk storage area to the fast picking area; the time needed depends on the average number of cartons picked per order Q_i (as already introduced in Paragraph 2.2) and the number of cartons available in the forward area ($q_{c,i}$ in the case of picking from a rack, $q_{p,i}$ in the case of picking from a pallet).

(2) Cartons refill from pallet to rack: the warehouse operators put the cartons in the racks for subsequent picking; the time needed depends on the average number of cartons picked per order Q_i, divided by the number of cartons refilled simultaneously H_i.

(3) Carton picking: the pickers do the actual physical pick of the carton while processing the picking orders; again, the time needed depends on the average number of cartons picked per order Q_i

(4) Travel: the pickers move from one stocking location to another while processing the manual picking orders; the corresponding time is proportional to the number of picking lines requiring the product i in the considered time period Z_i

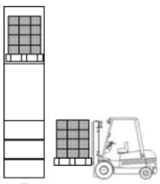
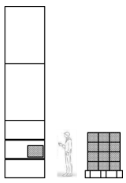
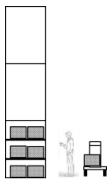
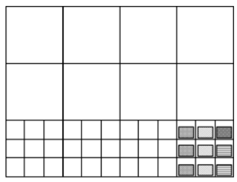
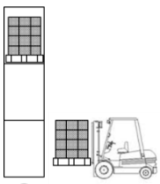
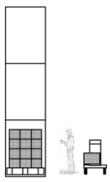
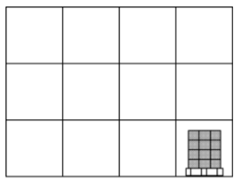
	① Pallet refill from reserve to forward	② Carton refill from pallet to rack	③ Carton picking	④ Travel
CARTON FROM RACK PICKING	$t_{REF\ c} \cdot \frac{Q_i}{q_{c,i}}$  ①	$t_{ref\ c} \cdot \frac{Q_i}{H_i}$  ②	$t_{PICK\ c} \cdot Q_i$  ③	$t_{TRAV\ p} \cdot \frac{L_{c,i}}{L_{p,i}} \frac{H_{c,i}}{H_{p,i}} Z_i$  ④
CARTON FROM PALLET PICKING	$t_{REF\ p} \cdot \frac{Q_i}{q_{p,i}}$  ①	~	$t_{PICK\ p} \cdot Q_i$  ③	$t_{TRAV\ p} \cdot Z_i$  ④

Table 2.10. Carton picking time factors.

Of course, while in the case of picking a carton from a rack all the listed activities are present, in the case of picking a carton from a pallet the second activity is not required.

Considering the time factors introduced, as reported also in Table 2.10, it can be derived that the total picking time in the case of picking a carton from a rack turns out to be the sum of all the four time factors:

$$T_{c,i} = t_{REF\ c} \cdot \frac{Q_i}{q_{c,i}} + t_{ref\ c} \cdot \frac{Q_i}{H_i} + t_{PICK\ c} \cdot Q_i + t_{TRAV\ p} \cdot \frac{L_{c,i}}{L_{p,i}} \frac{H_{c,i}}{H_{p,i}} Z_i \quad (2.12)$$

In the case of picking a carton from a pallet, the times considered lead to the following formula for the total picking time:

$$T_{p,i} = t_{REF\ p} \cdot \frac{Q_i}{q_{p,i}} + t_{PICK\ p} \cdot Q_i + t_{TRAV\ p} \cdot Z_i \quad (2.13)$$

In order to estimate the possible convenience of picking a product from a rack compared with picking it from a pallet, the two considered global times, $T_{c,i}$ and $T_{p,i}$, can be put in a ratio, obtaining the so-called Carton Pick from rack Convenience Index (*CPCI*), calculated for a certain product code *i*:

$$CPCI_i = \frac{T_{c,i}}{T_{p,i}} \quad (2.14)$$

In this way, it is easy to assess whether it is more convenient to pick a certain product from a rack than from the pallet, since it is sufficient to verify the following condition:

$$CPCI_i = \frac{T_{c,i}}{T_{p,i}} < 1 \quad (2.15)$$

By substituting the proposed times and by imposing the *CPCI* condition, the previous formula becomes:

$$\frac{t_{REF\ c} \cdot \frac{Q_i}{q_{c,i}} + t_{ref\ c} \cdot \frac{Q_i}{H_i} + t_{PICK\ c} \cdot Q_i + t_{TRAV\ p} \cdot \frac{L_{c,i}}{L_{p,i}} \frac{H_{c,i}}{H_{p,i}} Z_i}{t_{REF\ p} \cdot \frac{Q_i}{q_{p,i}} + t_{PICK\ p} \cdot Q_i + t_{TRAV\ p} \cdot Z_i} < 1 \quad (2.16)$$

At this stage, it is possible to make some algebraic elaborations. First of all, it has been hypothesized that

$$t_{REF\ c} = t_{REF\ p} = t_{REF} \tag{2.17}$$

and the easily demonstrable relation that follows is assumed:

$$\frac{q_c}{q_p} = \frac{L_{c,i}}{L_{p,i}} \frac{H_{c,i}}{H_{p,i}} \tag{2.18}$$

From this, it can also be obtained that

$$q_{p,i} \cdot \frac{L_{c,i}}{L_{p,i}} \frac{H_{c,i}}{H_{p,i}} = q_{c,i} \tag{2.19}$$

Then, the main formula becomes

$$\frac{\dfrac{q_{p,i}}{q_{c,i}} + \dfrac{q_{p,i} \cdot \dfrac{t_{ref\ c}}{H_i} + q_{p,i} \cdot t_{PICK\ c} + t_{TRAV\ p} \cdot \dfrac{Z_i}{Q_i} \cdot q_{c,i}}{t_{REF}}}{1 + \dfrac{q_{p,i} \cdot t_{PICK\ p} + t_{TRAV\ p} \cdot \dfrac{Z_i}{Q_i} \cdot q_{p,i}}{t_{REF}}} < 1 \tag{2.20}$$

This can be elaborated as follows:

$$\frac{q_{p,i}}{q_{c,i}} - 1 < \frac{q_{p,i} \cdot t_{PICK\ p} + t_{TRAV\ p} \cdot \dfrac{Z_i}{Q_i} \cdot q_{p,i} - \left(q_{p,i} \cdot t_{PICK\ c} + q_{p,i} \cdot \dfrac{t_{ref\ c}}{H_i} + t_{TRAV\ p} \cdot \dfrac{Z_i}{Q_i} \cdot q_{c,i}\right)}{t_{REF}} \tag{2.21}$$

At this point, one can introduce the ratio

$$R_{c/p,i} = \frac{t_{PICK\ c} + \dfrac{t_{ref\ c}}{H_i}}{t_{PICK\ p}} \tag{2.22}$$

Hence,

$$\frac{q_{p,i}}{q_{c,i}} - 1 < \frac{q_{p,i} \cdot t_{PICK\ p} \cdot (1 - R_{c/p,i}) + t_{TRAV\ p} \cdot \dfrac{Z_i}{Q_i} \cdot (q_{p,i} - q_{c,i})}{t_{REF}} \tag{2.23}$$

After some further mathematical elaborations, the following final relation is obtained:

$$\frac{Q_i}{Z_i} < \frac{t_{TRAV\,p}}{t_{REF}} \cdot \frac{q_{c,i}}{\left(1 - \frac{q_{p,i} q_{c,i}}{q_{p,i} - q_{c,i}} \cdot \frac{t_{PICK\,p}}{t_{REF}} \cdot (1 - R_{c/p,i})\right)} \tag{2.24}$$

in which $q_{p,i}$, considering (2.19) and $x_i = \frac{L_{p,i}}{L_{c,i}} \frac{H_{p,i}}{H_{c,i}}$, can be substituted with $x_i \cdot q_{c,i}$:

$$\frac{Q_i}{Z_i} < \frac{t_{TRAV\,p}}{t_{REF}} \cdot \frac{q_{c,i}}{\left(1 - \frac{x_i}{x_i - 1} \cdot q_{c,i} \cdot \frac{t_{PICK\,p}}{t_{REF}} \cdot (1 - R_{c/p,i})\right)} \tag{2.25}$$

This last expression represents the general convenience condition for a carton from rack picking with respect to a carton from pallet picking, here called *CPCC*, the Carton Pick from rack Convenience Condition. This is a comparison that involves the average number of cartons picked for a single order Q_i/Z_i, the number of cartons stored in the forward area for the product *i* in the case of cartons from rack picking $q_{c,i}$, the refill time t_{REF}, the single picking line processing time in the case of pallet storage $t_{TRAV\,p}$, the actual pick from pallet time $t_{PICK\,p}$ and the ratios $R_{c/p,i}$ and x_i. This formula represents a very synthetic and effective way of evaluating the possibility of storing a certain item for carton from pallet picking versus carton from rack picking. In particular, assuming such a comparison is true, the corresponding item can be stored on racks; otherwise, it is more suitable to consider the storage of the product on pallets.

Specific cases

Starting from the CPCC obtained in the previous section, some particular but realistic cases can be presented, leading to a simplification of formula (2.25).

For example, in the case that picking an item from a pallet and picking it from a rack require the same time $t_{PICK\,c} = t_{PICK\,p}$, and considering $\frac{t_{ref\,c}}{H_i} \cong 0$ (for example, because the number of cartons picked simultaneously during the refill activity H_i is much higher than the time needed for this activity $t_{ref\,c}$), it can be obtained that $R_{c/p,i} = 1$. Hence, the *CPCC* formula becomes

$$\frac{Q_i}{Z_i} < \frac{t_{TRAV\,p}}{t_{REF}} \cdot q_{c,i} \tag{2.26}$$

Another simplification is possible when the two picking times $t_{PICK\,c}$ and $t_{PICK\,p}$, in addition to being equal to each other, are equal also to the unitary carton refill time from pallet to rack ($t_{PICK\,c} = t_{PICK\,p} = t_{ref\,c}$), and when the specific item is refilled from pallet to rack a carton at time ($H_i = 1$). In fact, in this case the $R_{c/p,i}$ ratio is equal to 2, and the *CPCC* consequently turns out to be

$$\frac{Q_i}{Z_i} < \frac{t_{TRAV\,p}}{t_{REF}} \cdot \frac{q_{c,i}}{\left(1 + \frac{x_i}{x_i - 1} \cdot q_{c,i} \cdot \frac{t_{PICK\,p}}{t_{REF}}\right)} \tag{2.27}$$

2.3.3 Parametrical analysis

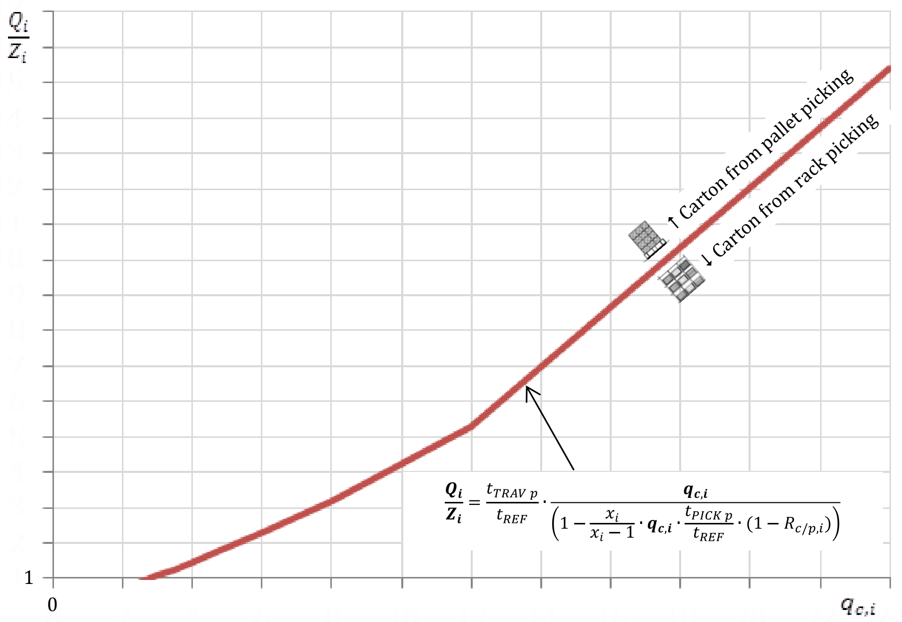


Figure 2.10. Example of CPCC frontier

Since the formula of the Carton Pick from rack Convenience Condition (*CPCC*) puts into relation the average number of cartons picked per picking line Q_i/Z_i to the number of cartons available in the forward area for that product code $q_{c,i}$, it is possible to display this mathematical expression also in a graph. In fact, considering a generic warehouse, in which several different products are stored, with various physical and commercial characteristics, it can be useful to have a unique report that shows the items' different features in order to understand how to store all these products. In particular, the graph has to report the *CPCC* as a convenience threshold, and hence as a line on the plot area. Then, products that are placed below the *CPCC* line should be stored on racks, while those that turn out to be above this line should be stored in pallets (Figure 2.10).

As can be seen from the formula of the *CPCC* (2.25), the profile and the position of the convenience threshold depend on the values of the times ($t_{TRAV\,p}$, t_{REF}, $t_{PICK\,p}$) and on the value of $\frac{x_i}{x_i-1}$ and $R_{c/p,i}$. For example, when $R_{c/p,i} = 1$ (corresponding to one of the specific cases presented in the previous paragraph), the *CPCC* threshold is represented by a straight line (indicating a linear relationship between $q_{c,i}$ and Q_i/Z_i). For this reason, the following analysis shows some of the possible behaviours that can characterize the *CPCC* frontier according to the values that can be assumed by the different parameters (Figure 2.11). The y-axis of the graphs starts from $Q_i/Z_i = 1$ since all the values that are lower than this threshold are not relevant for the analysis. In fact, in a picking context, the average number of cartons picked per picking list (Q_i/Z_i) is obviously always at least equal to 1, meaning that the picker picks only one carton of the product *i* per picking tour (so each time the picker stops in front of the corresponding picking location he picks only one carton of that product).

The analysis shown considers the variation of the three variable parameters that characterise the CPCC formula: $t_{REF}, t_{TRAV\,p}$ and $R_{c/p,i}$. In particular, for $R_{c/p,i}$ the displayed values refer to the values of $t_{PICK\,c}$, $t_{PICK\,p}$ and H_i as reported in Table 2.11.

		$t_{PICK\,p}$		
H_i	$t_{PICK\,c}$	8	12	16
1	8	2.00		1.00
	12	3.00	2.00	1.50
	16			2.00
2	8	1.50	1.00	0.75
	12		1.50	
	16	3.00	2.00	1.50
5	8	1.20		
	12		1.20	
	16			1.20

Table 2.11. $R_{c/p,i}$ values varying $t_{PICK\,c}$, $t_{PICK\,p}$ and H_i

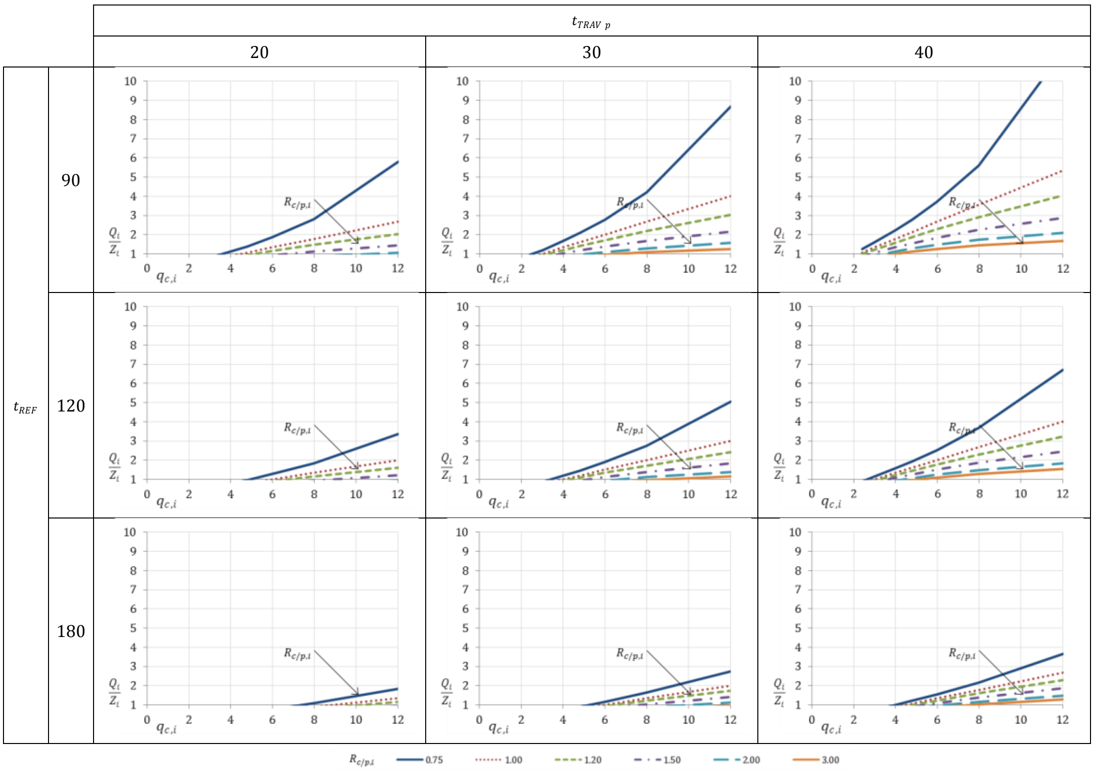


Figure 2.11. CPCC frontier parametrical analysis, varying t_{REF}*,* $t_{TRAV\ p}$ *and* $R_{c/p,i}$

Figure 2.11 shows that changing the single order line processing time in the case of cartons from pallet picking $t_{TRAV\ p}$ leads to a shift of the *CPCC* threshold: by increasing $t_{TRAV\ p}$ the *CPCC* threshold moves upwards. In fact, if the time needed to retrieve a general product code from a warehouse in which the items are stored in pallets is higher, it is logical that the convenience of picking cartons from the rack area becomes greater. On the contrary, increase of the unitary pallet refill time from the forward area to the reserve area t_{REF} makes picking the cartons from pallets more convenient, with a lowering of the *CPCC* threshold.

Finally, by varying $R_{c/p,i}$, it is possible to see that with the increase of this parameter the *CPCC* threshold moves down, always becoming more flat when $R_{c/p,i} > 1$. In fact, for these values of $R_{c/p,i}$ the carton from rack convenience area becomes very small and refers only to products that are picked with a few cartons per time (low values of Q_i/Z_i). Moreover, from Figure 2.11 it can be seen that for $R_{c/p,i} = 1$ the CPCC threshold is represented by a straight line. Then, considering fixed the value of $R_{c/p,i}$, it can be observed that the position of the threshold is influenced more by the change in the values of t_{REF} than of $t_{TRAV\ p}$.

2.3.4 Carton picking convenience full procedure

Starting from the Carton Pick from rack Convenience Condition introduced and studied in the previous section, a decision making procedure is proposed here. Figure 2.12 shows the full procedure, which considers the obtained result as a criterion for the decision concerning the item storing mode, comparing the carton from pallet picking with the carton from rack picking.

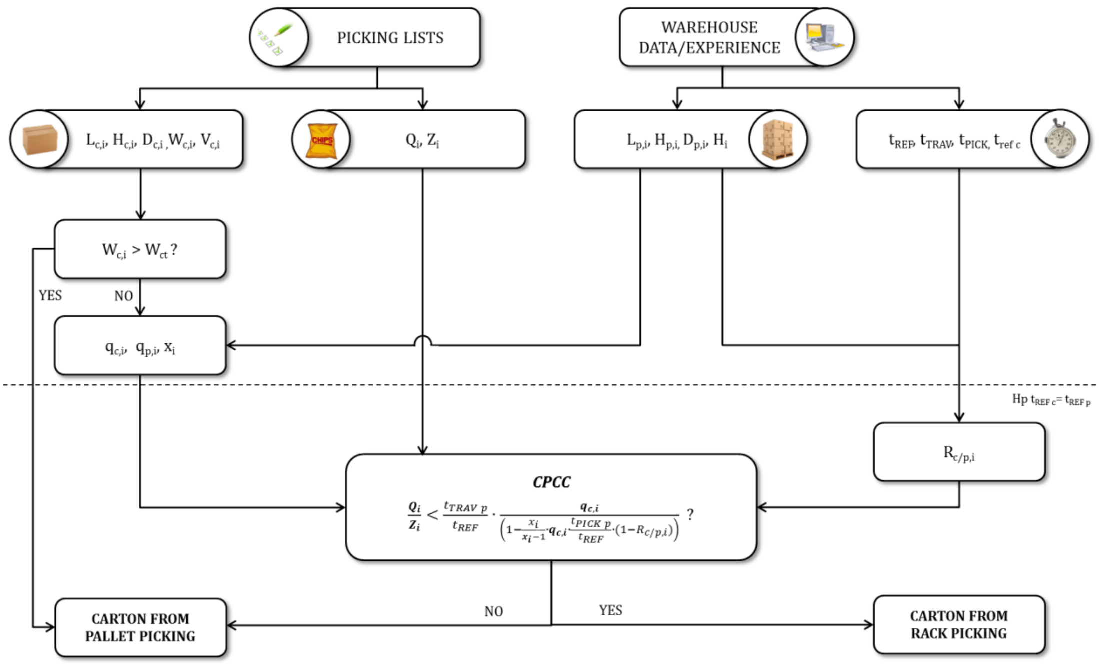


Figure 2.12. Carton picking convenience procedure considering CPCC

The main necessary input data come from the picking lists and from the warehouse characteristics or the user's experience. From the picking lists it is possible to obtain (or compute):

- the carton information: frontal dimension $L_{c,i}$, depth $D_{c,i}$, height $H_{c,i}$, weight $W_{c,i}$ and volume $V_{c,i}$;
- the item information: number of picking rows Z_i processed in the analysed time period and number of cartons Q_i picked in the same time range.
- Starting from either the warehouse characteristics or the user's experience, there can be the extraction (or the assumption) of:
- the pallet information: frontal dimension $L_{p,i}$, depth $D_{p,i}$, height $H_{p,i}$, as well as the number of cartons that are eventually packed together in the

pallet, corresponding also to the number of cartons refilled simultaneously for item i H_i;

- the time data: unitary refill time t_{REF}, single order line processing time $t_{TRAV\ p}$, picking time t_{PICK} and unitary carton refill time from pallet to rack $t_{ref\ c}$.

Once all these data are known, the first step to perform is to check the weight. In fact, if the weight of the carton of the considered product is greater than the carton weight that has been chosen as a threshold, for example, taking as a reference a specific ergonomic requirement (Waters et al., 1993), it is suggested to pick the corresponding item directly from pallets instead of putting its cartons on the racks, in order to avoid a double movement of heavy objects, to refill the racks and then to process the picking order (Calzavara et al., 2015; see also Chapter 4). If the weight is less than this threshold, however, the procedure continues with the calculation of $q_{c,i}$, $q_{p,i}$ and x_i, which are, respectively, the number of cartons available in the forward area in the case of carton from rack picking and in the case of carton from pallet picking, and their ratio. Then, before calculating the Carton Pick from rack Convenience Condition (*CPCC*), it is necessary to determine the value of the ratio $R_{c/p,i}$. Once all the factors are known, the *CPCC* (2.25) can be applied, in order to establish the best picking mode for every product code: if the comparison is true, the cartons of the corresponding item can be stored on racks; otherwise, the product has to be picked directly from a pallet.

Full procedure application in a case study

The proposed case study deals with a warehouse of a major supermarkets supplier, where various kinds of food and non-food products are stored. The analysis concerns the picking mode decision for 11,343 different product codes. Table 2.12 reports all the general data that have been calculated or assumed for the application of the procedure introduced in Figure 2.12.

After applying the weight threshold limit $W_{ct} = 20$ kg, the number of items that have to be put directly in a carton from pallet picking mode is 156, while those that can be further analysed total 11,187. In particular, for each of these last product codes, the parameters $q_{c,i}$ and $q_{p,i}$ can be calculated with:

$$q_{c,i} = \frac{D_p}{\sqrt[3]{V_{c,i}}} \tag{2.28}$$

$$q_{p,i} = \frac{V_{p,i}}{V_{c,i}} \tag{2.29}$$

assuming that these approximations are acceptable for the desired analysis.

Parameter	Value
t_{REF}	120 s
$t_{TRAV\ p}$	30 s
$t_{PICK\ p}$	10 s
L_p	800 mm
D_p	1200 mm
W_{ct}	20 kg

Table 2.12. Input values

$\frac{x_i}{x_i - 1}$ \ $R_{c/p,i}$	1.0-1.1	1.1-1.2	1.2-1.3	1.3-1.4	1.5-1.6	1.9-2.0	Total
1-2	468	61	22	5	13	10,608	11,177
2-3	2					2	4
3-4						4	4
4-5						2	2
Total	470	61	22	5	13	10,616	11,187

Table 2.13. Classification of the products according to $R_{c/p,i}$ and $\frac{x_i}{x_{i-1}}$

Then, in order to continue the study, the ratios $R_{c/p,i}$ and $\frac{x_i}{x_{i-1}}$ have to be calculated for each product. In fact, both these parameters vary according to the characteristics of the product but, at the same time, they influence the trend of the *CPCC* frontier. It follows that the various products cannot be studied all together; however, the items can be grouped exactly according to their values of $R_{c/p,i}$ and $\frac{x_i}{x_{i-1}}$. A summary of the results obtained for these two parameters is given in Table 2.13, reporting a classification of the various product codes according exactly to their $R_{c/p,i}$ and $\frac{x_i}{x_i-1}$. It can be observed that most of the product codes have $1 \leq \frac{x_i}{x_i-1} < 2$, meaning that x_i is often much higher than 1. Then, there are two main groups of items: one group of 468 items having $1 < R_{c/p,i} \leq 1.1$ and another one of 10,608 codes having $1.9 < R_{c/p,i} \leq 2$. As a consequence, the proposed analysis continues with the focus on these two main groups of product codes.

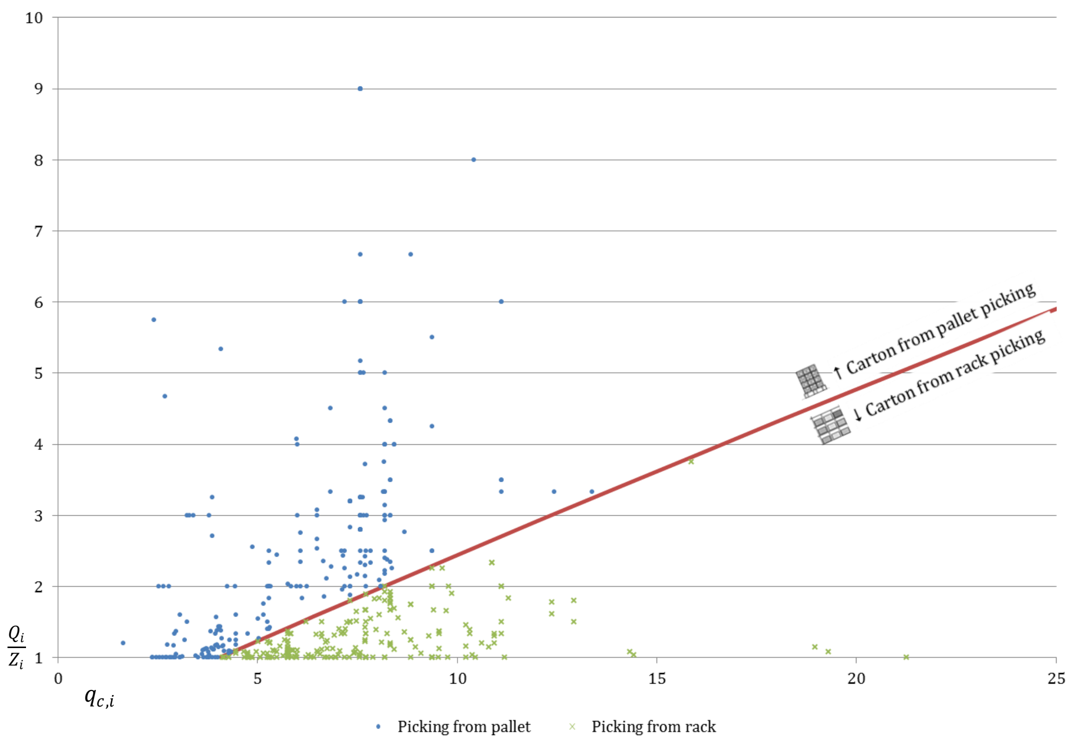
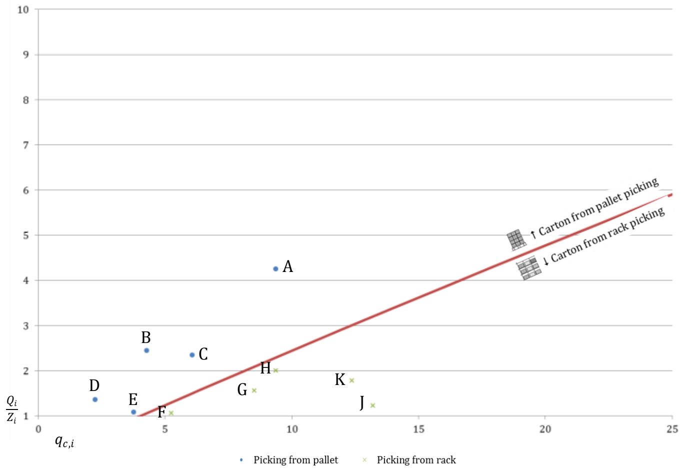


Figure 2.13. Application of the procedure to the products having $1 \leq \frac{x_i}{x_i-1} < 2$ *and* $1.0 < R_{c/p,i} \leq 1.1$

Figure 2.13 shows the application of the *CPCC* to the first group made up of 468 items, having $1.0 < R_{c/p,i} \leq 1.1$. For each one of the product codes, characterised by a specific value of $q_{c,i}$ and of Q_i/Z_i, there is a corresponding point on the graph. The figure is focused on the area of the graph that includes the *CPCC* frontier, which is the line shown. It can be seen that, since $R_{c/p,i} \cong 1$, the *CPCC* frontier is very similar to a straight line. The 227 products that turn out to be positioned under the *CPCC* frontier are those that can be stored for carton from rack picking, while the other 241 that are positioned above the line are more suitable to be picked directly from the pallet. In Figure 2.14 some examples of both kinds of products (for pallet picking and for rack picking) are reported: besides their $q_{c,i}$

and Q_i/Z_i values, their position on the plot and a generic description are shown.



	Product	$q_{c,i}$	Q_i/Z_i	Picking mode
A	LED bulb	9.37	4.25	Pallet
B	Microfibre cloth	4.29	2.44	Pallet
C	School diary	6.08	2.35	Pallet
D	Anatomic pillow	2.24	1.35	Pallet
E	Nylon ladle	3.78	1.08	Pallet
F	Pencil with eraser	5.24	1.06	Rack
G	Cotton gloves	8.53	1.56	Rack
H	Squared notebook	9.37	2.00	Rack
J	DVD+R	12.38	1.78	Rack
K	Boxcutter	13.21	1.22	Rack

Figure 2.14. Examples of products having $1 \leq \frac{x_i}{x_i - 1} < 2$ *and* $1.0 < R_{c/p,i} \leq 1.1$

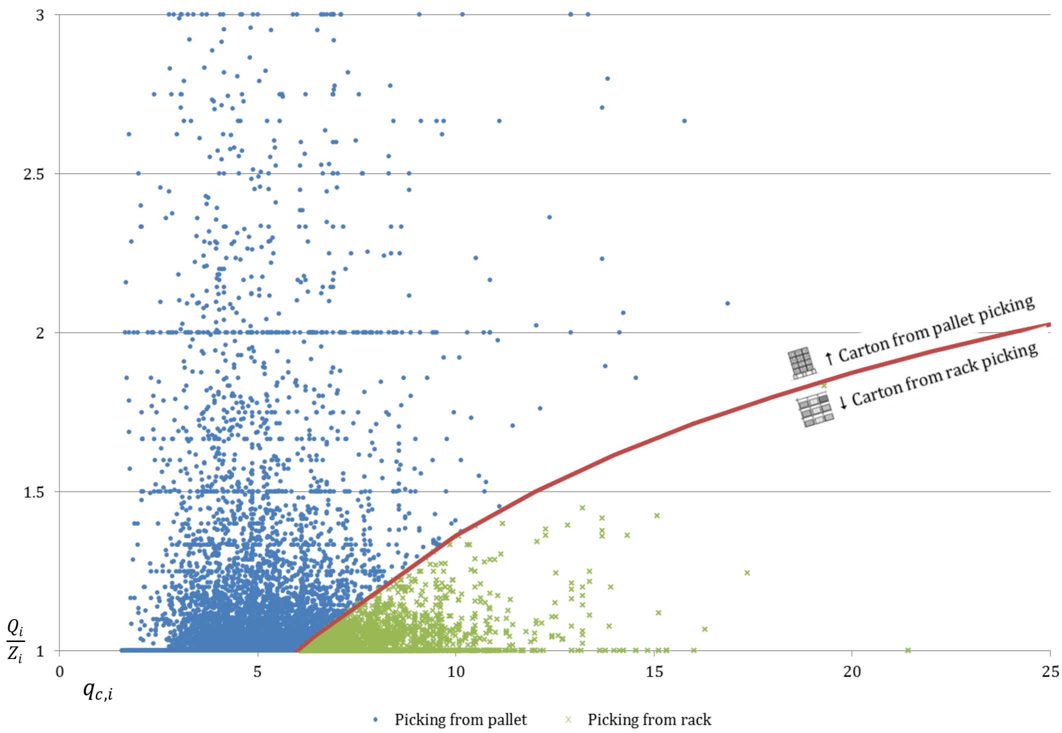
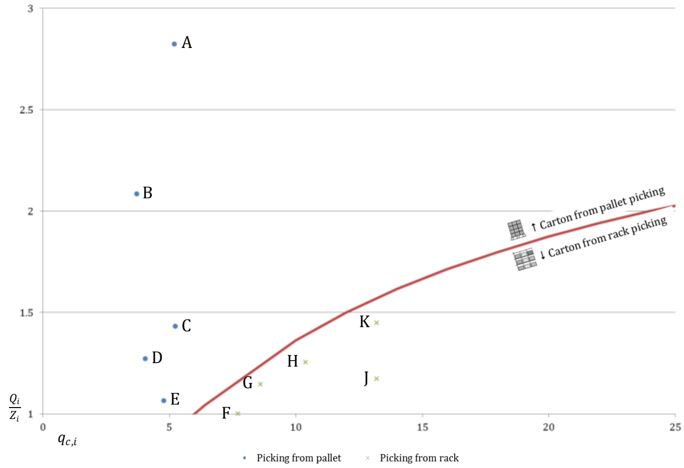


Figure 2.15. Application of the procedure to the products having $1 \leq \frac{x_i}{x_i - 1} < 2$ *and* $1.9 < R_{c/p,i} \leq 2.0$

Figure 2.15 reports the same analysis, performed for the group of 10,608 products having $1.9 < R_{c/p,i} \leq 2.0$. In this case, too, the figure is focused on the area of the graph with the *CPCC* frontier. The products whose results are above the *CPCC* frontier and that can be picked directly from the pallet number 8,032, while the products that can be stored on the racks and picked from them total 2,576. Some of these products are proposed as an example in Figure 2.16.



	Product	$q_{c,i}$	Q_i/Z_i	Picking mode
A	White flour	5.20	2.82	Pallet
B	Apricot jam croissant	3.72	2.08	Pallet
C	Body wash	5.24	1.43	Pallet
C	Laundry detergent	4.06	1.27	Pallet
E	Peeled tomatoes can	4.79	1.07	Pallet
F	Face cream	7.73	1.00	Rack
G	Chocolate bar	8.62	1.15	Rack
H	AA batteries	10.39	1.25	Rack
J	Roll-on deodorant	13.21	1.17	Rack
K	Chewing gum	13.21	1.45	Rack

Figure 2.16. Examples of products having $1 \leq \frac{x_i}{x_{i-1}} < 2$ *and* $1.9 < R_{c/p,i} \leq 2.0$

2.3.5 Discussion of results

The case study presented in the previous section can offer some interesting insights about the results obtained as well as on the general application of the method. From the analysis of the graphs reported in Figure 2.13 and Figure 2.15, it can be highlighted that a great number of the items analysed, with a weight $W_{c,i} < 20\ kg$, are characterised by a $Q_i/Z_i < 1.5$, meaning that every time the warehouse operators pick such products the number of picked cartons is very low, typically 1 or 2. Many products (4,048 items) even have exactly $Q_i/Z_i = 1$. This also represents an important confirmation of what has been pointed out as a common and recent trend in picking warehouses, in which customers are requiring ever smaller quantities per product (De Koster et al., 2007; Lu et al., 2015).

As far as the *CPCC* frontier is concerned, it can be seen that in the case of $1.0 < R_{c/p,i} \leq 1.1$ it intersects the x-axis for $q_{c,i} \cong 4$, while for $1.9 < R_{c/p,i} \leq 2.0$ the intersection is for $q_{c,i} \cong 6$. Since $q_{c,i}$ is the number of cartons available in the forward area, it follows that the products that are more suitable for carton from rack picking are those that have a medium-small carton volume, hence, medium-small average carton physical dimensions and that are picked in small quantities per picking list (right-bottom area of the graph). Then, the convenience threshold has an increasing trend, since the convenience of putting the product in racks with respect to pallets increases if the item has a higher $q_{c,i}$, hence, it has a smaller volume and it occupies a smaller space in the warehouse, even if it is averagely picked at a higher number of cartons per time (higher values of Q_i/Z_i).

Considering the cases reported in Figure 2.14, it emerges, for example, that the products E and F, having a very similar Q_i/Z_i, are more suitable to be stored in two different ways: the nylon ladle, with a lower $q_{c,i}$, can be picked from the pallet, the pencil with eraser ($q_{c,i} = 5.24$) from the rack. On the other hand, although the products A and H have the same $q_{c,i}$, the first one has to be stored in pallets while the second one on racks, since they have a significant difference in the number of cartons required per time (resulting in, respectively, a high and a low value of Q_i/Z_i). Similar differences are reported in Figure 2.16: although the average number of cartons picked per picking tour Q_i/Z_i is very similar for almost all the proposed products, the way they have to be stored for picking is different, considering their $q_{c,i}$, and hence, their volume.

Nevertheless, it is fundamental to underline that the *CPCC* frontier and the two consequent areas of the graph that have been identified depend strongly on the input times t_{REF}, $t_{TRAV\ p}$ and $t_{PICK\ p}$, which can normally be considered as general parameters of the warehouse. As shown in the parametrical analysis of Section 2.3.3, provided that the time needed to perform a pallet refilling is substantially higher than the single order line processing time, the carton from rack picking area is interesting and can involve a significant number of storable items. If this ratio decreases, however, the carton from rack picking convenience turns out to affect only a few items. In fact, although the presented method proves to be very effective as well as easily applicable, it requires particular attention to the way the input data are obtained and managed. This is especially true in the case of the refill time t_{REF} of the single order line processing time $t_{TRAV\ p}$ and of the unitary picking time $t_{PICK\ p}$.

Furthermore, the convenience study presented in this paper could be applied also in another interesting way. In fact, once all the other characteristics of the warehouse and of a certain analysed product are known, from the *CPCC* formula it is possible to calculate a so-called "threshold $q_{c,i}$", $q_{ct,i}$, representing the minimum number of cartons that have to be put in the forward area to make the carton from rack picking more convenient than the carton from pallet picking:

$$q_{ct,i} = \frac{Q_i/Z_i}{\frac{Q_i}{Z_i} \cdot \frac{x_i}{x_i - 1} \cdot \frac{t_{PICK\,p}}{t_{REF}} \cdot (1 - R_{c/p,i}) + \frac{t_{TRAV\,p}}{t_{REF}}} \tag{2.30}$$

Finally, it is important to point out that the application of such a procedure in a picking warehouse can lead to important benefits in terms of the volume occupied by the items, avoiding useless waste of warehouse space. As a consequence, this reduction leads to a decrease of the average distances that are travelled by the picking operators, with an important positive impact on the overall warehouse performance (Tompkins et al., 2010; Thomas and Meller, 2015).

2.4 Conclusions

In a manual picker-to-parts picking warehouse, travel time represents the 50% of the total time needed to process a picking order (Tompkins et al., 2010): any action that aims at reducing this major time component can soon lead to great benefits for the overall performances of a picking system. Indeed, in the years several researches have focused on the proposal of methods and procedures useful to decrease both travelled distances and, hence, travel time.

Chapter 2 contributed to this research scope with the introduction of two important design techniques. Paragraph 2.2 has presented the new SA&TDE (Storage Assignment and Travel Distance Estimation) joint method: a basic procedure that gives some guidelines in picking warehouse design and warrants great benefits in terms of reducing travelled distances and, hence, improving picking orders processing efficiency, as far as manual picker-to-parts picking is concerned. The model consists of considering the various inputs that could affect picking performances and evaluating the best configuration with a synthetic parameter. Such factor, the total travelled distance *L*, is calculated through the application of the multinomial probability distribution to all the possible combinations of product codes that can make up a picking order. Moreover, it has also been shown that the SA&TDE joint method can be easily applied at different levels of detail, by gradual steps, or considering every level independently, simply by aggregating the picking orders accordingly, and it is valid also for different routing policies, such as the traversal and the return one. The SA&TDE joint method represents an interesting guide for picking systems design, considering simultaneously the effects of storage assignment and routing policy on the distances the operators have to travel to process the different picking orders, representing a possible solution for a crucial problem that has been pointed out from several researches: the need of a full procedure for manual picking systems design (Rouwenhorst et al. 2000; De Koster et al., 2007; Gu et al., 2010).

Subsequently, Paragraph 2.3 has introduced a new synthetic decision making procedure that can be used to understand how to store all the various products that are in a picking warehouse. In particular, it refers to the choice between storing a product in pallets or in racks within the forward area. Starting from the times needed to perform both kinds of picking, which depend on simple and easily obtainable item and warehouse information, the so-called Carton Pick from rack Convenience Condition (CPCC) has been formulated. After having proposed a parametrical analysis, the full design procedure has been described. Moreover, the application of the new method has been shown in a real industrial case study, dealing with a food and non-food picking warehouse of a big supermarkets supplier. The proposed procedure turned out to be particularly interesting since it is easy and fast to apply; furthermore, it can be suitable for several different contexts, concerning warehouse manual picking as well as assembly lines feeding picking.

2.5

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3

SEARCH AND PICK TIME REDUCTION

"To reduce the time needed to pick items once the picker is at the correct storage rack, a task guidance system can be used."

Guo et al., 2014

3.1

Highlights and Problem outline

Although, over the years, different automated solutions for order picking have been proposed and studied (Bozer and Cho, 2005; Lehrer et al., 2006; De Koster et al., 2007), the most widespread solutions are still based on manual picking, characterized by a high human factor impact. Such aspect becomes even more crucial considering the manufacturing and warehousing recent trends of high flexibility and efficiency in processing orders that are always smaller and needed in very short turnaround time (De Koster et al., 2007; Dallari et al., 2009). For this reason, it could be interesting to focus the researches on the improvement of warehouse manual picker-to-parts picking, and in particular on picking orders processing time reduction and on picking accuracy improvement, in order to warrant higher efficiency and effectiveness (Hsieh and Tsai, 2006; Grosse et al., 2015). One of the possible strategies to obtain some benefits in this sense is the adoption of a paperless order picking system (De Koster and Van Der Poort, 1998; Baumann et al., 2012).
In this chapter the topic of paperless picking is faced in Paragraph 3.2 through the description of the project that has led to the development of a new integrated system, the *RFID pick-to-light system*. Then, in Paragraph 2.4, a method useful for the *technical and economical comparison of different paperless picking technologies* is reported.

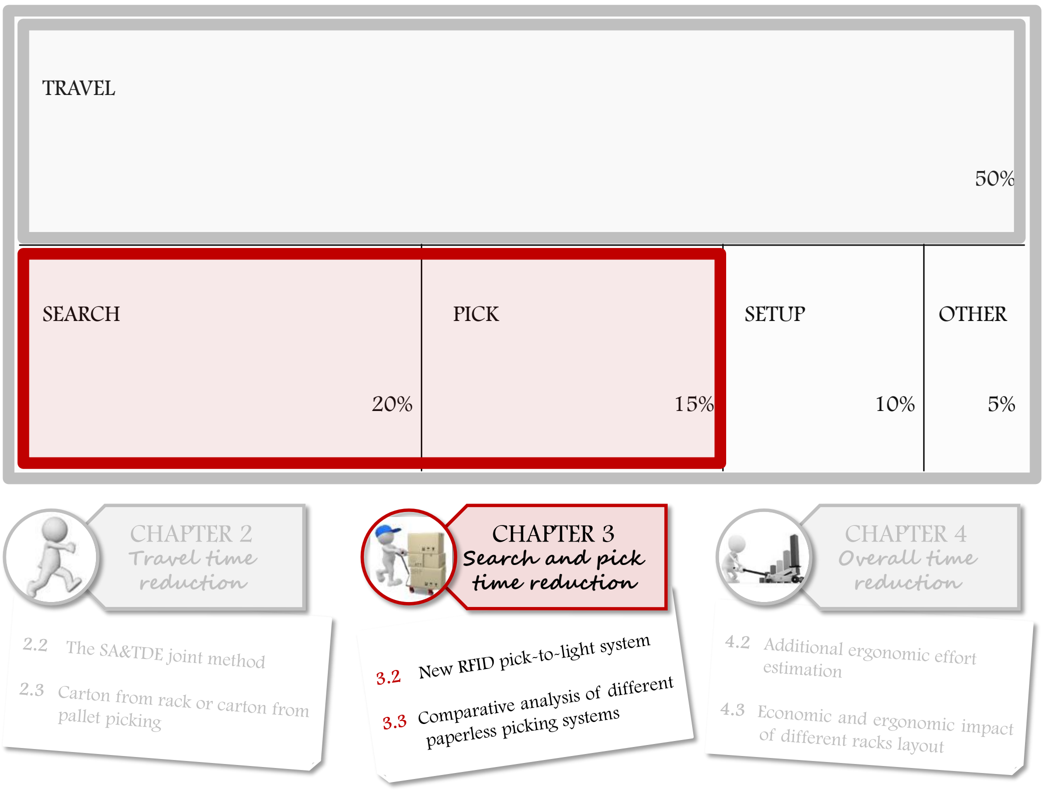


Figure 3.1. Research framework: Search and pick time.

3.1.1 Actions for search and pick time reduction

Considering that most of the order picking systems are characterised by manual activities performed by human operators, a possible approach for increasing the productivity of order picking systems could focus on pickers' productivity, in terms of reducing the time needed to fulfil an order, and also the reduction of possible errors (Grosse and Glock, 2013; Grosse et al., 2013). In the recent study by Grosse et al. (2015), "Proposition 1" underlines the importance of investigating other objectives besides travel time minimisation in an order picking system. In particular, the need to develop studies that focus on picking error reduction is pointed out, including, for example, consideration of the precise possible trade-offs between the cost of investment in paperless information technology and the return on investment from reduced picking errors. Furthermore, according to De Koster and Van Der Poort (1998) and Poon et al. (2009), paperless order picking systems can be a useful strategy to obtain benefits in an order picking warehouse, as validated also in the case studies of some authors in the literature (Berger and Ludwig, 2007; Reif et al., 2010; Yeow and Goomas, 2012). All these studies have concluded that a possible solution that would reduce picking errors and hence improve picking performances is the adoption of paperless picking technologies. According to Frazelle (1988) and Tolliver (1989) the adoption of a computer-aided system for manual order picking can actually simplify the tasks of human pickers. For example, it has been estimated that a light-directed picking system with automated data entry can reduce human error by 95% as well as increase productivity by 10%.

A paperless picking system is constituted of a set of devices designed and adopted to facilitate and expedite the work of the operators, mostly in terms of getting information on the product to be picked and finding the corresponding storage location (De Koster and Van Der Poort, 1998; Gleißner and Möller, 2011; Guo et al., 2014). The most traditional paperless order picking can be via mobile, handheld or with terminals and printers that are vehicle-mounted. However, a new frontier of paperless picking is represented by the use of important devices that have been developed to speed up picking activities and to avoid picking errors, such as LED displays or digital screens, voice-activated devices (voice picking), wireless appliances and lighting systems (pick-to-light). Pickers and warehouse staff are connected online with the warehouse information system, enabling updated stock information, immediate reactions to particular situations and the real-time monitoring of operational status, leading to an overall productivity increase.

Moreover, once the decision to adopt a paperless system in a picking warehouse has been taken, the action that follows is the establishment of the technology that best fits the needs of the particular context being considered. In this sense, it is important to perform an accurate evaluation, which takes into account the technological characteristics of all the different systems, their practical features as well as their economic impact. Guo et al. (2014) proposed a study comparing three different paperless picking systems with traditional paper picking, while Iben et al. (2009) focused on the performances of different picking systems. However, very few contributions have reported evaluations of the economic aspects of the adoption of such solutions (Baumann et al., 2012; Baumann, 2013).

This chapter is organized in two main sections. Paragraph 3.2 describes a new pick-to-light system, developed by me and other three Ph.D. students in Industrial Plants and Logistics of the University of Padua (Alessandro Andriolo, Umberto Peretti, Francesco Pilati), that relies on RFID (Radio Frequency Identification), a technology that has recently achieved the deserved success in various warehouse applications, especially in managing and controlling the flow of products through the whole supply chain (Lee et al., 2010; Chen et al., 2013). Similarly to traditional pick-to-light systems, the new system drives an operator through the various storage locations he has to visit by using different kinds of lighting devices that can send clear light signals; these lights can be turned on or off according to the picking list. Moreover, in the new system the lights are of different colours, and they are linked to a control system able to recognize whether the operator, who is wearing a particular glove containing a UHF RFID reader, is accessing the right storage location or not and to alert him with a set of visual (and/or acoustic) signals, preventing him from completing the wrong picking action. In order to understand the potential of the new system, this is also compared to other existing technologies.

Subsequently, Paragraph 3.3 presents a comparative analysis of different paperless picking systems, and considers how the different characteristics of the devices impact on the picking time and on the error possibility. In particular, this analysis is conducted by means of a promising method based on the study of the hourly costs related to each paperless picking solution. The developed cost function allows to take into account the systems' different characteristics, such as the technology employed, the fields of application, their performance and their limits, together with the different picking error probabilities. Such a model can be used in a number of industrial contexts to help arrive at the most suitable paperless picking solution, taking into account the characteristics of the employed devices and of the warehouse. To better explain its applicability, the new model is also validated in a case study, which concerns two different warehouse configurations.

Before continuing with the presentation of the methodologies of the next two paragraphs, in the following a general description of some of the existing paperless picking technologies is reported.

3.1.2 Paperless picking systems state of the art

Thanks also to the availability of new technologies, and to their consequent affordability also in industrial contexts, in the recent years different kinds of paperless picking devices have been invented and developed. These systems typically differ in terms of applied technology, and, therefore, of possible level of automation (Gleißner and Möller, 2011). Among all the existing systems, the ones here described are: *barcode handheld scanner* and *barcode ring scanner*, *RFID handheld scanner*, *pick-to-voice*, *pick-to-light*, *head-mounted device*, *fully automated system*.

One of the first devices adopted to facilitate the picking process, and also one of the best known paperless picking systems is certainly the barcode scanner handheld. The operator uses it to confirm his pick, through the scanning of the barcode tag which is put on the various stock locations of the warehouse, corresponding to the different stocked items. Handhelds are often able to emit acoustic signals, too: this feature generally helps the user to understand whether the scanner has correctly read the barcode, but it can also be used to provide notification that the product scanned is exactly what the picker was expected to take. Moreover, the picking information can immediately be communicated to the warehouse information system. Although such system can be used also together with paper picking lists, the recent trend is to integrate the lists directly with the handheld device, so that once an item has been picked, the screen of the handheld device shows the following product to take (Guo et al., 2014). Moreover, an interesting evolution of barcode scanners is represented by the so-called Zebra ring scanner, a particular barcode scanner that can be put on one finger of the operator, so that he has both hands free to perform the picking activities in an easier and more efficient way (Zebra website, accessed on 14 July 2015).

Recently, handheld radio frequency identification (RFID) scanners have also become available. The operating principle of RFID scanners is similar to that of barcode scanners, except that the SKUs or the stock locations are tagged with RFID passive tags instead of barcodes. The working frequency is mostly LF (Low Frequency) or HF (High Frequency); hence, the tags are detectable at small reading distances of the handheld device (Baudin and Rao, 2005; Hou and Huang, 2006; Karagiannaki et al., 2011). Nevertheless, some recent solutions are also proposing an operation at Ultra High Frequency (UHF).

In addition, and sometimes also as an alternative to such systems, other examples of task guidance technologies have been developed. They are often referred to as *poka-yoke* (literally 'mistake-proof') solutions, because they perfectly reflect the principle according to which, in order to avoid mistakes, it is important to eliminate every chance of their happening (Baudin and Rao, 2005). The most widespread techniques are voice picking, also called pick-to-voice, and pick-to-light.

A voice picking system is a voice-directed device that uses speech recognition to allow warehouse operators to communicate with the warehouse management system. Pickers are equipped with a headset and a microphone to receive instructions about the picking by voice, and then to verbally confirm their actions back to the warehouse system (Berger and Ludwig, 2007, Matopoulos, 2011). The warehouse operator, for example, reads back the last digits of the code corresponding to item he has picked so that the system can check whether the correct item has been selected, then it can give the next instruction.

On the other hand, in a pick-to-light system operators are guided by lights that are installed on the warehouse shelving. Each stock location has one light that turns on if the operator has to pick a corresponding product from that location. In order to complete every single pick, the picker usually has to press the button of the relevant stock location and, in some cases, he also has to scan the barcode of the picked item. If more than one picker in the same warehouse area needs to work simultaneously, such system has to be integrated with paper picking lists, with digital displays or with handhelds, so that every picker can understand which lights are turned on for his or her order. A possible evolution of the traditional pick-to-light is represented by the employ of the RFID technology (Friedlos, 2011), while the simultaneous work of several pickers in the same area is possible for example through the adoption of particular systems, like the one presented in a German patent in 2009 (Kusen et al., 2009).

Another recent frontier for warehouse manual picking is represented by special glasses or head-mounted displays that can be worn by the operator and that report on the lenses all the needed information, making the picking activity easier (Iben et al., 2009; Weaver et al., 2010; Guo et al., 2014). Finally, some companies are proposing automated pick-to-light configurations, in which picker's activities are fully assisted: even the progress and the stops of the picking cart are guided by the composition of the order (Baumann, 2013).

3.2 New RFID pick-to-light system: operating characteristics and potential

Warehouse manual picking is traditionally characterized by a high human factor impact, which derives that improving such a system requires a reduction of both orders processing time and human possible errors. In this sense, a possible strategy can be the development and employment of technological systems able to support operators during their picking tours. The aim of this study is to present a new pick-to-light design solution capable of driving different operators through their activities, preventing or reducing errors by a new real-time control and alert system, based on the main potentialities of the RFID technology. After the description of the technical characteristics and of the operation of the new solution, a qualitative comparison with other existing paperless picking systems is also proposed.

3.2.1 Project steps

The project for the development of the new RFID pick-to-light system has involved me and other four Ph.D. students (Alessandro Andriolo, Umberto Peretti, Francesco Pilati) for about one year (Andriolo et al., 2013). Figure 3.2 reports the main steps that have characterized our activity, reflecting also the structure of the present paragraph.

First of all, it has been performed an important context characterization, starting from the analysis of the currently available technologies able to support warehouse picking activities, continuing with a gap analysis of the existing systems and then concluding with the study of the possible basic technology useful to be employed in the new system. Subsequently, it has been defined the possible structure and the configuration of the new RFID pick-to-light system, thinking on its possible operating characteristics. Then, in order to get the effective potential of the new system, it has been realized a prototype, which has been used also for some important tests that fostered the understanding of the new system strengths and weaknesses. The results of the tests and the critical analysis of the new system have also been useful to set the comparison of the system to other already existing solutions from a qualitative point of view, together with the proposal of some possible system applications.

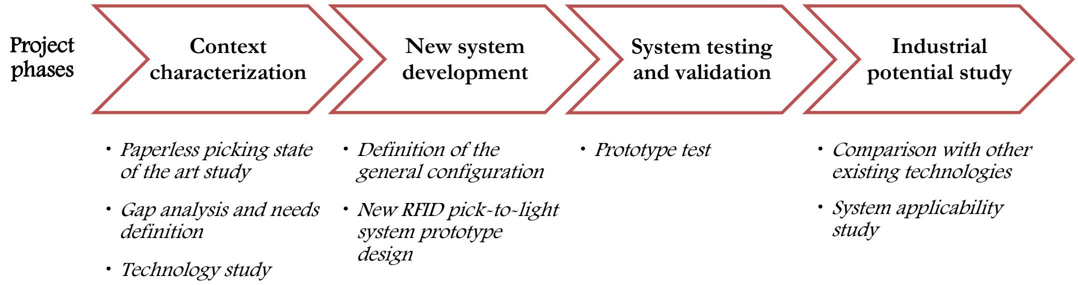


Figure 3.2: Project steps

3.2.2 Context characterisation

Gap analysis and needs definition

From the state of the art analysis reported in Paragraph 3.1, it is possible to notice that the existing technologies are often lacking of some smart characteristics that can justify their full and wide application. For example, although they are well widespread in industry, the scanners solutions have the problem that the picker has to keep the handheld in hand, with a consequent lower picking efficiency. Both the pick-to voice and the traditional pick-to-light systems, instead, allow the performing of the picks with both hands, but, while the first one can potentially lead to the reduction of its benefits slowing down the overall picking activity (Baumann, 2013), the second one requires the pressing of the buttons to confirm the picks of the products (Park, 2012). The head-mounted systems are still in a first phase of development; their possible fields of application, together with their limits, are still not so clear (Jäckel, 2013). Finally, the fully automated solutions have the great problem of leading to rigid configurations, also requiring high economic efforts.

Starting from the analysis of the existing systems and considering the main needs that generally characterize warehouse picking activities, a list of different targets has been pointed out, which have been considered as the main drivers to follow in the development of the new solution (Table 3.1 and Figure 3.3). In particular, the identified objectives belong to three different categories: there are targets that reflect the main desires of the business staff, some targets that concern the practical operation of the system and some other ones that refer to technological aspects. As far as the first category is concerned, the two main criticalities of warehouse picking have been considered: the need of reducing the picking time (De Koster et al., 2007; Tompkins et al., 2010) together with the need of controlling the possible errors while performing the picking of the items (Berger and Ludwig, 2007; Reif et al., 2010; Grosse et al., 2015). Furthermore, the functional targets that should be achieved by the new system concern:

- its ease of implementation, therefore without the requirement of extreme investments in terms of time and resources;
- its wide applicability, that is, the possibility of installation in several warehouse contexts, that could differ, for example, for dimension, for the kind of products stored and/or for the way the products are stored within (Park, 2012);
- its ease of use by the warehouse operators; the more the system is intuitive, the more the time needed for training the picker is reduced.

The last reported targets category is focused on the technology that should be employed in the definition of the system. In particular, it has been highlighted the essential need of exploiting an existing and stabilized technology, easily available on the market and, therefore, easily usable in industry. Moreover, the need of warranting an easy applicability in industry leads also to the definition of the last reported target, that is, the development of a system that does not require excessive economic efforts. Finally, as far as the economic aspect of the system is concerned, it is important to underline that, of course, such system has to be sustainable from an economic point of view. That is, the cost of the whole system (for example purchase, installation, management, maintenance) does not have to be higher than the benefits and the economic advantages that such system can lead to.

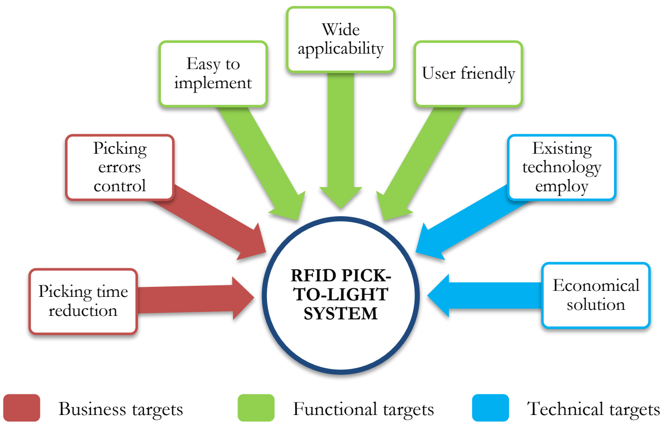


Figure 3.3. Drivers for the new system definition.

Type	Description	Details
BUSINESS TARGETS	Picking time reduction	Need of a system able to speed up picking activity, mainly acting on some picking time components (search time, actual pick time).
	Picking errors control	Need of a system able to prevent (or at least limit) picking mistakes, through a proper control system.
FUNCTIONAL TARGETS	Ease of implementation	The system has to be easy to install, and also in an already existing warehouse.
	Wide applicability	The system has to be applicable in different warehouse contexts.
	User friendly	The system has to be intuitive, not requiring a relevant training effort.
TECHNICAL TARGETS	Existing technology employ	In the development of the system it is important to refer to the existing available technology, in order to warrant its easy spread in industry.
	Economical solution	The system should not require a high investment in terms of costs.

Table 3.1. Definition of the different objectives for the new paperless picking system.

Technology study

The choice of the most proper technology for the new system has been driven by the needs already detailed in the previous sections. In particular, it has been observed that RFID (Radio Frequency Identification) technology can perfectly meet such requirements. First of all, it represents a widespread technology that has been already successfully applied in industry for various applications (Raza et al., 1999; Zhu et al., 2012). Among the others, one of the main advantages of RFID is that it does not require the direct contact or the perfect alignment between the reader and the tags to retrieve the needed information that are stored in the tags (Baudin and Rao, 2005). According to the context of operation, the tags can store data related to the products but also, more simply, a unique serial number that creates the connection to the actual data in a database, which can be easily accessed even with a wireless connection (Battini et al., 2009). Finally, the employ of passive tags can lead to the development of economical but, at the same time, very effective practical applications (Dobkin, 2012).

In fact, the transponders can be of two types: active or passive. The first ones have an own power supply (a battery) that enables them to transmit at higher power levels, hence to be read and written at greater distances (also over 100 m). On the contrary, passive tags obtain their energy from the electromagnetic field of the reading device, so they are very small and economical, and, hence, easily usable also when their application requires the presence of a high number of tags. A RFID system can differ in terms of the frequency range in which it operates, too. In particular, there are three worldwide established frequencies: Low Frequency (LF), < 135 kHz, High Frequency (HF), 13.56 MHz and Ultra High Frequency (UHF), between 850 and 960 MHz. Every frequency is more suitable for some applications than for others: when a RFID project is under development it is important to perfectly understand what are its needs (Zhu et al., 2012). Low Frequency systems are well-suited to industrial use, above all when working near metals and water is required. High Frequency systems are characterised by greater ranges and higher reading speeds. The simultaneous reading of multiple tags is possible, but it could be influenced by the presence of metal objects. For warehousing and goods tracking, UHF systems are more suitable: they enable very high data transfer rates and long ranges (up to six meters), even if signals typically do not pass through most of the materials (Miles et al., 2008; Dobkin, 2012). The basic principle, however, is that full advantages of RFID are obtained when the application, the manufacturing process and the supply chain are considered as a whole (Weinstein, 2005; Karagiannaki et al., 2011; Busato et al., 2013). In warehousing and manufacturing passive tags and UHF readers are the most widespread; this certainly happens because passive tags are very cheap and versatile. They are often used as an alternative to barcodes, but with better performances. In particular, they have a high reading capacity without needing of line-of-sight and a good writing/modifying capacity for storing data. According to Baudin and Rao (2005) it is possible to obtain more benefits in the contexts in which a high rate of scanning is needed, hence, where warehouse operators or workers have to scan a lot of tags in a very short time, exactly as in the case of warehouse order picking. Hence, for the development of the new paperless picking system it has been chosen to adopt RFID technology working at UHF with passive tags. An example of pick-to-light using RFID has already been presented in 2011 in the RFID Journal (Friedlos, 2011). In the reported test case, RFID readers are installed at some points beneath the conveyor belt, while RFID passive tags are attached to the plastic buckets in which workers place the products required to fulfil the orders. When the bucket reaches an RFID reader point on the conveyor belt, this sends a signal turning on the lights of the required products, so that the operator can easily and quickly identify them.

3.2.3 New RFID Pick-to-light system development

Presentation of the general configuration

The background idea of the solution presented in this paper is the desire to create a pick-to-light system able to drive the picker through the locations he has to visit in a smart as well as simple way. In particular, the main objective is to exploit the benefits of RFID technology, according to which there is no need of direct contact between the reader and the tag to obtain the information stored in the tag. Another important aspect that has been considered is to give the picker a RFID reader that does not need to be kept in hand, so that he can perform the picks using both hands. To do this, a wearable RFID reader is needed. The best found solution is to provide the operator with a particular glove containing the RFID reader. Some examples of similar solutions have been already developed, for various applications, such as iGlove and iBracelet, invented by the Intel Research Seattle group (Fishkin et al., 2005) or the SCIPIO WInspect Glove proposed by the Technologie-Zentrum Informatik of the University of Bremen, (SCIPIO WInspect Glove Datasheet, 2006). These devices not only are able to interact with unobtrusively tagged objects, but in some cases the glove can also report whether the grasp of the object is with the palm or with the fingerprints. Medynskiy el al. (2007) use a wearable RFID reader for gaming applications. Muguira et al. (2009) propose the RFIDGlove system, consisting of a glove with an integrated RFID reader, an organic micro display and a communication system. They also highline the usefulness of such device for inventory and warehousing activities, as all the movements performed by warehouse operators are completely traced. Lee et al. (2010) created a wireless RFID glove for interactive learning and for a meal aid system useful for blind people. Most of the existing devices can be used with passive tags and work at high frequency (13.56 MHz), which means that the read distances cannot be much larger than 1 meter. The application of a RFID glove in an order picking system has then been presented and studied also by Wölfle and Günthner (2011) as well as by the Fraunhofer institute for factory operation and automation (IFF website, accessed on 14 July 2015). Furthermore, the RFID-enabled glove developed by Deister Electronic GmbH, was initially designed mainly for research purposes, but it was then also appreciated by some practitioners (Collins, 2006). However, all these presented systems do not consider the possible integration of the RFID glove with a pick-to-light system.

As far as the proposed configuration is concerned, it is composed of three main units (Figure 3.4). The first one is a system of lights and tags installed on the shelving, so that every stock location has one UHF passive tag (or more, depending on the available storage room and on the kind of product stored) that identifies that particular stock location, one red light alerting the picker in case he enters the wrong location and as many different coloured lights as the number of pickers that are working at the same time in the same picking area, so that every picker follows only the lights of a particular colour, turned on or off according to the picker's picking list. Even with several pickers working in the same area, it is sufficient to have only one red light in every stock location. This because the red light turns on only if the corresponding location is entered by a picker by mistake, so the picker understands unequivocally that who is wrong is exactly himself. The second unit consists of a wireless UHF RFID reader that every warehouse operator wears thanks to an appropriate glove, so the picker has both hands free and can pick the items he needs in a better and faster way (Grosse et al., 2015). The system of lights installed on the shelving and the reader are managed and controlled by the third component of the configuration, a centralized control system (CCS). The operating principle of the system is reported in the diagram of Figure 3.5, corresponding to the case of a picker which has to follow the blue lights.

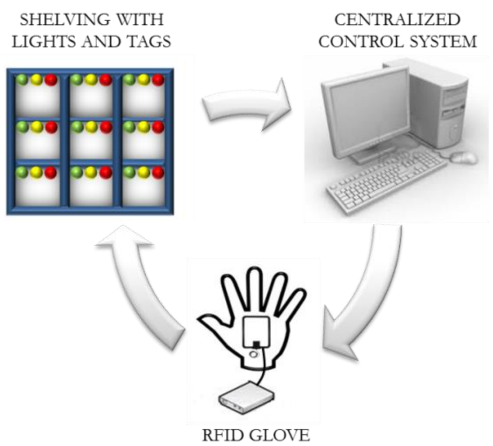


Figure 3.4. RFID pick-to-light system main units

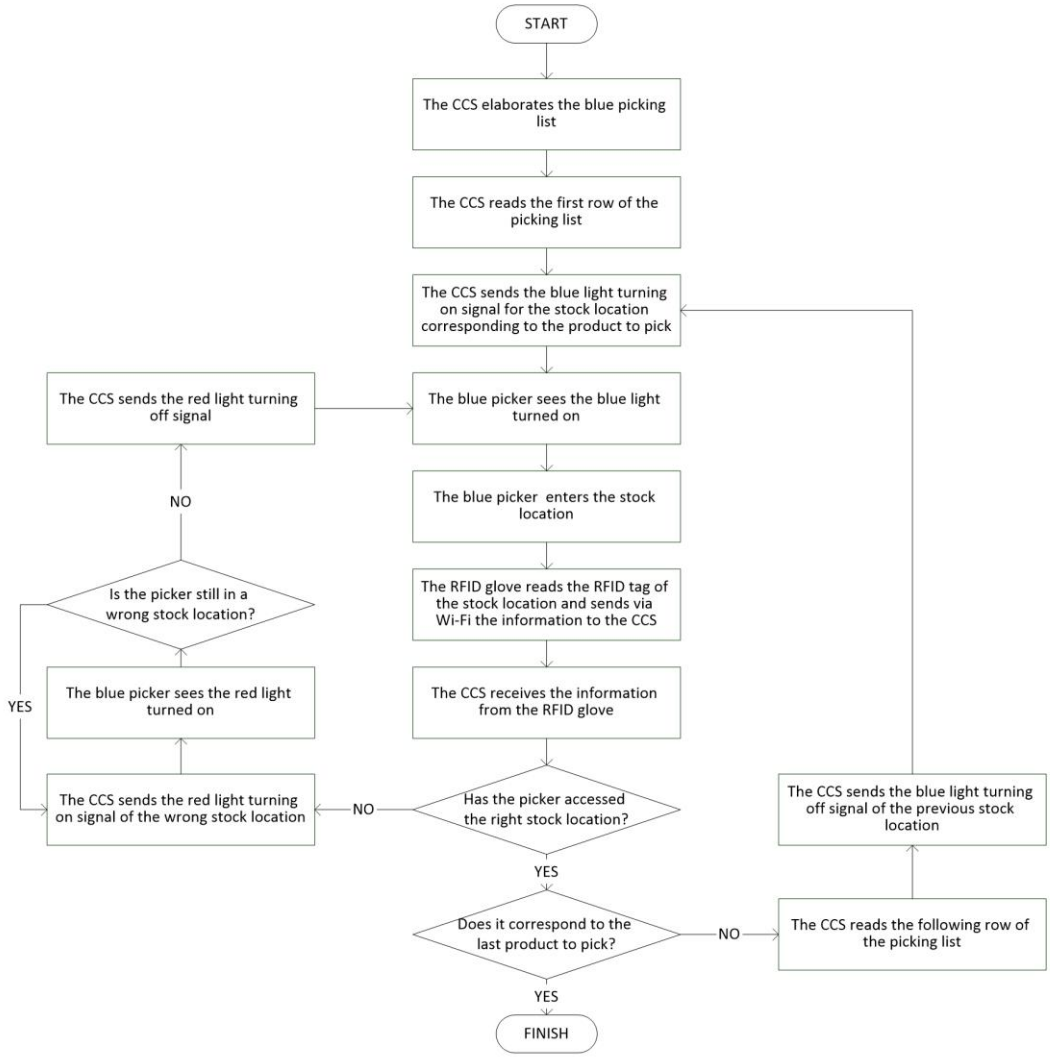


Figure 3.5. Operating flow chart of the new RFID pick-to-light system

The CCS takes as input the various picking lists (one for each picker) coming from the warehouse information system and sends the signals to turn on and off the appropriate lights on the shelving, each colour corresponding to a specific operator. Furthermore, such system is able to monitor the pickers' activities, in order to highlight possible picking errors by turning on red lights. According to the routing policy that is adopted in the warehouse, the light of the first location the picker has to visit is turned on, so that the picker can easily and immediately understand where the item is located. When the picker, wearing the glove that includes the RFID reader, reaches the particular location there are two possibilities: he enters the right stock location or he enters a wrong stock location. In both cases, the reader reads the tag corresponding to the stock location and sends via Wi-Fi the read code to the CCS, that acts accordingly. In case of correct access, once the system has verified that the code received from the RFID reader is the right one, corresponding to the stocking location in which there is the item the operator has actually to pick, it sends the signal of turning off the coloured light of that location (for example, the blue one) and of turning on the coloured light of the following location, corresponding to the following line of the picking list or to the same one, in case of a multiple pick of the same product code (Figure 3.6). In this case, it could be useful to associate an acoustic signal to confirm the correct picking. If the picker makes a mistake in the stock location and tries to pick the wrong item, the CCS receives from the RFID reader a code corresponding to a stock location of a product different from what it expects, and it sends the signal of turning on of the red light for the wrong stock location, so that the picker immediately realizes that he is not in the right place (Figure 3.7). When the operator pulls out his hand from the wrong location the centralized control system does not receive the wrong code from the RFID reader anymore, so the red light is turned off.

It is important to underline that every picker can perform his work independently, as every operator wears his own RFID reader, and the centralized control system can perfectly recognize the different signals coming from the various pickers, hence, is perfectly able to manage separately the different lights. Moreover, tag reading errors can be avoided or adequately controlled through the proper adjustment of the RFID antenna, with the choice of a good position for the RFID tags and with the equipping of the warehouse with a proper metal shelving. The correct reading of the tags can also be warranted by the control system, acting on the received signal.

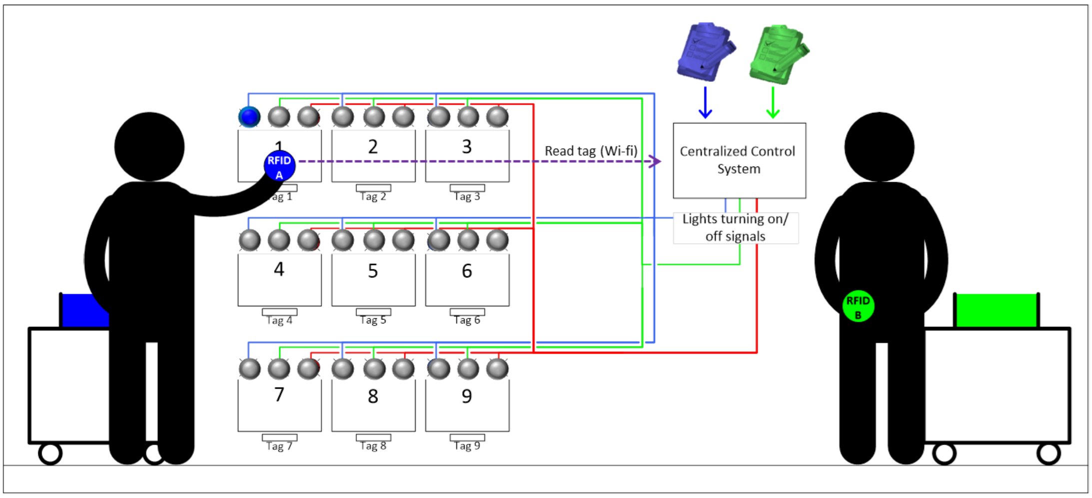


Figure 3.6. Operating scheme of the new RFID pick-to-light system: the picker enters the right stock location.

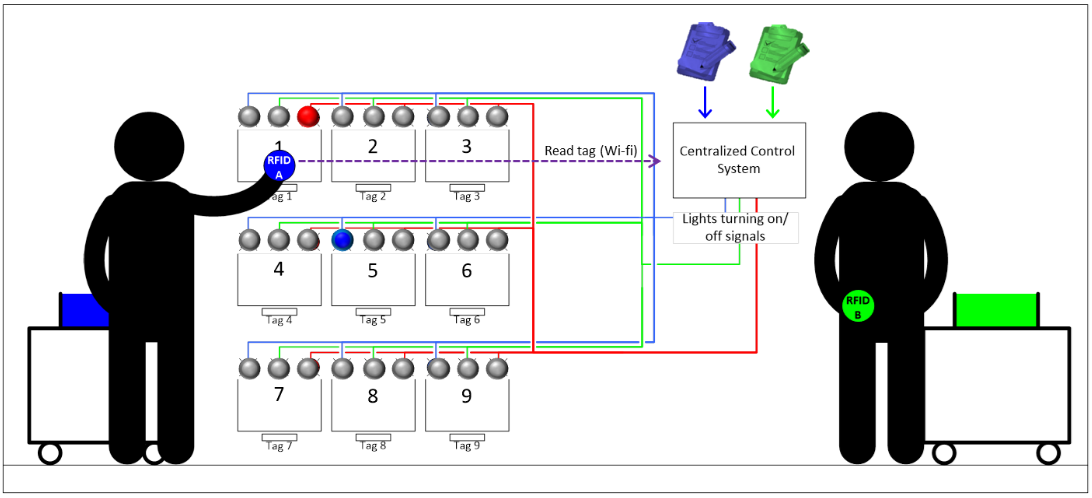


Figure 3.7. Operating scheme of the new RFID pick-to-light system: the picker enters the wrong stock location.

New RFID pick-to-light system prototype design

In order to properly assess the potential of such configuration and to test the various technologies that have been used, a prototype of the new RFID pick-to-light system has been developed, to manage two operators that work simultaneously, in a warehouse with steel shelving and nine stock locations, each of which has three leds, green for the first operator, yellow for the second operator and red to indicate the picking errors. All the leds are connected to a microcontroller that sends the signals of turning on and off of the lights. Every stock location has also one passive tag, used to identify every stock location and, hence, the corresponding products stored. The UHF RFID readers are composed of a wireless reader unit, of a linear polarized UHF antenna and of a 12 V lithium battery (Figure 3.8), and is worn by the operator through a glove, where the antenna is on the upper part of one of his hands and the reader unit is on his forearm, and the battery can be hooked, for example, at his waist. The data read by each reader are sent to a personal computer via Wi-Fi. The PC represents the centralized control system: in addition to receive the information of the RFID readers it has a LabVIEW™ project that has been developed to manage all the control logic. In particular, the program is able to read two different picking lists from a Microsoft Excel™ file and to send the appropriate signals to turn on the green and yellow leds according to the order lines. The RFID readers are interfaced with the LabVIEW™ project through a TCP/IP Socket that receives the information of the read tags as a Wi-Fi input and transmits them to the rest of the LabVIEW™ project. The remaining logic is necessary to compare the tags read by the RFID readers to the order lines of the picking lists, in order to understand whether the picker is picking the right product or not. If the operator picks the right item the system sends to the microcontroller the command of turning off the led corresponding to that product and of turning on the led corresponding to the following line of the picking list. Otherwise, it makes the red led come on to indicate that the picker has entered a wrong stock location.

Figure 3.8. Details of the RFID pick-to-light system prototype (Left: Microcontroller and lights; Middle: stocking location with lights system and RFID tag; Right: operator wearing the RFID glove while entering a stocking location).

Prototype test

The prototype, also characterized by a relatively low overall realization cost, has been used to perform some interesting tests: above all to estimate the possible interferences due to the employ of the UHF RFID technology, but also to evaluate whether the performances of the communication via TCP/IP are acceptable for the application in a picking context. The tests have focused on the picking of different kinds of products by an operator wearing the RFID glove reader, and has revealed that the function is not affected by items containing liquid substances or metal objects. Furthermore, it is exactly the material of the shelving that helps to shield the signal and to avoid wrong tags readings. As far as tags reading and lights turning on and off speeds are concerned, the test has revealed that the data are practically real-time. Table 3.2 reports the scope and the description of the performed tests, together with the obtained results and some comments.

Scope	Description	Results and Comments
UHF RFID Antenna/Picker hand interference	Reading of RFID tags with the RFID glove	The tested antenna is quite affected by the proximity of the picker hand; however, by inserting in the glove a proper shielding the reading distances stay acceptable, up to 20 cm
UHF RFID Antenna/Shelving interference	Picking of objects from a metal shelving with RFID tags, the picker wearing the RFID glove	The metal shelving suitably shields the RFID signal, allowing the RFID glove to read the correct tag, corresponding to the proper stocking location
UHF RFID Antenna/Picked material interference	Picking of metal objects and of products containing liquids from a metal shelving with RFID tags, the picker wearing the RFID glove	The RFID pick to light system is not affected by the well-known operational limits of UHF with liquids and metals, since in the present configuration the RFID glove reads the tag just before the picking of the products
Reading distance	Reading of RFID tags with the RFID glove, progressively distancing the RFID glove and/or the tags	The distance mainly depends on the presence of the picker hand; however, it has been observed that the distances are acceptable for the considered application.
Reading speed	Reading of RFID tags with the RFID glove	The information of the read tag is sent to the centralised control system in real time
RFID reader battery duration	Reading of one RFID tag by the RFID glove with a notification via Wi-Fi to the centralized control system every 2 seconds	In such operating conditions the battery has lasted 9 hours and 30 minutes; it derives that the battery does not represent a critical aspect of the system

Table 3.2. RFID pick-to-light tests summary

In general, from the analysis of the reported prototype tests and of the corresponding results, it turns out that the new RFID pick-to-light system can represent a smart and interesting solution for paperless picking. In fact, the overall proper operation is confirmed by the various performance measurements: the reading of the tags is in real-time, the picked objects do not interfere with the RFID reader reliability and the RFID reader battery life does not represent a working issue. The main open problem concerns the interference arisen between the hand of the operator and the RFID glove: the RFID glove reading range significantly decreases due to the presence of the picker's hand. However, the reading range remains acceptable when the system is employed for small objects picking. On the other hand, in case of picking from pallets or from other bigger containers, it would be necessary to work on the power of the RFID antenna to improve its reading distance. Finally, it is important to underline that the tests refer to a laboratory prototype, developed to test the technology and the effective possibility of connecting the different components of the new RFID pick-to-light system. Consequently, next researches should focus on a further study to understand its applicability in an industrial context.

3.2.4 RFID pick-to-light system potential discussion

Comparison with other existing technologies

The new RFID pick-to-light system has been compared to some existing solutions (barcode scanner handheld, RFID tags scanner handheld, pick-to-voice, traditional pick-to-light, fully automated pick-to-light), considering some technological and practical aspects (Table 3.3 and Figure 3.9). The values reported in Table 3.3 and, then, displayed in the radar plot of Figure 3.9 derive from a qualitative analysis that has been done from the authors considering the evaluation of the usability of the devices, as well as their efficiency and effectiveness, based on the authors' practical experience, on some laboratory tests and on the existing literature (Miller, 2004; Baudin and Rao, 2005; Zhu et al., 2012). The proposed criteria have been grouped according to the main scope they can have impact on, referring to warehouse general characteristics, to the picker and to the device. In particular, these criteria are:

- Flexibility: possibility of easily changing the configuration of the warehouse, in terms of number of operators, items allocation and assignment
- Modularity: ease of increasing or reducing the dimensions of the system, in terms of number of racks and of pickers
- Ease of use: device ease of handling, both in terms of practical usage during the picking and in terms of its real operation understanding
- Picking time: time needed to perform the pick of the products
- Pickers simultaneity: possibility of simultaneous picking by different warehouse operators in the same area
- Environment influence: work environment side effects on the whole picking process

- Reading distance: average distance at which the picked product data are readable from the device
- Errors interception: capability of identifying a picking error

	WAREHOUSE		PICKER			DEVICE		
	Flexibility	Modularity	Ease of use	Picking time	Pickers simultaneity	Environment influence	Reading distance	Errors interception
Barcorde handheld	High (5)	High (5)	High (5)	Medium (3)	Possible (5)	Medium (3)	Few centimete rs (1)	After barcode scanning (3)
RFID tags handheld	High (5)	High (5)	High (5)	Medium (3)	Possible (5)	Medium (3)	Up to 2 m (4)	After tag scanning (3)
Voice picking	High (5)	High (5)	Medium (4)	Medium (3)	Possible (5)	High (2)	Not applicable (0)	After code communicati on (3)
Traditional pick-to-light	Medium (4)	Medium (4)	High (5)	Medium (3)	Difficult (3)	Low (4)	Not applicable (0)	At the end of picking (1)
RFID pick-to-light	High (5)	High (5)	High (5)	Short (5)	Possible (5)	Medium (3)	Up to 2 m (4)	Immediate (5)
Fully automated pick-to-light	Very low (1)	Medium (4)	Medium (4)	Short (5)	Not possible (0)	Low (4)	Not applicable (0)	Immediate (5)

Table 3.3. Comparison of the new RFID pick-to-light system with other paperless picking systems

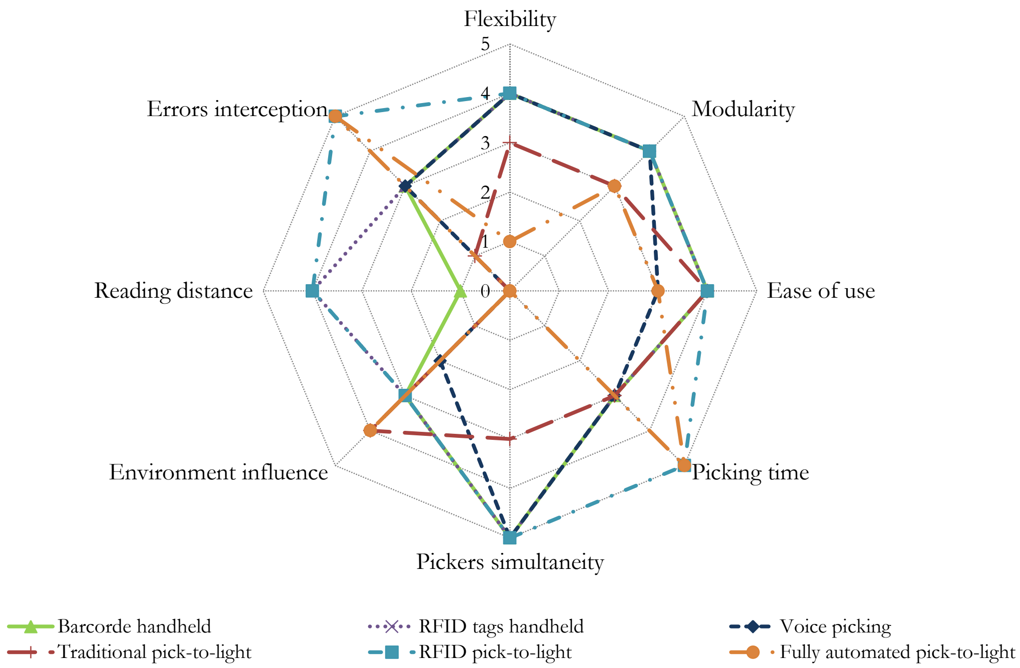


Figure 3.9. Comparison radar plot of the six paperless picking systems (higher scores assigned to positive values of the features)

Each paperless picking technology presents various features, with different strengths and weaknesses (Baudin and Rao, 2005; Zhu et al., 2012). In particular, as far as the impact on the warehouse is concerned, the flexibility of each paperless picking system in terms of number of operators is particularly ensured when every warehouse picker has his own device. The changing in the items assignment and allocation, instead, is easier when the warehouse shelving is equipped with simple systems that can be quickly adapted or programmed (barcode tags and RFID tags). Then, the paperless systems that rely on such tags, as the new RFID pick-to-light system, turn out to be the more flexible ones. Furthermore, all such paperless technologies are also more modular, referring to the meaning that has been presented at the beginning of the paragraph. Focusing on the characteristics that mostly are depending on the picker, since the new RFID pick-to-light configuration does not require for the operator the using of any particular device, it proves to be very easy to use. In fact, the RFID reader is directly integrated within the glove, so the picker has only to focus on the physical picking of the products, without scanning barcodes or, as in the case of the pick-to-voice, without any other kind of picking confirmation (Wölfle and Günthner, 2011). Moreover, given their diffusion in the everyday life, both the barcodes handheld and the RFID tags handheld can be by now considered as familiar devices; on the other side, also a traditional pick to light system is easy to use since the operator activities are typically settled by the turning on and off of the lights. The only system that could be slightly more difficult to use is the voice picking system: it generally requires a particular training in order to understand its actual operation (Helo and Szekely, 2005). The simplicity of the new RFID pick to light system also implies that the picking time is short, because the picking action is just limited to reaching for the required item and to putting it in the picking cart; in other systems, instead, every pick could be associated to other operations, for example the scanning of the barcode or of the RFID tag. The possibility of simultaneous work of more pickers in the same warehouse area depends on the picker equipment and on the shelving hardware: it is possible for barcode and RFID handhelds and for voice picking systems, as well as for the presented RFID pick-to-light system (every stock location has as many different coloured lights as the number of operators working in such area). Working at the same time in the same area can be quite hard, instead, in a traditional pick-to-light system, as for the pickers it is difficult to understand which are the lights that are turned on for him and which are not, even if the most recent pick-to-light solutions have the possibility of mounting more than one light. As far as the performances of the different devices are concerned, in some cases operators' activities can be influenced by the environment they work in. This is particularly true for voice picking, as surrounding noises could prevent a correct communication between the system and the operator of the code to pick and of its following confirmation. Besides, for such systems a wrong pronunciation of the numbers could cause a useless delay in picking activities. Also the scanning of barcodes could have some problems, since it requires a clean, high-contrast environment, and often more than one attempt (Baudin and Rao, 2005). On the contrary, pick-to-light is generally not affected by its context of application. For the RFID pick-to-light system the only issue concerning the application environment could derive from the interference of RFID waves with the shelving, the products stored and with the body of the operator. It is therefore fundamental to carefully study the configuration of the whole system, in order to prevent some side effects and/or take advantage of some other ones. The reading distance of the different solutions varies from the few centimetres of the barcodes to the two metres of the RFID handhelds (particularly the UHF ones) and of the UHF RFID pick-to-light system presented in this paper. This feature can be more or less relevant according to the considered application of the system. For example, the systems that have such a reading distance can be suitable for being applied also for a picking performed directly from pallets (Bartholdi and Hackman, 2011).

Last evaluation criterion proposed in the present analysis is the possibility of recognizing and signalling a picking error. Such feature is definitely crucial considering its possible impact on the overall picking performances (Tompkins et al., 2010; Grosse et al., 2015). In this sense, the best result is obtained by the RFID pick-to-light system, in which the picker can understand right away whether he has picked the right product or not. In case he puts his hand in the wrong stock location, the red light turns on in order to prevent him from completing the wrong picking action. In some other configurations, instead, there is the risk for the picker of discovering picking errors only once the item has been picked, the order is complete, or, even worse, when the order is delivered to the customer.

Finally, another great benefit of the presented pick-to-light solution is that it uses RFID technology and the data are available in real time, since the handheld devices are connected to the centralized control system: this way, it is quite easy to obtain useful data about all pickers' activities, for example the number of picks per hour, that could be used as a starting point for possible improvements of the whole system (Hou and Huang, 2006; Poon et al., 2009).

System applicability

The use of paperless systems for supporting warehouse picking is described in literature as one of the most effective solutions to speed up picking activities and reduce picking errors (Frazelle, 1988; Reif et al., 2010). Moreover, several case studies showing the practical application of such solutions have confirmed their validity, which sometimes is also accompanied by a short payback period (Hou and Huang, 2006; Yeow and Goomas, 2012; Dobkin 2012). However, it is important to highlight that not all paperless picking solutions are appropriate for all the possible warehouse picking needs. In fact, each context could require different configurations and applications, considering also the expected performance and, hence, the possible technological limits. For example, barcode handhelds are easy to use but they could cause some delays during the picking of the items if the barcode is not sufficiently readable by the scanner. Voice picking is widespread since it has no particular limitations concerning both the kind of warehouse and the kind of product stored. On the other side, a fully automated solution is more suitable when the picking activity is quite stable and concerns objects with similar physical volume (Baumann, 2013).

Considering its characteristics, the here introduced RFID pick-to-light system results to be applicable in different warehouse contexts and for different kinds of picking: pallet pick, case pick, and broken-case pick (Park, 2012). Moreover, the great potential of such a system turns out to be fully used in the case of intensive picking in small areas. An example could concern the picking for feeding an assembly line, in which some operators are dedicated to the creation of the assembly components kits accessing the related supermarket warehouse (Battini et al., 2010). However, thanks to the employed technology and to its particular overall configuration, it is important to point out that such a system is perfectly usable also for warehouse picking in wide areas, as demonstrated also by the study reported in Paragraph 3.3.

3.3 Comparative analysis of different paperless picking systems

In recent years, more efficient and better performing systems for manual warehouse picking have been developed, employing various technological solutions that can support human pickers during their work. During the consideration of an investment on a paperless picking solution, it could be useful to rely on a simple instrument that can help the choice of the system that is more suitable for the specific warehouse context.
The present paragraph introduces an evaluation and comparison method, also applying it to five paperless picking systems (i.e. barcodes handheld, RFID tags handheld, voice picking, traditional pick-to-light, RFID pick-to-light). Starting from the operating schemes for the solutions, an hourly cost function is developed, which also takes into account the different errors arising and their probability of occurrence. The validity of the proposed model is also demonstrated through two case studies, corresponding to different warehouse configurations. The proposed approach contributes to the understanding of the performance of different technologies in different application fields; in fact, it turns out that some solutions are more suitable for a low-level warehouse, while other ones bring greater benefits in the case of picking from multilevel shelving.

3.3.1 Notations

Notation	Description
e_i	Error
c_{SL}^{j}	Stock location unitary cost for paperless system j
n_{SL}	Number of available stock locations
h_{SL}	Stock location devices total usage hours
$c_{h,P}$	Picker hourly cost
$c_{d,P}^{j}$	Picker devices cost for paperless system j
$h_{d,P}$	Picker devices total usage hours
n_R	Number of requested picking rows
$\dot{p}^{j}$	Picking rate for paperless system j
c_{E}^{j}	Error unitary cost for paperless system j
$p_{e_i}^{j}$	Occurrence probability for each error e_i

$t_{e_i}^j$	Error time
n_R	Number of requested picking rows
c_F^j	Fixed costs for paperless system *j*
h_F	Fixed elements total usage hours
C_h^j	Total hourly cost for paperless system *j*
$C_{h,SL}^j$	Stock locations hourly cost for paperless system *j*
$C_{h,P}^j$	Picker hourly cost for paperless system *j*
$C_{h,E}^j$	Picking errors hourly cost for paperless system *j*
$C_{h,F}^j$	Fixed hourly cost for paperless system *j*
t_{tot}^j	Total picking time for paperless system *j*
t_{trav}	Travel time
t_{net}^j	Net picking time for paperless system *j*
t_i^j	Time for getting the information of the product to pick for paperless system *j*
t_s^j	Search time for paperless system *j*
t_p^j	Actual pick time for paperless system *j*
t_c^j	Confirm time for paperless system *j*
n	Number of SKUs to pick

Table 3.4. Notations

3.3.2 Working schemes and functional comparison

The analysis starts with the definition of the working schemes of the considered paperless picking systems, with a particular focus on the main activities that are typically performed during the picking process (getting information, searching, picking, confirming). In particular, during such activities different kinds of errors can arise, which, considering the impact of the whole process, can typically be distinguished as 'detectable errors' and 'propagating errors'. The first of these categories can easily be intercepted, since the wrong item confirmation immediately advises the operator and allows the pick to be corrected; however, the second category of error is hidden and, hence, hardly recognizable, leading to further work at the end of the picking tour (Grosse et al., 2013). Table 3.5 shows the errors considered to arise together with their proposed notation and description, and the actions needed to correct them. The four reported errors refer to the most common mistakes that can be made during the picking activity, as indicated in several literature contributions and also validated by the authors' practical experience (Poon et al., 2009; Baumann, 2013; Guo et al., 2014).

Type	Notation	Description	Following actions
Detectable	e_1	Right item picked but wrong item confirmed	Confirmation of the right picked item
	e_2	Wrong item picked and wrong item confirmed	Wrong item stocked and right item picked
Propagating	e_3	Wrong item picked but right item confirmed	Wrong item stocked and right item picked (at the end of the picking tour)
	e_4	Wrong quantity picked	More items picked or extra items stocked (at the end of the picking tour)

Table 3.5.: Possible arising errors during a picking tour.

The usual operation of each of the considered paperless picking technologies has been analysed in order to identify a possible working scheme by which the four different actions are reported, together with the behaviour of the different picking errors (Figure 3.10). The sequence of the actions is always the same for all the systems; the only thing that eventually changes is related to the possibility of the simultaneous performance of some of them. In particular, for the barcode and RFID handhelds, all the activities from getting the information to the picking confirmation are done consecutively; however, for the voice picking system the physical picking and the confirmation are done together, because the operator can confirm the pick into the microphone while doing the other action. In the case of a traditional pick-to-light system, the information about the product to pick and the search of the stock location represent a unique activity since turning on the light allows the needed information to be immediately obtained and the right stock location to be identified. Furthermore, for the RFID pick-to-light system, the picking activity is also simultaneous with the confirmation since the RFID glove worn by the picker communicates with the centralised control system during the physical pick, without any further action being required by the picker.

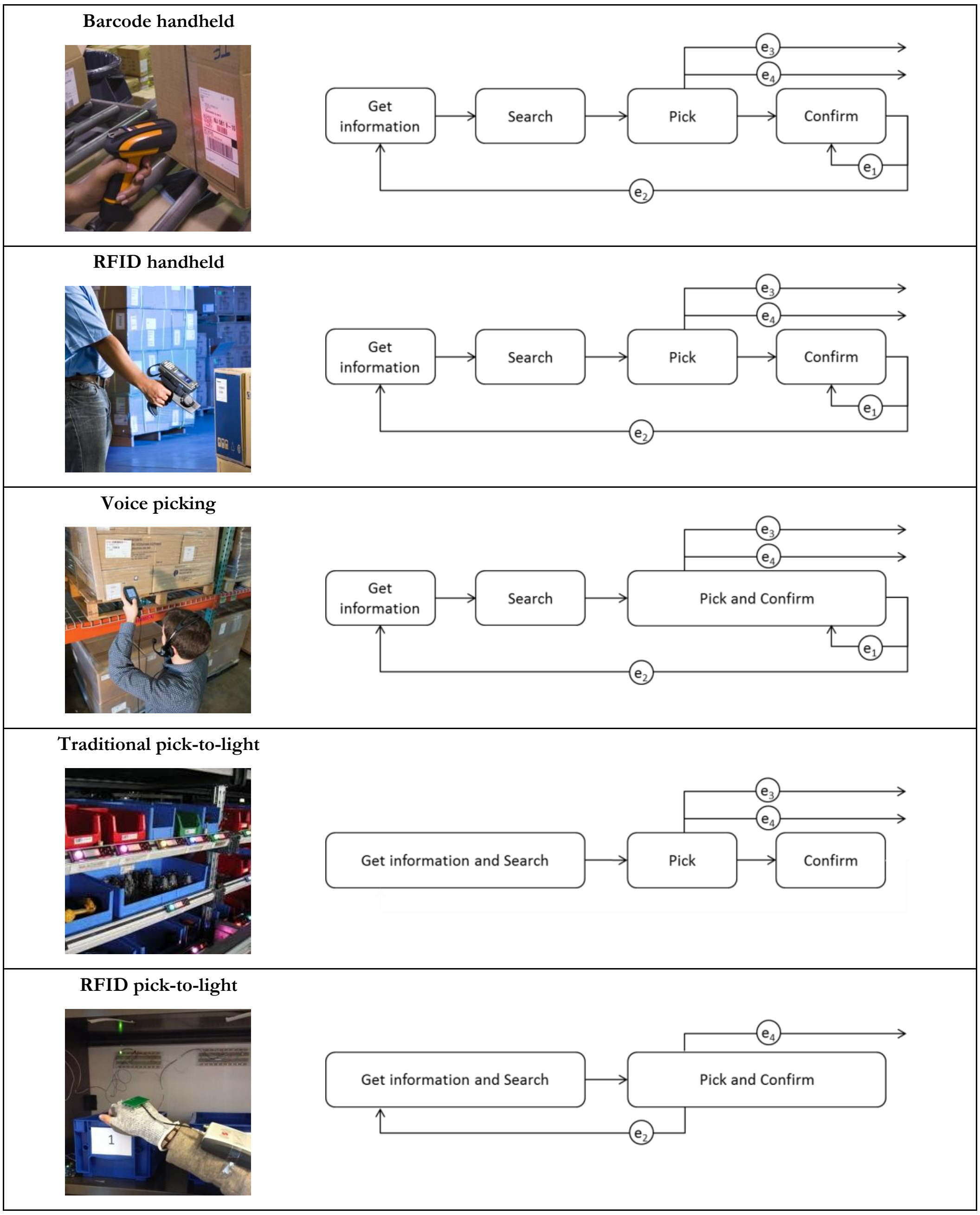


Figure 3.10. High level operating schemes of paperless picking systems.

As far as the errors arising are concerned, for the barcode and RFID handhelds all four kinds of error are present: the detectable errors e_1 and e_2 are recognised during the pick confirmation, which allows their immediate correction; for e_1 only the confirmation has to be repeated, while for e_2 the picking process has to be repeated completely. The propagating errors e_3 and e_4, instead, arise during the physical pick of the item but are intercepted only at the end of the picking tour. The same errors are present also for the voice picking systems, while for the traditional pick-to-light system the two detectable errors are missing; in fact, in this case it is impossible for the operator to confirm the picking of a wrong item since the light is obviously turned on only in the stock location corresponding to the right item. Finally, for the RFID pick-to-light system proposed in Paragraph 3.2.3, the errors e_1 and e_3 are not applicable, because the pick confirmation is immediate and always corresponds to the stock location from which the operator has picked the product; hence, such a system is characterised by the possibility of having the propagating error e_4, which refers to the picking of a wrong quantity of SKUs and of having the error e_2, even if this is detectable before the physical picking, thanks to the turning on of the red light.

3.3.3 Economic evaluation of the different paperless picking solutions

Starting from the working schemes proposed in Section 3.3.2, a cost function is derived, which is useful from an economic point of view for conducting a quantitative comparison of the different paperless picking solutions (Baumann, 2013). This cost function, called the hourly cost function C_h^j, where j is the considered technology, comprises four main hourly cost components:

- Hourly cost depending on the number of stock locations, $C_{h,SL}^j$
- Hourly cost depending on the number of pickers $C_{h,P}^j$
- Hourly cost depending on the picking errors $C_{h,E}^j$
- Hourly fixed cost $C_{h,F}^j$

$$C_h^j = C_{h,SL}^j + C_{h,P}^j + C_{h,E}^j + C_{h,F}^j \tag{3.1}$$

Considering the notations reported in Table 3.6, the previous formula can now be set out as follows:

$$C_h^j = \frac{n_{SL} \cdot c_{SL}^j}{h_{SL}} + \left(c_{h,P} + \frac{c_{d,P}^j}{h_{d,P}}\right) \cdot \left\lceil \frac{n_R}{\dot{p}^j} \right\rceil + c_E^j \cdot n_R + \frac{c_F^j}{h_F} \tag{3.2}$$

where $\dot{p}^j$ is the picking rate, which is the number of performable picks per unit of time:

$$\dot{p}^j = \frac{1}{t_{tot}^j} \tag{3.3}$$

Cost component		Expression
Stock locations hourly cost	$C_{h,SL}^j$	$\frac{n_{SL} \cdot c_{SL}^j}{h_{SL}}$
Picker hourly cost	$C_{h,P}^j$	$\left(c_{h,P} + \frac{c_{d,P}^j}{h_{d,P}}\right) \cdot \left\lceil \frac{n_R}{\dot{p}^j} \right\rceil$
Picking errors hourly cost	$C_{h,E}^j$	$c_E^j \cdot n_R$
Fixed hourly cost	$C_{h,F}^j$	$\frac{c_F^j}{h_F}$

Table 3.6. Hourly cost function components.

The corresponding picking time t_{tot}^j for each considered technology j can be expressed as the sum of two terms:

$$t_{tot}^j = t_{trav} + t_{net}^j \tag{3.4}$$

where the first addend t_{trav} represents the time needed for travelling and for getting on and off the picking cart, and the second, t_{net}^j, includes all the terms that depend on the used paperless picking technology j, according to the working schemes defined before:

$$t_{net}^j = t_i^j + t_s^j + n \cdot t_p^j + t_c^j \tag{3.5}$$

where t_i^j is the time needed for getting the information of the product to pick, t_s^j is the search time, t_p^j is the actual pick time, which also comprises the time for storing the picked product on the cart that is multiplied by the number of SKUs to pick n, and t_c^j is the confirm time (De Koster et al., 2007; Schwerdtfeger et al., 2011).

In fact, the paperless picking technologies do not influence all these time factors in the same way. Some of the factors are totally independent of the devices that are employed in the warehouse, such as the time spent in travelling from one stock location to another and getting on and off the picking cart. However, the actual picking time and the time for the storing of the product on the cart could be affected by the kind of device that it is used, taking account of whether the operator has both hands free or not; furthermore, such times are also influenced by the kind of product that is picked, its weight and volume. Finally, the time necessary to find the right stock location and the one needed to confirm the pick are the factors mostly influenced by the paperless picking technology being considered. For the scope of this paper, it could be concluded that it is sufficient to focus only on the time factors that depend on the device used. However, in the next sections it will be shown that, in order to conduct a complete cost evaluation, it is fundamental to consider also the travel time t_{trav}, which strongly influences the activities related to the error correction and differs also according to the considered technology (Table 3.5). Furthermore, in case of warehouse picking performed over a wide area, the travel time component becomes predominant (Tompkins et al., 2010), making the benefits observable in the net picking time t^j_{net} potentially irrelevant.

Then, in equation (3.1) the error unitary cost c^j_E, considering the different errors introduced in Table 3.5 and the operator hourly cost $c_{h,P}$, can be expressed as:

$$c^j_E = c_{h,P} \cdot \sum_{i=1}^{4} p^j_{e_i} \cdot t^j_{e_i} \tag{3.6}$$

where p_{e_i} is the occurrence probability for each kind of error e_1, e_2, e_3, e_4, expressed as a percentage, and $\mathrm{t}_{\mathrm{e_i}}$ is the corresponding time, both of which vary according to the considered technology (Figure 3.10 and Table 3.7).

Table 3.8 reports some of the possible main cost items for each of the considered paperless picking systems. The costs related to the number of stock locations generally consist of two main components: the cost of purchase of the required specific equipment and the cost of installation of such materials. The picker costs relate to the devices supplied to the picker and the hourly pay. Finally, for all the technologies the reported fixed costs concern the purchase of the management server and of the software.

	$t^j_{e_1}$	$t^j_{e_2}$	$t^j_{e_3}$	$t^j_{e_4}$
Barcodes handheld	t^j_c	$2 \cdot t^j_{net}$	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
RFID tags handheld	t^j_c	$2 \cdot t^j_{net}$	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
Voice picking	t^j_c	$2 \cdot t^j_{net}$	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
Traditional pick-to-light	-	-	$2 \cdot t^j_{net} + t_{trav}$	t^j_{tot}
RFID pick-to-light	-	$2 \cdot \left(t^j_{net} - t^j_c\right)$	-	t^j_{tot}

Table 3.7. Paperless picking technologies time factors per error type.

	c^j_{SL}	$c^j_{d,P}$	c^j_F
Barcodes handheld	-Barcode cost -Barcode installation cost	-Barcode reader handheld cost -Picker cart cost	-Server and software cost
RFID tags handheld	-Tags cost -Tags installation cost	-RFID tag reader handheld cost -Picker cart cost	-Server and software cost
Voice picking	-Barcode cost -Barcode installation cost	-Headset and microphone cost -Picker cart cost	-Server and software cost
Traditional pick-to-light	-Lights cost -Confirmation device cost -Lights and/or confirmation device installation cost	-Handheld cost -Picker cart cost	-Server and software cost
RFID pick-to-light	-Tags cost -Lights cost -Tags and lights installation cost	-RFID glove -Picker cart cost	-Server and software cost

Table 3.8. Paperless picking technologies main cost items.

3.3.4 Application to real case studies

This section reports on some case studies with the aim of presenting an example of the application of the model in order to better show the correlation of the different factors, the points on which it would be interesting to focus and their consequent impact on the hourly cost function. Such functions were plotted for all the analysed paperless picking technologies for two different proposed warehouse configurations, which have both been derived from the simplification of two different case studies. The first case study concerns a low-level picking warehouse using voice picking technology, with a proposed configuration composed of 20 shelving units, 100 meters long with 100 stock locations each; therefore, with a total number of stock locations n_{SL} equal to 2,000. The second configuration consists of multilevel picking shelving (dimensions 3 m · 1.5 m) with a total of 50 stock locations (average dimensions 0.3 m · 0.3 m); this refers to a real case study in which a traditional pick-to-light system was adopted. The data for the two case studies have been used to set up the first two cost configurations, on the basis of which some parametric analyses are proposed.

Both warehouse layouts affect in different ways some of the components of the picking time, in terms of net picking time and travel time. In particular, in the case of the second warehouse configuration (picking from single shelving) the time needed to search for the item and to pick and to store it in the cart were observed to be slightly lower than in the first configuration, due to the fact that in this case the operator can more identify easily the products to pick and can store the picked items in a faster way since he or she does not need to move from the initial position. Furthermore, the considerations made for this configuration are even more interesting because the net picking time t_{net} is very close to the total picking time t_{tot} (due to absence of time spent in travelling and getting on and off of the picking cart, t_{trav}).

In order to perform the analysis of the existing systems and their comparison with the other different paperless picking technologies, the corresponding times and the error percentages have been calculated or estimated through observations carried out in the field at the two warehouses (for the barcode handhelds, the voice picking system and the traditional pick-to-light system) and some laboratory tests (for the RFID tags handhelds and the RFID pick-to-light system), which in some cases have also been integrated with the data obtained for the other solutions and with assumptions derived from the authors' experience. Table 3.9 presents the information time, search time, actual pick time, confirm time and consequent net picking time obtained for each paperless picking technology, together with the average travel time t_{trav} and the consequent total picking time t_{tot}. For the estimation of the actual pick time and of the store time, the product to pick that was considered is a normal carton box, which is easily graspable and accessible, and picked one at a time ($n = 1$). In the case of $n_{SL} = 2{,}000$, the considered box is 20 cm³ and 400 g, while in the case of $n_{SL} = 50$ the average dimensions are 10 cm³ and 200 g. Consistent with what is represented in Figure 3.10, the search time t_s is equal to 0 for the two pick-to-light solutions since the operator gets the information about the product to pick and at the same time sees where it is located; furthermore, the confirm time t_c is not present for the voice picking system and for the RFID pick-to-light system: in the first case the confirm activity is done by the operator during the storing of the product on the cart, while in the second the picking confirmation is performed automatically by the RFID glove during the physical pick, without any further activity required from the picker.

		t_i^j	t_s^j	t_p^j	t_c^j	t_{net}^j	t_{trav}	t_{tot}^j
Barcodes handheld	$n_{SL} = 2{,}000$	2.98 s	7.96 s	4.87 s	4.02 s	19.83 s	120.00 s	139.83 s
	$n_{SL} = 50$	2.98 s	2.05 s	2.53 s	4.02 s	11.58 s	20.00 s	31.58 s
RFID tags handheld	$n_{SL} = 2{,}000$	2.98 s	7.96 s	4.87 s	2.48 s	18.29 s	120.00 s	138.29 s
	$n_{SL} = 50$	2.98 s	2.05 s	2.53 s	2.48 s	10.04 s	20.00 s	30.04 s
Voice picking	$n_{SL} = 2{,}000$	4.85 s	8.12 s	2.97 s	0.00 s	15.94 s	120.00 s	135.94 s
	$n_{SL} = 50$	4.85 s	2.00 s	1.99 s	0.00 s	8.84 s	20.00 s	28.84 s
Traditional pick-to-light	$n_{SL} = 2{,}000$	4.85 s	0.00 s	2.86 s	0.98 s	8.69 s	120.00 s	128.69 s
	$n_{SL} = 50$	2.16 s	0.00 s	1.54 s	0.98 s	4.68 s	20.00 s	24.68 s
RFID pick-to-light	$n_{SL} = 2{,}000$	4.85 s	0.00 s	2.86 s	0.00 s	7.71 s	120.00 s	127.71 s
	$n_{SL} = 50$	2.16 s	0.00 s	1.54 s	0.00 s	3.70 s	20.00 s	23.70 s

Table 3.9. Net picking time and respective time components, travel time and total time for the analysed paperless picking solutions.

Table 3.10 shows the error percentages for the four different kinds of error: the values for the detectable errors 1 and 2 have been estimated by interviewing the warehouse managers, while the propagating error percentages have been calculated from the analysis of sample data collected from the picking tours performed in one month. These calculated data have then been extended to all the studied paperless systems. Finally, Table 3.11 reports the various cost components obtained from specific industry catalogues and from information derived from the warehouse managers interviews. For the calculation of h_{SL}, $h_{d,P}$ and h_F two years were considered, with an 8-hour work shift for 220 days a year. It is important to underline that obtaining and handling all the input data is a fundamental phase that can require a great effort for people to take part in the field analysis or manager interviews; however, a parametrical analysis of the output data can also be performed to enable the impact of the choice of values to be understood.

		$t^j_{e_1}$	$p^j_{e_1}$	$t^j_{e_2}$	$p^j_{e_2}$	$t^j_{e_3}$	$p^j_{e_3}$	$t^j_{e_4}$	$p^j_{e_4}$
Barcodes handheld	$n_{SL} = 2{,}000$	4.02 s	4.5%	39.66 s	4.5%	159.66 s	4.5%	139.83 s	5.0%
	$n_{SL} = 50$	4.02 s	4.5%	23.16 s	4.5%	43.16 s	4.5%	31.58 s	5.0%
RFID tags handheld	$n_{SL} = 2{,}000$	2.48 s	4.5%	36.58 s	4.5%	156.58 s	4.5%	138.29 s	5.0%
	$n_{SL} = 50$	2.48 s	4.5%	20.08 s	4.5%	40.08 s	4.5%	30.04 s	5.0%
Voice picking	$n_{SL} = 2{,}000$	1.00 s	4.5%	31.88 s	4.5%	151.88 s	4.5%	135.94 s	5.0%
	$n_{SL} = 50$	1.00 s	4.5%	17.68 s	4.5%	37.68 s	4.5%	28.84 s	5.0%
Traditional pick-to-light	$n_{SL} = 2{,}000$	-	-	-	-	137.38 s	2.0%	128.69 s	5.0%
	$n_{SL} = 50$	-	-	-	-	29.36 s	2.0%	24.68 s	5.0%
RFID pick-to-light	$n_{SL} = 2{,}000$	-	-	15.42 s	1.0%	-	-	127.71 s	5.0%
	$n_{SL} = 50$	-	-	7.40 s	1.0%	-	-	23.70 s	5.0%

Table 3.10. Error picking time factors and corresponding occurrence probability for the analysed paperless picking solutions.

Cost component	Factor		Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
	c_{SL}^{j}		1.10 €	1.30 €	1.10 €	50 €	22.30 €
$C_{h,SL}^{j}$	n_{SL}		2,000 or 50	2,000 or 50	2,000 or 50	2,000 or 50	2,000 or 50
	h_{SL}		3,520 h	3,520 h	3,520 h	3,520 h	3,520 h
	$c_{h,P}$		30 €/h	30 €/h	30 €/h	30 €/h	30 €/h
	$c_{d,P}^{j}$		2,800 €	2,900 €	3,000 €	2,800 €	2,600 €
$C_{h,P}^{j}$	$h_{d,P}$		3,520 h	3,520 h	3,520 h	3,520 h	3,520 h
	$\dot{p}^{j}$	$n_{SL} = 2{,}000$	25.75 r/h	26.03 r/h	26.48 r/h	27.97 r/h	28.19 r/h
		$n_{SL} = 50$	114.00 r/h	119.84 r/h	124.83 r/h	145.87 r/h	151.90 r/h
$C_{h,E}^{j}$	c_{E}^{j}	$n_{SL} = 2{,}000$	0.135 €	0.131 €	0.126 €	0.077 €	0.054 €
		$n_{SL} = 50$	0.040 €	0.036 €	0.033 €	0.015 €	0.010 €
$C_{h,F}^{j}$	c_{F}^{j}		30,000 €	30,000 €	30,000 €	30,000 €	30,000 €
	h_{F}		3,520 h	3,520 h	3,520 h	3,520 h	3,520 h

Table 3.11. Cost components values for the analysed paperless picking solutions.

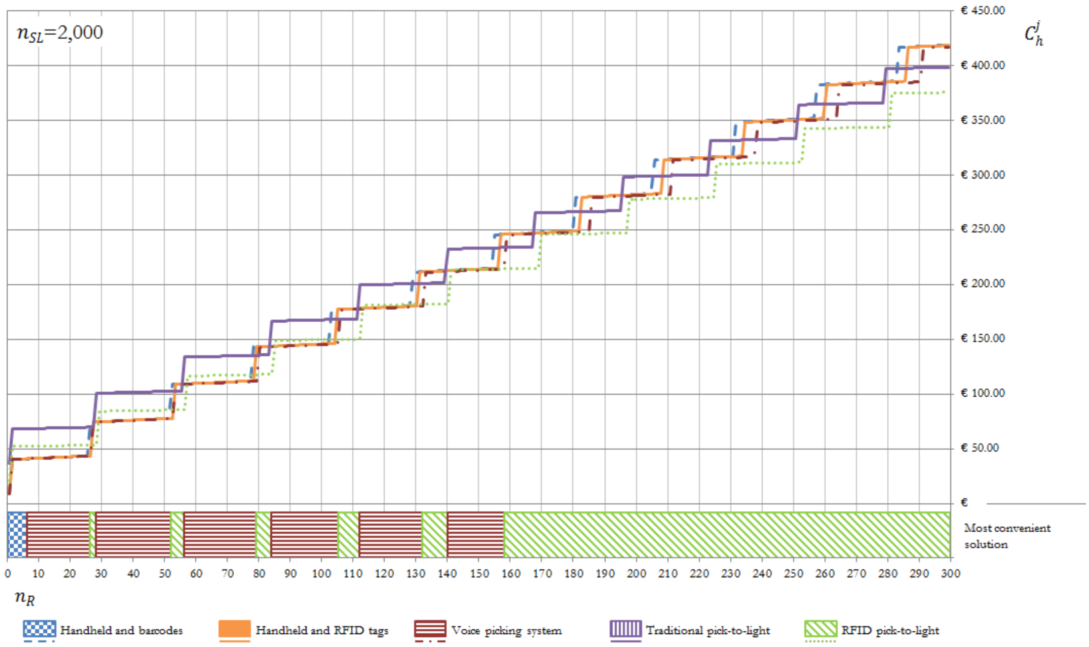


Figure 3.11. Hourly cost function of the different paperless picking technologies, $n_{SL} = 2{,}000$.

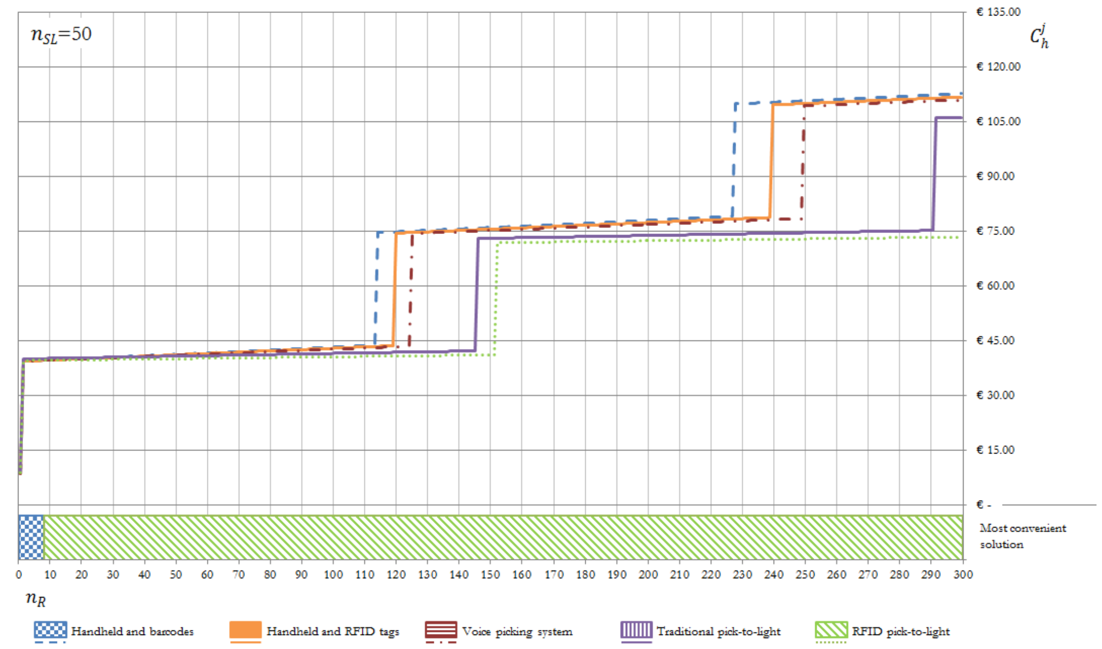
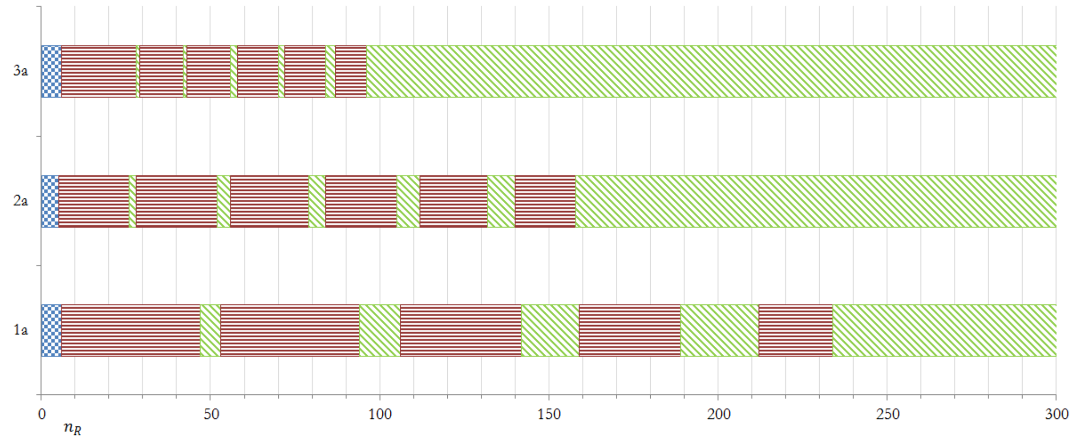


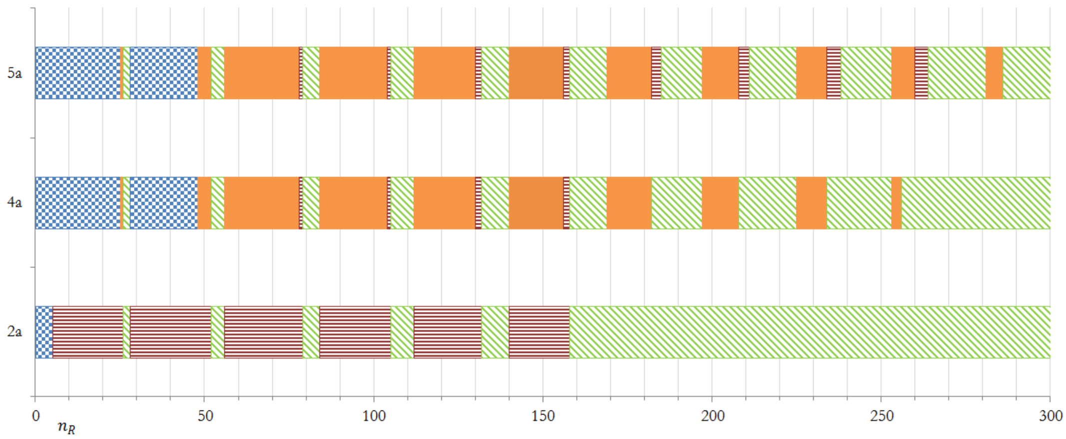
Figure 3.12. Hourly cost function of the different paperless picking technologies, $n_{SL} = 50$.



Code	Parameter	Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
3a	t_{trav}	240 s	240 s	240 s	240 s	240 s
2a	t_{trav}	120 s	120 s	120 s	120 s	120 s
1a	t_{trav}	60 s	60 s	60 s	60 s	60 s

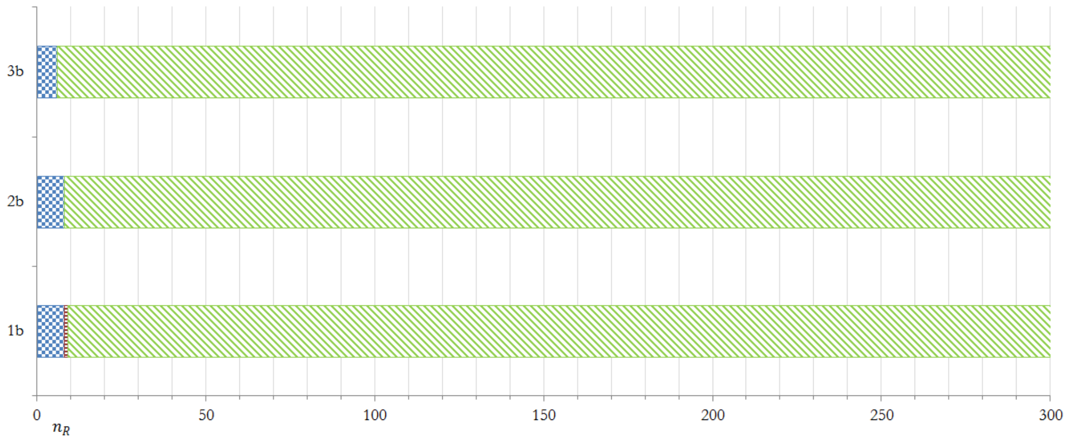
Figure 3.13. Hourly cost function analysis for the different paperless picking technologies, changing t_{trav}, $n_{SL} = 2{,}000$ *and* $c_F^j = 30{,}000$ €.

The first parameter that has been varied in the plotting of the hourly cost function for the two proposed warehouse configurations is the number of picked rows n_R (Figure 3.11 and Figure 3.12): besides the line charts of the different solutions, in the lower part a bar graph is shown, reporting the areas of convenience for the various systems; that is, the most convenient system, according to the different numbers of requested picking rows, is each time reported. This last representation is also employed in the subsequent analysis in which two parameters, c_F and t_{trav}, have been changed with respect to the starting configurations, called 2a in the case of $n_{SL} = 2{,}000$ and 2b for $n_{SL} = 50$ (see Figure 3.13, Figure 3.14, Figure 3.15 and Figure 3.16).



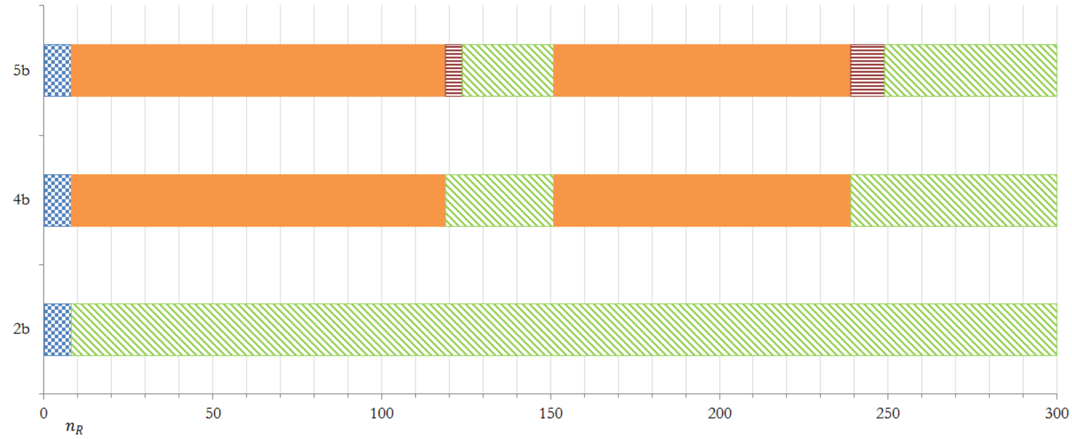
Code	Parameter	Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
5a	c_F	30,000 €	30,000 €	60,000 €	90,000 €	90,000 €
4a	c_F	30,000 €	30,000 €	60,000 €	60,000 €	60,000 €
2a	c_F	**30,000 €**	**30,000 €**	**30,000 €**	**30,000 €**	**30,000 €**

Figure 3.14. Hourly cost function analysis for the different paperless picking technologies, changing c_F^j, $n_{SL} = 2{,}000$ and $t_{trav} = 120\ s$.



Code	Parameter	Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
3b	t_{trav}	40 s	40 s	40 s	40 s	40 s
2b	t_{trav}	**20 s**	**20 s**	**20 s**	**20 s**	**20 s**
1b	t_{trav}	10 s	10 s	10 s	10 s	10 s

Figure 3.15. Hourly cost function analysis for the different paperless picking technologies, changing t_{trav}, $n_{SL} = 50$ and $c_F^j = 30{,}000$ €.



Code	Parameter	Barcodes handheld	RFID tags handheld	Voice picking	Traditional pick-to-light	RFID pick-to-light
5b	c_F	30,000 €	30,000 €	60,000 €	90,000 €	90,000 €
4b	c_F	30,000 €	30,000 €	60,000 €	60,000 €	60,000 €
2b	$\mathbf{c_F}$	**30,000 €**	**30,000 €**	**30,000 €**	**30,000 €**	**30,000 €**

Figure 3.16. Hourly cost function analysis for the different paperless picking technologies, changing c_F^j, $n_{SL} = 50$ and $t_{trav} = 20\ s$.

From the observation of the graphs reported for the different cost values in Figure 3.11 and Figure 3.12, some interesting considerations and comparisons can be performed. In general, it is observed that the increase in the number of picked rows n_R leads to an increase in the trend observable for all the curves, mainly due to the increase in the number of pickers needed to satisfy the requested warehouse performance. Focusing on the different considered technologies, it is evident that, apart from the values assigned to the different cost components, a traditional pick-to-light system is more suitable for multilevel picking on single shelving ($n_{SL} = 50$), since in this case the hourly cost is lower than in a low-level picking warehouse configuration, in which the stock locations cost is absolutely impacting, making such a paperless picking solution not competitive. The case of systems relying on barcode scanner and RFID tag scanner handhelds is different: they turn out to be quite competitive for both warehouse configurations, above all for low values of n_R. The trend of the hourly cost function for voice picking is quite regular and similar to the two handhelds solutions; in the case of $n_{SL} = 2{,}000$ this solution is the most advantageous, together with those for the handheld and barcodes and the handheld and RFID tags, for $n_R < 160\ picks/h$. As far as the RFID pick-to-light system is concerned, it turns out to be the most competitive for $n_{SL} = 50$ and $n_R > 10\ picks/h$, since it warrants short picking times and error percentages; therefore, it can also be successfully employed for feeding picking for assembly systems (Battini et al., 2013). However, for warehouse picking over a wide area

($n_{SL} = 2{,}000$) such a system becomes competitive only for higher values of n_R.

Figure 3.13 and Figure 3.14 show the results for $n_{SL} = 2{,}000$ concerning the change of t_{trav} and c_F^j, respectively. In the first figure, the halving of the travel time leads to an increase of the convenience intervals for the voice picking system with respect to the RFID pick-to-light system. On the other hand, its doubling makes such intervals narrower and more concentrated on the left side of the graph, corresponding to lower values of n_R. For the analysis of the change of the fixed costs c_F^j it was decided to show a possible difference in this parameter for the various solutions, since an equal change for all the paperless picking systems would not have any effect on the convenience thresholds. Considering the voice picking system and the two pick-to-light systems that have a higher c_F^j it is noticeable that the handheld with the RFID tags becomes the more convenient solution for some intervals of n_R, instead of the voice picking system and the RFID pick-to-light system (Figure 3.14, code 4a). If the two pick-to-light systems have an even higher c_F^j (Figure 3.14, code 5a), the RFID pick-to-light convenience area decreases, while the voice picking system and the handheld with RFID tags are also suitable in the case of a higher number of picked rows per hour. A comparable trend is observable for $n_{SL} = 50$ (Figure 3.15 and Figure 3.16), where the most convenient solutions are the handheld with barcodes for very low values of n_R, the handheld with RFID tags, the voice picking system and the RFID pick-to-light system. In particular, the increase of the travel time t_{trav} leads to a reduction of the convenience threshold of the barcode handheld (Figure 3.15). The introduction of different fixed costs for the various solutions makes the RFID handheld convenience intervals wider, and in case the pick-to-light solutions have a very high c_F^j, the voice picking also gains a little convenience area (Figure 3.16, code 5b).

3.4 Conclusions

Manual picker-to-parts order picking represents a crucial activity for every warehouse since it is particularly time and labour intensive, and it requires great attention and efforts in terms of picking order processing time and errors reduction (De Koster et al., 2007; Grosse et al., 2015). In the present chapter it has been acknowledged that a possible way of obtaining improvements in this direction is represented by the employment of devices able to support and help the pickers during their work, such as the paperless picking systems.

After a brief introduction concerning paperless picking in general, in Paragraph 3.2 a new low-cost paperless picking technology, which combines the benefits of RFID to the simplicity and effectiveness of pick-to-light, has been presented: the RFID pick-to-light system. According to this solution, every warehouse operator wears a glove in which a UHF RFID reader is installed, while every stock location has a RFID tag to identify the corresponding product stored. When the RFID reader reads the tag, a signal is sent via Wi-Fi to a centralized control system that checks whether the picker has taken the right item or not and that sends the signals of turning on and off of the appropriate lights. Some of the benefits that such support device can typically provide are the increased accuracy and errors reduction, since pickers can quickly understand whether they are collecting the right item or not; the increased productivity, as picking is made easier and more focused on other activities; a reduction on the time needed to look for the right picking location or to remedy errors; and the reduction of training time: finding the various locations is more intuitive and immediate and pickers do not have to learn to use complex devices. The new system has also been compared to other manual picking supporting devices from a qualitative point of view, highlighting its validity and its great potential, also for a real industrial application.

Paragraph 3.3 has instead introduced a procedure useful to compare different paperless picking systems, both from a technological and an economic point of view. In particular, starting from the functional description of the analysed solutions, the procedure focuses on pointing out the different arising errors, so that these errors can also be taken into account in the development of the hourly cost function. In fact, the proposed cost function is composed of four main hourly cost factors: the stock locations cost, the pickers cost, the picking errors cost and the fixed cost. The method has then been applied for the evaluation of five different paperless picking systems (i.e. handheld and barcodes, handheld and RFID tags, voice picking system, traditional pick-to-light, and the new RFID pick-to-light), thanks also to a case study that proposed to analyze two different warehouse configurations: a low level manual picking warehouse, composed of different racks and aisles, and a multilevel picking shelving. The study outcomes show that the best paperless picking solutions for the low level manual picking warehouse with a medium–low number of picked rows per hour are the handheld solutions (both those with barcodes and those with RFID tags) and the voice picking system, while the RFID pick-to-light solution is the best one when the number of picks per hour is high. On the contrary, in the case of the multilevel picking shelving, the most convenient technology is the RFID pick-to-light system for almost all the numbers of picked rows per hour. The proposed model represents an interesting approach which is considered useful for evaluating different paperless picking technologies, considering also their practical employment within a specific warehouse characterised by a certain layout configuration and a particular picking rate. Furthermore, its simplicity makes it easy for warehouse staff to apply directly; in any event, the engagement of warehouse managers is certainly needed in order to obtain and eventually verify the most accurate times, errors and cost values. In fact, an important point for attention in such a method is the need for the correct estimation of the input data.

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4

OVERALL TIME REDUCTION

"It is clear that in planning order picking processes, the combined effects of order picking design and human factor have to be considered to achieve a good performance."

Grosse et al., 2015

4.1
Highlights and Problem outline

Most of the existing researches on warehouse manual picker-to-parts picking are proposing different mathematical models with the aim of improving picking performances and picking system throughput. A possible approach to achieve this objective can concern the reduction of the time needed to process the picking orders (De Koster et al., 2007; Tompkins et al., 2010). However, some researchers have recently pointed out that there is also another way of improving picking performances. In fact, they interestingly refer to the possibility of studying and, then, improving, the ergonomics working conditions of a warehouse operator (Neumann and Dul, 2010; Grosse et al., 2015).
In this chapter it is investigated how the improvement of the ergonomic working conditions of warehouse pickers can impact on the overall time reduction. Paragraph 4.2 proposes a model to evaluate ergonomics in manual picking systems, through the concept of *additional ergonomic effort*, also considering its relation to pickers availability and rest allowance needs. Then, in Paragraph 4.3, a mathematical model useful to evaluate the possible *impact of different racks layouts*, both from an economic and ergonomic point of view, is reported.

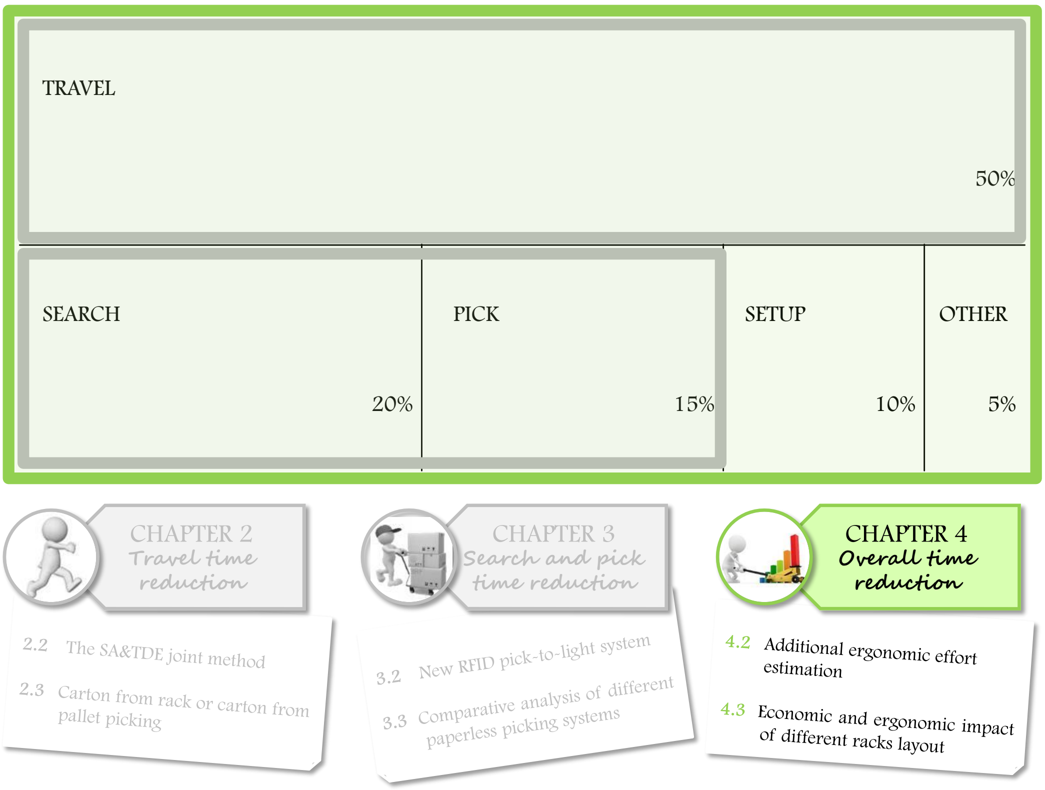

Figure 4.1. Research framework: Overall time.

4.1.1 Actions for overall system improvement

During his work, a warehouse picker performs different but at the same time repetitive tasks, requiring a certain overall ergonomic effort. First of all, he has to walk from a stocking location to another, or, alternatively, he has to go up and down from the picking cart, to reach the products he needs to pick. Then, once he is in front of the picking location, he has to take the required cartons, which in most cases are stored on traditional pallets on the ground floor of the warehouse. Therefore, the picker usually has to bend, stretch or lean, as well as lifting and moving items that potentially can also be quite heavy (Weisner and Deuse, 2014; Grosse et al., 2015). All these aspects expose workers to a high risk of developing injuries due to a gradual and cumulative deterioration of the musculoskeletal system, also referred to as musculoskeletal disorders (MSDs). The fact that MSDs are a pressing problem in order picking is frequently reflected in occupational illness figures (Lavender et al. 2012, Grosse et al. 2015). In the UK, for example, the total number of MSD cases in 2013/14 accounted for over 43% of all work-related illness cases (Buckley 2014). In the European transport and storage sector, MSDs accounted for over 62% of all work-related health problems in 2007 (Eurostat 2009a). In total, 100 million Europeans are meanwhile affected by MSDs (Lidgren et al. 2014). The ongoing increasing financial burden of MSDs is up to 2% of the gross national product in the European Union (Schneider and Irastorza 2010).

In the EU, 40% of the total workforce, i.e. 80 million individuals, are exposed to factors that can adversely affect physical health (Eurostat 2009b). In order picking, these factors and related risks for developing MSDs are mainly determined by the design of the operations system (cf. Neumann and Village 2012). Examples of order picking design aspects that physically affect human work are the height and depth of racks, the weight of items or the light level (Grosse et al. 2015). As to the rack layout, the design (or the choice of a specific rack) determines both the time to pick items from storage positions and the energy expenditure that is needed for workers to fulfil these task. Especially picking from pallets often requires workers to twist, bend, kneel and stretch, which increases the risk of developing MSDs (Denis et al. 2006).

A recent study showed that decision support models for order picking have mainly focused on improving economic goals (such as reducing order picking time), and that they neglected the interaction between the design of the order picking system and human factors, leading to a significant research gap (Grosse et al. 2015). By integrating ergonomic performance measures into decision support models for order picking, it is possible to design the order picking process in such a way that health risks resulting from order picking are minimized in addition to economic performance goals. Improving ergonomics in order picking may not only contribute to a positive work-life-balance for workers, but also improve performance goals by reducing illness cases and absence from work (Grosse et al. 2015).

Since the relevance of ergonomics in warehouse picking and its importance for picking performances improvement is acknowledged, the present chapter focuses on the proposal of two studies concerning the ergonomics evaluation of order picking systems. In particular, Paragraph 4.2 proposes a model and a procedure to consider and evaluate the impact of human availability and rest allowance on picking warehouse throughput. The developed method allows the estimation of the additional effort and of the additional effort cost due to the ergonomics working conditions of the operators, referring to two alternative operative conditions for a warehouse: the first one considers directly employed operators, while the other one is with indirectly employed operators. Moreover, it is reported also an interesting industrial case study, which shows the easily applicability of the method.

On the other side, Paragraph 4.3 develops a mathematical model that can be used to evaluate how the layout of storage racks and the way products are stored on racks in the warehouse impact economic (in terms of time) and ergonomic performance measures. The ergonomics impact is expressed in terms of energy expenditure, a method which has already been proven by other contributions to be based on a suitable ergonomics indicator (Garg et al., 1978; Battini et al. 2015a). The focus of this study is a situation where items are picked from pallets, half-pallets and/or half-pallets equipped with a pull-out system. The model proposed can also be used as a decision support tool to assess the best combination of the rack alternatives, which contributes to reducing order picking time and costs as well as worker illness caused by poor working postures. Also in this case, the model is evaluated in a numerical analysis, too.

4.1.2 Ergonomics study for warehouse manual picking

A closer look at existing decision support models reveals that the specific characteristics of human workers and implications of the planning outcome on the workers (such as health risks) have largely been overlooked in prior research. The impact of manual material handling on workers has, however, been studied in the human factors engineering literature. Works in this area mainly focused on ergonomic evaluations of order picking tasks and possible interventions to improve working posture and to reduce the risk of developing MSDs (e.g., Garg 1986; Kuorinka et al. 1995; Waters et al. 1998; Marras et al. 1999; St-Vincent et al. 2005; Denis et al. 2006). Apart from the documented physical impact, human factors can also affect the performance and quality of order picking. This is why several authors recently called for the integration of ergonomic aspects into decision support models and an integrated view on the implications of economic and ergonomic objectives in order picking (Grosse et al., 2015; Boysen et al., 2015).

The need of considering and studying ergonomics in picking activities was highlighted already in 1986 by Garg (1986); nevertheless, from then only few works have considered human factors in decision support models for order picking. These studies include

- the effects of worker learning on order picking performance and quality (Grosse and Glock 2013; Grosse et al. 2013; Grosse and Glock, 2014),
- the impact of the location of materials within shelves (e.g. height) and material characteristics (e.g. weight and packaging) on pick time (Neumann and Medbo, 2010; Finnsgård and Wänström 2013),
- the implications of user acceptance and worker personality of paperless picking technologies on performance (De Vries et al. 2015) as well as on the occurrence of errors (Battini et al. 2015b),
- methods to evaluate simultaneously task times and related body postures of workers during picking activities (Neumann 2004; Battini et al. 2014),
- and measures to avoid occupational accidents (De Koster et al. 2011).

However, there is still a dire need for more research on integrated economic and ergonomic approaches in order picking.

4.2 Additional effort estimation due to ergonomics conditions in order picking systems

Within a warehouse, the picking activity often relies on human operators. Therefore, when designing and evaluating a manual picking system, it is important to consider that, besides the high flexibility the pickers are able to warrant, they inevitably require an additional effort due to their ergonomics working conditions. In this paper the authors propose a new model to consider such additional effort, starting from the concepts of human availability and rest allowance. The new method allows the evaluation of the current configuration of a certain warehouse, considering two different operative situations (directly employed operators and indirectly employed ones). Moreover, it allows to estimate and to understand the benefits that can be achieved by introducing some ergonomics improvements. The proposed procedure has been also applied to a real industrial case study.

4.2.1 Notations

Notation	Description
EL	Ergonomics Level
t	Percentage of time spent for travel activity
s	Percentage of time spent for search activity
p	Percentage of time spent for actual pick activity
u	Percentage of time spent for set up activity
o	Percentage of time spent for other activities
OI_t	Travel activity OWAS index
OI_s	Search activity OWAS index
OI_p	Actual pick activity OWAS index
OI_u	Set up activity OWAS index
OI_o	Other activities OWAS index
A_h	Human Availability
$A_{h\,sb}$	Human Availability of the stand-by picker

N_{inj}	Number of injuries
$\bar{t}_{inj}$	Average recovery time
$\bar{t}_{sb}$	Average working time of the stand-by operator
T	Referred time period
RA	Rest Allowance
a	Multiplicative parameter for A_h
b	Exponential parameter for A_h
c	Multiplicative parameter for RA
d	Exponential parameter for RA
AE_d	Additional effort in case of directly employed operators
AEC_d	Additional effort cost in case of directly employed operators
AE_{id}	Additional effort in case of indirectly employed operators
AEC_{id}	Additional effort cost in case of indirectly employed operators
c_h	Hourly wage of a picker
Q	Lower productivity factor for the stand by picker
MES_d	Marginal ergonomic saving in case of directly employed operators
MES_{id}	Marginal ergonomic saving in case of indirectly employed operators
PI_d	Profitability index in case of directly employed operators
PI_{id}	Profitability index in case of indirectly employed operators
EIC	Ergonomic intervention cost

Table 4.1. Notations.

4.2.2 Ergonomics evaluation

Ergonomics level EL

The study of ergonomics has gained always more importance in the last years, arousing interest both of researchers and practitioners. In particular, some studies demonstrated that the future long-term muscular pains, such as musculoskeletal disorders (MSDs), can depend on working conditions and work manual tasks (Burgess-Limerick, 2007; Hamberg-van Reenen et al., 2008; Euzenat, 2010). Moreover, MSDs are one of the most reported causes of absence from work, 52% of all the work-related illnesses (Schneider and Irastorza, 2010), representing a central issue also for public health institutions (Larco Martinelli, 2010). Other studies have pointed out that including the ergonomics evaluations in human operations analyses is a win-win approach, due to the existing interaction between productivity and motion efficiency, as well as operational safety (Battini et al., 2011).

Although its importance, the integration of ergonomics on warehouse picking has not received until now enough attention in literature (Grosse et al., 2015). Among all the existing contributions, some analyses indicate the need of proposing methods that help the understanding of the elements that mostly affect the ergonomics level of the order-picking activities. For example, Garg (1986) has been one of the first authors that pointed out the importance of ergonomics in warehouse picking, suggesting some changes in warehouse racks configurations. Also Grosse et al. (2015) highlight that ergonomics improvements and, hence, long-term benefits, such as costs reduction of the whole system, can be reached though the definition of a maximum acceptable pick height and depth of the storage racks in the storage assignment and the limitation of the weight transportable by each picker in the routing policies. Moreover, Weisner and Deuse (2014), confirm that the body posture of the warehouse operators is inevitably influenced by size, weight and type of the packaging and by the configuration of the shelving. In fact, they propose to consider the storing of the various products according to their picking frequencies: hence, the items with a low picking frequency and/or a high weight should be located in the lowest rack, while the items that are picked more often should stay up to maximum 0.85 meters at shoulder height.

A possible way of considering ergonomics during the study of a production or a logistic system can be by calculating an index that summarizes the ergonomic impact of the various activities that are performed by the operators. Battini et al. (2015c), refer to a so-called Ergonomics Level EL, that can be calculated by using one of the currently available techniques, like OCRA, RULA or OWAS methods. In particular, they propose to use OWAS (Ovako Working posture Analysing System). The OWAS method is normally employed for full body ergonomics evaluations of body postures. It allows to consider the trunk, arms and legs movements, together with the eventual carried load (Karhu et al., 1977; Louhevaara et al., 1992). The body movements and the load parameters are expressed through a set of different values, that depend on the postures assumed by the operator during the analysis and that increase with the ergonomic worsening of the posture. Then, the OWAS analysis relies on a summary table reporting the various risk indexes, corresponding to the combinations of the codes of the different possible body postures. Finally, all the various risk indexes assigned to each activity are collected to compute the overall OWAS Index OI. In the present paper the authors propose to use a similar approach: the Ergonomics Level EL is calculated by associating an OWAS index to each activity performed by the pickers during their picking tours and by multiplying each risk index to the percentage of time the picker spends doing the corresponding activity:

$$EL = t \cdot OI_t + s \cdot OI_s + p \cdot OI_p + u \cdot OI_u + o \cdot OI_o \quad (4.1)$$

where t, s, p, u and o are the percentages of time of the different activities as described by Tompkins et al. (2010, see Figure 1.5) and OI_t, OI_s , OI_p, OI_u, OI_o are the respective OWAS indexes.

Human availability A_h and Rest Allowance RA

When a manual picking warehouse is considered, in which human operators usually work, the throughput and the performance of the overall system inevitably depend on the availability of the human resources and on their rest allowances needs.

The human availability of a picking warehouse can be obtained considering the unavailability of the operators, which is the product of the number of injuries N_{inj} and the average recovery time $\bar{t}_{inj}$, in the referred time period T:

$$A_h = 1 - \frac{N_{inj} \cdot \bar{t}_{inj}}{T} \quad (4.2)$$

Moreover, in the previous research by Battini et al. (2015c) it has already been introduced the possibility to express the human availability A_h as a function of the Ergonomics Level *EL* introduced in the previous subsection, where *EL* is expressed with an OWAS scale. In particular, it has been observed that, analyzing these two parameters in similar industrial contexts, with different workload and environmental conditions, by increasing the ergonomics level *EL* (that is, by worsening the working ergonomics conditions) the human availability A_h has a decreasing trend:

$$A_h = 1 - aEL^b \quad (4.3)$$

On the contrary, when the ergonomics level *EL* increases (hence, when the ergonomic effort is higher) the Rest Allowance percentage (Rohmert, 1973, Battini et al., 2013), that describes the need of resting to compensate a previous fatigue, increases, with an exponential trend:

$$RA = cEL^d \quad (4.4)$$

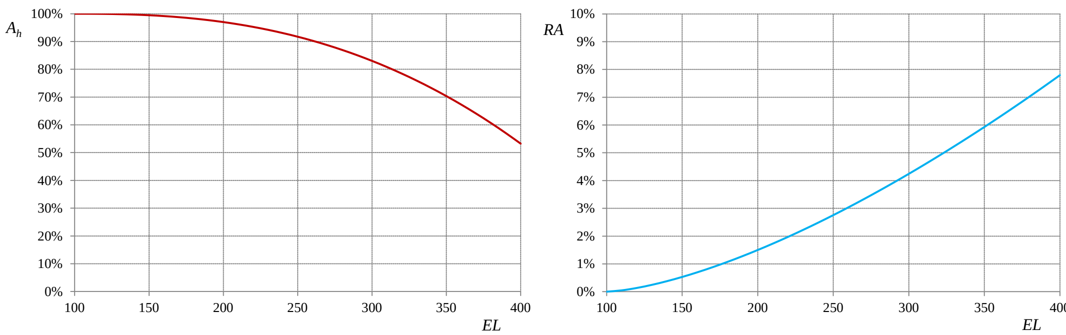

Figure 4.2. Plots for A_h and RA in function of EL.

Figure 4.2 represents a possible plotting of the A_h and the RA in function of *EL*. In particular, it can be observed that when *EL* = 100 the human availability A_h= 100%, meaning that there are not sick leaves related to the picking activity. On the other side, for the minimum value of *EL* the *RA* is equal to zero.

4.2.3 Additional effort percentage and cost modelling

In the first chapter of this thesis it has already been reported a main classification of the various warehouse picking systems, together with the description of all the activities that are normally performed within a picking warehouse. Another important distinction that can concern a picking warehouse, here considered, is related to the way the operators are employed. In fact, besides the traditional situation, in which the pickers are direct employees of the company, there is the possibility of temporarily hiring a certain number of operators from another company. These third party companies are specialized on the management of the operators and, hence, on always warranting the right number of resources required by their customers. As a consequence, if it has to be considered the pickers availability and rest allowance needs, it can be useful to distinguish between warehouse picking systems with directly employed operators and warehouse picking systems with indirectly employed operators. As can be seen in Figure 4.3, there is an important difference between the two systems when it occurs an injury or a sick leave of an operator. In particular, in case of directly employed operators, when a picker is absent from work the company inevitably has to wait all his recovery time. In case of indirectly employed operators, instead, once a picker is injured there is the possibility of hiring another picker, even if it is only for a short period of time.

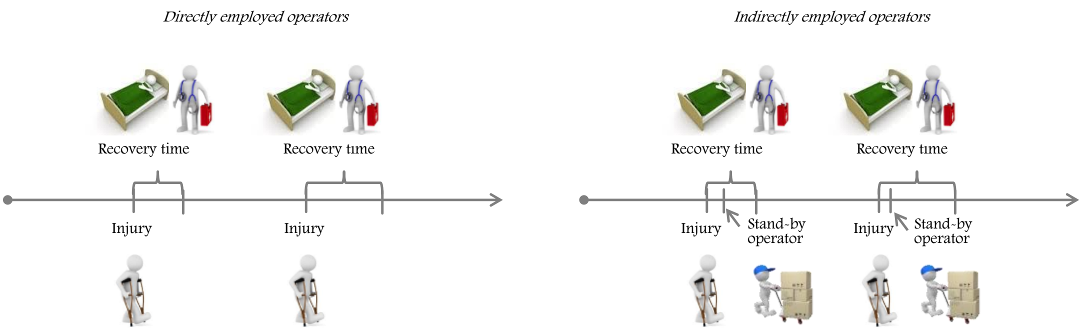

Figure 4.3. General operating scheme in case of directly and indirectly employed operators.

System with directly employed operators

In case of directly employed operators the additional effort due to the ergonomics conditions of his work can be assumed to depend on his effective availability, that is the time of presence at work, and on the needed rest allowance, that has to be considered during the time intervals in which the picker is available. Hence, the additional effort in case of directly employed operators can be expressed as:

$$AE_d = (1 - A_h) + RA \cdot A_h \tag{4.5}$$

where A_h represents the human availability of the operator and RA his Rest Allowance percentage (Rohmert 1973). Once the additional effort percentage AE_d is defined, and considering c_h the hourly wage of a picker, the Additional Effort Cost in case of directly employed operators can be calculated with:

$$AEC_d = AE_d \cdot c_h \cdot T \tag{4.6}$$

System with indirectly employed operators

When the pickers are not direct employees of the company the additional effort due to ergonomics conditions has to take into account, besides the human availability and the rest allowance of the main picker, the presence and the contribution of the so-called stand-by operator. Considering his characteristics, the human availability of the stand-by picker can be defined as follows:

$$A_{h\,sb} = \frac{N_{inj} \cdot \bar{t}_{sb}}{T} \tag{4.7}$$

where $\bar{t}_{sb}$ is the time the stand-by operator works in the warehouse to substitute the injured picker.

$$AE_{id} = (1 - (A_h + A_{h\,sb})) + RA \cdot A_h + RA \cdot A_{h\,sb} + (1 - Q) \cdot A_{h\,sb} \tag{4.8}$$

Unlike the AE_d formula, in this case the first term represents the unavailability of both pickers (standard and stand-by ones), and the further last term is added to take into account that the stand-by operator generally has a lower productivity than the standard operator (Grosse and Glock, 2014). Here, for example, this aspect is considered with a parameter, Q, expressing the lower productivity of the new picker.

Similar to the formula (4.3) introduced in the previous section, the Additional Effort Cost in case of indirectly employed operators is:

$$AEC_{id} = AE_{id} \cdot c_h \cdot T \tag{4.9}$$

Additional effort estimation procedure

After having introduced the formulas for calculating the additional effort percentage and the additional effort cost, for both cases, in the present section the overall additional effort procedure is reported. In fact, such a definition of the additional effort cost can be useful to estimate the potential impact and, then, the benefits of an eventual intervention that can be done within a warehouse with the aim of improving the ergonomics working conditions. In fact, before making a certain investment for ergonomics conditions improvement it is important to understand whether this action will lead also to an adequate improvement of the picking performances, and, hence, to a reduction of the picking activity cost.

Figure 4.4 reports the scheme of the full procedure: first of all, it is necessary to estimate the three warehouse parameters, the OWAS indexes of the various activities and the corresponding ergonomics level *EL*, the Human availability A_h and the rest allowance *RA*. Once these parameters are defined, the relations of $A_h$and *RA* in function of *EL* can be derived, obtaining also the parameters of the two curves. Then, the Additional Effort percentage and, subsequently, the Additional Effort Cost can be calculated, choosing the right formulas, according to the way the pickers are employed in the warehouse. Once the current situation has been outlined, the analysis can continue with the evaluation of the future one. In particular, starting from the definition of the expected new ergonomics level *EL'*, that can refer also to the improvement of only one specific activity performed by the picker, the new Human availability A'_h and the new Rest Allowance *RA'* can be estimated. These parameters can then be used for the calculation of the new additional effort costs (AEC'_d or AEC'_{id}).

Finally, it can be useful to define two further terms. The first one is the Marginal Ergonomic Saving, which in case of directly employed operators is:

$$MES_d = \frac{AEC_d - AEC'_d}{AEC_d} \tag{4.10}$$

The second formula, instead, allows the calculation of the Profitability index *PI*, calculated with the ratio of the Marginal Ergonomic Saving *MES* and the Ergonomic Intervention Cost *EIC*, that is the cost of the investment needed for improving the ergonomics level.

$$PI_d = \frac{MES_d}{EIC} \tag{4.11}$$

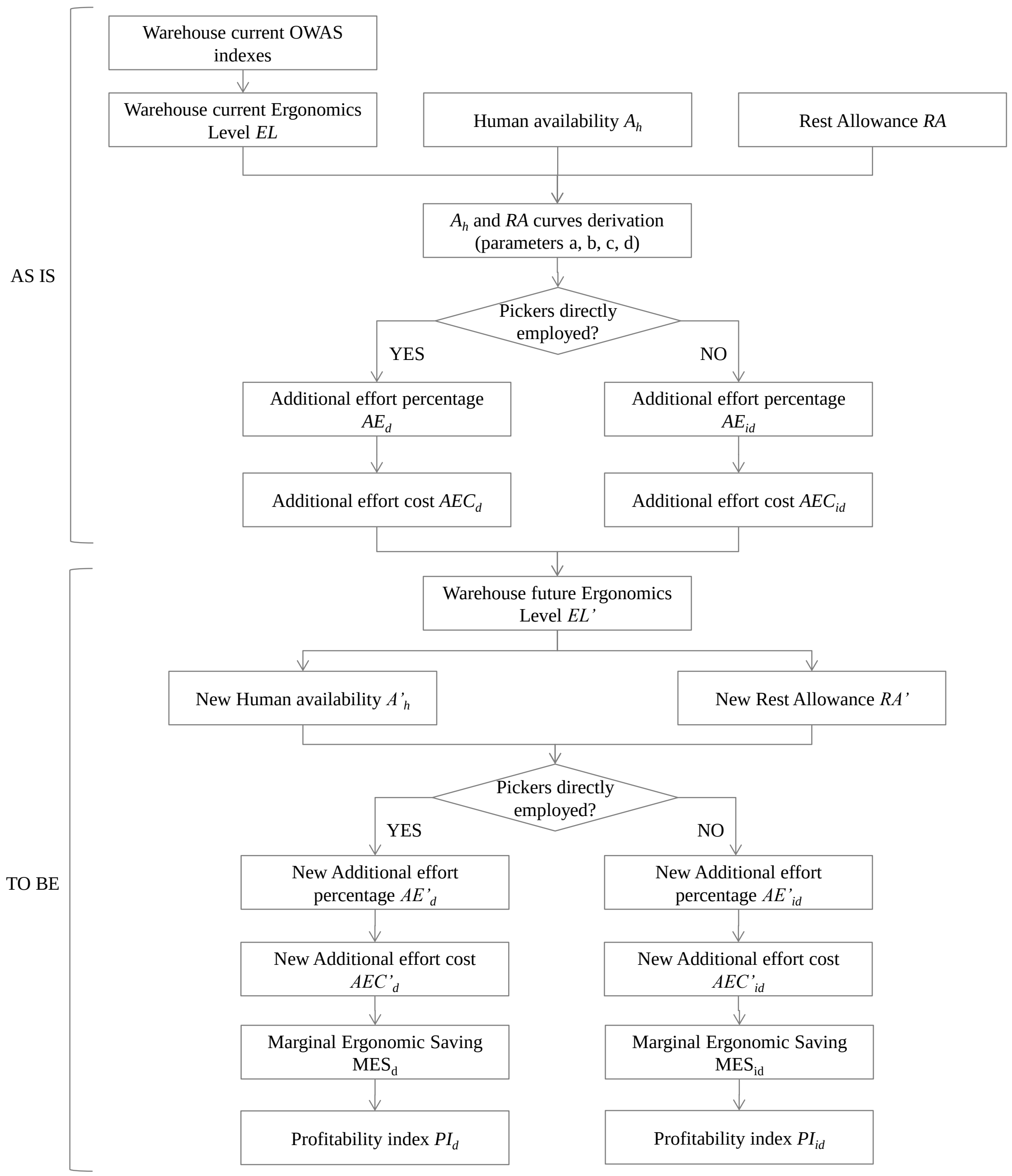

Figure 4.4. Scheme for ergonomic additional effort evaluation.

4.2.4 Case study

The proposed case study deals with the analysis performed in two different picking warehouses storing food and no-food products. One of the two warehouses (here called “Warehouse 1”) is used for the storage of items of small and medium dimensions and weights; moreover, it has 40 directly employed operators, each of them working 1,760 hours per year. On the other side, in the second warehouse (here called “Warehouse 2”) the company can rely on indirectly employed pickers, that mainly have to handle heavy and medium-heavy items. The study concerns the evaluation of the current ergonomics conditions of the operators in both cases, and the subsequent estimation of the potential benefits of an investment that is under investigation, having the main purpose of reducing the time for processing the picking orders but with an important impact also from an ergonomic point of view.

In both warehouses, during the processing of the picking orders, the pickers travel within the picking area on board of picking carts. Once a picker reaches a certain stocking location, corresponding to a product reported on his picking list, he picks up the required number of cartons and he puts them on the pallet on the picking cart. Once the mixed pallet, containing the products for a certain customer, is full, the picker has also to wrap it with a transparent film, in order to facilitate the transportation of the shipping unit, also preventing the possible fall of some products.

The “as is” analysis starts with the measurement of the Ergonomics Levels of the warehouses, in this case derived from OWAS indexes. In order to obtain these parameters a special motion capture system is used, called Ergo-Log (Battini et al., 2014). In particular, the OWAS indexes are weighted considering the various percentages of time that the picker spends for the different activities. In fact, it has been observed that in this case a picker spends on average 60% of his time for travelling, 13% for search and set up activities, 15% for picking and the remaining 12% for other activities, including the manual film-wrapping of the shipping units, that can be pallets or rolltainers. Then, the human availabilities and the rest allowances of both warehouses are calculated. Table 4.2 reports all the data collected and derived for the two warehouses; Figure 4.5 shows the plots obtained for the human availability A_h on the left and for the rest allowance RA on the right.

	WAREHOUSE 1		WAREHOUSE 2	
	AS IS	TO BE	AS IS	TO BE
EL	150	140	180	170
A_h	99.47%	99.70%	98.28%	98.77%
$A_{h\,sb}$	-	0.48%	1.55%	1.11%
RA	0.53%	0.38%	1.07%	0.89%
AE_d	1.058%	-	-	-
AEC_d	466 €/year	-	-	-
AE_{id}	-	0.628%	2.480%	1.886%
AEC_{id}	-	277 €/year	1,091 €/year	830 €/year

Table 4.2. Case study data and results, "as is" and "to be" scenarios.

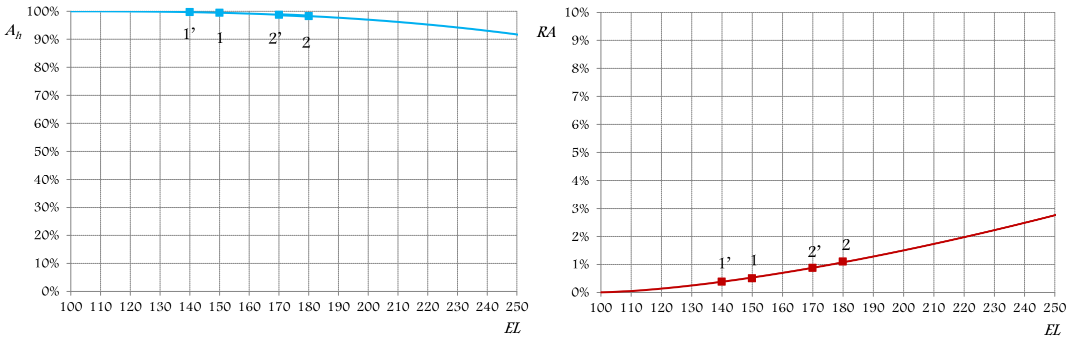

Figure 4.5. Ah curve and RA curve for the two analysed warehouses.

As far as Warehouse 1 is concerned, the "to be" analysis is mainly focused on the evaluation of two possible actions. The first one deals with the possibility of avoiding the manual film wrapping activity, by introducing some new wrapping machines. In this way, there would be the reduction of the time needed for this activity, together with a reduction of its ergonomics impact. In fact, it is calculated that with this intervention the *EL* for the overall picking activity would decrease from 150 to 140. As a consequence, this reduction potentially leads to an increase of the human availability A_h of the operators, and to a decrease of the rest allowance, as can be seen from the plots reported on Figure 4.5 (points labeled with 1'). The second action for this first warehouse is the evaluation of hiring indirectly employed pickers during the absence of the directly employed ones. In this way, the company has the opportunity of gaining the benefits of such a human resources management, reducing the human unavailability impact of its employees. Therefore, it follows a further reduction of the additional effort percentage and, hence, of the additional effort cost, as reported in Table 4.2. Moreover, it is possible to calculate the *MES* and the *PI* for Warehouse 1; it turns out that *MES*=0.406, while, considering the economic investment required for the purchase of the wrapping machines, the profitability index PI is equal to 0.050%.

The analysis of Warehouse 2 is limited only to the evaluation of the investment related to the purchase of the wrapping machines. Similarly to the case of Warehouse 1, here it turns out that the Ergonomics Level decreases, and, hence, the corresponding values of A_h and *RA* change accordingly (Figure 4.5, points labeled with 2 and 2'), also warranting lower values of *AE* and *AEC* (Table 4.2 and Figure 4.6). Finally, in this case *MES*=0.239 and *PI*=0.029%. In both warehouses the values of marginal ergonomic saving and of the profitability index are quite low, since the considered investment impacts only on the wrapping activity, which represents a small percentage of the total time.

On the left of Figure 4.6 it can be seen that the two additional effort costs AEC_d and AEC_{id} have a similar increasing trend. The main difference is that in case of AEC_{id} the curve has a lower slope, thanks to the employ of the stand-by operators.

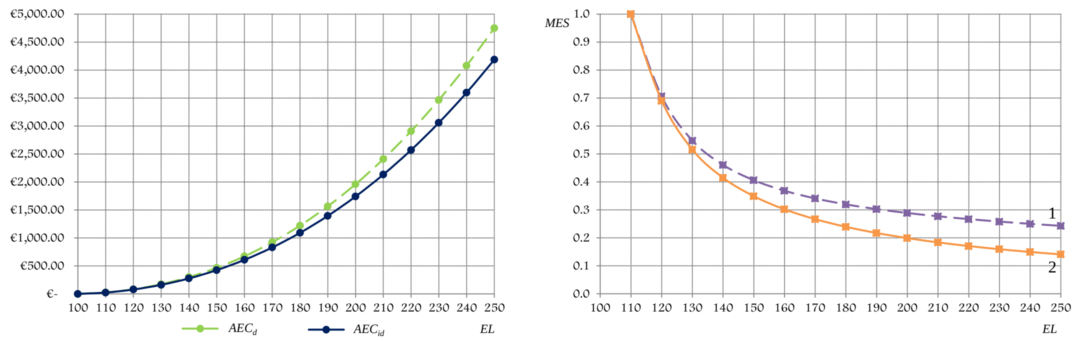

Figure 4.6. Plot for AECd and AECid (left) and MES trends plotting (right).

A last comment concerning the here introduced model is related to the graph on the right of Figure 4.6, reporting the plotting of the Marginal Ergonomic Saving *MES* expressed in function of the Ergonomics level *EL*. In fact, this graph allows the understanding of the effect that a certain intervention or investment for the improvement of the ergonomics working conditions has in terms of costs saving.

4.3 Analysis of economic and ergonomic performance measures of different rack layouts in an order picking warehouse

Since order picking is still performed manually with technical support in most warehouses, human workers play an important role for order picking performance. Although it is recognized that manual material handling activities in warehouses expose workers to a high risk of developing musculoskeletal disorders, integrated planning approaches that consider both economic and ergonomic objectives in order picking design are still rare. This paragraph represents a contribution for closing this research gap by developing economic and ergonomic performance measures for the case where orders are picked from pallets, half-pallets and half-pallets equipped with a pull-out system. The comprehensive analysis of the different rack layouts shows that there are opportunities to replace the traditional pallet storage system by half-pallets with pull-out system on the lower rank to improve both ergonomics and economic performance.

4.3.1 Notations

Notation	Description
H_P	Pallet height
D_P	Pallet depth
L_P	Pallet width
V_P	Pallet volume
$q_{P\ i}$	Number of items per pallet
$q_{HP\ i}$	Number of items per half-pallet
$q_{PO\ i}$	Number of items per half-pallet with pull-out system
α	Extra space factor for the half-pallet
β	Extra space factor for the pull-out system
Q_i	Picked items per month for product i
Z_i	Picking lists per month for product i
Q_i/Z_i	Picked items per picking list for product i
$V_{C\ i}$	Item volume
$W_{C\ i}$	Item weight
$t_{p\ P}$	Average pick time for an item on a full pallet

$t_{p\ HPL}$	Average pick time for an item on a half-pallet, lower rack
$t_{p\ HPU}$	Average pick time for an item on a half-pallet, upper rack
$t_{p\ POL}$	Average pick time for an item on a half-pallet with a pull-out system, lower rack
$t_{p\ POU}$	Average pick time for an item on a half-pallet with a pull-out system, upper rack
t_{PO}	Average time for pulling out (or pushing in) a half-pallet
t_{FIX}	Time for fixed activities (reading pick lists, barcode scanning etc.)
t_{ST}	Pallet and half-pallet stock time
t_{REF}	Pallet and half-pallet refill time
C_1	Hourly cost of the operator in the reserve area
C_2	Hourly cost of the operator in the pick area
C_3	Monthly cost per square meter of the warehouse
c_4	Purchase cost of the pull-out system
C_4	Monthly cost of the pull-out system
$C_{P\ i}$	Unitary total cost per pick for an item on a full pallet
$C_{HPL\ i}$	Unitary total cost per pick for an item on a half-pallet, lower rank
$C_{HPU\ i}$	Unitary total cost per pick for an item on a half-pallet, upper rank
$C_{POL\ i}$	Unitary total cost per pick for an item on a half-pallet with pull-out system, lower rank
$C_{POU\ i}$	Unitary total cost per pick for an item on a half-pallet with pull-out system, upper rank
$\dot{E}_{p\ P}$	Energy expenditure for picking an item on a full pallet
$\dot{E}_{p\ HPL}$	Energy expenditure for picking an item on a half-pallet, lower rank
$\dot{E}_{p\ HPU}$	Energy expenditure for picking an item on a half-pallet, upper rank
$\dot{E}_{p\ POL}$	Energy expenditure for picking an item on a half-pallet with pull-out system, lower rank
$\dot{E}_{p\ POU}$	Energy expenditure for picking an item on a half-pallet with pull-out system, upper rank
$\dot{E}_{FIX}$	Energy expenditure for fixed activities
$\dot{E}_{PO}$	Energy expenditure for pulling out (or pushing in) a half-pallet
$\dot{E}_{P\ i}$	Unitary energy expenditure per pick for an item on a full pallet
$\dot{E}_{HPL\ i}$	Unitary energy expenditure per pick for an item on a half-pallet, lower rank
$\dot{E}_{HPU\ i}$	Unitary energy expenditure per pick for an item on a half-pallet, upper rank
$\dot{E}_{POL\ i}$	Unitary energy expenditure per pick for an item on a half-pallet with pull-out system, lower rank
$\dot{E}_{POU\ i}$	Unitary energy expenditure per pick for an item on a half-pallet with pull-out system, upper rank

Table 4.3. Notations.

4.3.2 Problem description

The proposed study considers a warehouse that uses racks for storing items, where each rack has a zone that order pickers can easily access without requiring additional technical devices (such as forklift trucks, ladders etc.), also called forward zone (Bartholdi and Hackman, 2011). In practice, such a zone would usually not be higher than 2 meters. Above this lower-level pick zone, instead, there could be the reserve area, an additional storage space available to be used as a bulk storage area for replenishing lower-level zones. Figure 4.8 illustrates a warehouse as the one considered here. The proposed methodology has the aim of evaluating different rack layouts for a pick zone as the one described above, considering both economic and ergonomic performance measures. Moreover, this approach helps to gain insights into how a lower-level pick zone should be designed to facilitate both an economic and ergonomic picking of products. Three technical design options for racks that permit different ways of storing items in a lower-level pick zone of a manual order picking warehouse are considered: 1) traditional pallets, 2) half-pallets, and 3) half-pallets equipped with a pull-out system. A half-pallet is defined as a pallet that stores up to 50% of the items stored on a full pallet. A pull-out system, in turn, is a device that enables the order picker to manually pull out a pallet from the rack, which permits a more ergonomic picking of items due to less bending and stretching. After all picks have been performed, the pallet needs to be pushed back in again to avoid that the aisle is blocked. Clearly, a half-pallet/pull-out system at the upper layer can be combined with a half-pallet/pull-out system at the lower layer. Thus, there are five different configurations derived from the combination of the three described design options for racks (the five combinations are illustrated in Figure 4.7 for the case where two products are stored):

(1) Both products are stored in full pallets located in the lower-level zone.

(2) The lower-level zone is split up into two layers, and both products are stored on half-pallets.

(3) The lower-level zone is split up into two layers, with one product being stored on a half-pallet on the upper rank, and one product being stored on a half-pallet equipped with a pull-out system on the lower layer.

(4) The lower-level zone is split up into two layers, with one product being stored on a half-pallet equipped with a pull-out system on the upper rank, and one product being stored on a half-pallet on the lower one.

(5) The lower-level zone is split up into two layers, with both products being stored on half-pallets equipped with a pull-out system.

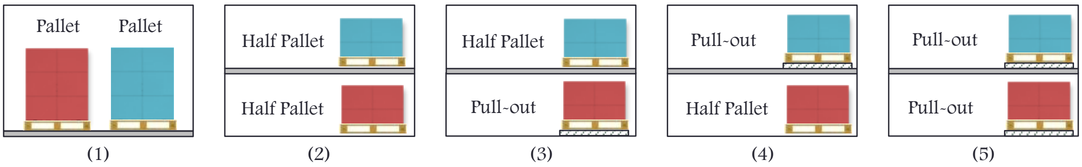

Figure 4.7. Possible combinations for storing two types of products.

The economic and ergonomics models proposed in the next section help to evaluate these different rack layouts and to derive guidelines for the design of storage locations.

4.3.3 Model development

The development of the models for evaluating the five rack layouts represented in Figure 4.7 is split up into two parts, namely the proposal of an economic model (cost) and the proposal of an ergonomics model (human energy expenditure); all notations used are listed in Table 4.3. For developing the objective functions of the economic and ergonomic models, we split up the pick process into different tasks that are then evaluated both from an economic and an ergonomic point of view. In the economic evaluation, we also consider the cost of the storage space occupied by the stock keeping unit. Figure 4.8 graphically illustrates the various terms of the function:

- Pallet stocking and refilling: the pallets or half-pallets are stored in the reserve area of the warehouse after receipt into inventory, and they are forwarded to the forward (pick) area with the help of a forklift truck whenever a storage location in the forward area has been depleted.
- Item picking: for each incoming order, the worker picks the items of the products that have been requested in the order from the storage locations in the forward zone of the warehouse.

- Occupied space: each rack configuration requires a different amount of space. The opportunity cost of storage space are considered in the economic models.

Figure 4.8. Activities illustrations for the five different storage systems.

In the following, it is shown how these activities influence the economic and ergonomic evaluation of the five rack layouts. The following abbreviations are used: P = Pallet, HPU = Half-pallet upper rank, HPL = Half-pallet lower rank, POU = Pull-out upper rank, POL = Pull-out lower rank.

Economic models

The economic analysis considers a unitary total cost (*C*) for traditional pallet (*P*), half-pallet (*HP*), and half-pallet storage with pull-out system (*PO*), expressed in €

per physical pick Q_i (€/pick). Q_i is the number of items that are picked for product i in the considered time period. Hence, it corresponds to the number of times that the picker physically has to pick the product *i*. This total cost is mainly composed of three cost components, derived from the time needed to perform the corresponding activities, namely "pallet handling cost" (C_1) and "picking cost" (C_2), and the physical space of the warehouse that is occupied by the stock keeping unit, resulting in a "space cost" (C_3).

Pallet handling costs refer to the stocking activity (the pallet is stocked in the reserve area) and the refilling activity (the pallet is moved from the reserve area to the forward area to refill empty locations). The formula describing this type of cost is the same for all considered warehouse solutions; however, the number of replenishments may differ from rack layout to rack layout.

Picking costs deal with the actual picking activity and considers the physical pick and all additional activities that are needed for retrieving an item (i.e., product barcode scanning, product verification etc.). Moreover, in case an item is picked from half-pallets equipped with a pull-out system, an additional cost factor has to be considered here, namely the time that is required for pulling out the pallet from the rack and, subsequently, for pushing it back in (t_{PO}).

In order to consider the space cost of the different configurations, the monthly warehouse cost per square meter (C_3) is multiplied by the area physically occupied by the pallet. Hence, in case a half-pallet or a half-pallet with a pull-out system is used, the area required by the pallet is divided by two, since it is possible in this case to store two pallets in the same zone of the rack. The factors α and β are introduced to account for the fact that for these two systems, an extra space in height is required due to the presence of an extra pallet and/or the pull-out equipment, combined with an additional space requirement for handling.

Finally, in case of use of the pull-out system, a further term is needed, which measures the monthly cost of the pull-out system C_4, obtained by dividing the purchasing cost c_4 by the months of use.

The economic measures are now defined as follows:

Traditional pallet

$$C_{P\,i} = \frac{\left(t_{ST} \cdot \frac{Q_i}{q_{P\,i}} + t_{REF} \cdot \frac{Q_i}{q_{P\,i}}\right) \cdot C_1 + \left(t_{p\,P} \cdot Q_i + t_{FIX} \cdot Z_i\right) \cdot C_2 + L_P \cdot D_P \cdot C_3}{Q_i} \qquad (4.12)$$

Half-pallet, upper rank

$$C_{HPU\,i} = \frac{\left(t_{ST} \cdot \frac{Q_i}{q_{HP\,i}} + t_{REF} \cdot \frac{Q_i}{q_{HP\,i}}\right) \cdot C_1 + \left(t_{p\,HPU} \cdot Q_i + t_{FIX} \cdot Z_i\right) \cdot C_2 + \frac{L_P \cdot D_P}{2} \cdot C_3 \cdot \alpha}{Q_i} \quad (4.13)$$

Half-pallet, lower rank

$$C_{HPL\,i} = \frac{\left(t_{ST} \cdot \frac{Q_i}{q_{HP\,i}} + t_{REF} \cdot \frac{Q_i}{q_{HP\,i}}\right) \cdot C_1 + \left(t_{p\,HPL} \cdot Q_i + t_{FIX} \cdot Z_i\right) \cdot C_2 + \frac{L_P \cdot D_P}{2} \cdot C_3 \cdot \alpha}{Q_i} \quad (4.14)$$

Half-pallet with pull-out system, upper rank

$$C_{POU\,i} = \frac{\left(t_{ST} \cdot \frac{Q_i}{q_{PO\,i}} + t_{REF} \cdot \frac{Q_i}{q_{PO\,i}}\right) \cdot C_1 + \left(t_{p\,POU} \cdot Q_i + t_{FIX} \cdot Z_i + t_{PO} \cdot Z_i\right) \cdot C_2 + \frac{L_P \cdot D_P}{2} \cdot C_3 \cdot \beta + C_4}{Q_i} \quad (4.15)$$

Half-pallet with pull-out system, lower rank

$$C_{POL\,i} = \frac{\left(t_{ST} \cdot \frac{Q_i}{q_{PO\,i}} + t_{REF} \cdot \frac{Q_i}{q_{PO\,i}}\right) \cdot C_1 + \left(t_{p\,POL} \cdot Q_i + t_{FIX} \cdot Z_i + t_{PO} \cdot Z_i\right) \cdot C_2 + \frac{L_P \cdot D_P}{2} \cdot C_3 \cdot \beta + C_4}{Q_i} \quad (4.16)$$

Ergonomic models

For evaluating the ergonomic impact of the rack layouts, it is proposed to use the energy expenditure estimation concept proposed by Garg et al. (1978). This concept develops different equations that can be used as a reference for the estimation of the energy expenditure required for performing manual activities, expressed in kilocalories per minute. The energy expenditure concept advocates that higher cumulative energy expenditure leads to higher levels of fatigue and higher injury risks, thus reducing the ergonomic quality of the activity under consideration. From an ergonomics points of view, companies should try to reduce the energy expenditure associated with performing a particular task.

The ergonomics analysis performed here estimates the energy expenditure that is required for performing picking operations. Hence, all direct physical activities involved in picking items are considered, namely physical picking, additional operations (such as product barcode scanning, product verification etc.) and, for the pull-out system, pulling out and pushing back in the pallet. The total energy expenditure ($\dot{E}$) is expressed in kilocalories per pick (kcal/pick), obtained by dividing the total energy expenditure expressed in kcal/min by Q_i, i.e. the number of picks for product *i*.

In defining the objective functions for the ergonomic analysis, we consider that a "kcal per pick"-analysis promotes a net comparison of the different systems. In fact, with a "kcal per minute"-approach, the pull-out system would be penalized as it leads to a faster picking process on average, which results in more picks per minute and, consequently, a higher energy expenditure.

The ergonomic measures are defined as follows:

Traditional pallet

$$\dot{E}_{P\,i} = \frac{\dot{E}_{p\,P} \cdot Q_i + \dot{E}_{FIX} \cdot Z_i}{Q_i} \tag{4.17}$$

Half-pallet, upper rank

$$\dot{E}_{HPU\,i} = \frac{\dot{E}_{p\,HPU} \cdot Q_i + \dot{E}_{FIX} \cdot Z_i}{Q_i} \tag{4.18}$$

Half-pallet, lower rank

$$\dot{E}_{HPL\,i} = \frac{\dot{E}_{p\,HPL} \cdot Q_i + \dot{E}_{FIX} \cdot Z_i}{Q_i} \tag{4.19}$$

Half-pallet with pull-out system, upper rank

$$\dot{E}_{POU\,i} = \frac{\dot{E}_{p\,POU} \cdot Q_i + \dot{E}_{FIX} \cdot Z_i + \dot{E}_{PO} \cdot Z_i}{Q_i} \tag{4.20}$$

Half-pallet with pull-out system, lower rank

$$\dot{E}_{POL\,i} = \frac{\dot{E}_{p\,POL} \cdot Q_i + \dot{E}_{FIX} \cdot Z_i + \dot{E}_{PO} \cdot Z_i}{Q_i} \tag{4.21}$$

4.3.4 Numerical analysis of different scenarios

The economic and ergonomic models introduced in the previous section are now used to compare the performance of the five proposed rack configurations (Figure 4.7). In the following analysis, we study the impact of different product characteristics, in terms of pick frequency, item volume and weight, on the economic and ergonomic performance of the rack configurations. This analysis helps evaluating which rack configuration should be used for which type of product, also considering the characteristics of the products. The study starts with a benchmark case that uses the input values reported in Table 4.4. The same table also shows alternative values for the parameters Q_i, Q_i/Z_i, $V_{c\ i}$, and $W_{c\,i}$ that were used in all possible combinations (except those that would lead to unrealistic items, for example with a volume $V_{c\ i}$ equal to 0.001 m^3 together with a weight of $W_{c\,i}$ = 20 kg or $W_{c\,i}$ = 15 kg) to generate different scenarios for the analysis. The total number of different combinations for the various products is 36,864. Furthermore, Table 4.5 reports the various energy expenditure values that have been calculated with the formulas from (4.17) to (4.21) varying the weight of the item $W_{c\ i}$.

Figure 4.9 shows the results of the economic analysis performed by applying the cost models to all possible rack configurations for two products with different characteristics (compare Figure 4.7). The two products are referred to using the numbers 1 and 2, respectively, while the different rack layouts are reported using the already introduced abbreviations (P, HPU and HPL, POU and POL). On the left side of each graph, the values of the various varying parameters are shown, while the x-axis is used to display values of Q_i/Z_i and $V_{c\,i}$ of product 2. The y-axis, in turn, reports how often the respective rack configuration outperformed the other alternatives, expressed as percentages. For example, looking at the third bar chart of Figure 4.9, in case of Q_i/Z_i = 1 and $V_{c,i}$ = 0.001 for product 2, this means that:

- in 81% of the considered cases (different scenarios), the best layout configuration is “1. P 2. P”, i.e., both products 1 and 2 should be stored on full pallets.

- in 11% of the considered cases, the best layout configuration is “1. HPU 2. HPL”, i.e., product 1 should be stored on a half-pallet on the upper rank and product 2 on a half-pallet on the lower rank.
- for the remaining 8% of the scenarios, the best layout configuration is “1. HPU 2. POL”; thus, product 1 should be stored on a half-pallet on the upper rank and product 2 should be stored on a half-pallet with pull-out system on the lower rank.

The same logic is employed in Figure 4.10, concerning the ergonomic analysis.

RACK	H_P	D_P	L_P	V_P	$q_{P\,i}$	$q_{HP\,i}$	$q_{PO\,i}$	α	β
	1.5 m	1.2 m	0.8 m	1.44 m^3	$V_p/V_{c,i}$	$q_{P\,i}/2$	$q_{P\,i}/2$	1	1

ITEM						
Q_i	10		500		1,000	2,000
Q_i/Z_i	1		5		10	
$V_{C\,i}$	0.001 m^3		0.027 m^3		0.125 m^3	
$W_{C\,i}$	0.25 kg	2.5 kg	5 kg	10 kg	15 kg	20 kg

TIMES	$t_{p\,P}$	$t_{p\,HPL}$	$t_{p\,HPU}$	$t_{p\,POL}$	$t_{p\,POU}$	t_{PO}	t_{FIX}	t_{ST}	t_{REF}
	5.5 s	6.5 s	5 s	4 s	4 s	5 s	10 s	180 s	180 s

COSTS	C_1	C_2	C_3	c_4	C_4
	15 €/h	15 €/h	4.17 (€/m^2)/month	400.00 €	6.67 €/month

Table 4.4. Values for the input parameters of the analysis.

	Item weight $W_{c\,i}$					
Parameter	0.25 kg	2.5 kg	5 kg	10 kg	15 kg	20 kg
$\dot{E}_{p\,P}$	0.43	0.48	0.54	0.66	0.78	0.89
$\dot{E}_{p\,HPU}$	0.37	0.42	0.48	0.61	0.73	0.85
$\dot{E}_{p\,HPL}$	0.55	0.62	0.70	0.86	1.02	1.18
$\dot{E}_{p\,POU}$	0.30	0.35	0.41	0.52	0.64	0.75
$\dot{E}_{p\,POL}$	0.42	0.47	0.54	0.66	0.79	0.92
$\dot{E}_{FIX}$	1.80	1.80	1.80	1.80	1.80	1.80
$\dot{E}_{PO}$	0.23	0.23	0.23	0.23	0.23	0.23

Table 4.5. Energy expenditure values.

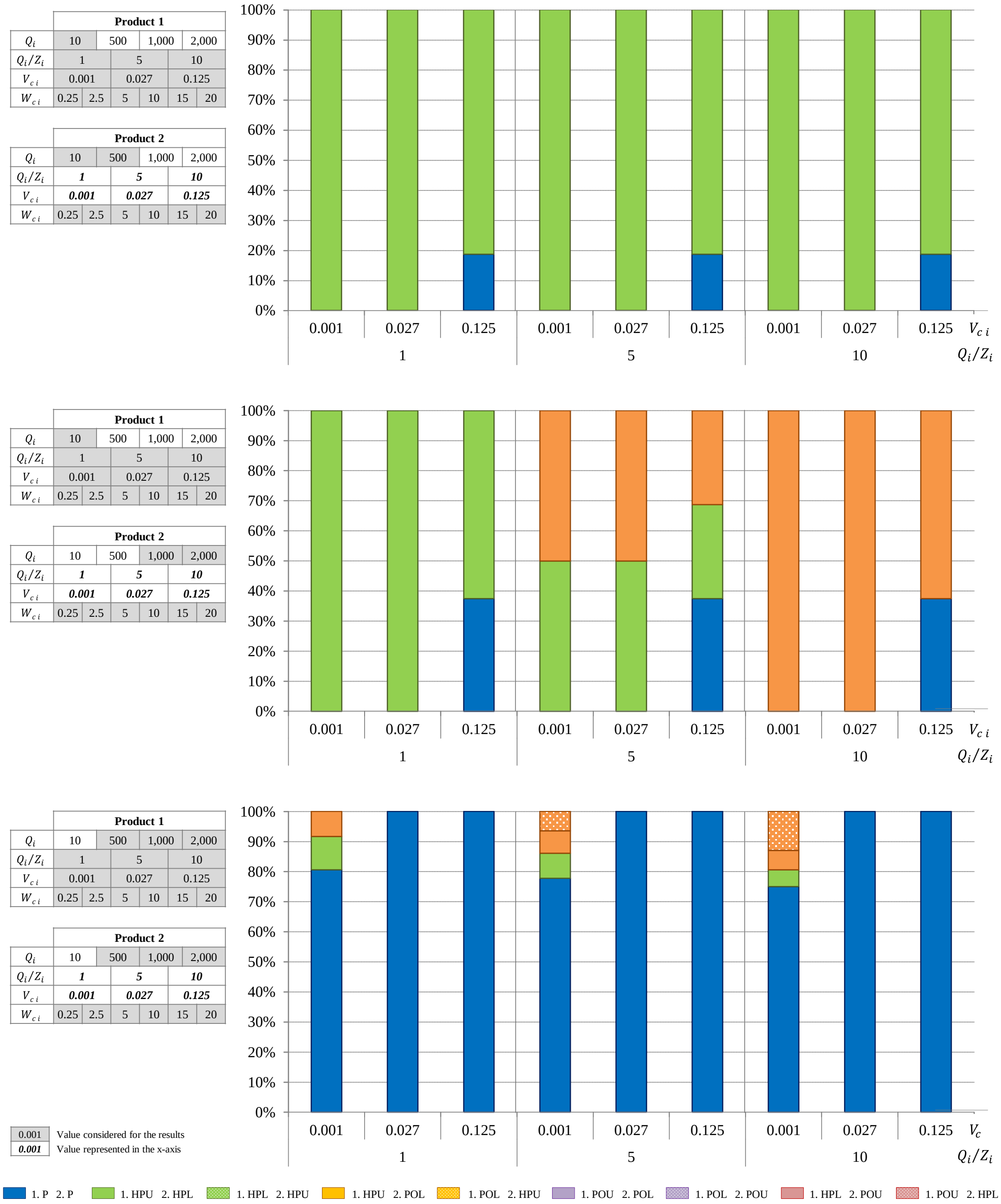

Figure 4.9. Best rack layouts for two products with different characteristics, economic evaluation.

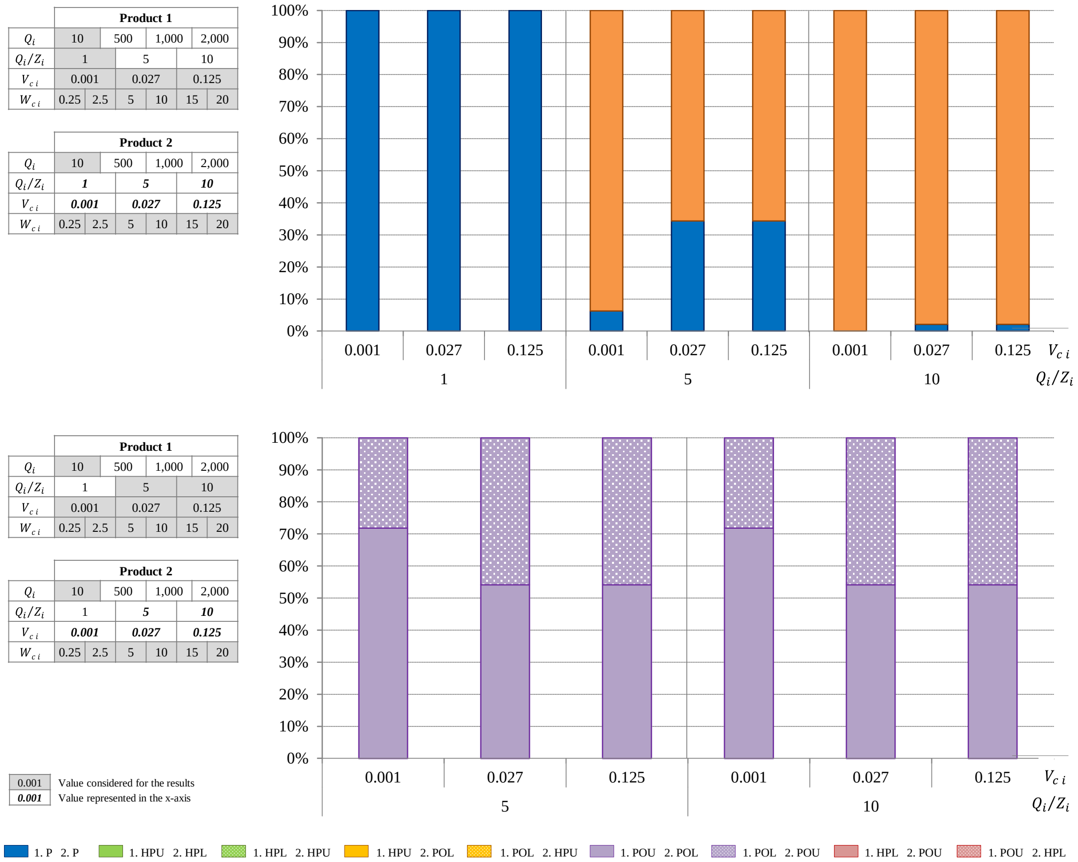

Figure 4.10. Best rack layouts for two products with different characteristics, ergonomic evaluation.

4.3.5 Discussion

Economic comparison

A closer analysis of Figure 4.9 shows that for products that are only picked a couple of times per month (here: Q_i=10), the best rack configuration from a cost perspective is always the one with two half-pallets. Storing products on traditional pallets, in turn, becomes more economical when the product is picked with a higher frequency (here: Q_i=500) and/or the products have a large volume (here: $V_{c\,i}$=0.125). Clearly, using full pallets in this case helps to avoid frequent pallet replenishments, which helps to reduce cost in the reserve area of the warehouse.

The second graph of Figure 4.9, instead, reports the case in which product 1 is picked only infrequently, while product 2 is picked with a high frequency. In this case, items with a large volume (here: $V_{c\,i}$=0.125) should be stored again on full pallets. Apart from this, the results depend on the value of the ratio Q_i/Z_i of product 2. In particular, when product 2 is picked with one item per pick list (Q_i/Z_i=1), it is more suitable to store the items on half-pallets. On the other hand, when Q_i/Z_i=10, the best rack configuration is the one with product 1 stored on a half-pallet on the upper rank and product 2 on a half-pallet with pull-out system on the lower rank. Finally, in the intermediate case where Q_i/Z_i=5, all three rack layouts mentioned before can potentially be used, according to the number of picked items per picking list or the volume of the products. In fact, when the number of picked items per picking line, Q_i/Z_i, increases, storing a product on a half-pallet with a pull-out system turns out to be more economically convenient than storing it on a simple half-pallet.

The last graph of Figure 4.9 illustrates the case in which both products are picked with a medium or high frequency per month (here: Q_i=500, 1,000 and 2,000). In this case, the solution that warrants the best result in most of the considered scenarios is the storage on full pallets. The only exceptions are the cases in which both products have a small volume ($V_{c\,i}$=0.001), where it would be better to store the items on half-pallets, and, if their picking frequency is high, to adopt a pull-out solution.

Ergonomic comparison

As the results of a parametrical evaluation of the ergonomic measures do not vary with the number of picked items per month, Q_i, this analysis focuses only on the outcomes obtained for one particular value of this parameter; for example, the graphs reported in Figure 4.10 all assume that Q_i=10. Looking at the first graph of Figure 4.10, it can be seen that when Q_i/Z_i=1 for both products, the best storage configuration are two traditional full pallets, for all values of item volume and weight. This solution becomes less ergonomically preferable when one of the two products is picked with a higher number of items per pick list (here: Q_i/Z_i=5 and 10). In this case, it is suggested to store the items on half-pallets, product 1 on the upper rank and product 2 on the lower one, with the lower half-pallet equipped with a pull-out system. In these scenarios, the storage on pallets remains the most suitable solution when the item weight is high. The second bar-chart of Figure 4.10 focuses on the scenarios in which both products 1 and 2 are picked with Q_i/Z_i=5 or 10. It can be seen that in these cases, the best solution is the one in which both products are stored on half-pallets with a pull-out system.

	ECONOMIC ANALYSIS	ERGONOMIC ANALYSIS
Rack layout	*The configuration is the best one when…*	*The configuration is the best one when…*
P – P	• Both products have a large item volume and at least one product is picked with a medium-high frequency. • Both products have a medium item volume and they are both picked with a medium-high frequency. • Only one product has a small item volume and both products are picked with a medium-high frequency. • Both products are picked with a high frequency and have a small item volume.	• Both products are picked with a single item per pick list, for all picking frequencies. • Only one of the two products is picked one item per pick list, while the other product has a high item weight.
HP – HP	• Both products are picked with a low frequency. • Both products have a small-medium item volume, one product is picked with a low frequency, the other product with a medium and high one.	• Never.
HP – PO	• One product is picked with a low frequency, the other product with a high one and with a high number of items per pick list.	• One product is picked with a low number of items per pick list, the other product with a medium-high number of items, and both have a low-medium item weight.
PO – HP	• Never.	• Never.
PO – PO	• Never.	• Both products are picked with a medium-high number of items per pick list, for all picking frequencies.

Table 4.6. Racks configurations recommendations summary.

General evaluation

From the proposed analysis, concerning a “cost-per-pick” and an “energy expenditure-per-pick” evaluation, it turns out that some of the rack configurations that are convenient from an economic point of view are not suitable when considering ergonomic indicators. On the other side, some solutions that are interesting from an ergonomic point of view can be the best one also from an economic one, since they allow performing the picks in a faster way. Table 4.6 summarizes recommendations for the use of a suitable rack layout with regard to different item characteristics (see also Appendix A.2).

4.4 Conclusions

The study of ergonomics in industrial contexts is becoming one of the most important issues faced by academics and appreciated also by practitioners (Staudt et al., 2015). Due to the large amount of manual material handling, the order picking zone represents one of the most critical areas of a warehouse both with respect to time, quality, and health risks. In fact, in a manual picking warehouse, the processing of the orders relies on human operators that travel within the warehouse aisles, with a certain consequent ergonomic effort (Richards, 2014; Grosse et al., 2015).

The present chapter contributes to this part of the literature by incorporating human factors in analytical order picking models, which has been demonstrated to be an under-researched area. First of all, Paragraph 4.2 has presented a new model useful to estimate the ergonomic effort of the typical picking activities, starting from the concepts of human availability and rest allowance, that have been proved to depend to the ergonomics working conditions (Battini et al., 2015c). Moreover, besides the possibility of evaluating the current situation of the analysed warehouse, the method has allowed to understand the impact and the potential benefits of future interventions, comparing the required economic investment to the obtainable ergonomics improvements.

On the other side, Paragraph 4.3 proposed a new approach to analyse different technical design options for rack (i.e., traditional pallets, half-pallets, and half-pallets equipped with a pull-out system) from an economic as well as ergonomic point of view. Mathematical models representing both perspectives were developed and applied in a multi-scenario analysis in order to comprehensively evaluate the different rack configurations. This analysis revealed that the storage of products on traditional pallets, both in terms of costs and energy expenditure savings, is actually suitable only in some cases, especially when the products have a large item volume, are picked with a high frequency but with a low number of picked items per pick list. If the item volume of the products is small, or the number of picked items per pick list is high, the other rack configurations perform better. However, it has been also found that some configurations are not complementary to each other, which is why their use should be reassessed in industrial practice. For example, the storage of products only on half-pallets is convenient from an economic perspective, but this configuration is not suitable from an ergonomic point of view. In contrast, using a pull-out system for half-pallets consistently is the best ergonomic solution for most of the considered scenarios, but it turned out to result in relatively high costs. Finally, the configuration with a half-pallet on the upper rank and a half-pallet with a pull-out system on the lower rank leads to a fair trade-off between economic efforts and ergonomic benefits, according to the item volume of the products, their picking frequencies and the number of picked items per period of time.

As for managerial implications, it can be concluded that considering only the cost associated with ergonomic interventions (such as implementing pull-out systems) falls short as the long-term benefits of improved ergonomics (return-on-investment) in order picking are difficult to quantify as compared to the pure purchase cost. Generally speaking, improving ergonomics will contribute to improved performance, quality and less worker illness in the long-run.

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5

CONCLUSIONS

"There is no one-size-fits-all design for case-picking warehouses, and hundreds of designs are possible. Moreover, the decision variables in warehouse design are interrelated, and this further complicates the design process."

Thomas and Meller, 2015

5.1 Final comments

5.1.1 Dissertation recap and implications

Due to the recent changes in customers' needs, warehouses are facing the crucial need of processing several different orders, ensuring a high service level, in an always smaller time window (De Koster et al., 2007). Therefore, it follows that all the warehousing activities have to be adequately efficient, as well as effective, to reach this fundamental goal. Of all the activities related to the fulfilment of a customer order, warehouse picking ranks among the most cost and time consuming ones: it derives that acting on this area has the highest priority in order to gain important overall paybacks. One of the possible ways for improving the performances of the picking process is based on the reduction of the time needed to the human picker to process a picking order (Tompkins et al., 2010).

Starting from this analysis of the current logistics context, together with the study of the existing scientific literature, the present Ph.D. thesis has concerned the proposal of innovative methods and procedures for warehouse manual picker-to-parts picking systems design. Based on the definition of the time components of the picking activity defined by Tompkins et al. (2010), the thesis suggests to act on travel time reduction, product search time reduction, item physical pick time reduction and, finally, overall time reduction.

As far as travel time reduction is concerned, Chapter 2 aims at contributing to this by acting on the reduction of the distances travelled by the operators. In particular, this is achieved though the introduction of two new solving approaches to as many topics that have been already extensively addressed in literature. These methods are the *Storage Assignment and Travel Distance Estimation (SA&TDE) joint method*, allowing the evaluation of the impact of storage assignment on the travelled distances, and the *Carton from pallet or carton from rack selection procedure,* related to the forward-reserve problem (Bartholdi and Hackman, 2011). Subsequently, Chapter 3 has focused on search and physical pick time reduction, which, as reported in the literature, can be improved thanks to the employ of paperless picking systems (Guo et al., 2014). In this case, there has been the study of a new paperless picking system, the *RFID pick-to-light*, and the development of a mathematical model for the *technical and economic comparison* *of different existing paperless picking technologies*. Finally, Chapter 4 considered the possibility of gaining an overall time reduction thanks to the study of the human factor in warehouse picking activities (Grosse et al., 2015). This has been performed with two contributions: the first one deals with the concept of human availability, deriving a method for the estimation of the *ergonomics additional effort*; the second one, instead, concerned a method that can be employed to *compare different racks layouts*, taking into account both economic and ergonomic aspects.

An important driver of this thesis has been the will of making available in the scientific literature, but, above all, to logistics practitioners, simple-to-apply methods and procedures able to warrant tangible benefits in picking warehouses, both in the short-medium term and in the long term. Moreover, all the introduced methods have always been tested and validated with numerical examples and real industrial case studies.

Finally, it can be concluded that the design of a warehouse picking system requires the consideration of several interrelated aspects. Moreover, considering the current operating context of a picking warehouse, it is fundamental not to focus only on a low-term cost minimization, rather on considering the system as a whole, also taking into account the important positive (as well as critical) contribute due to the presence of human operators.

5.1.2 Further possible researches

Of course, although this thesis aimed at proposing new methods covering several different aspects of warehouse picking systems design, researches about this topic are not over at all. As already widely detailed, warehouse picking represents a complex issue that surely will deserve important studies and contributions also in the future. Here below, some suggestions in this sense are reported.

For the reduction of travel time, besides the further extension of the existing optimization methods, it could be interesting to consider the possible employ of other storage systems, for example for small objects, in order to make the picking area more compact (Battini et al., 2015). As far as the methods proposed in Chapter 2 are concerned, further research useful to develop the SA&TDE joint method could focus on evaluating its possible applicability on other types of picking systems, i.e. automated systems and parts-to-picker systems. Then, a possible analysis could concern also the optimization of the storage assignment within single-shelving or multi-shelving layouts considering the distances travelled both in the horizontal and in the vertical direction. Finally, the method could be integrated with a model that allows the understanding of the possible effects of congestion on picking time and travelled distances, taking into account all the factors that could influence such circumstance, as, for example, the picking volumes, the means of transport used, the characteristics of the aisles, the adopted routing policy and the possible creation of picking waves. On the other side, future research concerning the Carton from pallet or carton from rack selection procedure is primarily intended to a further validation in real case studies. Then, it will be extended in order to allow the estimation of the actual saving obtainable through the storage of some items in racks instead of in pallets, in terms of reduction of the time needed to perform the picking tour and, as a consequence, in terms of reduction of the picking costs.

The research related to search and pick time has absolutely to continue with the investigation of the potential of paperless picking. The deep and fast technological development that characterise our times promises great possibilities also for an industrial general improvement. Referring to the aspects reported in Chapter 3, first of all the RFID pick-to-light system will be further studied and refined, arriving to the definition of a possible commercial solution of the system. As far as the technical and economic comparison of existing technologies is concerned, the future studies will be focused on the enrichment of the economic comparison by introducing other technologies, on the study of other warehouse configurations and on the evaluation of their applicability to the picking for the feeding of assembly systems.

Finally, since the most widespread picking systems rely on human operators, an important contribution to the reduction of the overall time, and, hence, to the improvement of picking performances, is related to the ergonomics study of picking activities, in order to guarantee the most proper working conditions for the pickers. Both the researches reported on Chapter 4 can be extended. For example, the model presented in Paragraph 4.2 will be validated through a further data collection and an analysis of real human availabilities and rest allowances, by applying it also to other industrial contexts. The extension of the research work on different racks layout evaluation, instead, could concern the derivation of the introduced method for other rack configurations, also considering small boxes storage instead of pallets or half-pallets. Moreover, future works could apply the developed model to case studies using empirical data. Finally, the mathematical formulations could be further arranged and improved, leading to the development of a joint evaluation model that allows the understanding of the best rack configuration, considering both economic and ergonomic aspects with a single formula.

5.2

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6

APPENDICES

Appendix A.1
The Multinomial probability distribution

The SA&TDE joint model presented in Chapter 2 is based on the use of multinomial probability distribution, a generalization of the binomial distribution. Given n independent trials made from an urn containing a set of different marbles, each of which leads to a success for exactly one of the s categories, this statistical distribution allows the calculation of the probability of any particular combination of numbers of successes for the various categories, considering that each category has a given fixed success probability p_i. In particular, the probability of the different combinations are described by the following formula, which represents the probability mass function of the multinomial distribution:

$$P(k_1, \ldots, k_s) = \binom{n}{k_1, \ldots, k_s} \prod_{i=1}^{s} p_i^{k_i} = \frac{n!}{\prod_{i=1}^{s} k_i!} \prod_{i=1}^{s} p_i^{k_i} \qquad \text{(A.1)}$$

where k_i is the number of marbles drawn from the category i and n is the total number of draws (sum of all k_i).

The multinomial distribution considers that the n independent trials are made with replacement, that is, every subsequent draw of a marble from an urn is performed every time with all the marbles inside the urn.

Different is the case treated by the multivariate hypergeometric distribution, in which the trials are dependent, i.e. without replacement of the marbles.
In this case, the probability mass function of the distribution is as the following:

$$P(k_1, \ldots, k_s) = \frac{\prod_{i=1}^{s} \binom{h_i}{k_i}}{\binom{n}{r}} = \frac{\prod_{i=1}^{s} \frac{h_i!}{k_i!\,(h_i - k_i)!}}{\frac{n!}{r!\,(n-r)!}} \qquad \text{(A.2)}$$

where k_i is the number of marbles drawn from the category i and h_i is the cardinality of the category i (number of marbles belonging to the category), while r and n are, respectively, the number of total draws and the sum of the cardinalities of all s categories (total number of marbles). It can be demonstrated that the two probability distributions are completely equivalent when the number of marbles extracted from each category k_i is sufficiently smaller than the total number of marbles of the corresponding category h_i. Indeed, in this case whether the drawn marbles are reinserted or not it is irrelevant, because of the huge amount of marbles that forms each category.

Appendix A.2
Different rack layouts comparison

The present Appendix reports an useful summary view of the analysis introduced in Paragraph 3.34.3. In particular, Figure 6.1 shows the best rack configuration (among Pallet – Pallet, Half pallet – Half pallet, Half pallet – Pull out, Pull out – Pull out, Pull out – Half pallet) from the economic perspective, for various combinations of Product 1 and Product 2. A different elaboration of the same results is also reported in Figure 4.9.

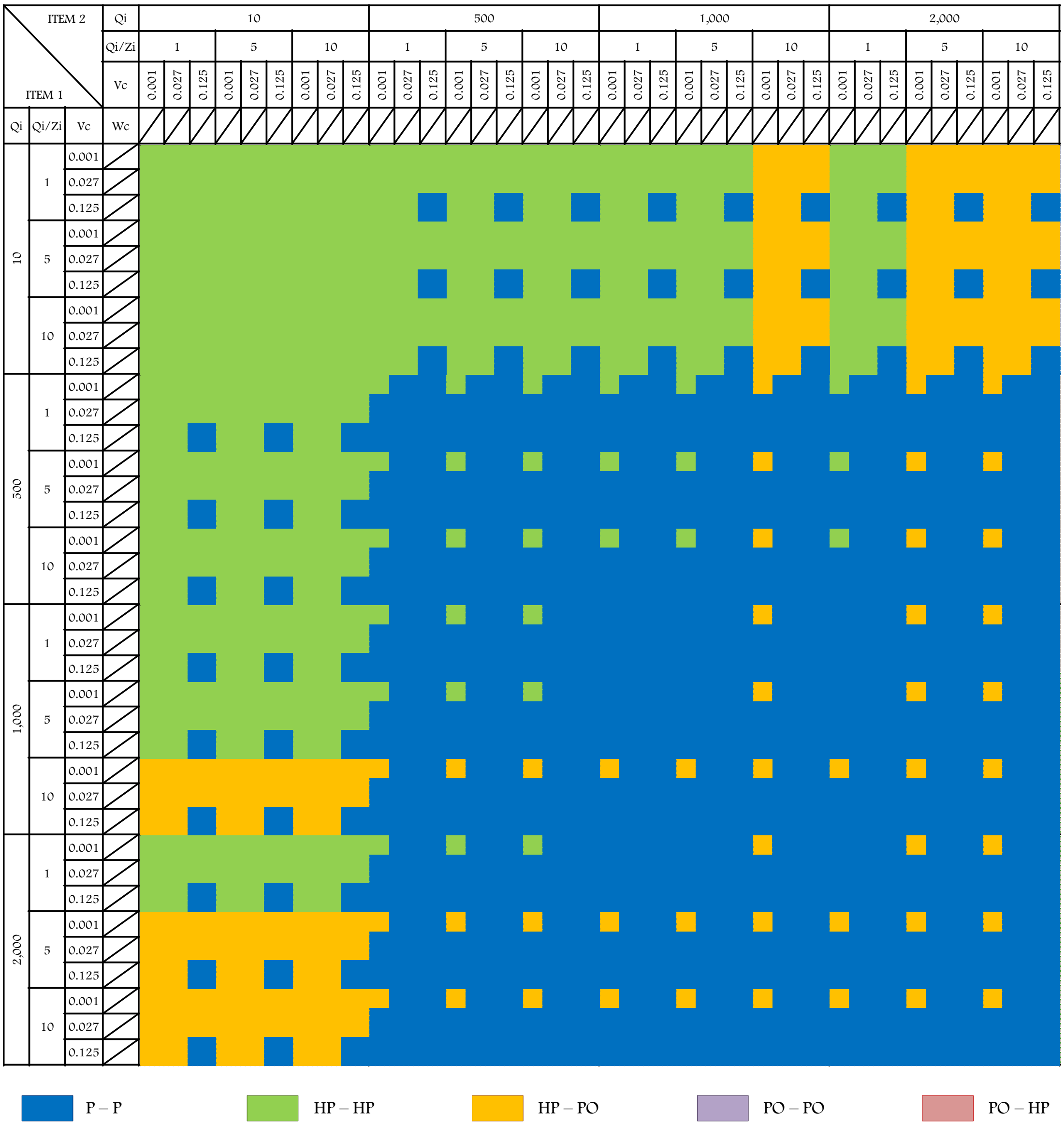


Figure 6.1. Overall view of the best rack layouts for two products with different characteristics, economic evaluation.

Similarly to Figure 6.1, Figure 6.2 shows the best rack configuration (among Pallet – Pallet, Half pallet – Half pallet, Half pallet – Pull out, Pull out – Pull out, Pull out – Half pallet) from the ergonomic perspective, for various combinations of Product 1 and Product 2. A different elaboration of the same results is also reported in Figure 4.10.

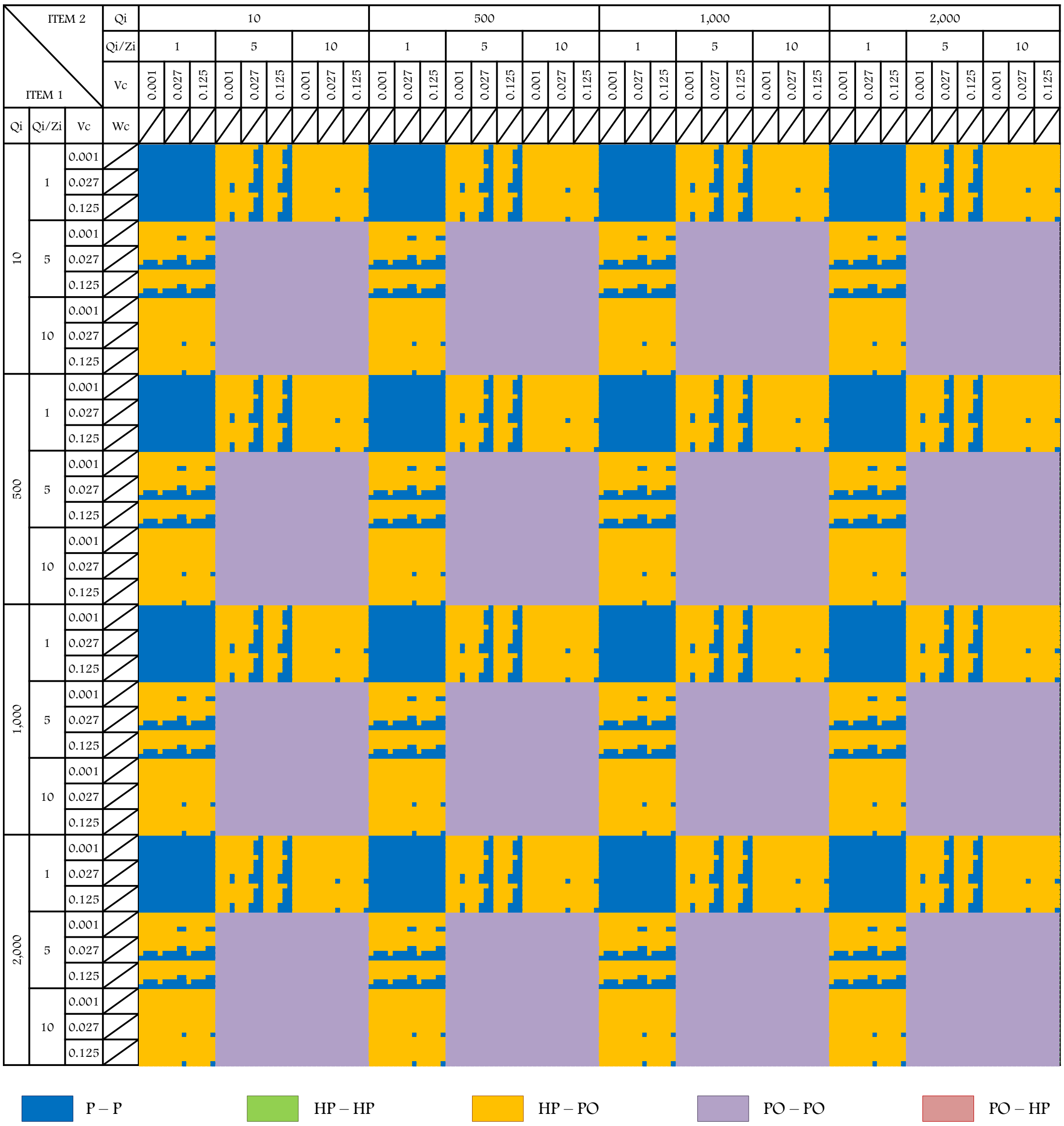
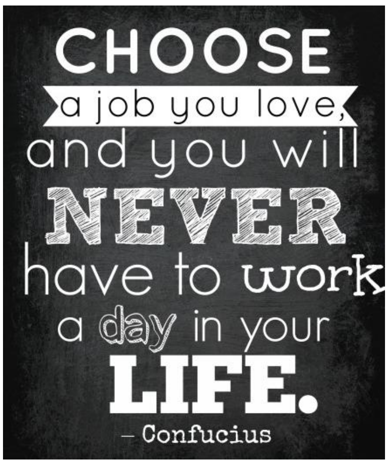


Figure 6.2. Overall view of the best rack layouts for two products with different characteristics, ergonomic evaluation.


CHOOSE
a job you love,
and you will
NEVER
have to work
a day in your
LIFE.
– Confucius