POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Warehouse design in the omnichannel context: challenges, configurations and trends

TESI DI LAUREA MAGISTRALE IN
MANAGEMENT ENGINEERING
INGEGNERIA GESTIONALE

Author: **Andrea Villa**

Student ID: 992845
Advisor: Marco Melacini
Academic Year: 2023-2024

Abstract

In recent years, due to the growth of the online channel, companies have faced the need to integrate it into the existing operations, allowing customers to seamlessly shift between channels. This Thesis focuses on the design of warehouses operating in this omnichannel context, which creates complexity in warehouse operations. To address this subject, a qualitative methodology has been employed, adopting a systematic literature review to assess the current academic landscape and identify research gaps, a case study analysis to gain insight into real-world applications of omnichannel warehouses, and an experts' group consultations to validate findings from the previous approaches. The first step of this study is the analysis of the omnichannel challenges related to the warehouses, defining a complete list of challenges and categorizing them into four distinct categories. Then, starting from these challenges, the impact of each challenge on the warehouse areas and management variables is investigated, aiming to understand the effect of the omnichannel context on warehouses and the possible countermeasures to mitigate these complexities. From this analysis, the need for a study related to the decision between the integration or specialization of the warehouse areas between the different channels emerges. Furthermore, the analysis of the impact of omnichannel on warehousing highlights the need for flexibility in warehouse automation, especially in the picking activity. A possible way to reach this flexibility is through the automation technology and for this reason, an analysis of the different warehouse automation solutions has been performed. Furthermore, another possible solution to reach this need for flexibility is the adoption of a new automation paradigm, called Robots-as-a-Service (RaaS) and this thesis assesses the current state of RaaS development both in the literature and practical applications, considering its potential to enhance flexibility in the context of omnichannel warehousing.

Key-words: omnichannel warehous*, omnichannel challenges, warehouse automation, Robots-as-a-Service

Abstract in italiano

Negli ultimi anni, a causa della crescita del canale online, le aziende hanno dovuto affrontare la necessità di integrare questo canale nelle operazioni esistenti, consentendo ai clienti di passare facilmente da un canale all'altro. Questa Tesi si concentra sulla progettazione di magazzini che operano in questo contesto omnicanale, che crea complessità nelle operazioni di magazzino. Per affrontare questo argomento, viene utilizzata una metodologia qualitativa, adottando una revisione sistematica della letteratura per valutare l'attuale panorama accademico e identificare le lacune nelle attuali pubblicazioni scientifiche, un'analisi di casi di studio per avere informazioni sulle applicazioni reali di magazzini omnicanali e la consultazione di un gruppo di esperti per convalidare i risultati ottenuti dagli approcci precedenti. Il primo passo di questo studio è l'analisi delle sfide dell'omnicanalità legate ai magazzini, definendo un elenco completo di sfide e classificandole in quattro categorie distinte. Quindi, a partire da queste sfide, l'impatto di ciascuna sfida sulle aree del magazzino e sulle variabili di gestione è analizzato, con l'obiettivo di comprendere l'effetto del contesto omnicanale sui magazzini e le possibili contromisure per mitigare queste complessità. Da questa analisi emerge la necessità di uno studio relativo alla decisione tra l'integrazione e la specializzazione delle aree di magazzino tra i diversi canali gestiti. Inoltre, l'analisi dell'impatto dell'omnicanalità sul magazzino evidenzia la necessità di flessibilità nell'automazione del magazzino, soprattutto nell'attività di picking. Un modo possibile per raggiungere questa flessibilità è attraverso la tecnologia di automazione, pertanto, è stata eseguita un'analisi delle diverse soluzioni di automazione del magazzino. Inoltre, un'altra possibile soluzione per soddisfare questa esigenza di flessibilità è l'adozione di un nuovo paradigma di automazione, chiamato Robots-as-a-Service (RaaS). Questa tesi valuta lo stato attuale dello sviluppo del RaaS sia in letteratura che nelle applicazioni pratiche, considerando il suo potenziale nel contesto del magazzino omnicanale per migliorare la flessibilità.

Parole chiave: magazzino omnicanale, sfide omnicanalità, automazione nel magazzino, Robots-as-a-Service

Contents

1 Research background

1.1. Overview of the omnichannel context

In recent years, due to the increasing significance of e-commerce, companies have the opportunity to select from various strategies (*Figure 1.1*) to operate in the market [1]:

- **Single channel**
  In this strategy, companies operate within a single touchpoint, involving a singular point of interaction with the customer. This interaction can occur through either a physical store or an online platform.
- **Multi-channel**
  The second strategy involves multiple channels that operate independently without overlap. In this scenario, data is neither integrated nor shared across channels, and synergies between channels are absent. The growth of e-commerce sales in the past two decades across major markets has prompted traditional companies to adopt multi-channel strategies by incorporating online sales into their operations. Companies that choose this strategy maintain the separation between traditional and online channels, with each channel operating independently and without coordination [2].
- **Omnichannel**
  The omnichannel is a competitive strategy based on integrating different sales channels aimed at providing a seamless experience to customers. In this case, data are integrated and shared across channels. The term "omnichannel" indicates that, from the customer's perspective, there is no longer a distinction between traditional and online channels. Unlike a multi-channel context, an omnichannel strategy considers the integration of business processes and the synergetic management of multiple channels [2]. This last strategy is the focus of this Thesis.

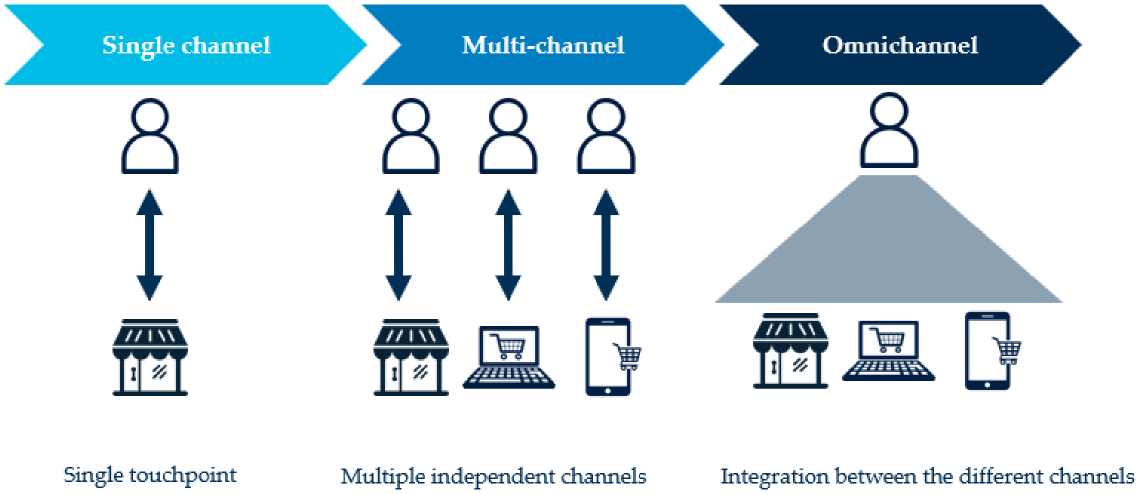

Figure 1.1: Scheme of the different strategies (Source: [1]*)*

In omnichannel retailing, retailers seamlessly integrate their physical stores and online channels, resulting in the convergence of inventories and order fulfillment processes. Customers can place orders through one channel (e.g., on a smartphone), opt for pickup or delivery through another channel (e.g., home delivery), and even return products through a third channel (e.g., a physical store) [3].

Traditional retailers are currently undergoing a significant shift, transitioning from the traditional "brick and mortar" model to a modern "bricks and clicks" approach by adopting multiple touchpoints to communicate and transact with consumers [4]. The "bricks and clicks" strategy reflects the imperative for a seamless shopping experience across physical and digital channels to meet consumer needs and expectations.

Within the omnichannel strategy, there is an opportunity to leverage synergies between the channels. However, managing operations in this context is more complex than the other two cases because it involves handling orders with different characteristics and needs. The challenge companies face when implementing an omnichannel strategy is integrating and coordinating operations across traditional and online channels to offer a seamless customer experience, regardless of the channel used [5]. Unlike single-channel or multi-channel strategies, where operations are often more compartmentalized, the omnichannel strategy requires the harmonization of diverse orders that may exhibit varying attributes and needs.

The omnichannel strategy combines the traditional channel's value, such as proximity, direct contact, and logistics cost optimization, with the value offered by the online channel, which includes an expanded product range, convenience, and the opportunity to gather information [1].

In the omnichannel context, the channels managed together can be of different typologies. However, it's commonly observed that one of the pivotal channels in this context is the B2C e-commerce channel, that is the sales of products and services via the Internet to end consumers [1]. Integrating this channel with other physical and digital touchpoints creates a seamless experience, allowing customers to transition effortlessly from browsing online to engaging in-person interactions if needed.

1.2. Introduction to warehousing

Warehouses are the points in the supply chain where the product pauses, however briefly, and are commonly used to consolidate a range of products, match supply and demand and reduce transportation costs and lead times from order placement to delivery [6]. The objective of warehouse management, which includes all planning and control procedures, is to coordinate all warehouse processes and activities efficiently and effectively.

Warehouses play a critical intermediate role between supply chain members, affecting both supply chain costs and service [7] and in the transformation toward omnichannel retailing, the warehouse is highlighted as a critical component for meeting the customer demand [8]. Effective warehouse management can lead to cost efficiencies and streamlined operations, directly influencing the competitive edge of businesses.

The warehouse is a fundamental component of the logistics distribution network, and its primary functions are [1]:

- **Storage**
  This entails the management of inventories to ensure a specified service level, often achieved through the utilization of safety stock. Furthermore, warehouses play a role in decoupling asynchronous processes, such as production and demand. They also function as protective environments for stocks, safeguarding them against damage or deterioration.
- **Material handling**
  Warehouses coordinate the transformation of product flow across various stages. This involves the transition from full pallet loads to customer orders, from unpacked products to packed products, and from generic products to customized products.

Two distinct typologies of warehouses can be identified based on their primary functions:

- *Warehouse, depots, distribution center*: Warehouses in which the storage and the flow management functions are present. Within these facilities, goods are received, stored, and subsequently retrieved through picking activities when required.

- *Logistics platform, transit point, hub*: Warehouses where only material handling is performed. No storage activity is involved, and these transit points are primarily used for sorting and optimizing transportation activities.

In this Thesis, the focus is on the warehouses that also perform the storage activity because of the critical role that storage activity plays in managing omnichannel warehouses.

The main areas that are possible to identify in a warehouse, according to [3], are the following:

- **Receiving**
  This area includes:
  - *Receiving of incoming goods*: This involves the transfer of goods into the facility from the upstream segment of the logistics network. During this phase, goods are unloaded from vehicles and subsequently moved to the designated receiving dock.
  - *Handling returns*: Another crucial function within the receiving area is processing returned items. When returned goods arrive, they undergo an assessment of their condition and if the items are in suitable condition, they are reintegrated into storage just like regular items, while items deemed unsuitable for storage are appropriately discarded.
  - *Eventual sorting of items*: Depending on the diversity of incoming items, a sorting process may be necessary within the receiving area. This ensures that products are appropriately categorized and directed for subsequent storage or processing based on their characteristics.
- **Put-away, storage**
  This area includes two activities:
  - *Put-away activity*: This operation involves the movement of goods from the receiving docks to their designated storage locations within the facility. This task includes a series of steps, starting with the identification of an appropriate storage location for the product, then once the location is determined, the product is transferred to the chosen spot.
  - *Storage*: Following the put-away process, the goods enter the storage phase, in which the goods are stocked in the warehouse and wait for the following phases.
- **Picking, sorting**
  This area includes activities such as:
  - *Replenishment*: An essential operation within this area is replenishment, which includes restocking the picking area with goods retrieved from

the storage area. In the warehouses employing the picker-to-parts system, this activity consists of simply lowering of goods in the warehouses.

- *Picking*: Based on the order size, orders can be fulfilled using full pallet retrieval or the picking activity.
- *Sorting of items*: After picking, a sorting activity becomes necessary based on the chosen picking method. This sorting task aims to consolidate items according to the specific requirements of the customer order.

- **Packing, shipping**
  This area involves the following activities:
  - *Packing items*: When the products arrive at the shipping preparation area, the items are placed in a shipping package or a pallet that could be wrapped. Moreover, the shipping label, containing the customer's address information, is affixed to the shipping package.
  - *Consolidating orders*: The consolidation of orders involves merging goods from different areas within the warehouse into a single truck. This activity streamlines the shipping process by optimizing the utilization of transportation resources.
  - *Shipping*: The final step in this area entails the preparation for shipping, in which the goods are transitioned from the staging area to the loading dock and are loaded onto the carrier vehicle designated for their onward journey.

1.3. Role of warehouse in the omnichannel network

In an omnichannel logistics network, the warehouse can assume different roles [1], which can be analyzed through three dimensions:

- *Stock shown on the eCommerce website*: This dimension involves the decision regarding which inventory can be used to fulfill online orders. Possible options include using only items stored in the distribution center, only items available in the physical stores, or the stock available in the entire network.
- *Level of stock sharing*: This dimension pertains to stock allocation within a warehouse. There are two possible approaches: dedicated stock, in which inventory within a warehouse is exclusively allocated to a specific channel, ensuring specific stock availability for that channel's orders, and shared stock, where warehouse inventory is shared across multiple channels, allowing for greater flexibility in stock allocation based on fluctuating demand.
- *Order allocation to fulfillment points*: The ways to allocate orders to fulfillment points can be categorized into two approaches.

If the point from which a specific order is fulfilled is determined in advance, it's called static allocation. Conversely, if fulfillment points are dynamically determined based on real-time factors, optimizing order fulfillment based on factors such as proximity, stock availability, and other variables, is known as dynamic allocation.

In an omnichannel network, the different alternatives for the role of the warehouse are as follows [1]:

1. **Dedicated network**

   In this first case, as illustrated in *Figure 1.2*, a separate logistics channel is designated for each commercial channel. One or more warehouses are exclusively dedicated to serving each specific channel and suppliers directly replenish these warehouses, each with its designated storage, picking, and packing capacities.

   By assigning specific warehouses to the online channel, operational efficiency can be optimized to meet the unique requirements of online order fulfillment. This approach streamlines logistics, ensuring dedicated stock availability and predictable fulfillment processes. However, this separation might result in a certain degree of isolation between the two channels, potentially limiting opportunities for shared resources and cross-channel optimization.

   Analyzing the three dimensions:

   - *Stock shown on the eCommerce website*: The stock displayed on the B2C eCommerce website is sourced from the inventory in dedicated online warehouses.
   - *Stock of online sales*: Stock allocation for online sales exclusively resides in the dedicated online warehouses.
   - *Order allocation*: Orders are statically allocated to predetermined fulfillment points within the dedicated online warehouses.

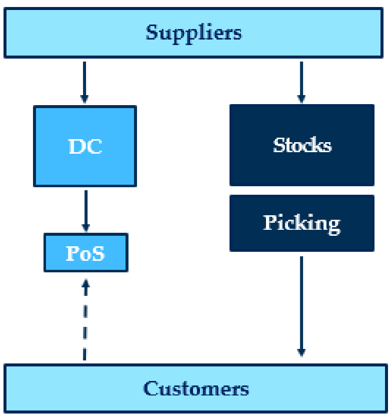

Figure 1.2: Dedicated network

2. **Dedicated picking warehouse**

In the second scenario, as illustrated in *Figure 1.3*, a dedicated picking warehouse with picking capacity is exclusively dedicated to the online channel. In this case, suppliers replenish a large distribution center where goods are stored without a distinction between channels. Then, the picking warehouse is replenished with the inventory from the distribution center and the stock is used to fulfill online orders.

This approach involves shared inventory within the distribution center, with the inventory becoming dedicated to the online channel only when it enters the specialized picking warehouse.

This option enables synergies in the procurement phase since suppliers need to replenish only the distribution center.

Analyzing the three dimensions:

- *Stock shown on the eCommerce website*: The stock displayed on the B2C eCommerce website is sourced from the dedicated picking warehouse.
- *Stock of online sales*: Inventory allocated for online sales remains dedicated, but it is selectively drawn from the picking warehouse within the larger distribution center.
- *Order allocation*: Order allocation is primarily static, but it is dynamic in scenarios with multiple warehouses.

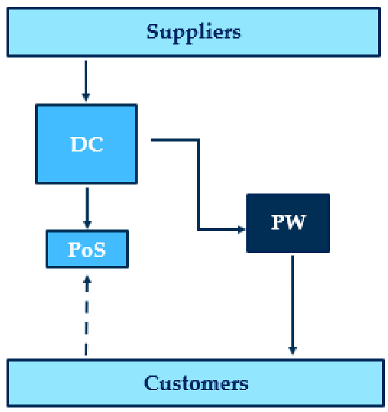

Figure 1.3: Dedicated picking warehouse

3. **Shared warehouse**

As illustrated in *Figure 1.4*, the third configuration is characterized by a shared warehouse approach where storage and picking activities are shared among different channels. In this scenario, suppliers replenish a shared warehouse where storage and picking are carried out in the same building for various channels. Goods are then delivered through a separate distribution process.

This option allows for synergies in the procurement phase and warehouse operations, and it encourages collaborative resource utilization, with a single warehouse serving the demands of different channels. However, it requires careful coordination to ensure adequate stock availability for all channels and effective order allocation.

Looking at the three dimensions:

- *Stock shown on the eCommerce website*: A portion of the total inventory is allocated for display on the B2C eCommerce website.
- *Stock of online sales*: Inventory is shared across online and traditional sales channels.
- *Order allocation*: Order allocation remains static, with predefined points for fulfillment based on the shared inventory.

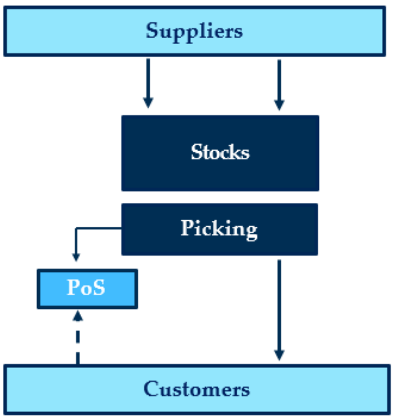

Figure 1.4: Shared warehouse

4. **Point of sale based network**

The point of sale based network, as illustrated in *Figure 1.5*, is an alternative primarily used by retailers due to its reliance on physical stores. In this scenario, suppliers replenish the distribution center, and then goods are delivered to individual point of sale locations.
This strategy generates synergies in the distribution phase, reducing costs for reaching market areas. Furthermore, it facilitates item collection and returns at the physical store level without requiring dedicated logistics infrastructure.
The main drawback of this solution pertains to stock management, as it may encounter quality issues typically associated with point of sale locations.

Looking at the three dimensions:

- *Stock shown on the eCommerce website*: The stock displayed on the B2C eCommerce website reflects the availability at individual point of sale location.
- *Stock of online sales*: Inventory is shared between online and traditional sales channels.
- *Order allocation*: Order allocation can vary; it might be static or dynamic, contingent on the chosen strategy.

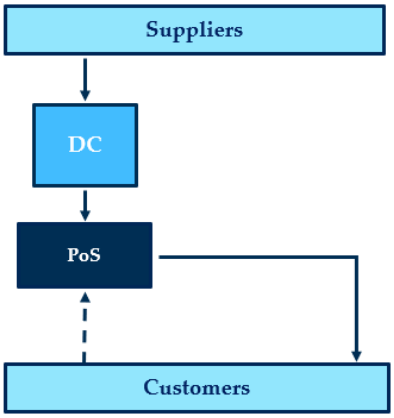

Figure 1.5: Point of sales based network

The point of sale can take on different logistics roles in executing eCommerce orders, as illustrated in *Figure 1.6*. These roles can be determined based on:

- *The delivery mode to the consumer*. This dimension considers how goods reach the consumer, and two primary delivery modes exist:
  - *Home delivery*. In this scenario, the point of sale is the origin of local distribution. The store becomes the launch point for the last-mile delivery process, capitalizing on its proximity to customers for efficient order fulfillment.

    - *Pickup in the store*. Alternatively, customers themselves visit the store to collect their ordered goods. The store functions as a convenient pickup location for customers who prefer this option.
- *The preparation of the order*. This dimension focuses on where the order preparation occurs, and there are two different preparation modes:
    - *In an upstream warehouse*. In this case, the store does not stock items for the online channel. The store holds only items from the online channel that have already been ordered. When an order is placed, the store accesses its upstream warehouse to fulfill the order.
    - *In the store*. In the second approach, the store maintains inventory for both online and in-store sales. When an item is ordered, the store retrieves the required stock directly from its inventory.

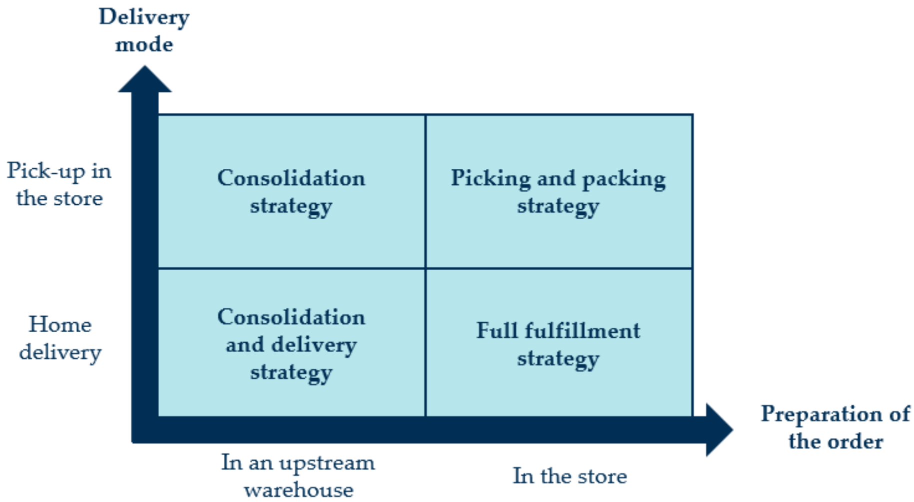

Figure 1.6: Point of sales roles

Crossing the two axes allows the identification of four alternatives:

1. *Consolidation strategy*: This approach involves performing the picking and packing processes within the central warehouse. Completed orders are then sent to the point of sale locations, where customers collect their goods. This strategy optimizes transportation costs as order consolidation occurs before items are sent to the store.

2. *Consolidation and delivery strategy*: In this scenario, stores serve as transit points. Picking and packing of orders take place within the distribution center. Afterward, the goods are dispatched to the stores, where local distribution processes are initiated to ensure efficient customer delivery.

3. *Picking and packing strategy*: Under this strategy, order fulfillment relies on the inventory stored within physical stores. When an order is received, items are sourced from the available store stock, and customers visit the store to collect their orders in person.
4. *Full fulfillment strategy*: In this solution, store inventory is utilized for the entire fulfillment process. Picking and packing are executed in the store, and after this process, deliveries start directly from the store.

It's crucial to emphasize that the various network solutions are not mutually exclusive but can coexist within a broader omnichannel strategy.

Within the context of this Thesis, the focus is directed toward the last two configurations: the "*Shared Warehouse*" and the "*Point of Sale Based Network*". These configurations are of particular interest because the operations of different channels are managed in the same warehouse, increasing the complexity of operational management.

1.4. Warehouse configuration in the omnichannel context

The central focus of this Thesis is the analysis of warehouse configuration within the omnichannel context.

It's important to underline that warehouse configuration refers to the combination of operations, design aspects, and resources [6] and it provides valuable insights into how a warehouse should be strategically organized. Common warehouse areas described in the literature include receiving, put-away, storage, picking, sorting, packing and shipping [8]. To manage operations effectively and efficiently, various design variables are considered, such as Information Technology (IT), automation, planning and human resources.

The warehouse configuration in the omnichannel context differs from that of traditional warehouses due to the unique peculiarities of this environment, which influence all warehouse operations, bringing distinctive implications for the structure and functioning of the warehouse.

2 Research design and methodology

2.1. Research objectives and research questions

The objective of this chapter is to explain in a clear and scientific way the methodology followed in this Thesis.

Given the breadth of the topics covered in the Thesis and the need for a well-defined structure, the following four research questions have been defined:

1. *What are the main characteristics and challenges that omnichannel warehouses have to deal with?*
2. *How do the identified characteristics affect the warehouse areas and the management variables of the warehouse?*
3. *What is the level of integration and specialization of functional areas in the omnichannel warehouse?*
4. *How it is possible to manage flexibility in presence of automation?*

These research questions serve as the foundation for addressing various aspects of the topics under examination, enabling a structured exploration of the subject.

As represented in *Figure 2.1*, the research begins by identifying the challenges faced by omnichannel warehouses. Subsequently, the impact of each challenge on the warehouse configuration is defined. From this broad analysis, two needs arise:

- The first is the need for a study related to a specific decision in the omnichannel warehouse, which is the choice of integration or specialization of warehouse areas between channels.
- The second is the need for flexibility in automation, which is an important requirement in the omnichannel warehouse.

The four research questions have been analyzed separately, each being approached through a specific method, leading to distinct results.

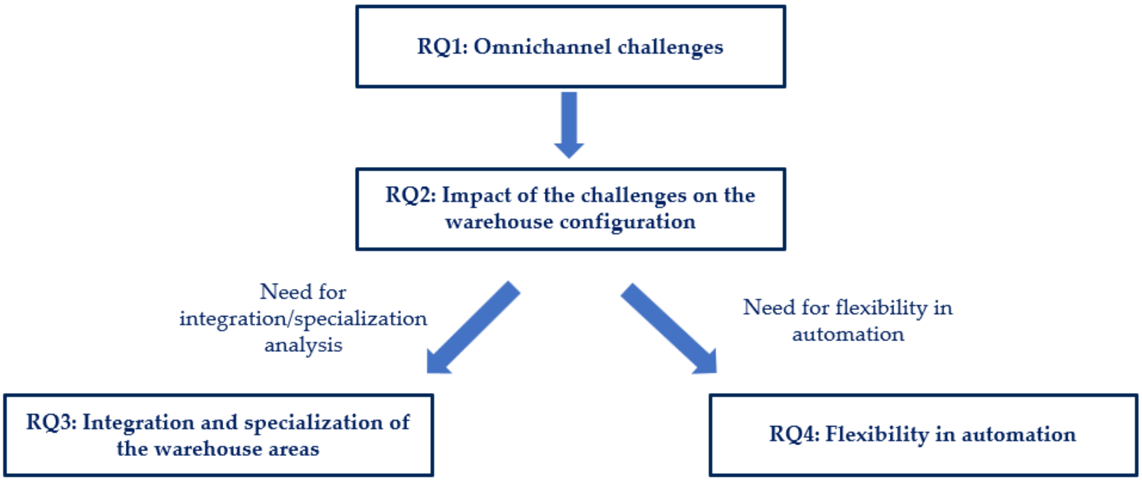

Figure 2.1: Structure of the Thesis

The necessity for this study arises from a comprehensive review of the existing literature, which reveals a lack of emphasis on warehouse organization within the omnichannel context. In particular, the identified gap that this Thesis aims to address by answering the four research questions, is the absence of a cohesive framework that starts from the challenges related to the omnichannel warehouse and explores the impact of these challenges on warehouse configuration. Presently, most current papers predominantly concentrate on singular aspects, failing to provide a holistic vision encompassing the entirety of omnichannel warehousing considerations.

In this Thesis, the four research questions identified earlier have been systematically investigated, to effectively address and bridge the gaps recognized in the current literature. Through a methodical examination of these research questions, the study aspires to offer valuable insights and a comprehensive understanding of the specific area of investigation.

2.2. Methodology

To address the defined research questions, a methodology (*Figure 2.2*) divided into two main phases is adopted:

1. **Phase 1**
   In the first phase, the research background of this Thesis has been analyzed through the methodology of secondary source analysis.

2. **Phase 2**
   Starting from the background defined as output of the first phase, the context description has been performed. Specifically, starting with the definition of the research questions, appropriate research strings have been formulated to facilitate a systematic literature review. The findings of this literature review aid the author in the definition of the preliminary structure of interviews used in the case study analysis. The analysis of both the literature review results and the case study contributes to the formulation of a set of questions intended for a survey to be proposed to an expert group.

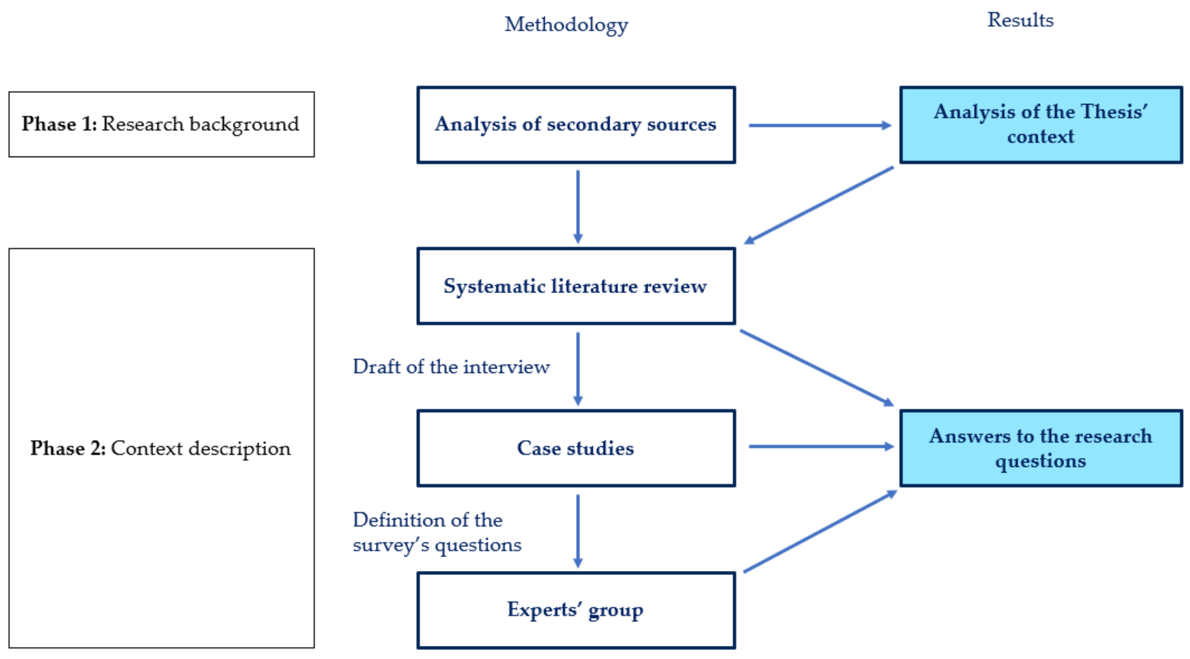

Figure 2.2: Thesis methodology

2.2.1. Phase 1: Research background

The introductory stage, as presented in the first chapter of this Thesis, plays a crucial role in laying the groundwork for the study. It introduces the topics explored in subsequent sections of the Thesis, providing essential context to facilitate the comprehension of the research work. This initiation involves offering a comprehensive overview of the research field and identifying the central theme that will be explored. This, in turn, establishes the foundation for the subsequent analysis, encompassing an examination of the omnichannel context from a logistics perspective and an introduction to warehouse management.

2.2.1.1. Analysis of secondary sources

In the pursuit of understanding omnichannel warehousing, the methodology employed involves the analysis of secondary sources, with an exploration of scholarly works using Scopus, as well as academic material related to the subject. This approach provided a general context for the Thesis, facilitating the formulation of research questions and an exhaustive list of keywords. These preparatory steps are essential for enabling a rigorous and methodical literature analysis in subsequent phases.

It is crucial to underscore that the process of identifying seminal articles deviated from a purely scientific method. Instead, this identification process heavily relies on the author's diligence and meticulous examination.

2.2.2. Phase 2: Context description

In this chapter, the systematic approach employed is explained [9], outlining the design and execution of the study as well as the procedural analysis. This systematic approach incorporates a rigorous methodology to ensure the reliability and validity of research findings and by adhering to a systematic approach, this study aims to ensure rigor and coherence throughout the research process.

To effectively address the four research questions derived from the research background, this study employs a combination of three methods:

- **Systematic literature review**
  The first method employed is a systematic literature review, to comprehend the state of knowledge, validate research gaps, and derive theoretical insights [10]. By comprehensively analyzing a wide range of existing scholarly works, the literature review provides a solid foundation for the subsequent research steps and aids in formulating a preliminary framework for interviews used in the case study analysis.

- **Case studies analysis with semi-structured interviews**
  The findings of the literature review are reflected in the light of a qualitative, explorative study applying semi-structured interviews [10]. This method facilitates in-depth exploration and understanding of the subject from the perspectives of industry experts, enabling the collection of rich qualitative data to further analyze the research questions and provide valuable insights.
- **Experts' group**
  The final method utilized to address the research questions involves conducting a survey and discuss the results within a group of logistics experts during a workshop organized by the Observatory Contract Logistics "Gino Marchet" of Politecnico di Milano, to validate and complement the results obtained from the previous two steps. The survey conducted within the experts' group serves as a quantitative method for collecting data from a larger sample size compared to the case study analysis, enabling the validation of findings and offering a more comprehensive perspective.

The selected methodological approach, primarily utilizing qualitative methods, was employed due to the underdeveloped nature of the literature concerning omnichannel warehouses, despite the concept is not an emerging trend. For this reason, a qualitative approach facilitates inductively expanding, transferring and verifying existing hypotheses and concepts [10]. Moreover, qualitative methods are applied in the context of omnichannel warehouses due to the pronounced contextual dependence inherent to decision-making in this domain. Decisions in omnichannel warehousing are not universally applicable, but they strongly depend on the context in which they are made.

Despite qualitative methods are still infrequently used in operations management [11] and it's criticized that these methods don't justify the assertion [9]; on the other hand, it's widely agreed that a more systematic observation of current industrial phenomena through qualitative methods is necessary to assist managers in addressing their practical challenges [11]. In the contemporary complex and dynamic business environment, there is a diminished need for extensive hypothesis testing, and a greater emphasis on systematic observation that can offer valuable support to managers in addressing their real-world problems [11].

The qualitative research approach is adopted in this Thesis because it facilitates the exploration of "how" questions, analyzing the mechanism, processes and contextual aspects, rather than "how many" [12]. In particular, this typology of research aims to achieve a comprehensive understanding of the subject, going beyond mere numerical data and encompassing a broader understanding of the phenomenon.

Through the analysis of the literature and discussions with experts, this research can identify recurring themes, common challenges or generate new insight into omnichannel warehouse operations because qualitative research provides a profound and comprehensive understanding of complex, multifaceted phenomena, by enabling a deep dive into real-life experience as well as expanded, flexible exploration [13], perfectly adapting to the omnichannel warehouse topic.

The methodology employed in this Thesis encompasses two perspectives: the academic vision, facilitated by the systematic literature review, and the business and managerial perspective, investigated through the case studies analysis and the experts' group. By integrating both perspectives, the research aims to comprehensively understand the topic, ensuring that no essential aspect is overlooked from either standpoint. The systematic literature review enables the integration of academic insights, theoretical framework and existing knowledge on the topic, while the inclusion of case studies and the experts' group enables the examination of real-world business practices and managerial perspectives. This holistic approach acknowledges the potential divergence in terminology and viewpoints between the academic and business realms, as highlighted in [9]. Therefore, comprehensive research must consider both perspectives, ensuring that research findings are pertinent and applicable in both academic discourse and practical business contexts.

The subsequent section will provide a comprehensive exposition of the methodologies employed to address the research questions, offering a detailed insight into the specific approaches used.

2.2.2.1. Systematic literature review

The first phase of the methodology is the systematic literature review, a reproducible and transparent method aimed at reducing subjectivity and increasing the reliability and validity of the research [14].

The literature review has a fundamental role in this Thesis as it enables to define and understand the topic of omnichannel warehousing from an academic perspective. More specifically, through the literature review, the researcher acquires insights into the existing body of knowledge and identifies the key themes, theories, and research gaps related to omnichannel warehousing, establishing a strong theoretical foundation for the study and helping to contextualize the research within the broader academic landscape.

Furthermore, the literature review forms the basis for the subsequent phase of semi-structured interviews, aiding in developing the interview guide. By identifying key concepts and pertinent findings from the literature, the researcher can structure the interview questions to elicit valuable insights from participants, ensuring that the interviews are focused and aligned with the research objectives.

Among the various typologies of literature reviews, the chosen methodology for this study is the systematic literature review. This approach stands out for its systematic process, which entails the methodical identification of existing studies, meticulously selecting and evaluating their contributions, and subsequently analyzing and synthesizing the gathered data [15]. This methodology provides a structured and rigorous process for conducting a comprehensive review of the literature relevant to the research topic and it brings a replicable, scientific and transparent approach, that minimizes bias and ensures transparency and reproducibility [15]. The systematic literature review methodology adds rigor and credibility to the research process, contributing to the overall reliability and validity of the study.

The choice of starting the analysis from the systematic literature review is based on the methodology's ability to analyze a broad range of existing research on the topic and provide a deep and complete understanding of the current state of knowledge in the field, allowing to identify existing gaps or areas of limited research within the domain of omnichannel warehousing and contribute to filling those gaps.

To maintain a structured approach in conducting the systematic literature review, the five steps methodology proposed by [15] has been employed:

1. **Question formulation**
   The initial phase of the systematic literature review involves delineating the scope of the research and formulating precise research questions, which act as guiding principles for selecting studies for the review. This analysis draws upon insights gained in the first phase of the methodology, related to the research background.
   To define robust research questions, the CIMO framework, as defined by [13], is employed. The acronym stands for:

   - *C: Context*
     The context refers to the surrounding factors (external and internal environment) such as individuals, interpersonal relationships and aspects of interest.
   - *I: Interventions*
     Intervention refers to the actions of interest. It’s important to note that it is necessary to examine not just the nature of the intervention but also how it is implemented.
   - *M: Mechanism*
     Mechanism refers to the underlying processes or causal pathways that explain the relationship between interventions and outcomes.
   - *O: Outcomes*
     Outcomes represent the effects of the intervention in its various aspects and involve assessing how the outcomes will be measured.

This approach allows for the formulation of the logic for the design proposition [16] and the application of this method to the unit of analysis brings the following result:

- *Context: Omnichannel warehouses*
  The context of the analysis is the omnichannel warehouses, where the emergence of the omnichannel trend presents novel challenges that need examination. Understanding the challenges and configuring the warehouse accordingly is crucial for effective omnichannel operations.
- *Interventions: Configuration of omnichannel warehouses*
  The interventions of the analysis are the strategic configuration of omnichannel warehouses, encompassing a range of strategies, processes, technological implementations, and organizational adaptations. These interventions primarily aim to proactively address the challenges identified within the context of omnichannel warehousing.
- *Mechanism: Warehouse areas and management variables*
  The mechanism is related to the diverse array of warehouse areas and management variables within the context of omnichannel warehousing.
- *Outcomes: Addressing the omnichannel challenges*
  The outcomes encapsulate the results and impacts generated by the implemented interventions within the omnichannel warehouse configuration. Different approaches can be used to address the omnichannel challenges.

The result of this process is the definition of the four research questions:

1. *What are the main characteristics and challenges that omnichannel warehouses have to deal with?*
2. *How do the identified characteristics affect the warehouse areas and the management variables of the warehouse?*
3. *What is the level of integration and specialization of functional areas in the omnichannel warehouse?*
4. *How it is possible to manage flexibility in presence of automation?*

2. **Locating papers**

In the second step of the systematic literature review, an exhaustive search has been conducted to identify relevant papers capable of addressing the formulated research questions.

The research has been performed through the Scopus website and the search scope encompassed articles up to the beginning of 2023, without imposing any restrictions on the publication date.

The research strings employed in the search consisted of the following components:

- *Boolean operators* were used to refine research strings and control the combination of keywords. Specifically, the following Boolean operators were applied:
  - *OR*: This operator was used in the search to retrieve documents containing either of the specified terms.
  - *AND*: This operator narrows down results by requiring documents to contain all specified terms.
  - *AND NOT*: This operator excludes certain terms from search results.
- *Simple operators*, such as truncation characters, were employed to facilitate comprehensive searches by capturing variations of root words. The truncation character enabled the retrieval of words with various endings or forms.

Moreover, all the research strings have been applied to the Title, Abstract or Keyword fields to encompass a broad range of pertinent studies in the systematic literature review.

It is worth noting that RQ2 and RQ3 share similarities, and therefore the same research strings and papers are utilized. This is attributed to the common theme of examining omnichannel warehouse configuration in both research questions.

Applying the defined methodology to the respective research questions, the following research strings have been formulated:

RQ1. (*omnichannel* OR *omni-channel*) AND *logistic**

This research string identifies the principal characteristics and challenges of omnichannel warehouses within the logistics field.

RQ2/RQ3. (*warehous** OR *intralogistics* OR (“*distribution center*”) OR (“**fulfillment center*”)) AND (*omnichannel* OR *omni-channel* OR “*e-commerce*”) AND NOT (*last-mile*)

This research string investigates all papers addressing omnichannel warehousing to assess its impact on warehouse-related topics.

RQ4. (*warehous** OR *intralogistics* OR (“*distribution center*”) OR (“**fulfillment center*”)) AND (*omnichannel* OR *omni-channel* OR “*e-commerce*”) AND (*automat** OR *robot**) AND NOT (*last-mile* OR *network*)

This research string centers on exploring how automation can be employed to manage omnichannel operations.

The utilization of these research strings produced the following number of results for each research question:

- *RQ1*: 189 results
- *RQ2/RQ3*: 973 results
- *RQ4*: 180 results

The outcome of this phase is a comprehensive list of papers equipped to address the defined research questions.

3. **Papers selection and evaluation**
The systematic literature review employs a set of explicit selection criteria to evaluate the relevance of each paper in addressing the review question [15]. Three consequential selection stages have been conducted during the selection process:

   1. **Screening stage**
   In the initial phase of selection, three distinct filters have been applied:
      - *Article or review type filter*: Papers are limited to articles or reviews, focusing exclusively on specific academic contributions to narrow the scope of the analysis and focusing only on specific academic contributions.
      - *Language filter*: Papers are required to be in English to ensure consistency and ease of comprehension during the analysis, as English is the predominant language of academic and research publications.
      - *Journal ranking filter*: To ensure research quality, papers are selected from journals with a ranking of Q1 or Q2. This filter aimed to prioritize papers from journals with high rankings, signifying a higher standard of quality and rigor. Given the substantial number of papers for each research question, this selection criterion is introduced to emphasize articles that have undergone rigorous peer-review processes.

   2. **Eligibility stage**
   In this second selection phase, criteria have been established to determine which papers to include in the analysis. Due to the distinct nature of each research question and the pivotal role of the literature in obtaining results, no specific inclusion or exclusion criteria have been employed. Instead, the following approach has been applied to each research question:

      - *RQ1*: In the first research question, papers that cited at least one omnichannel challenge impacting the warehouse are included.

- *RQ2/RQ3*: In the second and third research questions, papers that expounded on the design of warehouse areas and management variables in response to omnichannel peculiarities, offering insights into integration and specialization of areas, are included.
- *RQ4*: In the last research questions, all papers analyzing automation solutions in the picking activity are included.

To facilitate the author's work in selecting relevant papers, this approach is progressively applied to:

- Title
- Abstract
- Full-text

3. **Final selection**

In the final selection phase, the author analyzed the identified papers and assessed their relevance to the research questions under examination. Moreover, a cross-referencing procedure has been executed to ensure the inclusion of relevant papers that may not have been identified through the initial search using the research strings. This cross-referencing process involved examining the reference lists of the selected papers to identify additional sources that could address the research questions.

During the cross-referencing process, additional papers have been identified and incorporated into the selection:

- *RQ1*: 2 papers
- *RQ2/RQ3*: 3 papers
- *RQ4*: 16 papers

It is noteworthy that the notably high number of cross-referenced papers in the RQ4 can be attributed to the inclusion of an additional 13 papers initially discovered through string searches for RQ2 and RQ3. While these papers originated from the second research string, they proved valuable for addressing RQ4 due to their focus on warehouse automation. Therefore, these 13 papers were not utilized for RQ2/RQ3 but they were instead included in the analysis of the last research question.

The total number of papers in the different research questions and stages is defined in *Table 2.1*. It's important to underline that the total number of papers identified through the research strings is 113 due to some overlapping across the various research questions.

Phase	Criteria	RQ1	RQ2/RQ3	RQ4
First research	String search	189	973	193
Screening	Articles/reviews	132	490	99
Screening	English language	129	465	97
Screening	Journal ranking	113	358	82
Eligibility	Title	95	121	61
Eligibility	Abstract	81	78	43
Eligibility	Full-text analysis	47	27	33
Final inclusion	Cross-reference	49	30	49

Table 2.1: Number of papers in the screening and eligibility stages

4. **Analysis and synthesis**
During this analysis stage, the primary objective is to break down individual studies into constituent parts and describe how each relates to the other [15]. To facilitate the extraction of relevant information from the selected papers, the author maintained an Excel database, creating separate sheets for each list of papers related to different research questions. The following information have been collected for each paper:
    - Title
    - Author(s)
    - Year of publication
    - Journal
    - Method
    - Research question to which it pertains

In the subsequent sections, a comprehensive description of the key attributes and characteristics of the analyzed papers is provided.

- **Publications by year**
Following an initial analysis of the identified papers, an examination of their distribution across various years has been conducted. As depicted in *Figure 2.3*, it becomes evident that omnichannel warehousing and associated automation is a relatively recent area of study, with most papers published after 2016.

  Another notable finding is the consistent increase in the number of papers published annually, indicative of a growing interest within the academic community. Even in the current year of 2023, the year in which the analysis is performed, with papers gathered up until early 2023, there are 14 papers. This trend suggests that the current year may witness the highest volume of papers, potentially surpassing even the 28 papers of 2022.

It's important to mention that this trend was disrupted in the year 2020, likely influenced by the COVID-19 pandemic. During that year, there appears to have been a reduction in publications.

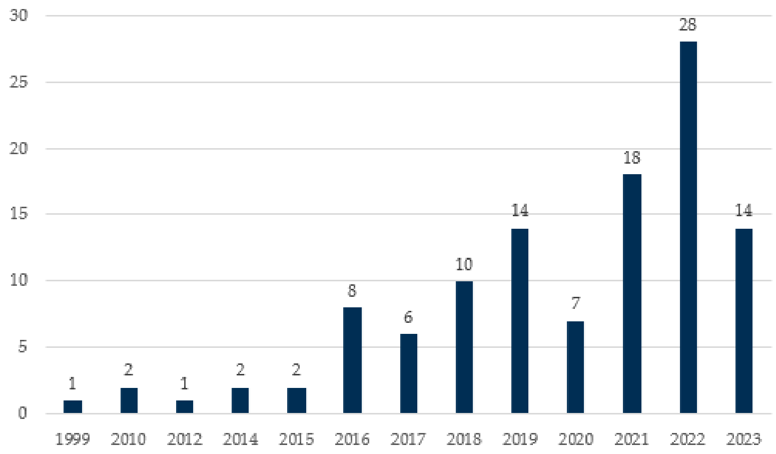

Figure 2.3: Publications by year

- **Publications by method**
  When examining the methods employed in the chosen papers, as illustrated in *Figure 2.4*, a notable trend emerges: a substantial portion of the papers employ quantitative models to investigate the topic. An interesting observation pertains to the preponderance of quantitative methods in papers originating from RQ4, which centers on investigating the application of automation in the omnichannel warehouse. These papers employ quantitative methods to evaluate the performance of the automation solutions under scrutiny.

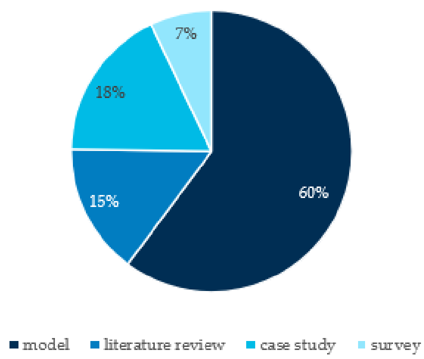

Figure 2.4: Publications by method

Excluding this specific subset of papers, the subsequent analysis depicted in *Figure 2.5* reveals more homogeneity between the methods, but still with most papers that use quantitative methods.

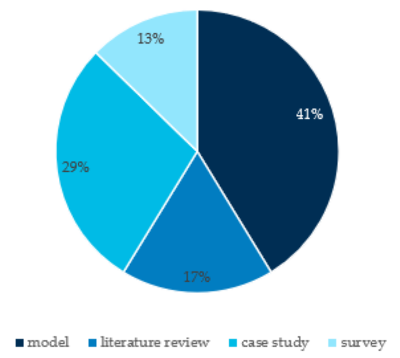

Figure 2.5: Publications by method (exclusion of RQ4)

- **Publications by country**
  To conduct this analysis, the affiliation of the first author is considered as a proxy for the geographical origin of the papers. From this analysis, it is discovered that most papers come from China, with 25 out of 113 papers. Notably, a significant portion of the papers from China is focused on the automation topic. Additionally, Germany and the United States were prominent contributors to this analysis, accounting for 19 and 15 papers, respectively. Another important country is Sweden, with 10 papers; the relevance of this country is due to the group of research at Lund University that strongly contributes to the research in the omnichannel warehouse field. The remaining papers are sourced from various other countries, as illustrated in *Figure 2.6*.

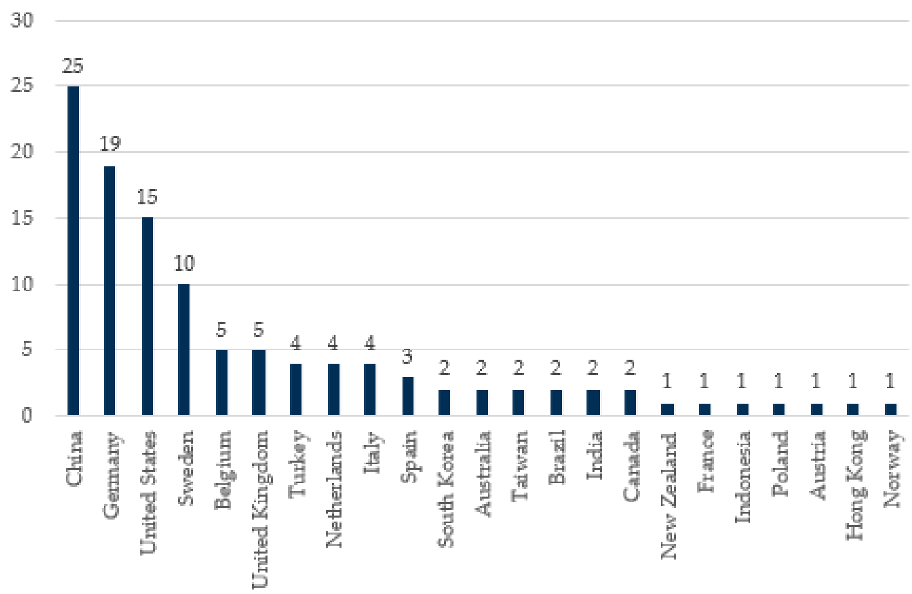

Figure 2.6: Publications by country

- **Publications by investigated area**
  The final analysis focuses on the distribution of papers across the different research questions (*Figure 2.7*). The primary findings from this analysis are as follows:
  - *RQ1*: This category boasts a relatively high number of papers, primarily due to the broad scope of the research string, encompassing various aspects of omnichannel operations. Furthermore, all papers referencing any challenges related to omnichannel warehousing were included in this count.
  - *RQ2/RQ3*: Despite their pivotal role in the Thesis, the number of identified papers in these categories is relatively low. This can be attributed to the relatively underdeveloped state of the topic of omnichannel warehouse configuration in the existing literature.
  - *RQ4*: In the last research question, the number of papers analyzed is notably high. This can be attributed to the comprehensive nature of the research string, which encompasses automation in the online context.

  It's worth noting that some papers are shared between different research questions due to the similarity of the topics studied. Specifically, the total number of unique papers across all research questions is 113, even though the initial total count is 128 due to overlapping.

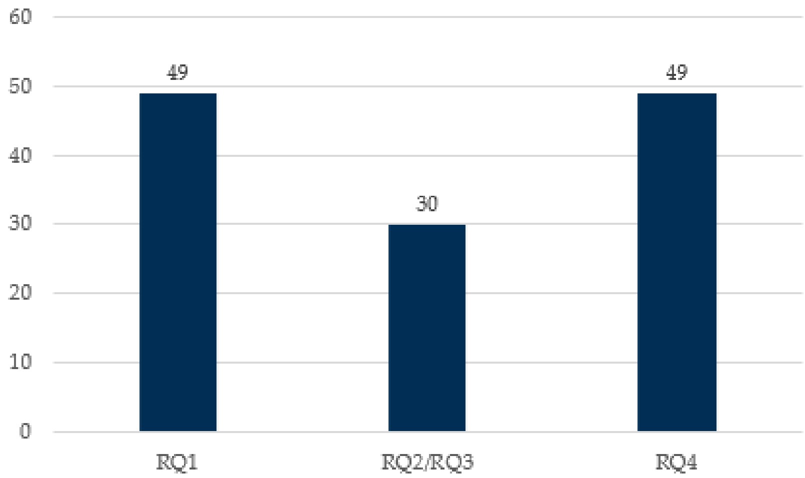

Figure 2.7: Publications by investigated area

5. **Reporting and using the results**
   The last step of the research process involves summarizing the main findings derived from the selected papers. Given the methodology's incorporation of various techniques to integrate and validate findings, a dedicated section specifically focused on analyzing the literature is omitted. Instead, a more comprehensive analysis of results is carried out within the results chapter, where outcomes from diverse methodologies are amalgamated and explored in detail. This approach facilitates a holistic understanding of research conclusions by encompassing different viewpoints and methodologies applied throughout the study.

2.2.2.2. Case studies

The second part of the methodology involves the analysis of case studies through the adoption of qualitative interviews, a well-established method in qualitative research that involves speaking with individuals [17]. Qualitative interviews can take various formats, including structured, semi-structured, or unstructured approaches.

Among the different possibilities for this Thesis, the chosen approach is the semi-structured interview, which is the most frequently used type [17]. Semi-structured interviews rely upon an interview guide, but the questions are open-ended and interviewers often expect to deviate from their set of questions based on the interviewees' answers [17]. Semi-structured interviews allow an analysis of perceived causal relations, help in insights into the perceived reality, and facilitate the assessment of an interviewee's perception [18].

By opting for the semi-structured interview format, it's possible to find a balance between providing a framework for the interview process and allowing flexibility in the discussion, enabling the interviewees to express their perspectives and insights in a more free manner, capturing rich qualitative data that can contribute to the research objectives.

The interview became a guided dialogue or discussion with the interviewee and enabled analysts to see the world from the perspective of others [17]. In particular, to succeed in using this methodology, the analyst must allow the interviewee "to take the lead" and adjust interview questions to the answers that the interviewee is giving [17].

Compared to fixed interviews with questions and answers, semi-structured interviews offer more flexibility due to the opportunity to explore topics in greater depth and adapt the interview based on the participants. This flexibility is crucial in this research due to the diverse nature of the companies involved, with two different typologies. Firstly, companies operating within the omnichannel context, offering valuable insights into their experiences in managing omnichannel warehouses.

Secondly, companies specializing in intralogistics solutions for warehouses, which have different perspectives based on the projects with their customers.
Since the omnichannel warehouse is a complex and multidimensional concept, semi-structured interviews allow to adapt the interview based on the participants' role and company, tailoring the questions to gather insights from different perspectives.

The semi-structured interviews also serve as a bridge between the academic and the business worlds, helping to bridge the gap between theory and practice. In particular, due to the difference between the two perspectives, as underlined by [9], if the interview is designed only around existing theory and methodology, there is the risk of missing key aspects of the sensemaking of the people interviewed. Semi-structured interviews mitigate this risk by allowing for flexibility and freedom in the interview process. Unlike fixed interviews, which strictly address a predefined set of questions, semi-structured interviews provide the opportunity for participants to share their perspectives, experiences, and sensemaking in a more open-ended manner, allowing to create an environment that encourages interviewees to express their interpretations of the phenomenon under investigation enabling a deeper exploration of the participants' perspectives.

To define how to conduct the qualitative interviews with a cross-organizational approach, four major steps have been followed, as stated by [10]:

1. **Selection of the cases and interview partners**

   This activity is critical because the population defines the set of entities from which the research sample is to be drawn and helps to define the limits for generalizing the findings [19].

   In this study, the cases have been selected among the companies participating in the Observatory Contract Logistics "Gino Marchet" of Politecnico di Milano. This approach offered the advantage of including companies from diverse industries, thus helping to control environmental variations [19].

   Furthermore, as previously mentioned, the analysis encompassed two key categories: companies actively engaged in omnichannel operations and providers of automation solutions tailored for the intralogistics of omnichannel-oriented companies. This dual perspective has been adopted to ensure maximum heterogeneity in terms of industry and outlook, facilitating a comprehensive understanding of the omnichannel warehousing landscape [10]. In line with the recommendation to ensure maximum heterogeneity [10], the included companies also varied in terms of their size and revenues. This approach enabled the exploration of diverse perspectives on how to navigate omnichannel challenges across companies dealing with different order volumes.

The people interviewed for each case study held managerial positions in the company and this choice gave the interviewees a high-level vision and insights from individuals with decision-making responsibilities and a deep understanding of the company's operations.
All the cases and warehouses analyzed are located in Italy, a measure adopted to control for potential location-based effects [20].
The last remark is that it's guaranteed anonymity, as suggested by [9].

A total of 16 interviews have been carried out to provide insights from the real case applications. It is noteworthy that Case study 13 is characterized by two different variants (13.1 and 13.2) because it presents two different warehouses with different characteristics.
Detailed information about the case studies and the featured warehouses are presented in the subsequent chapter.

2. **Preparation of the interview guide**
The second step involves the creation of the interview guide, following the guidance provided by [17] and starting from the results obtained from the systematic literature review.
Even in semi-structured interviews, where questions are not rigidly predetermined, it remains vital to ensure that the initial interview protocol is tailored to focus on the research questions and free from leading-the-witness questions, as suggested by [9].
According to the methodology of [17], the interview guide is structured into three key phases:

    - *Introductory questions*: These questions are designed to be straightforward and provide personal data or background information about the interviewee. They help establish a relationship with the interviewee and create a comfortable environment for the interview to begin.
    - *Core questions*: The core questions are derived from the research study's central topics and objectives, and they are typically based on relevant literature. These questions are related to the specific areas of interest and aim to gather in-depth insights and perspectives from the interviewee.
    - *Closing questions*: The closing questions address any remaining topics or clarify any points that may need further explanation or elaboration. They also allow the interviewee to share additional insights or raise any relevant issues that may not have been covered in the interview but are relevant to the research study.

The interview guide used it’s the following:

a) *Introductory questions*

1. Section 1
   - Focus: Basic information
   - Content: Job title, work history, company context, omnichannel in the company

b) *Core questions*

2. Section 2
   - Focus: Peculiarities of omnichannel
   - Content: Open questions and discussion related to the main challenges detected in their omnichannel warehouse
3. Section 3
   - Focus: Omnichannel warehouse
   - Content: Open questions related to the impact of the omnichannel on the warehouse configuration (warehouse areas, management variables, integration or separation)
4. Section 4
   - Focus: Warehouse automation
   - Content: Open questions related to the automation used in the omnichannel warehouse

c) *Closing questions*

5. Section 5
   - Focus: Conclusion
   - Content: Topics not addressed yet

3. Conduction of the interview

The third step in the interview process involves conducting the interviews and, to minimize bias and ensure consistency [17], the interviews have been conducted by the same team of researchers in May 2023, providing a specific timeframe for the study and enabling the collection of up-to-date information.

Having the same team of researchers conduct the interviews ensures consistency in the interview process, helping maintain the reliability and validity of the interview findings while minimizing potential biases that may arise from different interviewers.

Each interview had an approximate duration of about an hour, but it's important to note that the actual duration may vary based on the information provided and the availability of the interviewees.

This flexibility in duration allows for in-depth exploration of the topics and the collection of comprehensive insights from the interviewees.

4. **Analysis of the interviews**

   In this final phase, based on the transcription of the interviews, the research team held meetings to analyze information, address the research questions, and apply the findings to the existing literature.

   The interviews have been transcribed by two different researchers and then integrated to avoid missing parts or misunderstandings, ensuring accuracy and completeness. The decision to create a team for the interviews and hold meetings for the integration of the notes and thoughts helped to avoid the risk of "going native" suggested by [9], which means being too close and essentially adopting the informant view, thus losing the higher-level perspective. By working as a team and integrating different perspectives, the researchers can maintain objectivity and critically analyze the interview data within the larger context of the research study.
   The meetings and discussions among the researchers during the analysis phase provide valuable opportunities to interpret and synthesize the interview findings, identify emerging themes, and develop frameworks that align with the research objectives.

2.2.2.3. Experts' group

The final step of the methodology used in this Thesis involves conducting a survey in a panel of experts about the most important themes explored in the research, that took place during the workshop organized by the Observatory Contract Logistics "Gino Marchet" of Politecnico di Milano.

The workshop was held in presence on June 13th, 2023 and brought together various managers and functionaries working in the logistics environment, with a significant representation of job titles related to warehouse management. During this event, the research findings derived from the literature review and case studies analysis have been presented, initiating a discussion among the participants on these themes, providing an opportunity for the participants to exchange ideas, share their perspectives, and engage in a fruitful dialogue regarding the research findings and their implications.

During this interactive discussion, a survey has been conducted to capture the opinions and insights of the participants. This methodology allowed the participants to provide their feedback, perspectives, and opinions on the key themes explored in the research, allowing to gather quantitative data for the analysis, that were combined with the qualitative evidence from the literature reviews and the case studies. After conducting the survey, the responses were gathered and subsequently presented to the participants, who engaged in discussions regarding the survey results.

The questions made through the survey and the different alternatives have been defined based on the results obtained through the literature review and the case studies analysis.

During this survey, participants were asked to express the degree of relevance, using a score from 1 (minimum relevance) to 4 (maximum relevance), for different questions. Specifically, the questions relevant to this Thesis are as follows:

1. *Given the omnichannel challenges categories found in the literature review and the case studies, which is the relevance degree, according to your experience?*
2. *Given the five configurations of the warehouse, which are the factors that push toward the adoption of specific solutions?*
3. *Concerning flexibility required at the warehouse level, which factors/levers do you consider most useful to act?*

Participation in the survey was not mandatory, and out of the total number of participants, 24 people answered the first questions, while 23 people answered the second and third questions.

To objectively evaluate the different options, a score was assigned to each option based on the sum of scores given by each participant. The scores provided by the participants are aggregated for each option to calculate an overall score that reflects the collective perspective of the respondents, allowing for a quantitative assessment of the options based on the input provided by the participants.

By assigning scores and aggregating the responses, it becomes possible to compare and rank the options based on the participants' assessments. This objective evaluation helps to identify the options that are perceived as more important or relevant by the respondents, providing valuable insights into their perspectives and preferences.

3 Case studies

In this chapter, the case studies (*Table 3.1*) used in this Thesis are presented and the detailed description of each case is articulated.

Case study	Role of the interviewee	Industry	Revenues [bilion euro]
Case study 1	Sales Network Manager	Large scale food retailer	15
Case study 2	Business Development Manager	Intralogistics system integrator	1
Case study 3	Distribution manager	Furniture retailer	42
Case study 4	Leader Supply Chain B2C Transport Manager B2C	DOY accessories retailer	9
Case study 5	Business Unit Manager – Supply Chain Head of pre-sales department	Software solutions provider	0,05
Case study 6	Head of intralogistics solutions Sales Manager Director of Strategic Marketing	Material handling equipment manufacturer	8
Case study 7	Supply chain Director	Foods retailer	1,5
Case study 8	COO	Home appliances retailer	3

Case study 9	Head of Sales Head of Solution Development	Warehouse automation solutions provider	0,1
Case study 10	Director Automated system Head of product specialist & sales management	Handling equipment manufacturer	5
Case study 11	President Logistics director	Automotive accessories retailer	0,02
Case study 12	Sales Director	Material handling systems retailer	15
Case study 13.1 and 13.2	Logistics Director	Sporting goods retailer	11,5
Case study 14	Key account manager	Automatic handling retailer	0,05
Case study 15	Logistics Distribution Manager Logistics Director	Apparel retailer	1,5
Case study 16	Warehouse director	Apparel retailer	3

Table 3.1: List of case studies

1. **Case study 1**
   The first case study centers on a prominent food retailer operating in Italy, with revenue of 15 billion euros in 2022 and a presence across the country with over 1000 markets, including more than 100 hypermarkets. The primary interviewee for this case study was the Sales Network Manager, who bears the responsibility for implementing the project introducing the e-commerce channel within the company. Additionally, the Managing Director of the automation solutions provider was also present during the interview, providing valuable insights into the company's requirements and the implementation of the solutions.

Historically, this company primarily operated in traditional brick-and-mortar retail. However, the onset of the pandemic underscored the necessity for an e-commerce platform to efficiently manage online customers orders. Consequently, the company had to manage both traditional and online channels simultaneously, necessitating a sophisticated warehouse management approach to effectively handle this heightened complexity.

2. **Case study 2**
   The second case study is related to a system integrator of automated warehouse solutions based in Austria. This company specializes in the comprehensive design, manufacture, implementation, and management of end-to-end fulfillment solutions, encompassing activities ranging from goods receipt to warehousing, order picking, and shipping. This multinational corporation has executed numerous automation and warehouse implementation projects globally, and it achieved revenues of approximately €1 billion in 2022. The interviewee for this case study was the Business Development Manager, who provided detailed insights into several omnichannel warehouses where their automation hardware played a pivotal role.
   Among their various projects, the interview explores in-depth a warehouse designed for a leading sportswear retailer. This warehouse boasts an impressive capacity, featuring 713,000 storage locations and managing 122,000 SKUs.

3. **Case study 3**
   Case Study 3 centers on a multinational conglomerate headquartered in the Netherlands, specializing in the design and sale of ready-to-assemble furniture, kitchen appliances, decoration, home accessories, and various other goods and home services with revenues of €42 billion in the fiscal year 2022. Two key personnel were interviewed: the Distribution Manager, who offered a comprehensive overview of the company's logistics strategies with a specific focus on omnichannel approaches, and the Warehouse Manager, who conducted an in-depth analysis of their omnichannel warehouse.
   The focus of the interview was the analysis of the implementation of an omnichannel strategy from a logistics point of view and their distribution center located in the north of Italy. Within this warehouse, distinct sections are dedicated to servicing the B2B channel, where palletized shipments are dispatched to stores, and a separate segment caters to the B2C channel.

4. **Case study 4**
   Case study 4 refers to a company operating in large-scale retail trade, specializing in a wide array of offerings encompassing DIY, construction, gardening, decoration, and bathroom furnishings, with revenues of €9 billion in the fiscal year 2022. The interviews within this context included insights from the Leader of the Supply Chain B2C and the Transport Manager B2C.
   The primary focus of the interview centered on the Distribution Center situated in the North of Italy. This warehouse manages both B2B and B2C orders, with e-commerce orders representing a percentage of the total orders ranging between 3% and 6%. At this logistics site, a total of 85,000 SKUs are handled, and it processes approximately 7,000 orders daily. The main complexity of this warehouse lies in managing different flows, which include home delivery, in-store delivery, handling returns, and direct drop-shipping from suppliers.

5. **Case study 5**
   Case Study 5 pertains to a provider of warehouse software solutions, specializing in Warehouse Management Systems (WMS) designed for the automation of both manually and automatically controlled warehouses, with specific solutions for e-commerce warehouses. This company has active projects in Italy, Europe, Middle & Far East, USA, America, in the Food & Beverage, Large-Scale Retail, Pharma, Manufacturing, Design & Fashion, and in 2022, the company reported revenues totaling €50 million. The individuals interviewed during this case study were the Business Unit Manager and the Supply Chain Head of the Pre-Sales Department, providing a unique perspective on their warehouse software solutions.
   This case study presents various scenarios where their software solutions were successfully implemented in warehouses. Among these cases, a standout example involves deploying a warehouse solution for a retailer specializing in eyeglasses, where in the same warehouse, the company manages two distinct order types: e-commerce orders, typically consisting of single pieces, and orders for distributors. In this project, our featured company played a pivotal role in implementing the WMS and the software integral to automation management.

6. **Case study 6**

   Case study 6 is related to a German multinational material handling equipment manufacturer. Their core product portfolio encompasses intralogistics solutions, warehouse automation equipment, and industrial trucks. In 2021, this company became the largest manufacturer of forklift trucks and warehouse equipment in the EMEA (Europe, Middle East, and Africa) region, boasting revenues of €11 billion in 2022. Their extensive experience spans a wide array of omnichannel warehousing projects, offering invaluable insights into the evolving trends within the omnichannel warehousing landscape.

   The people interviewed during this case study were the Head of Intralogistics Solutions, the Sales Manager, and the Director of Strategic Marketing.

   Although the case study doesn't delve into the specifics of a particular warehouse implementation, it provides a panoramic view of omnichannel warehousing, drawing on the expertise garnered from numerous projects with a diverse range of omnichannel customers.

7. **Case study 7**

   Case study 7 refers to an Italian company specializing in the production and retailing of foods, with a particular emphasis on cured meats. In 2022, this company reported impressive revenues of €1.5 billion. The interview for this case study featured insights from the Supply Chain Director, offering a high-level overview of the company's omnichannel strategy implementation within their warehouses.

   Within this company, two primary channels coexist: the traditional channel, which involves selling products to physical stores, and the e-commerce channel, introduced three years ago and enables end customers to conveniently order products online and have them delivered to their homes. This channel constitutes a modest percentage, typically ranging between 1% to 2% of the total sales volumes.

   The focus of this interview was on the most important warehouse of the company, a central warehouse located in the North of Italy. From this warehouse starts the distribution in Italy, which can directly replenish the stores or the second level warehouse for e-commerce and the Horeca. During the interview, we couldn't delve into specific details regarding the automation implemented in this warehouse due to privacy concerns.

8. **Case study 8**
   Case study 8 refers to an Italian company that operates in the sector of air conditioning, heating and products for cooking, cleaning, coffee making and ironing, with revenues of €3 billion in 2022. The interview for this case study featured insights from the Chief Operating Officer (COO), providing a high-level perspective on the company's omnichannel strategy, focusing on the logistical complexities associated with its implementation and not on the operations of a specific omnichannel warehouse.
   Within this company's operational framework, two primary channels coexist: the traditional channel, involving the sale of goods to physical retail stores, and the e-commerce channel, dedicated to serving end customers directly.
   The journey toward implementing an omnichannel strategy commenced four years ago, marked by the introduction of the e-commerce channel, initially at the South European hub.

9. **Case study 9**
   Case study 9 refers to a globally active company specializing in integrated automation solutions for warehouses and distribution centers with revenues of 100 million euros in 2022. The interview for this case study featured insights from the Head of Sales and the Head of Solution Development, providing valuable information about the challenges and configuration insights relevant to omnichannel warehousing.
   While this case study did not delve into the analysis of a specific warehouse implementation, the comprehensive experience accumulated in the deployment of diverse omnichannel warehouse solutions allowed the author to draw meaningful conclusions from this interview.

10. **Case study 10**
   Case study 10 is related to a company specializing in the production and sale of handling equipment such as pallet trucks, transporters and elevators, trilateral trucks and automatic stacker cranes. Furthermore, they also offer the entire spectrum of warehouse technology and services, such as the design and implementation of complex logistics systems, shelving, warehouse management software (WMS) and AGVs, customizing them for each customer need. In 2022, this company reported revenues of €5 million. During the interview for this case study, the people involved were the Director of Automated Systems and the Head of Product Specialist & Sales Management. They analyzed various omnichannel warehouses that the company has been involved in, enabling the author to discern common trends within this domain. Similar to previous cases, this study did not involve an in-depth analysis of a specific warehouse implementation, however, it provided valuable insights into the automation trends observed across their portfolio.

11. Case study 11

Case study 11 is related to an Italian company specializing in automotive accessories, reporting total revenues of €20 million in 2022. The interviews for this case study featured insights from the President and the Logistics Director.

Within the company's operational framework, two primary channels are managed: large-scale replenishments for retail stores and serving resellers. Therefore, the dimensional differences between orders can vary significantly between these distinct channels.

The primary focus of our interview was on their central warehouse, which is responsible for managing orders from the different channels.

12. Case study 12

Case study 12 refers to an American company specializing in materials handling systems, software, and services. Their expertise encompasses the design and manufacturing of various products and equipment for materials handling, including conveyors, sortation systems, and order picking systems. Additionally, they provide consultative services, planning support, and software solutions like Warehouse Management Systems (WMS) to facilitate material flow and order picking operations. In 2022, this company achieved substantial revenues, totaling €15 billion. The person interviewed was the Sales Director.

Leveraging their extensive experience in implementing automation systems, this company's insights contribute significantly to the ongoing research exploring the impact of omnichannel strategies on warehousing operations and trends in warehouse automation.

13. Case study 13.1 and 13.2

Case study 13.1 and Case study 13.2 delve into two distinct warehouses operated by the same company, each offering unique insights and solutions. This company specializes in sporting goods retailing and reported revenues of €11.5 billion in 2022. This company manages two primary channels: the traditional channel, entailing the sale of goods to brick-and-mortar stores, and the burgeoning e-commerce channel, enabling end customers to purchase products directly online, with options for home delivery or in-store pickup. The e-commerce channel has gained significant prominence recently, necessitating specialized strategies to meet its demands. The person interviewed was the Logistics Director.

The decision to separate the two warehouses in these case studies is due to the possibility to delve deeply into each solution individually, given the differences in operational functions and automation solutions adopted.

14. **Case study 14**
    Case study 14 refers to an Italian company specializing in the automatic handling sector, renowned for its cutting-edge telescopic forks and pallet shuttle systems designed for the intra-logistics sector. In the year 2022, this company reported substantial revenues amounting to €50 million. The interview for this case study featured insights from the Key Account Manager, offering a comprehensive overview of the automation solutions offered by the company.

15. **Case study 15**
    Case study 15 delves into an Italian clothing company with revenues of €1.5 billion in the year 2022. The people interviewed were the Logistics Distribution Manager and the Logistics Director.
    The primary focus of our discussion was centered on the company's central warehouse, situated in the northern region of Italy. However, the information and details related to this case study are intentionally limited due to privacy concerns. Nevertheless, the insights provided by the Logistics Distribution Manager and the Logistics Director, within the bounds of privacy constraints, offer valuable perspectives on the warehousing operations and strategies employed by this prominent clothing retailer.

16. **Case study 16**
    Case study 16 focuses on an Italian company that manages several brands within the clothing sector, marketed through single-brand stores. In 2022, this company achieved total revenues amounting to €3 billion. The interview for this case study featured insights from the Warehouse Director.
    The warehouse discussed during the interview is the Italian central warehouse, which does not employ automation solutions.

4 Main challenges in omnichannel context

4.1. Introduction

The first research question addressed in this Thesis is: "*What are the main characteristics and challenges that omnichannel warehouses have to deal with?*".

The objective of this research is to identify the specific challenges faced by warehouses operating in the omnichannel environment, with a focus on understanding the key features and difficulties encountered by these warehouses. The structure of this research question is illustrated in *Figure 4.1*.

Through examining the literature and case studies, the chapter will provide insights related to the primary key features and difficulties encountered by warehouses in omnichannel operations, contributing to a deeper understanding of the challenges in this domain.

The methodology employed to address this research question consists of three different stages. The list of challenges is defined using a systematic literature review, which allows to identify the most important challenges from an academic point of view and semi-structured interviews, which allow for a deeper exploration and integration of the findings from the literature review. By engaging with industry experts and practitioners, valuable real-world experiences can be gathered to complement the theoretical understanding obtained from the literature. The last stage involves survey analysis conducted in an experts' group, which introduces a quantitative element to the methodology, providing a clear and defined measurement for each category of challenge, supporting the findings obtained from the qualitative stages.

The chapter is organized as follows. First, a list of challenges related to the omnichannel context is defined based on the analysis of the literature review and the semi-structured interviews. Then, a ranking of the different challenges is defined based on different metrics, and in the last phase, the results obtained from the different sources (literature review, case studies, and experts' group) are analyzed.

Figure 4.1: Structure of the RQ1

4.2. List of the challenges

In the first section of this chapter, a list of omnichannel challenges is identified through an analysis of existing literature and insights from semi-structured interviews.

To better structure the analysis, the list of challenges is divided into four different categories:

1. **Increase of the expectations regarding the service level**
   In an omnichannel context, customers have heightened expectations for fast and efficient deliveries across various locations and these service level expectations can vary between channels. These expectations include flexibility in delivery options and product availability.

2. **Changes in the order profile**
   The presence of multiple channels in an omnichannel environment necessitates the warehouse to handle orders with different dimensional profiles. Each channel may have distinct order characteristics, such as dimensions, packaging, units of picking, units of delivery, and order frequency.

3. **Changes in the demand profile**
   Different channels in an omnichannel context often exhibit varying demand profiles, including demand variability, peak periods and the wide assortment of products requested, which continually changes. Moreover, the online channel face significant and unpredictable growth.

4. **Constraints**
   When implementing omnichannel warehousing projects, companies often encounter constraints related to the warehouse facility, as the introduction of new channels in company operations could occur in already operational or existing buildings.

Other constraints needed to be taken into consideration are related to the information system and the time required for solution implementation.

The complete list of omnichannel challenges is the following:

1. **Increase of the expectations regarding the service level**

   - *Lead time reduction*
     Customer expectations regarding lead time reduction are fundamental for the success of a company in an omnichannel context. In particular, faster fulfillment is a key motivator for customers to transition from physical in-store visits to online orders with home or business delivery [21]. In recent years, many e-tailers have introduced same-day delivery options, sometimes even offering 1-hour or 2-hour delivery choices. The primary rationale for providing these options is to compete with brick-and-mortar retailers that can offer immediate product delivery [22]. Achieving customers' expectations for shorter lead times, such as same-day delivery, is critically reliant on the role of the omnichannel warehouse [8]. Case studies 1, 2, and 10 underscore that maintaining a high service level is the primary challenge for omnichannel warehouses because this heightened service level necessitates faster order fulfillment within warehouse operations.

   - *Different service levels for different channels*
     According to Case study 11, each channel may have distinct service level requirements and considering a warehouse that faces demand from different channels, a high level of complexity arises due to this heterogeneity. For example, there are notable differences between end customers and physical stores, with the end consumers that often expect home delivery and next-day delivery, while physical stores have different expectations, typically allowing for longer lead times for goods delivery [23], as also underlined by Case study 10.

   - *Flexible deliveries*
     While customers continue to prioritize fast service, the rise of omnichannel retailing and e-commerce has also fostered a growing demand for flexible delivery options tailored to their individual needs [24], introducing additional layers of complexity compared to traditional single-order mechanisms [25].

According to Case study 3, the need for flexible deliveries is a consequence of the increase in the number of touchpoints with the customer, which is typical of the omnichannel context.
In the omnichannel environment, the transportation of goods is characterized by a variety of modes due to the distinct characteristics and service requirements of different delivery points, to which different time slots in the warehouse are assigned, as underlined by Case study 7. These different transportation modes include standard delivery, such as next-day delivery, as well as express delivery (e.g., same-day delivery) and instant delivery (e.g., 4-hour deliveries) [26].
Furthermore, aside from flexibility in timing (when the customer wants the order), the omnichannel approach also offers flexibility in place, with the customer choosing different delivery points, such as home delivery and shop delivery, which necessitate the utilization of different warehouse operations, as highlighted by Case study 1.
Moreover, this temporal and spatial flexibility is also applied to returns [23], which requires flexibility related to the adoption of different return options to meet customer expectations [6].

- *Postponement of the cut-off/continuous receivement of orders*
  A peculiarity of the omnichannel context is the need to postpone the cut-off to receive orders that require same-day or next-day and delivery them quickly [6].
  Extending the cut-off time allows retailers to continue receiving orders beyond the traditional deadline while ensuring that these orders are processed and prepared for shipping within the next business day.
  As highlighted in a case study emphasized by [8], this solution allows the replenish of large retail stores first during the day (because the demand is known) and delays the cut-off time for online orders to pick them later in the day.

- *Important to guarantee product availability*
  In an omnichannel setup, where orders come from different channels, ensuring product availability across these channels is a critical component of logistics service quality in omnichannel retail [27].
  Moreover, it's essential to avoid that the stocks used in certain channels are not visible in the other channels [28].
  Customers in the omnichannel context have high expectations regarding product availability and seek real-time updates on stock availability, especially through online platforms [23].

Case studies 4 and 5 underscore the significance of ensuring product availability in various channels through information systems integrated between different channels.

2. **Changes in the order profile**

- *Dimensional difference in the order profile*
  In an omnichannel warehouse, managing different channels requires the handling of orders with distinct profiles. As emphasized by case studies 2, 5, and 9, there are notable differences in order sizes between stores and customers, with order sizes of stores that are significantly larger than those of customers [29]. In particular, the average items per store order is 34 times higher than for a direct-to-customer order [30] because store replenishment covers indirect demand, while online orders cover direct demand [8].

- *Different units of picking*
  Case study 9 highlights that in an omnichannel warehouse, the presence of varied order profiles necessitates the management of different units of picking tailored to specific channels, such as piece picking and carton picking.
  Managing different channels also leads to the requirement of handling various order profiles during the picking activity, with the need to handle single pieces for the orders and big replenishment for the traditional channel, as observed by Case study 11.
  When dealing with small goods that require frequent replenishment to smaller stores or for online deliveries, it is common practice to pick multiple orders simultaneously on a pallet. Conversely, for larger volumes destined for bigger stores with less frequent replenishment needs, single orders are picked using one or more pallets [6].

- *Different packaging and units of delivery*
  In the omnichannel context, varying order characteristics necessitate different packaging requirements, including cartons, boxes, and a wider range of stock-keeping units [6].
  Case study 11 highlights the growing importance of not only managing pallets in the warehouse but also handling smaller stock-keeping units, such as individual pieces, which requires different packaging.
  Additionally, a significant aspect is related to differences in the unit of delivery. For instance, in the warehouse described in Case study 3, the B2C channel handles single orders as the unit of delivery, while the B2B channel employs pallets as the unit of delivery.

- *Different order frequency*
  An essential characteristic of orders in the omnichannel context is the variation in the delivery frequency among different channels, as highlighted in Case study 2.
  Specifically, for e-commerce, the frequency of orders per customer has consistently increased while the size of each order has decreased, partly due to the popularity of free shipping services offered by retailers [31].
  Another contributing factor to this increase in frequency is the rise of express fulfillment services, resulting in substantial, high-frequency shipments with short lead times and fluctuating volumes [32].

3. **Changes in the demand profile**

- *Demand variability (often in a non-repetitive way)*
  One of the primary challenges in omnichannel operations is related to demand fluctuations, with high uncertainty in both long-term and short-term demand, which put pressure on warehouses to rapidly adjust their capacity [3], as explained also by case studies 2 and 5.
  The online channel significantly contributes to this demand uncertainty because online quantities exhibit greater volatility and are less predictable than bricks-and-mortar or catalog businesses [33].
  Since online customers can place orders at any time using their mobile devices, the arrival of orders from end consumers is dynamic and subject to significant fluctuations [29], resulting in varying workloads in the warehouse.
  This uncertainty is also determined by the presence of the different channels, that face frequent fluctuations in the day-to-day demand [34].

- *High peaks in terms of entity, period, duration*
  The omnichannel context is characterized by significant peaks in demand across different channels, adding complexity to the management of warehouse operations.
  Case study 10 identifies both predictable and unpredictable demand peaks. Predictable peaks may occur on specific days, at the end of the month (due to commercial logic), or due to seasonal factors.
  Nevertheless, there are also significant peaks of unpredictable nature, necessitating the handling of substantial order volumes during unforeseen moments.

Examples of predictable peaks are the demand peaks and variations connected to marketing campaigns such as Black Friday and Cyber Monday [3]; on such days, online purchases double, complicating resource management [35].
Furthermore, with the target customer of each e-retailer differing from each other in terms of, for example, geographical locations of the customer base, the peak periods of order arrival in different zones throughout the day varies and may be overlap [29].

- *Growth rate difficult to predict (unpredictability of the environment)*
  The growth rate of the different channels in the omnichannel context is difficult to predict, leading to uncertainty regarding future developments in the environment, as underlined by Case study 2.
  The omnichannel landscape is in a constant state of evolution and the current situation is expected to differ significantly in the future.

- *Incidence of the different channels that change in time*
  The distribution of orders among different channels fluctuates over time and the percentage of orders in each channel today may differ from tomorrow's percentage. Furthermore, the landscape related to the different channels is not static, and new channels can be introduced, adding uncertainty to the environment [36].

- *Relevance of the return flow*
  In omnichannel retail markets, managing return flows is a significant challenge. Case study 4 emphasizes the importance of handling returns efficiently because consumers place a high value on having flexible return options. Retailers can improve customers' perception of the buying process by providing flexible return options, helping to increase customer confidence and satisfaction [37]. However, implementing of such flexible return policies can also lead to an increase in the volume of returns.

- *Increase of the phase-in/phase-out frequency*
  Omnichannel retailing is characterized by a wide range of product variations and continuous changes in the product assortment [6].
  This dynamic environment leads to a significant turnover of products, characterized by a higher introduction of new products compared to traditional retail operations [3].

- *High growth rate of the online channel*
  As previously mentioned, one of the possible channels in the omnichannel context is the online channel. Case study 8 underlines the strong yearly growth of this channel, with the retail e-commerce sales in 2020 corresponding to 4,280 billion US dollars, with an impressive annual growth of 22 percent during the last 5 years [38].
  This growth is expected to continue in the following years, with a high growth rate, presenting various operational and planning challenges for online retailers and the warehouses responsible for fulfilling their orders [39].

- *Fragmented demand base*
  In an omnichannel context, demand is not concentrated solely in large points of sale but rather distributed among a combination of large and small demand points, leading to a highly fragmented demand base, comprising several thousand customers daily in each city [26].
  Case study 3 highlights that this fragmented demand base is a consequence of the increase in the number of touchpoints with customers.

- *Wide product assortment requested*
  In omnichannel retailing, the demand is characterized by a broad product assortment to meet customer expectations [6].
  This extensive product assortment is provided through e-commerce platforms and online marketplaces, where customers have access to a wide selection of products [3].
  Case study 1 emphasizes that online customers have high expectations in terms of product assortment, with the need to guarantee the widest possible assortment.

4. **Constraints**

- *Existing building*
  The presence of an existing building poses a constraint when expanding or adding new channels into a business's operations.
  This constraint requires careful planning and consideration of the existing infrastructure, influencing decisions regarding the allocation of space and the integration of new technologies or equipment, as underlined by Case study 1.

In this case, the implementation of the automated warehouse for the online channel took place within an existing building where traditional operations were already being managed.
An important constraint of the existing building is the height, which needs to be considered when adding a new channel, as suggested by Case study 12.

- *Warehouse already operative*
  When an existing warehouse is already operational, the implementation of new channels must consider and work within the constraints imposed by the existing operations and it necessitates a careful and efficient integration of new channels while also accounting for the existing warehouse operations, as underlined in Case study 15. In this Case study, the online channel was added in a warehouse where the traditional channel was already implemented and operative.
  Moreover, the presence of an already operative warehouse led to a reduced development timeline for the solution, as the foundational infrastructure is already in place due to the pre-existing warehouse setup, as underlined by Case study 13.2, which needs to change an operative warehouse.

- *Software not designed for omnichannel*
  The software is crucial in the management of omnichannel operations. However, existing software that lacks the omnichannel-specific characteristics can become a constraint because it may not adequately support the needs of omnichannel operations, leading to inefficiencies. Case studies 4, 5 and 12 underscore that omnichannel software requires specific characteristics of synchronization and integration between channels, which are not present in traditional systems. This leads to the need for specifically designed software.

- *Solution development/implementation time*
  Time constraints are critical factors in omnichannel operations when developing and implementing solutions. In the rapidly evolving omnichannel environment, it is essential to consider the time factor because if the development and implementation process takes too long, the solution may no longer be relevant or aligned with the dynamic needs of the omnichannel landscape.

Case study 3 highlights the importance of speed in developing omnichannel projects, given the continuously changing environment that requires rapid responses. In response to this need for agility, a "test and try" approach is proposed to expedite the project development process.

4.3. Rank of the challenges

After the definition of the list of challenges, the relevance of the different challenges is assessed using three different scores:

- **Literature score**
  The first score is related to the number of citations of the specific challenge in the literature review. In particular, the author counted the number of times that the papers of the first research string cited the specific challenge. This score indicates the level of attention and discussion that a particular challenge has received in the academic literature.
- **Case studies score**
  The second score is derived from the case studies conducted through semi-structured interviews. During these interviews, the experts identified and discussed the main challenges faced by omnichannel warehouses from their perspective, and the author counted the number of times that these challenges were mentioned by the experts during the interviews. This score provides insights into the challenges that are prominent in the practical experiences and observations of industry experts.
- **Experts’ group score**
  The last score is obtained by the experts’ group. During the workshop of the Observatory Contract Logistics “Gino Marchet”, the participants answered a survey regarding their perceived impact of the different categories of challenges based on their experience in the omnichannel warehouse context. This score provides a parameter for understanding the overall relevance of that category of challenges for a group of experts.

The scores for each omnichannel challenge are defined in *Table 4.1*.

Category	Challenge	Literature score	Case study score	Experts' group score
Increase of the expectations regarding the service level	Lead time reduction	22	4	70
	Different service levels for different channels	2	2	70
	Flexible deliveries	6	3	70
	Postponement of the cut-off/continuous receivement of orders	2	1	70
	Important to guarantee product availability	3	2	70
Changes in the order profiles	Dimensional difference in the order profile	8	4	71
	Different units of picking	2	2	71
	Different packaging and units of delivery	2	3	71
	Different order frequency	2	2	71
Changes in the demand profile	Demand variability (often in a non repetitve way)	7	2	69
	High peaks in terms of entity, period, duration	4	2	69
	Growth rate difficult to predict (unpredictability of the environment)	/	1	69
	Incidence of the different channels that change in time	1	/	69
	Relevance of the return flow	14	1	69
	Increase of the phase-in/phase-out frequency	2	/	69
	High growth rate of the online channel	26	1	69
	Fragmented demand base	3	1	69
	Wide product assortment requested	9	3	69
Constraints	Existing building	/	2	75
	Warehouse already operative	/	3	75
	Software not designed for omnichannel	/	3	75
	Solution development/implementation time	/	1	75

Table 4.1: Scores of the omnichannel challenges

The papers that cite the different challenges are defined in *Table B.1*, and the case studies that cite the different challenges are presented in *Table B.2*.

It is possible also to focus on the challenges categories, obtaining *Table 4.2*.

Category	Literature score	Case study score	Experts' group score
Increase of the expectations regarding the service level	35	12	70
Changes in the order profiles	14	11	71
Changes in the demand profile	66	11	69
Changes in the demand profile	/	9	75

Table 4.2: Scores of the omnichannel challenges categories

4.4. Conclusions and analysis of the results

Following the compilation of the challenges list and the corresponding scores obtained through the three different approaches, it's possible to state conclusions related to this first research question.

4.4.1. Analysis of the literature review

The analysis of the literature allows the author to define valuable insights to create an initial macro-list of the different challenges cited in the selected papers, and simultaneously it helps to understand if it's already present in literature a list of these challenges.

Analyzing the literature, it is evident that a comprehensive and exhaustive framework capturing the challenges encountered by omnichannel warehouses is notably absent, with no papers that have performed this analysis. This Thesis aims to close this literature gap by presenting a comprehensive list of unique attributes specific to omnichannel warehousing divided into four categories, obtained through the analysis of the literature, the analysis of the case studies and the experts' group.

By presenting this complete list, the Thesis contributes to the body of knowledge concerning omnichannel warehousing, addressing the need for a framework that comprehends the challenges specific to this context. Moreover, the presented list of challenges is not a pure list; also an associated score for the different challenges is defined, based on the citations in the literature, the case studies and the experts' group.

In the analyzed papers, the omnichannel challenges are not a central focus of the studies, but they are mentioned in the introduction of the paper and used as a context for the paper. This Thesis addresses this gap by dedicating a specific research question, employing a focused research string, dedicating specific questions in the interviews and a question during the experts' group.

Another issue addressed in this Thesis is the tendency of existing papers to discuss omnichannel challenges in a broad and generalized manner, without a focus on challenges that have direct implications for warehouse operations. In contrast, this Thesis places a distinct emphasis on the warehouse aspect and delves into challenges that directly impact warehouse operations. This refined research focus provides a more comprehensive understanding of the unique implications and complexities faced by warehouses within the omnichannel context.

From the analysis of the literature, it is observed that the most frequently challenge cited is the "*High growth rate of the online channel*", with a total number of 26 citations, mainly because many papers take into consideration the online channel as one of the main channels in an omnichannel context and this challenge is mentioned as an introductory remark in the papers to state the importance to conduct a study related to the online channel. Following this, the second mentioned challenge is "*Lead time reduction*", with a total of 22 citations, which emerges as the most important expectation related to the service level expectations category.
Also the challenge related to the "*Relevance of the return flow*" gained particular attention within the scholarly publication, with a total of 14 citations.

From the analysis of the three most cited challenges in the omnichannel warehouse context, it becomes evident that all three challenges are intrinsic characteristics of the online channel. This implies that within the omnichannel context, the online channel often holds a position of prominence and has a substantial influence on warehouse management.

4.4.2. Analysis of the case studies

After defining the initial list of challenges, the pivotal role played by semi-structured interviews with logistics experts becomes apparent in the validation and expansion of the challenges derived from the literature analysis, ultimately leading to the creation of a comprehensive list of challenges.

By engaging in discussions with logistics experts, the author was able to confirm the relevance of the challenges identified in the literature, with the ability of the case studies to mention almost all the challenges mentioned in the literature, except for "*Incidence of the different channels that change in time*" and "*Increase of the phase-in/phase-out frequency*", respectively with one and two citations from the papers, suggesting their not particularly relevance.

In addition to the confirmation of the relevance of most of the challenges identified in the literature review, the case studies also help in the identification of new challenges that were not previously addressed in the existing literature. An example is the category related to the constraints faced in the implementation of omnichannel warehousing. While the constraints were not identified in the current literature because the existing papers focus on more theoretical aspects of the omnichannel challenges, the case studies underscore their significance due to their importance in the practical implementation of omnichannel strategies. The category related to the constraints has implications for the managers who have to practically implement the omnichannel strategies and, for this reason, is strongly underlined by the case studies. Another significant challenge revealed through the case study analysis, which was not previously identified in the literature, is the "*Growth rate difficult to predict (unpredictability of the environment)*". Like the constraints category, this challenge holds substantial influence over managers' decision-making in the omnichannel context, yet it was not highlighted in the literature analysis.

The findings related to this new category and challenge emphasize the importance of not solely relying on existing academic research when investigating real-world complexities, as practical scenarios can present unique insight that might not have been extensively explored in previous studies.

From the interviews, the challenges with the highest number of citations are related to the "*Dimensional difference in the order profile*" and the "*Lead time reduction*", with 4 citations each. These two challenges were identified as important also in the literature analysis.

The comprehensive overview of the results from the literature scores and the case study scores is represented in *Figure 4.2.*
This figure reveals that the literature analysis presents significant peaks of citations for challenges highlighted in the previous section. In contrast, the case studies fewer citations overall due to their smaller quantity than papers, and they lack specific peaks. This figure illustrates the general confirmation of challenges through the case studies analysis, while also demonstrating that there is not always a direct correlation between the number of citations obtained through the two methods. This underscores the importance of employing a mixed-method approach, integrating literature-based research with real-world case studies, to enrich the Thesis's findings and support the development of more robust conclusions.

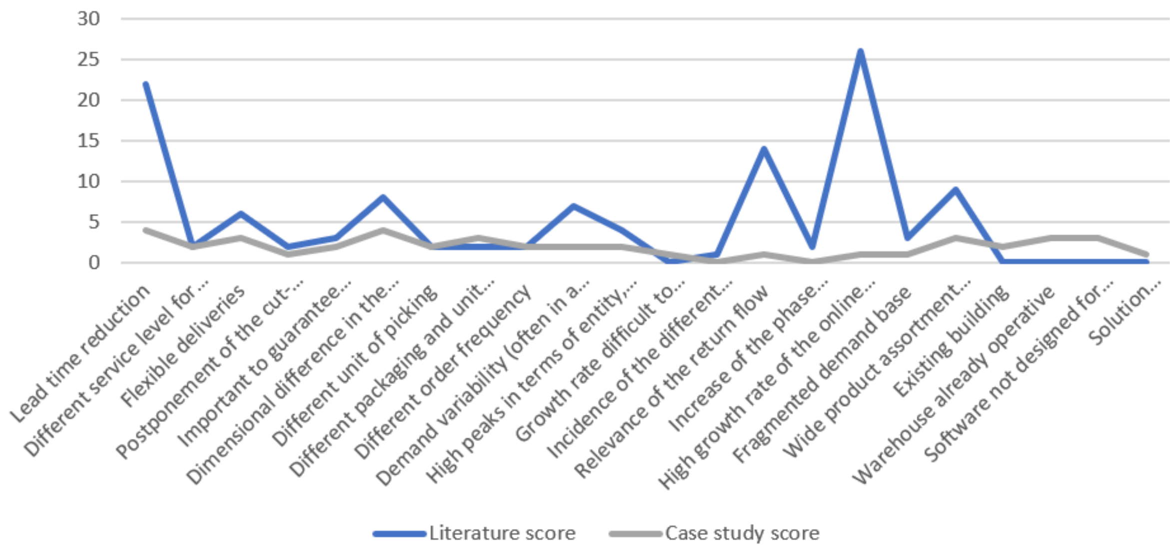

Figure 4.2: Comparison between literature score and case study score

4.4.3. Analysis of the experts' group

As part of this validation process, the results of the literature review and the case study were presented to a panel of experts to validate the findings of the research, as they provided insights from industry professionals who directly deal with omnichannel warehousing challenges in their day-to-day operations, ensuring a broader validation of the findings, making them more robust and applicable in a real-world scenario.

Based on the experts' group responses, the ranked categories of challenges in terms of their perceived relevance and impact on the omnichannel warehouses are the following:

- *Constraints*: 75
- *Changes in the order profile*: 71
- *Increase of the expectations regarding the service level*: 70
- *Changes in the demand profile*: 69
- *Constraints*: 69

The experts' group results serve as a general confirmation of the list of challenges identified through the literature review and the case studies analysis because the scores given by the participants to the different categories are very similar to each other and, as a result, validating the significance of the challenge categories identified through the literature review and case study analysis.

An important remark that arises from these results is that the constraints category emerged as the most important and impactful challenge in the experts’ group, underscoring the significance of incorporating different sources of information; in fact, this category was not mentioned by any paper in the literature review as a possible challenge for the omnichannel warehouse.
The rationale for the high number of citations related to this category aligns with what has been emphasized before: this category holds substantial influence over managerial decisions in real-world applications, rendering it a critical consideration.

5 Analysis of the impact of the omnichannel challenges on the warehouse

5.1. Introduction

The result of the first research question is the identification of a complete list of peculiarities of the omnichannel context, divided into macro-categories and the assignment of scores related to the identified challenges. Building upon these findings, the second research question is posed as follows: "*How do the identified characteristics affect the design and management of the warehouse?*".

The core of this research question is the analysis of the relationship between the identified omnichannel challenges and the consequence on the configuration of the warehouse. Additionally, it seeks to identify the countermeasures that can be integrated into warehouses to address these specific challenges effectively. The structure of this research question is illustrated in *Figure 5.1*.

To address this research question, a qualitative methodology is employed. The initial step involved an extensive literature review focused on the chosen subject. This literature review not only defined a significant number of correlations between the challenges and warehouse configuration but also laid the groundwork for the subsequent phase involving the analysis of case studies. The case studies provided invaluable managerial insights into warehouse configuration within the omnichannel context. These interviews not only augmented the framework with additional insights into the consequences of warehouse challenges on configuration but also enriched the chapter with practical industry expertise.

The structure of this chapter is organized as follows: it commences with an introduction to the research question, followed by the presentation of a framework outlining the causal relationship between challenges and their effects on warehouses. Subsequently, the third section details this framework through an in-depth analysis of the existing literature and the case studies. Finally, the chapter concludes with an analysis of the results.

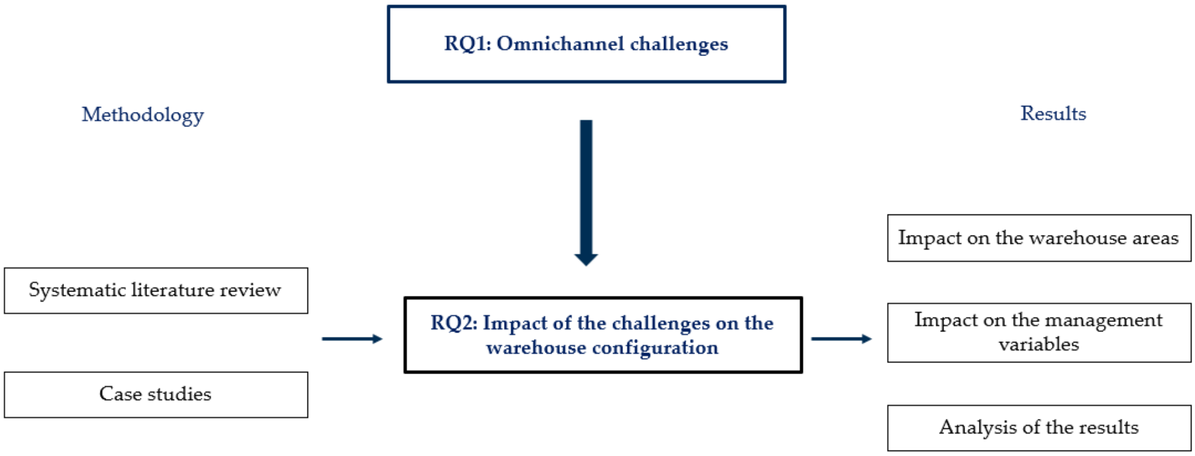

Figure 5.1: Structure of the RQ2

5.2. Framework of the relationship between challenges and impact on warehouse

The foundation of this analysis stems from the list of challenges defined in RQ1, with the primary objective of this chapter being to delineate their impact on warehouse configuration.

To provide a more precise understanding of the concept of warehouse configuration, two main categories on which the challenges have an impact have emerged from the examination of the literature and case studies:

1. **Warehouse functional areas**
   This category pertains to the various physical areas within the warehouse. A suggested framework for the identification of the warehouse areas has been proposed by [6], which identifies the following areas:
   - *Receiving*: This area includes the receiving of incoming goods, handling returns, and the eventual sorting of items.
   - *Put away, storage*: This area involves the storage of goods after they have been received.
   - *Picking, sorting*: This area includes activities such as replenishment, picking and sorting of items.

- *Packing, shipping*: This area involves activities related to packing items, consolidating orders, and preparing them for shipping.

2. **Management variables**
The second category addresses the various variables that necessitate consideration in the design of an omnichannel warehouse and that can be controlled to respond to the complexity of the omnichannel context. The variables under analysis are:
    - *IT*: This variable corresponds to the information system of the company, which plays a fundamental role in supporting warehouse processes.
    - *Automation*: The automation variable is related to the degree of automation implemented across the different areas of the warehouse.
    - *Planning*: The planning variable refers to the managerial activity that includes resource allocation, activity management, forecasting and flow management within the warehouse.
    - *Human resources*: The last variable is related to the management of human resources in the warehouse.

The findings of this chapter, which consists in the consequences of the omnichannel challenges on the warehouse and the countermeasures in the warehouse configuration to face these challenges, can be structured in a table. This table defines the relations between the omnichannel challenges and the related impacts on the warehouse, and the structure is the following:

- *Rows (Omnichannel challenges)*: The rows of the table contain the list of omnichannel challenges defined in the first research question.
- *Columns (Warehouse areas and management variables)*: The columns of the table contain the list of the four warehouse areas and the four variables under analysis. In particular, two tables are created: one related to the consequences of the challenges on the warehouse areas (*Table 5.1*) and one related to the consequences of the challenges on the management variables under analysis (*Table 5.2*).
- *Table cells*: The cells within the table correspond to the crossing of the omnichannel challenges and warehouse areas/management variables and they are designated with an "x" if the challenge in that row has a certain consequence on the warehouse area/key variable of the corresponding column.

Furthermore, to provide a comprehensive understanding of these tables, the text deeply explained each consequence of the challenges concerning the literature and case study findings to offer a detailed insight into the specific impact of each challenge on warehouse configuration.

	Warehouse areas			
Challenges	**Receiving**	**Put away, storage**	**Picking, sorting**	**Packing, shipping**
Lead time reduction	x	x	x	x
Different service levels for different channels		x	x	
Flexible deliveries			x	x
Postponement of the cut-off/continuous receivement of orders				
Important to guarantee product availability		x		
Dimensional difference in the order profile			x	x
Different units of picking			x	
Different packaging and units of delivery	x	x		x
Different order frequency			x	
Demand variability (often in a non repetitve way)		x	x	
High peaks in terms of entity, period, duration			x	
Growth rate difficult to predict (unpredictability of the environment)				
Incidence of the different channels that change in time				

Relevance of the return flow	x	x	x	x
Increase of the phase-in/phase-out frequency				
High growth rate of the online channel			x	x
Fragmented demand base			x	x
Wide product assortment requested		x	x	
Existing building		x		
Warehouse already operative				
Software not designed for omnichannel				
Solution development/implementation time				

Table 5.1: Impact of the challenges on the warehouse areas

	Management variables			
Challenges	**IT**	**Automation**	**Planning**	**Human resources**
Lead time reduction	x	x	x	
Different service levels for different channels	x	x		
Flexible deliveries				
Postponement of the cut-off/continuous receivement of orders			x	
Important to guarantee product availability	x			
Dimensional difference in the order profile		x		
Different units of picking				
Different packaging and units of delivery		x		
Different order frequency				
Demand variability (often in a non repetitve way)	x		x	x
High peaks in terms of entity, period, duration		x		x
Growth rate difficult to predict (unpredictability of the environment)	x	x	x	x
Incidence of the different channels that change in time				x

Relevance of the return flow	x		x	x
Increase of the phase-in/phase-out frequency		x		
High growth rate of the online channel		x	x	
Fragmented demand base			x	
Wide product assortment requested			x	
Existing building		x		
Warehouse already operative				
Software not designed for omnichannel	x			
Solution development/implementation time		x		

Table 5.2: Impact of the omnichannel challenges on the management variables

5.3. Literature review and case studies

The purpose of this section is to provide a structured explanation of the various impacts outlined in the table. The approach employed here entails a methodical analysis of each challenge and its effects on warehouse areas and management variables.

5.3.1. Warehouse areas

Lead time reduction

To reduce the lead time of receiving operation, cooperation with and control of suppliers is necessary, which can be achieved by reducing the number of suppliers, to focus more on selected partner relationships [6]. This cooperation leads to benefits, such as accurate and prompt goods registration and avoidance of problems in the receiving activity, which could result in delayed deliveries [6].

In the context of the reduction of lead time, storage activity becomes a critical area for optimization since storage assignments impact the length of picking trips. A proposed solution in the literature to optimize storage is the concept of "scattered storage" or "explosive storage policy," in which individual items are deliberately dispersed across multiple positions within the picking area [40] and it can reduce picking travel times by increasing the likelihood that items belonging to the same order can be found in nearby positions, speeding up the picking process [40].
The scattered storage can also be associated with the utilization of a very large number of small bin storage locations within the warehouse and with the commingled bin storage, which consists in different items simultaneously stocked in the same bin [41].

The reduction of the lead time pushes the picking system from the picker-to-parts to the parts-to-picker approach. The traditional picker-to-parts setup is often no longer efficient enough because human order pickers produce a lot of unproductive walking [42], while parts-to-picker systems, instead, transport the stock-keeping units toward stationary pickers, who can focus on the productive part of their work, which is the retrieval of pieces demanded by picking orders [42]. For this reason, warehouse managers greatly emphasize warehouse automation in the picking process, where human workers work in tandem with robots to minimize unproductive operations and increase efficiency [39].
When automation is not implemented in the picking activity and a picker-to-parts solution is adopted, order batching is a potential solution to reduce the lead time because it has a significant impact on picking productivity by reducing travel effort [43].

Sorting activity is important for lead time reduction because it enables faster order fulfillment [44] and to reduce the lead time of this activity is possible to introduce automated solutions where human putters are replaced by a sortation conveyor [45].
New technologies, such as autonomous sorting robots using artificial intelligence, are becoming increasingly popular for increasing the speed of execution of this activity [44]. Effective collaboration with suppliers also plays a role in sorting optimization. For instance, coordinating sorting activities with suppliers can allow for the preponing of sorting, where sorting is carried out by suppliers before goods arrive at the warehouse, with a reduction of the resources and time dedicated to inbound operations [44].

In the packaging area, the need for lead time reduction necessitates a faster packaging process [46] and, to facilitate employees in accurately selecting the appropriate package size for each order, a novel solution has emerged: a machine learning approach that uses historical data from past deliveries to predict suitable package sizes for new orders [46].
Another solution to increase the speed of the packaging phase is proposed by Case Studies 2,3 and 5, which propose the solution of the packaging on demand, a packaging concept that involves selecting the correct-sized carton by a machine based on the dimensions of the products, minimizing the handling of goods.

Different service levels for different channels

To ensure distinct service levels across various channels in the storage area, a commonly observed method in the literature and practical applications is the establishment of separate inventory for the different channels [47], enabling tailored strategies to fulfill the expectations of the different channels effectively.

Another approach to prioritize the online channel is implemented by Case 13.2, in which in the storage system, each product stored in the warehouse has at least one unit designated for the online channel, ensuring the avoidance of stockouts for online orders.

Differentiating the service level can also be achieved through actions in the picking activity. In particular, [48] proposes three methods for prioritizing different channels:

- Prioritize picking list: In the warehouse, orders are sequenced for picking. Thereby, items and thus orders can be reprioritized whenever a picker has completed his current job [48].
- Prioritize time slot: Omnichannel retailers can reserve time slots for certain orders just before the cut-off time for pickup of online orders at the warehouse. *Figure 5.2* represents the scheduling of picking with reserved time slot.

At (a), certain time slots during the day are always reserved for priority order picking. At (b), the time immediately before the cut-off for online orders is typically reserved for online order picking or prioritized online orders.
This enables prioritized orders to be handled in a reserved time slot for immediate shipping afterward and it guarantees that comparably late orders are shipped on the same day.

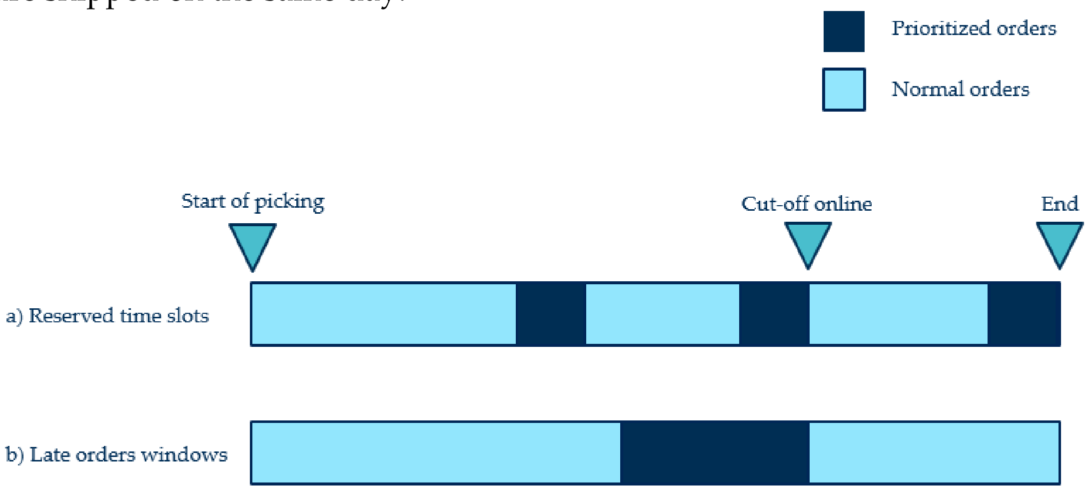

Figure 5.2: Picking with prioritized time slot (Source: [72])

- Creation of smaller batch size: Customer orders are grouped into batches to facilitate efficient processing of prioritized orders. Retailers can schedule smaller batches in short intervals instead of bigger batches in large intervals, increasing flexibility of the picking system and its ability to schedule a prioritized order before a regular order, even if the prioritized order is received after the regular order, right before the closure of the batch.

Another strategy for effectively managing varying service requirements in the picking activity is the implementation of dynamic order processing systems, which allow pick list updates even after the respective picking tour has started. Incoming urgent orders are instantaneously added to the current picker route and there is no need to waitlist them until the next wave is processed [45].

Flexible deliveries

The challenge associated with flexible deliveries impacts the sorting activity and effective countermeasures are required in this area. One potential solution is the implementation of flexible automated sorting systems, which enhance the similarity between different sorting activities, allowing to increase in logistics efficiency despite the complex and frequently changing sorting logic [44].

To address the challenge of flexible deliveries, Case study 1 employs an automated warehouse to synchronize the different flows originating from various delivery points, such as home delivery, click and collect, and express deliveries, that need a different consolidation based on the typology of delivery. The automated warehouse serves as an intermediary buffer and plays a fundamental role in coordinating daily appointments to ensure synchronization across different delivery options.

According to Case study 7, different transportation modes are characterized by different time slots in the warehouse, leading to increased complexity in outbound operations within the warehouse because they have to be managed separately.

Important to guarantee product availability

Guaranteeing product availability has an impact on the storage activity. In particular, to guarantee the availability of products across the different channels, the storage area needs systems able to support real-time synchronization of inventory stock levels [6]. An approach that is possible to implement in the storage area to ensure product availability is the utilization of sensors and scanners. For instance, an AI application for storing goods known as the automatization tridimensional storehouse (ATS) can be adopted, enabling real-time stock-in data of packed goods, synchronized with the Warehouse Management System [49].

Dimensional difference in the order profile

The dimensional difference in the order profile significantly impacts the sorting activity. This is particularly evident when retailers offer home delivery from the distribution centers, as the need for additional sorting arises since online customers often order multiple products. This extra sorting is crucial to ensure a unified delivery per customer [44].

The varying order sizes across channels influence the batch criteria in picking missions. In the omnichannel context, a combination of batch and picking criteria is often utilized to optimize efficiency in different order types. For instance, batch picking is applied for small online orders, whereas larger goods, such as those for store orders, result in fewer items being picked concurrently, leading to order picking [8].
Moreover, orders containing multiple distinct items, as seen in online orders, introduce increased complexity in the picking process [50] because, as underlined by Case study 3, in each picking mission, the picker has a limited number of locations to visit, resulting in a high level of non-productive walking.
Substantial differences in the order size among various channels also influence the decision of integrating picking across different channels, resulting in difficulties with the integration of the picking activity between the channels [3].

The difference in the order profile also has an impact on packaging; in particular, as online sales increase, packaging volumes increase due to the nature of small order sizes in B2C retail [51], with increasing workload in this area.

The dimensional differences also have implications for order consolidation. In Case study 3, variations in order dimensions between channels necessitate distinct consolidation methods. Larger orders (over 50 kg) undergo consolidation at the shipping bay, while smaller orders are consolidated by express couriers.
For the latter, to allow the express courier to perform the consolidation activity and deliver the orders on the specific day in the same truck, the goods must be delivered to the express courier within the same time horizon (day).

Different units of picking

Due to the different units of picking, Case study 9 proposes to adopt distinct picking systems based on the unit of picking.
Similarly, Case study 12 highlights the separation of picking activities between channels when there is a difference in the unit of picking. Due to this difference in terms of unit picked, it became difficult to manage the different channels in the same way.

Different packaging and units of delivery

The different packaging and units of delivery have implications for the receiving activity. Specifically, when handling online orders, an additional activity of unpacking becomes necessary. This process involves the removal of secondary packaging before customer orders are picked [50].

The increased variety of stock-keeping units adds complexity to inventory management, complicating integrated inventories and leading to increased logistics efforts [51].

The different unit of delivery significantly affect the packaging process, necessitating the implementation of new systems such as the utilization of flexible and adaptable shipping packaging. This type of packaging can be customized to accommodate varying shipment volumes, addressing the challenges posed by different packaging sizes [51].

Different order frequency

The different order frequency has an impact on the picking activity, as highlighted by Case study 13. In particular, the high order frequency typical of the online channel requires a correspondingly higher picking frequency, reaching up to three times per day. In contrast, the traditional channel, characterized by a lower order frequency, aligns with a reduced picking frequency, typically conducted just once daily.

Demand variability (often in a non-repetitive way)

The demand variability has an impact on the storage area because the day-to-day demand in the different channels faces frequent fluctuations, leading to difficulties in stock management. A possible countermeasure to cope with this challenge is the sharing inventory to absorb the demand shock in one channel using the other channel's inventory [34].

In addressing the challenge of demand variability, sorting activity can be enhanced through sorting postponement, which allows companies to cope with the complexity arising from demand uncertainties. There are three postponement types: time (delaying the forward movement of goods), place (storing goods at central locations), and form (delaying the final product customization). By strategically employing these types of postponement, companies can adapt to fluctuations in demand and enhance sorting efficiency [44].

High peaks in terms of entity, period, duration

To address the challenges posed by peaks in the omnichannel context, the literature presents various strategies for managing the picking activity, which is strongly impacted. One important approach involves adopting a traditional picker-to-parts system and enhancing its scalability during workload peaks by incorporating additional picker-cart tandems, reaching the goal of efficiently handling increased demand during peak periods [52].
In Case study 11, peak management in the omnichannel environment is tackled through careful dimensioning of the picking system and during these peak periods, more picking actions are performed.

Relevance of the return flow

In the omnichannel context, returns trigger increased activities in the receiving area. In particular, the need to assess the quality of returned products, determining whether they are saleable or require repairs, leads to additional tasks in the receiving process [37].

The return flow also has an impact on the storage area because it creates the need for inventory rebalancing.

When product returns through stores lead to inventory being in the wrong place, retailers must address this issue by rebalancing their inventory to ensure optimal availability and fulfillment [53].

Return flows also contribute to heightened demand for sorting activities due to the complexity introduced by returns, requiring effective sorting mechanisms to categorize and manage returned items efficiently [54]. Case study 12 highlights an effective approach for the return management by performing the sorting activity upon the arrival of returned items at the warehouse, followed by a reconditioning phase. This strategic approach ensures the separation of activities based on their efficiency levels, allowing for optimal handling of returns.

The return flow significantly affects the packaging aspect as well. Traditionally, customers demand packaging that is easy to open [51], but with the return flow, the shipping packaging is frequently used as return packaging. In this context, a new solution is the adaptable folding boxes, that can be manually reduced in volume by the customer [51]. This functionality proves beneficial when customers order multiple products but choose to keep only a part, thereby returning the remaining items, and this approach aids in reducing the volume transported within the return flow. An example of the application of this concept is observed in the fashion industry, where customers might order various sizes with the intent of keeping only a subset of them.

High growth rate of the online channel

The high growth rate has an impact on the final two warehouse areas: Picking, sorting and Packing, shipping. These warehouse areas appear to be the first to experience capacity shortages with growing volumes due to the online channel's rapid expansion [23]. Therefore, special attention is required to prevent bottlenecks resulting from the growth of the online channel.

Fragmented demand base

The fragmented demand base leads to an increase in the complexity of sorting activities due to the variety of final destinations and shipping times, given the range of ultimate destinations and delivery timelines [3].

Moreover, due to the increased variation in destinations, the distributed demand base, creates complexities in the consolidation activity because the higher the number of destinations, the higher the effort needed in the consolidation phase [8].

Wide product assortment requested

The wide product assortment has an impact on storage, leading to space problems. In the omnichannel context, one potential solution to address this problem is to manage inventory jointly across channels, enabling flexible and demand-driven inventory allocation, making it possible to keep less inventory overall [30].

The availability of a wider range of products on e-commerce results in increased picking complexity, leading to a higher number and variety of storage locations visited during order picking [3].
Due to the increased number of SKUs managed in the omnichannel warehouse, the adoption of zone picking as picking method can help to overcome this problem [8] because it allows for a reduction in the size of the picking area in which the operators have to walk, with a consequent reduction of the unproductive walk.

Existing building

Constraints related to existing buildings impact the storage area. In Case study 1, an automated Micro Fulfillment Center was implemented in an already existing warehouse that was operational for the traditional channel. The addition of the MFC for the management of online orders in the remaining space significantly affected the storage capabilities of the online channel.

In *Table B.3* the detail related to the number of papers and case studies that mentioned each impact on the areas is defined.

The detail with the complete list of papers and case studies for each impact of the different challenges on the different warehouses areas is presented in *Table B.4*.

5.3.2. Management variables

Lead time reduction

In the context of lead time reduction, the IT variable plays a crucial role. Shorter lead times necessitate reduced handling times in warehouse operations, which can be facilitated by the implementation of new IT functionalities, such as advanced systems for pre-notice of arriving goods and expedite receiving and put-away processes [54].

To address the challenges associated with lead time reduction in warehousing, automation emerges as a central strategy. In particular, an increased level of automation of various operations is adopted to improve the speed of material handling [3]. Case studies 1 and 2 specifically adopted automation solutions to reduce the lead time in warehouse operations.

The reduction of lead time has a substantial impact and complexities on the planning variable because the evolving demand from customers seeking rapid product orders and deliveries has resulted in increased planning uncertainties [55].
The expectation of shorter lead times applies pressure to reduce throughput times in omnichannel warehouses, leading to the emergence of new warehouse flows. For example, the warehouse may experience an increase in cross-dock flows where the put-away, storage and picking operations are cut out and goods instead move directly from receiving to packing and shipping [3].
Case study 3 highlights that the reduction of lead time reduces planning visibility, and, for instance, knowledge of orders scheduled for delivery on a specific day may only become available on that specific day. This dynamic gives rise to complexities in resource allocation and scheduling.

Different service levels for different channels

The requirement for different service levels among various channels underscores the need for prioritizing orders, which impacts information systems. Integrated information systems must support inventory reservation for different channels, and sophisticated systems are necessary to facilitate order prioritization [54]. It's essential to note that the prioritization of orders is feasible only if IT requirements are met [48].

Regarding the impact on automation, as highlighted in Case study 10, the difference in service levels among various channels leads to an increase in the number of flows within a warehouse. Each channel with distinct requirements and expectations necessitates separate handling and processing, resulting in diverse and heterogeneous flows within the warehouse. This situation increases the complexity of managing the warehouse automation because the automation systems require uniform flows that maintain a consistent volume throughout the year to function effectively and the presence of heterogeneous flows due to differing channel requirements disrupts this ideal operational balance.

Postponement of the cut-off/continuous receivement of orders

The postponement of the cut-off of the orders directly impacts the planning complexity. In particular, due to the postponement of the cut-off time, the picking orders are generated overnight, making it difficult to plan next-day operations because the period dedicated to the planning of the activity is reduced [6].

Important to guarantee product availability

Ensuring product availability across all channels in an omnichannel context is a significant challenge for IT systems. Meeting the increasing expectations for up-to-date inventory information across different nodes underscores the importance of implementing and integrating advanced information systems throughout the network [6]. These systems enhance the visibility of available inventory across various nodes, improving the customer experience and operational efficiency [54], allowing a cross-channel overview of stocks and customer buying behavior, addressing issues related to the lack of inventory transparency and complicate inventory allocation [48].
Case study 1 underscores the significance of synchronizing information systems between the Micro Fulfillment Center (MFC) managing online orders and the warehouse handling traditional orders to ensure alignment and product availability.
Case Studies 4 and 5 also highlight the need for integrated and synchronized information systems across different channels to guarantee product availability.

In particular, the retail stores' inventory information must be integrated and synchronized with the central warehouse (WMS) so that a customer can better understand how many and in which node of the network an article is stored and available for sale. Further, the systems must support real-time synchronization [6].
Implementing advanced inventory management systems can enhance the visibility and accuracy of customer orders and inventory, ultimately supporting the company's ability to guarantee product availability [54].

Dimensional difference in the order profile

Due to the dimensional difference of the orders handled in the warehouse, it's difficult to adopt automated solutions [6] because the deployment of automation encounters difficulties in effectively handling products with significant size differences. High variation in goods size, with both small, medium-sized and big bulky packages, increases the complexity and need for advanced and flexible automation solutions [8].
To address this obstacle, a viable strategy is to implement automation exclusively for small and standardized products. In particular, retailers faced with a broad spectrum of product sizes often opt for distinct zones equipped with varying levels of automation, allowing to accommodate the diverse size range while optimizing automation benefits [6].

Different packaging and units of delivery

The different types of packaging characteristics of the omnichannel environment impact warehouse automation. To efficiently manage warehouse operations through automation, it becomes important that packages fit the storage system [6].

In the omnichannel context, this issue holds significance because the different packaging typical of this environment could create problem in the compatibility with the automation system, which needs to be flexible to manage the different packaging.

Demand variability (often in a non-repetitive way)

In the landscape of omnichannel retail, IT systems, such as advanced store replenishment and forecasting systems, are highly important to allow companies to perform accurate forecasting in this complex environment [54]. To enhance demand forecasting accuracy to cope with demand variability, leveraging big data on historical sales and machine learning to develop and continually optimize sales forecasting algorithms is an effective strategy. By connecting the Warehouse Management System (WMS) with the real-time order database, it becomes easier to identify products with strong sales trends and frequent replenishment needs, enabling better management and timely replenishment of products [49].

Due to the significant demand variability, warehouses must contend with yearly, weekly, and daily demand fluctuations, particularly in the online channel. This reality significantly influences the planning of warehouse activities and while retailers may operate with fixed delivery patterns for stores, the online order volumes are often harder to forecast [3]. As a result, demand forecasting and determining staffing requirements become areas of paramount importance [56].
Due to variability in the demand and the difficulty in forecasting, flexibility in terms of capacity, which is typically difficult to achieve in streamlined warehouse operations, has thus become significantly more important for the success of omni-channels [3]. High uncertainty in both long and short-term demand makes capacity planning and allocation complex [3].

The fluctuating demand also has a notable effect on the management of human resources. In particular, demand fluctuations and uncertainty put pressure on warehouses to be able to quickly increase or decrease capacity, for example, by distributing or shifting labor resources over the week and across operations [3]. Additionally, the integration of temporary staff alongside permanent employees becomes a strategy to enhance flexibility [8], as performed by Case study 15, which utilizes human resources to gain flexibility to cope with the demand variability. They accomplish this by partnering with cooperatives, enabling the hiring of additional personnel during periods of high volume.
As highlighted in Case study 5, due to the difficulties in predicting the incoming order volume, accurately estimating the required workforce across different warehouse areas becomes challenging. To overcome this complexity, flexible warehousing arrangements that allow operators to shift to different work areas based on the workload are essential.

Case study 11 provides insights into how human resources can be used to cope with the demand variability, suggesting that human resources' flexibility can be exploited through the possibility of working on Saturdays and having flexibility in the work time with the use of overtime.

High peaks in terms of entity, period, duration

The high peaks of demand in the omnichannel have an impact on the choice of automation because this challenge requires the implementation of automation solutions capable of achieving scalability. In fact, for extreme demand peaks in various seasons (e.g. Black Friday) and for handling various customer requirements and flows, such as express orders, automation could become a constraint when facing such high peaks [6].

Case study 13.2 employs a distinctive approach to manage the peaks in omnichannel operations: oversizing the automation system. This approach involves designing the automation system with additional capacity to handle unexpected peaks in demand. Indeed, the oversizing approach is not an optimal strategy because this excess capacity remains unused, resulting in unnecessary costs and underutilization of valuable resources.

The high peaks of the omnichannel context also impact the management of human resources, which becomes a key variable for addressing this challenge. The manual work allows higher flexibility and scalability compared to most automation solutions and to handle demand peaks, temporary workers are used [23]. With the implementation of manual work in the picking system through the picker-to-parts warehouse, it’s possible to hire additional temporary staff to reach flexibility in peak times [57]. A possible approach in an omnichannel warehouse is to coexist picker-to-parts systems with robotized warehouses, providing a balance between manual labor's flexibility and adaptability and the efficiency of automation [57].

Growth rate difficult to predict (unpredictability of the environment)

The unpredictable environment of the omnichannel poses important challenges in IT, primarily due to the complexities involved in forecasting the future evolution of the environment and determining the required scale of the Information System. To address this need for adaptability, there is a growing interest in using IS provided by logistics service providers (LSP) [54], in which the retailers can easily modify and adjust the dimension of the Information System based on the changes in the environment.

Another solution for dealing with the unpredictability of the omnichannel environment is the adoption of cloud-based solutions for information systems because, thanks to the possibility to easily add or remove parts of the Information Systems, they offer the flexibility needed to cope with the continuously shifting landscape [54].

As underlined by Case 2, managers are hesitant to invest in automation solutions that lack flexibility and the ability to adapt to this ever-changing environment because the current situation will change in the future and the automation will probably not be suitable for the future.

Case study 5 underscores the profound unpredictability of the omnichannel environment, leading to constant changes in solutions and an increase in planning complexity. To address this challenge, one proposed solution is the adoption of a short-term planning approach, which reduces the planning period, thereby decreasing uncertainty.

The unpredictable growth rate also affects the management of human resources, potentially resulting in short-notice labor shortages. To address this issue, remedies such as implementing overtime and hiring external labor can be employed to manage and recover from these situations effectively [55]. Case study 5 suggests the strategy of overstaffing as a solution to address the complexity of the omnichannel project, allowing for a more adaptive response to the evolving demands of the environment.

Incidence of the different channels that change in time

The changing dynamics of different channels over time significantly impact human resources management. Specifically, in Case study 1, a Micro Fulfillment Center (MFC) is located in the same building as the traditional warehouse and a strategic approach is adopted to address the dynamics posed by changing channels over time. This strategy involves the ability to shift the resources from one channel to another, gaining flexibility. In this case study, there is a specialized team for e-commerce and while maintaining this specialized team, resources can be redirected to support the traditional channel during peak periods and vice versa.

Relevance of the return flow

The return flow significantly influences the Information system, primarily because if a product is returned, managers need information systems to know whether it will be returned in store, warehouse or by e-commerce [37]. In reverse logistics operations, the support of IT is needed to ensure positive economic and service quality [53], as the effective functioning of the return process relies heavily on the integration and optimization of Information Systems to manage these intricate operations.

The return flow introduces a heightened level of uncertainty, with significant implications in the planning process. This uncertainty manifests in several aspects [37]: firstly, the uncertainty regarding the quantity of items being returned, makes it unclear how many pieces of a product will ultimately be returned. Secondly, uncertainty surrounds the timing of these returns, as it's challenging to predict precisely when the returns will occur. Lastly, there's the uncertainty related to the mix of products being returned, which refers to the varied assortment of different products that will be returned. Due to this uncertainty in the volumes returned, it became difficult to plan the resources in the omnichannel warehouse operations accurately.

The process of handling product returns influences the management of human resources because it generates labor-intensive tasks, leading to an additional uncertainty in the labor demand [55].

Increase of the phase-in/phase-out frequency

The continuous changes in product assortments pose challenges for automation. Specifically, automation systems can be sensitive to shifts in product characteristics and variations in size and adapting automated solutions for companies that frequently introduce new products with diverse sizes and distinct handling requirements can be difficult [6]. Hence, flexibility in the automation system is needed to accommodate these product changes effectively.

High growth rate of the online channel

According to the case studies, the high growth rate of the online channel impacts the automation strategies. In Case study 1, the implementation of a Micro Fulfillment Center (MFC) was adopted to handle online orders and to address the challenge posed by the substantial growth in product volumes managed by the automation system, a strategy of oversizing was employed.

The high growth rate of the online channel has an impact on the planning variable because due to the requirement of the online channel for order delivery to customers within the next day or even the same day, their warehousing operations require rigorous planning for an efficient order fulfillment system [39].
Due to the high growth rate of the online channel, Case study 8 decided to open a new online channel starting from the facility where it is possible to have the highest flexibility. This decision can have an impact on the future because if the online channel continues to increase, there will be a possibility to support this growth.

Fragmented demand base

The fragmented demand base has a consequence on the planning and execution of activities within the warehouse. As underscored in Case study 3, the increase of the touchpoints with the customer results in a segmentation of warehouse flows into smaller ones, loosing of economies of scale and increasing the variability of each flow. This creates difficulties in the planning of the activities in the warehouse because there is the creation of distinct flows, each with different specificities, making it necessary to manage these smaller, separate flows, each with its characteristics.
Moreover, this fragmentation in the demand leads to fluctuant volumes [32], which can be challenging to predict and plan for effectively.

Wide product assortment requested

The extensive product assortment within the omnichannel context has a significant impact on the planning variable. Strategies are employed to decrease the volume of products handled within warehouses, as highlighted in Case Studies 4 and 11.
These strategies may involve increased utilization of drop-shipment, transshipped goods, and cross-docking to offer a broader assortment without the need for a substantial expansion of storage capacity in the warehouse [6]. With this solution, a broad assortment can be offered, distributed directly from the supplier, with limited inventory investment [8].

Existing building

The constraint related to existing buildings can pose challenges for warehouse automation, particularly concerning the height limitations of the available space. As proposed in Case study 12, an automation solution (AMR) capable of overcoming these constraints can be adopted. This solution requires a height of just 7 meters, making it a practical choice for existing facilities with limited vertical space.

Software not designed for omnichannel

The constraint associated with software not designed for omnichannel operations significantly affects IT. As highlighted in Case study 5, when the existing software is not tailored for omnichannel requirements, it is necessary to move to new information technology systems. These new systems must be synchronized and integrated seamlessly across the various channels to effectively address the challenges of omnichannel operations.

Solution development/implementation time

In omnichannel projects, the implementation time of the solution is a critical factor; therefore, the choice of an automation solution becomes crucial. In particular, Case study 13.2 adopted an automation solution necessitating just a 2-week interval for integration within the warehouse operations. This choice of automation solution effectively minimizes the implementation duration required for configuring the warehouse, subsequently reducing the period during which the warehouse's operational capabilities are suspended.

In *Table B.5*, the detail related to the number of papers and case studies that mentioned each impact on the management variables is defined.

The details with the complete list of papers and case studies for each impact of the different challenges on the different management variables is presented in *Table B.6*.

5.4. Conclusions and analysis of the results

The analysis of the literature underlines the lack of a structured analysis regarding the implications of omnichannel challenges on warehouse configuration. In particular, an important gap in the existing literature is the absence of a structured framework that defines the relationship between omnichannel warehouse challenges and their impacts on warehouse configuration and the corresponding countermeasures that can be employed to effectively address these challenges. This Thesis addresses this critical gap by structuring the chapter to provide an individual analysis of the consequences of these challenges. This approach offers a systematic and comprehensive understanding of how each challenge influences warehouse configuration and, consequently, the strategies that can be implemented to mitigate their effects.

Furthermore, this Thesis introduces a quantitative dimension to the impact assessment of omnichannel challenges on different warehouse areas and variables. This quantification is based on the frequency with which papers and case studies mention the impact on specific areas or variables. In particular, it can help to have a vision of the major impact and the focus on which it’s necessary to pay attention in an omnichannel environment.

5.4.1. Analysis of the impact of the challenges on the warehouse areas

After defining and elucidating the impacts of the challenges on various warehouse areas, it's possible to draw conclusions for this chapter.

A comprehensive analysis of the results presented in *Table B.3*, which detail the impact of omnichannel challenges on warehouse areas, reveals the following number of mentions for each area in papers and case studies:

- *Receiving*: 3
- *Put away, storage*: 12
- *Picking, sorting*: 27
- *Packing, shipping*: 12

Upon examination, it becomes apparent that the most substantial impact of omnichannel challenges is on the picking and sorting area. This area is mentioned a total of 27 times by the papers and case studies, underscoring their remarkable significance and management implications in the omnichannel context.

Additionally, the analysis underscores the notable importance of the packing and shipping, as well as put away and storage areas, each with 12 citations.
As expected, the impact on the receiving activity is relatively low, with only 3 citations, reflecting the comparatively lower operational complexity associated with the receiving process in the omnichannel warehouse.

By examining the breakdown of citations between the two sources, namely the literature review and the case studies, it is possible to obtain *Table 5.3*, which summarizes the distribution.

Warehouse areas	Literature review	Case studies	Total
Receiving	3	/	3
Put away, storage	10	2	12
Picking, sorting	20	7	27
Packing, shipping	6	6	12

Table 5.3: Number of papers and case studies on the warehouse areas

As expected, the number of citations from the papers is higher compared to the number of citations from the case studies because of the difference in terms of number of sources.

However, an important insight emerges in the context of the packing, shipping area, where case studies play a substantial role, contributing to half of the total citations in this category, highlighting the unique ability of case studies to uncover new trends and practices not extensively covered in existing literature. In this instance, the case studies shed light on emerging practices, such as "packaging on demand", which had not received significant attention in prior research.

The last analysis on the warehouse areas that is possible to perform it's related to the impact of the different challenge categories on the warehouse areas, illustrated in *Table 5.4*.

Category	Receiving	Put away, storage	Picking, sorting	Packing, shipping	Total
Increase of the expectations regarding the service level	1	7	10	5	23
Changes in the order profiles	1	1	8	4	14
Changes in the demand profile	1	3	9	3	16
Constraints	/	1	/	/	1

Table 5.4: Impact of the challenges categories on the warehouse areas

From this table, it's evident that the category with the most substantial impact on warehouse areas is the " *Increase of the expectations regarding the service level*" accounting for a total of 23 mentions across all areas, underscoring the significant challenges presented by rising service level expectations within the context of warehousing.

Moreover, despite the importance attributed to the challenges categorized as "*Constraints*" by the case studies and the experts' group, the impact of this category on warehouse areas is notably limited, with only one mention.

Additionally, no evident correlation pattern emerges between challenge categories and specific warehouse areas, suggesting that challenges within each category can affect various aspects of warehouse operations without exhibiting a consistent pattern based on category alone.

5.4.2. Analysis of the impact of the challenges on the management variables

Building on the previous analysis performed for warehouse areas, a similar examination can be conducted for the impact of omnichannel challenges on management variables.

From *Table B.5*, related to the impact of the omnichannel challenges on the management variables, the frequency with which each variable is mentioned in the literature and case studies is as follows:

- *IT*: 16
- *Automation*: 14
- *Planning*: 16
- *Human resources*: 11

Upon analysis, it becomes evident that there is no management variable that stands out as extensively studied or neglected, as was observed in the case of warehouse areas. Instead, a balanced distribution of citations is observed among the different management variables, with the only slight deviation in the case of human resources management, with a total of 11 citations, a lower value compared to the other variables. This suggests that both researchers and practitioners have maintained a relatively consistent focus on these management variables when addressing omnichannel challenges without a significant disparity in attention or emphasis.

Analyzing in more detail these number and dividing the two sources used for counting the number of citations, it's possible to obtain *Table 5.5*.

Management variables	Literature review	Case studies	Total
IT	12	4	16
Automation	6	8	14
Planning	10	6	16
Human Resources	6	5	11

Table 5.5: Number of papers and case studies on the management variables

This table allows for a deeper analysis of the distribution of citations between the literature review and case studies and a notable conclusion drawn from this breakdown is the relevance of case studies in assessing the impact of omnichannel challenges on management variables.

Specifically, case studies play a particular role in the analysis of automation, with more than half of the citations for these variables originating from case studies, highlighting the importance of real-world practical applications and insights provided by case studies in understanding the implications of omnichannel challenges on management variables. This relevance of case studies is particularly observed in the context of automation, planning and human resources.

The last analysis is on the impact of the omnichannel challenge category on the different management variables and *Table 5.6* summarizes the results.

Category	IT	Automation	Planning	Human Resources	Total
Increase of the expectations regarding the service level	10	4	4	/	18
Changes in the order profiles	/	3	/	/	3
Changes in the demand profile	5	5	12	11	33
Constraints	1	2	/	/	3

Table 5.6: Impact of the challenges categories on the management variables

Unlike the analysis conducted on warehouse areas, the examination of management variables reveals greater heterogeneity and notable correlation trends between omnichannel challenge categories and these variables.

There are significant differences in the number of impacts across challenge categories. The "*Constraints*" category remains relatively undercited, as the "*Changes in Order Profiles*" category, with 3 citations for each category. In contrast, the categories related to the " *Increase of the expectations regarding the service level*" and "*Changes in the Demand Profile*" received a substantial number of citations, totaling 18 and 33 citations, respectively.

The "*Changes in Demand Profile*" category is particularly noteworthy for the planning variable because the uncertainties in demand profiles contribute to increased complexity in planning warehouse operations. It has a strong impact also on human resource management, as the variability in demand can be addressed by leveraging the flexibility of human operators.

Notably, the "*Changes in Demand Profile*" category is the only one that impacts the human resources variable, highlighting its significance in managing workforce flexibility in response to demand fluctuations.

6 Integration or specialization of areas in the omnichannel warehouse

6.1. Introduction

The impact of the challenges posed by the omnichannel environment on the warehouse configuration highlights the importance of conducting an in-depth analysis of the decisions related to the integration or specialization within various functional areas of an omnichannel warehouse. In light of this, a new research question has emerged: "*What is the level of integration and specialization of functional areas in the omnichannel warehouse?*".

The motivation for this specific study is derived from the examination of the results of RQ2, with a total of 5 papers and 2 case studies (detail in *Table B.7*) which mention the integration or specialization of warehouse areas as a consequence of the omnichannel challenges. These findings indicate a compelling need for a dedicated investigation into the decision-making processes related to integration and specialization within omnichannel warehouse functional areas.

This research question aims to investigate the decision-making processes undertaken by companies regarding the integration or separation of different channels within the warehouse area. For each functional area, the decision lies between adopting a uniform approach to manage diverse channels without differentiation or opting to manage each channel as a distinct entity. The structure of this research question is illustrated in *Figure 6.1*.

To address this research question, an analysis of the literature review is conducted, and the findings are integrated with insights from the case studies and the experts' group.

The chapter is structured as follows: it begins with an analysis of the decision of integration and specialization of the storage and picking areas, building upon insights from the literature. It's worth highlighting that although this chapter is primarily associated with the literature review, the contribution of the case studies is integrated into this first analysis to offer practical illustrations that align with the insights derived from the literature findings.

Next, the chapter delves into the decision related to the integration and specialization of all warehouse areas, starting from the results of the case studies, offering real-world examples of how companies configure their omnichannel warehouses.
This chapter also deals with the decisional criteria that influence the choice between the different configurations. The final chapter is dedicated to the conclusions and the analysis of the results.

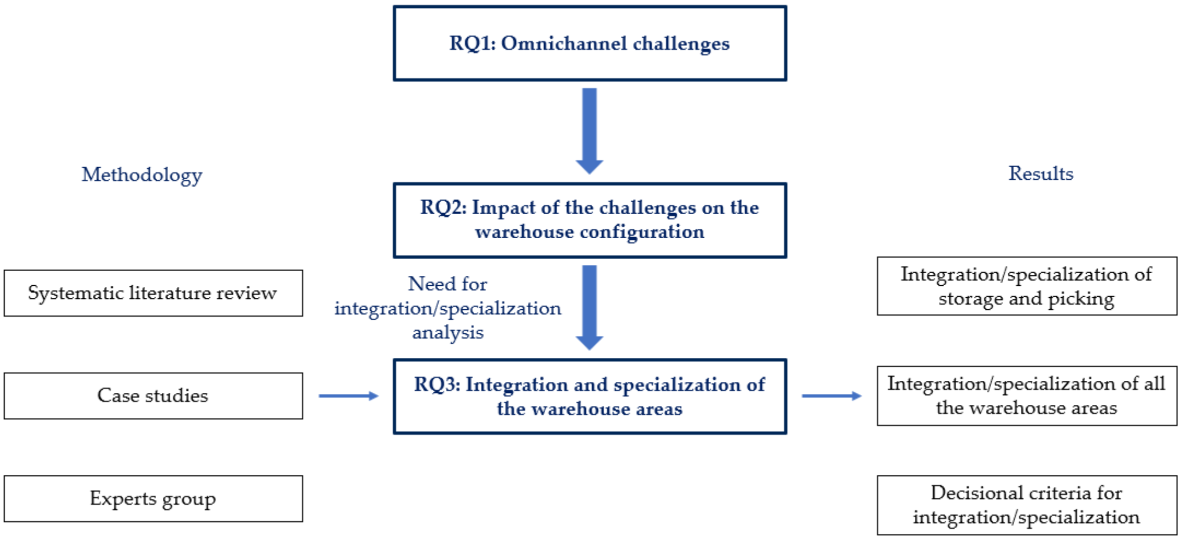

Figure 6.1: Structure of the RQ3

6.2. Integration or specialization of storage and picking

The analysis of the literature underscores the central focus on the integration or separation of the picking and storage activities within the omnichannel warehouse. These two areas are recognized as pivotal components of efficient warehouse operations, and companies face a strategic decision in determining the most effective approach to manage their resources.

In the omnichannel warehouse, companies are faced with the strategic decision of how to manage the resources in their warehouse, with the possibility of adopting two distinct approaches to respond to this challenge: the integration or the specialization of the channels. In case of integration of channels, existing resources are shared to manage the different channels, leading to economies of scale and streamlined operations [2], while the decision to manage channels separately entails dedicated management for each channel within the warehouse, allowing for tailored processes but increasing the effort and the utilization of resources.

6.2.1. Framework for the integration or separation of storage and picking

To establish a comprehensive framework outlining the decision-making process for omnichannel companies, a starting point can be derived from the schematic diagram presented in the study [30], illustrated in *Figure 6.2*.

This paper proposes a classification that distinguishes between three distinct warehouse types, categorized by the level of integration in their inventory and picking process:

- Type SI-SP involves separated inventories (SI) with separated picking (SP) for direct-to-customer and store orders.
- Type II-SP has cross-channel-integrated inventories (II) but separate picking zones.
- Type II-IP also has integrated picking (IP) zones for the different channels.

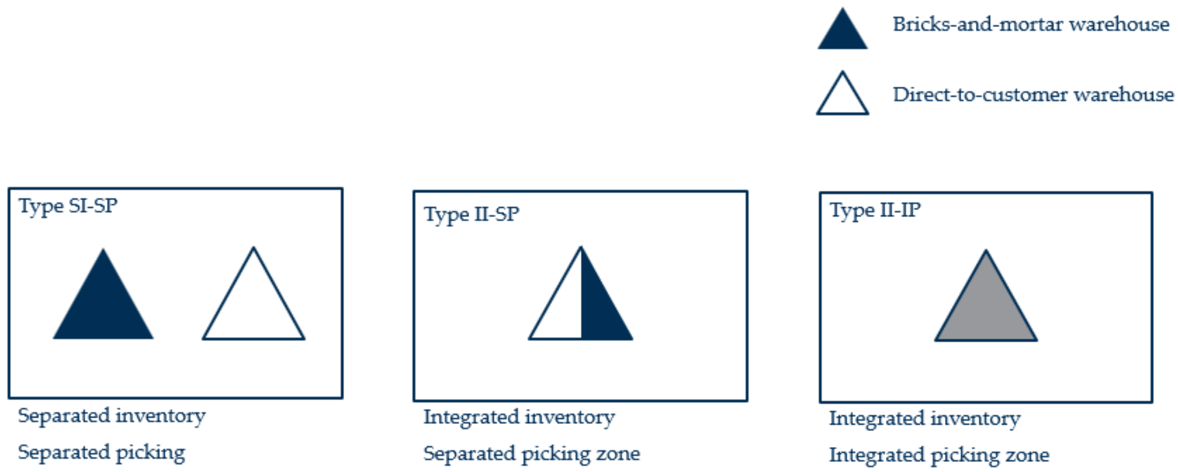

Figure 6.2: Warehouse configurations (Source: [30])

Based on the scheme illustrated in [30], a matrix (*Table 6.1*) can be developed to delineate potential warehouse configurations within the context of omnichannel operations in a shared warehouse. This matrix is specifically designed to address the integration and separation of picking and storage activities.

	Integrated picking	Separated picking
Integrated storage	Full integration	▪ Different picking methods ▪ Different staff ▪ Different time windows ▪ Different parts of the warehouse
Separated storage	/	▪ Separate part of the WH ▪ OFC/MFC for online

Table 6.1: Framework for the integration or specialization of storage and picking

The matrix functions as a well-structured framework for comprehending the various combinations of integrated and separated storage and picking activities in the context of omnichannel warehousing, providing a clear and specific framework related to the choices analyzed in the literature concerning the separation of storage and picking operations.

The two axes of the matrix represent the two key decisions:

- **Integrated or separated storage**
  This decision pertains to the integration of inventory between different channels. When choosing integration, the warehouse shares inventory without distinguishing among channels, while when opting for separation, each channel has a distinct inventory.
  Integrated storage for both store replenishment and online orders offers a solution to the problem related to the lack of space, also thanks to the possibility of having a single picking location for each handled item [6].
  Storage integration makes it possible to pool demand, allowing to absorb the demand shock in one channel using the other channel's inventory, facing the frequent fluctuations of the day-to-day demand in its different channels [34].
  The demand pooling requires fewer products to be stored, reducing capital tied up as inventory, contributing to more efficient space use [8] and creating the possibility of achieving a higher overall service level [3]. The possibility of pooling the demand pushes Case study 7 to maintain integrated storage across different channels to accommodate demand fluctuations and minimize the likelihood of product expiration. Furthermore, this decision was influenced by the fact that within this company, the e-commerce segment represents a mere 1-2% of the total volumes and due to the relatively small scale of the e-commerce operations, allocating dedicated space specifically for this low-volume channel was considered not cost-effective.

Shared inventory across channels also reduces shortage and disposal costs, along with overall inventory levels, thanks to the possibility of sharing safety stock [3]. This is the main factor that pushes Case study 8 to integrate storage between channels and the main explanation for which more than half of the retailers surveyed by [30] operate or plan to operate with integrated inventory across different channels.
Additionally, integrated storage allows for shared personnel handling store replenishment and e-commerce [3], reducing the need for resources, as operators can be allocated based on demand without being confined to specific channels.
In the grocery industry, the integration of stock also allows to compensate for the perishability of goods [34] because the stocks serve different channels with a reduction of the average time in the warehouse.

On the other hand, integrated stock positions for store replenishment and online orders require more advanced inventory management, with the increasing complexity of systems like ERP and WMS [6], as well as dedicated staff with new skills and competencies [8]. The integration of channels results in stocks fulfilling different, unconnected channels, adding complexity to inventory management [3].
Moreover, integrated storage carries the risk of inventory cannibalization from the online channel, which prompted Case study 4 and Case study 13.1 to opt for separate inventory.

- **Integrated or separate picking**
  This decision is related to the integration or not of the picking process between the different channels. When choosing integration, the same picking process, resources, and time slot are used for all channels, while separation involves differentiation between channels in the picking process.

  The integration of picking appears to have correlation with order fulfillment times, particularly in cases where retailers aim for very short fulfillment times for online customers. In such instances, a preference for integrated picking arises, as it can reduce the time required for picking [8]. A further positive factor for integration is leveraging picking zones by rotation speed. This shortens the picking for both channels because fast-movers are grouped within one area and the grouping is typically independent of the channel, while slow-movers can be picked separately, saving picking distances [33].
  Retailers that manage the picking activity in the same way for different channels can use the same picking personnel for all channels [30], exploiting synergies among different channels.

However, despite the mentioned advantages, this approach implies a more complex picking system, which requires assimilated infrastructures, resources and know-how for picking orders from both channels [48]. The differences between channels can make it challenging to achieve cost-efficiency in integrated picking operations [3].

Another challenge associated with the integration of channel picking is the necessity to handle the prioritization of different orders [6]. This prioritization is essential because multiple channels may have varying service level requirements that must be aggregated into an overall inventory policy [3]. In particular, companies often prioritize web orders that directly contribute to cash payment [6] since products ordered online are already sold to the customer, whereas store orders are primarily for replenishment [48].
The prioritization is not only necessary to distinguish online and store orders, but further prioritizations are made by customer type (e.g., loyalty card owners before others) or by delivery mode (e.g., express before standard delivery) [48].

6.2.2. Analysis of the alternatives of the framework

Crossing the two axes, four potential alternatives emerge:

- **Integrated storage – Integrated picking**
  This option involves maintaining a shared inventory and utilizing the same picking process for all channels, representing the highest level of integration.
  According to the survey conducted in [30], six out of ten retailers with integrated inventories pick across channels in a common zone, meaning that the picking zone is not separated by channels and this leads to higher overall warehouse efficiency [30]. In the case studies analysis performed by [8], two cases out of six featured fully integrated storage zones and picking processes for store replenishment and online orders.
  An example from the case studies analysis of this approach is in Case study 2, where a warehouse implements a solution featuring shared inventory for online and store orders.
  However, as highlighted by [8], this solution is not implemented in many cases, with companies benefiting from separation rather than integration because integrated storage and picking allow to exploit synergies, but also bring other issues due to the differences between the channels [6].

- **Integrated storage – Separated picking**
  In this case, the stocks are common for the channels, but the picking activity is differentiated.
  According to [33], nearly half of the companies interviewed separate the picking for each channel, even though products are stored together.

As indicated by Case study 12, this approach is frequently adopted due to its benefits: shared stock ensures synergies in product availability, while picking separation enhances efficiency by addressing the diverse order patterns between channels.

While integrating storage areas for replenishment and online orders, the actual process for store picking could be separated in different ways [8]:

- *Different picking process*
  Each channel employs a specific picking approach tailored to its unique requirements.
  In the context of Case study 5, a warehouse adopted an approach that combines integrated storage with separated picking activities. Specifically, the warehouse features alternating corridors where two distinct picking methods are employed, creating a dynamic equilibrium between the "man-to-goods" and "goods-to-man" paradigms: for orders dedicated to distributors, operators utilize a picker-to-parts system for picking items, while for e-commerce orders, a miniload system is adopted.
  Also Case study 12 implements a warehouse characterized by the integration of the storage activity and the separation of the picking activity between the different channels due to the difference in the number of order lines. In the illustrated case, pallets are handled for the retail channel, whereas for e-commerce, goods are brought to picking stations in which the operators pick a single piece.

- *Different staff*
  The picking activity is performed with the same method, but separate personnel are assigned to perform picking activities for each channel.
  In Case study 8, an omnichannel solution is implemented where the inventory is shared between the B2B and B2C markets, ensuring maximum coverage and availability of stock. Although the inventory remains shared across both channels, separation is maintained in the picking process, with distinct staff and dedicated areas for executing the picking activity.

- *Different time windows*
  In this option, the same picking methods and the same staff are used, but separate time slots are allocated for each channel. In a case underlined by [8], adopting this solution allows the replenish of large retail stores first during the day (because the demand is known), delaying the cut-off time for online orders and picking them later in the day.

Some retailers from the case studies analysis performed by [30], apply dedicated picking time slots for each channel, with no simultaneous picking of customer and store orders.
With this approach, store picking serves as a buffer because online orders have higher priority for achieving shorter lead times [33].
An example of sequence patterns for the time slots per day is explained in [33] and illustrated in *Figure 6.3*.

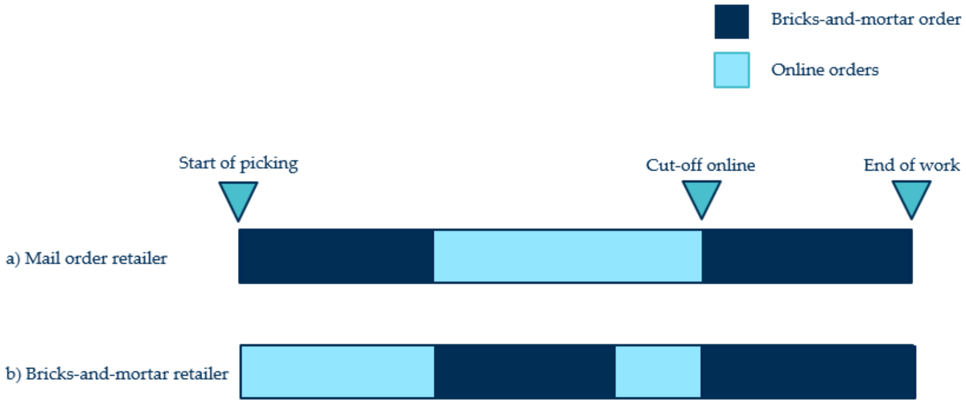

Figure 6.3: Examples of picking sequences (Source: [33]*)*

In both models, store picking serves as a buffer because online orders have higher priority for achieving shorter lead times, with a typical delivery time of 24 to 36 hours for store orders [33].

- **Separated storage – Integrated picking**
  When the storage is separated, the decision about the picking process is negligible from a cross-channel perspective since they can only be separated [30].
- **Separated storage – Separated picking**
  This approach involves the complete separation of both stock and picking activities between channels. This solution exhibits the highest level of separation between channels, and it can be implemented in two ways:
  - *Stock in the different parts of the warehouse*
    In this case, stocks are allocated to distinct sections within the warehouse and the entire warehouse is divided into separate areas, each holding dedicated stock for a specific channel.
    In the case studies analysis performed by [8], three cases out of six adopt the separation between the channels of both storage and picking and all three cases use a separate part of the warehouse for handling online orders.

In Case study 3, a warehouse is implemented where distinct sections are dedicated to B2C (online orders, in-shop orders, and home delivery) and B2B (shop replenishment) operations. The decision to separate the inventory arises from the differing ownership of goods in these two channels, which constrains the integration of inventory and prevents the exploitation of potential synergies.

- *Online Fulfillment Center (OFC) or Micro Fulfillment Center (MFC) for the online channel*
  In this solution, when one of the channels is online, the management of this channel is managed separately from the other stocks with an online fulfillment center (OFC) or a Micro Fulfillment Center (MFC).
  Recent studies highlight that companies benefit from separation rather than integration and companies maintain separated operations through Order Fulfillment Centers [8].
  It's important to underline that the focus of this Thesis is the warehouse where the omnicanality is managed in the same building and for this reason, despite the majority of companies implementing an OFC or MFC in a separate building, in this case, the focus is only on solutions where the OFC or MFC is implemented in the same building in which is managed the traditional channel.
  MFCs are logistics mini-hubs located near cities, characterized by high performance in managing online orders and a high degree of automation to ensure fast order fulfillment [58].
  Case study 4 introduces a solution characterized by the separation of the picking and storage operations for two distinct channels, with the adoption of an OFC for the management of the B2C orders located in the same warehouse of the B2B channel.
  Also Case study 1 decided to separate storage and picking activity, with the adoption of a MFC located in the same warehouse in which the traditional orders are managed, used to exclusively handle e-commerce orders, ensuring high throughput for online orders.

6.3. Integration or specialization of all the warehouse areas

The existing literature primarily focuses on the integration and separation of storage and picking, often neglecting other critical areas. This represents a gap in the literature that the author intends to address by conducting case studies to examine the decision process regarding the integration or separation of various warehouse areas, taking into consideration not only the storage and picking.

The analysis of the case studies serves as a tool for bridging this existing gap, offering comprehensive insight into the operations within their respective omnichannel warehouses, giving a broad vision of all the warehouse activity, from the receiving to the shipping.

6.3.1. Analysis of the warehouse configurations

In this analysis, the choice related to the integration or separation of the warehouse areas is extended to the ones analyzed in the previous chapters:

- *Receiving*
- *Put away, storage*
- *Picking, sorting*
- *Packing, shipping*

Based on the mentioned warehouse areas and the case studies' insights, it's possible to identify five different configuration alternatives:

1. **Integration of the receiving area**
   In this configuration (*Figure 6.4*), the synergy between channels is limited to the receiving area, where a unified approach for all the channels is employed to manage the goods in this area, while the other areas are separated between the channels. In this setup, the goods are initially treated uniformly in the receiving phase, then they are sorted and differentiated based on their designated channel and there is no further integration in the subsequent areas of the warehouse.

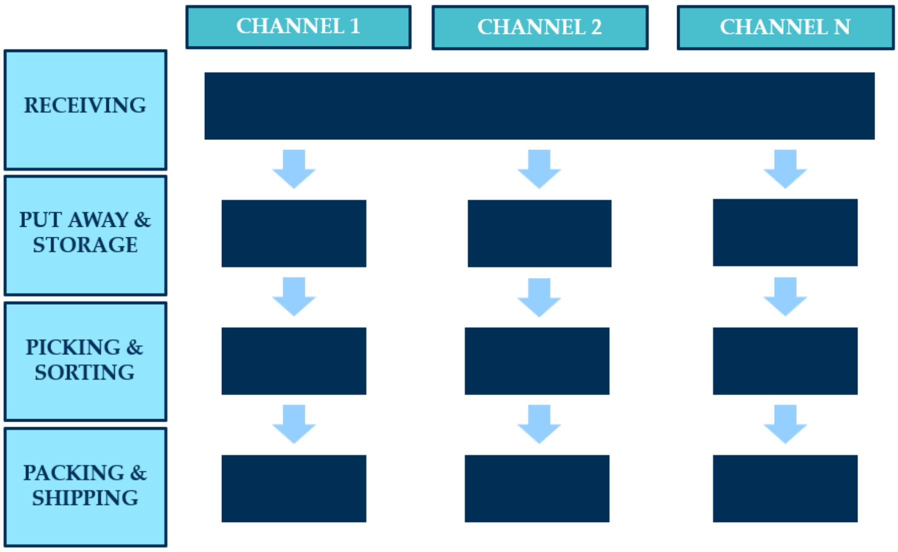

Figure 6.4: Integration of the receiving area

2. **Integration of the receiving and storage**
   The second configuration (*Figure 6.5*) underscores synergy across the receiving and put away, storage areas, while distinct operations are maintained in other areas. The stock is pooled and shared between channels, optimizing storage space utilization; however, as the picking activity begins, the warehouse's operations assume a channel-specific approach.

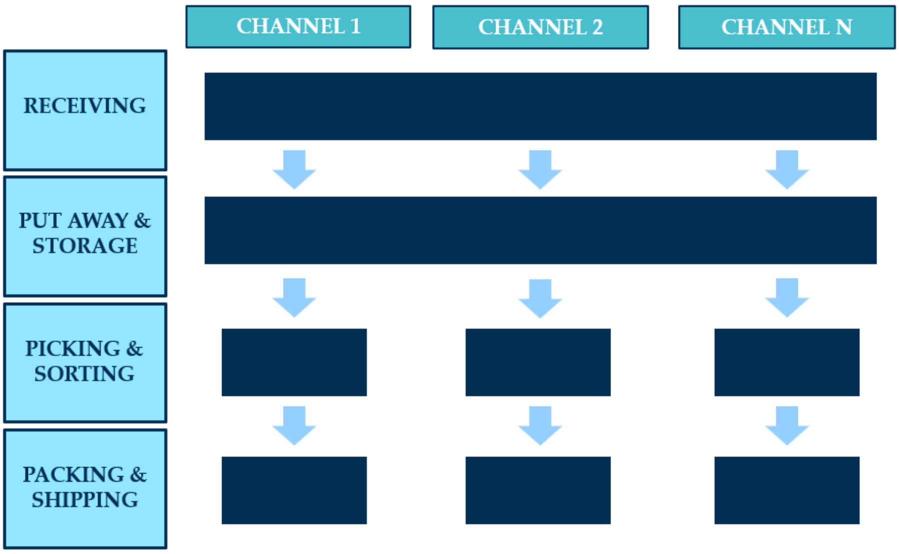

Figure 6.5: Integration of the receiving and storage

3. **Specialization of the picking, sorting**
   The third configuration (*Figure 6.6*) underscores synergy in the warehouse areas of receiving, put away, storage, packing, shipping, while the only differentiated area is picking, sorting. In this case, the receiving process and stocks are in common between the channels, and then there is the separation for the picking and sorting activity, with picking areas dedicated to the different channels. Following the channel-specific picking and sorting activities, the flows merge as a unified stream and in the last activity, related to packing and shipping, the operations are shared between the different channels.

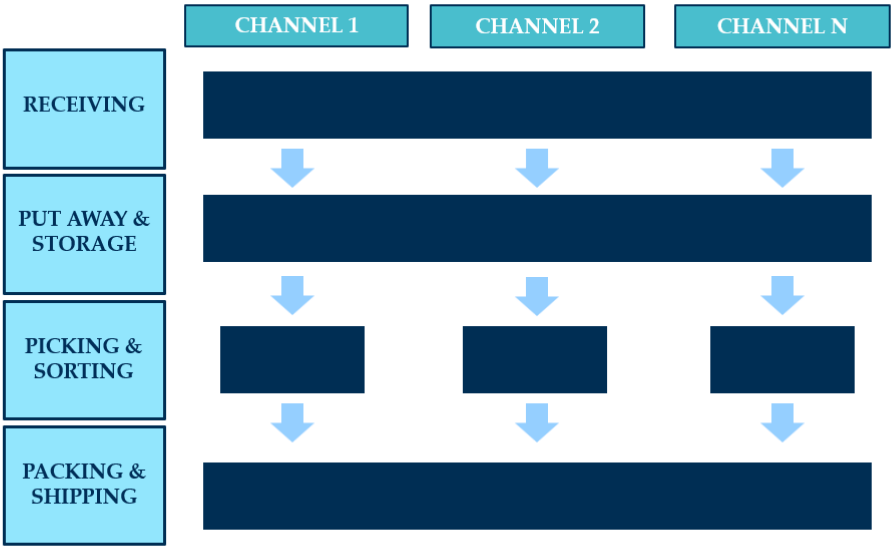

Figure 6.6: Specialization of the picking, sorting

4. **Specialization of the packaging and shipping**
   The fourth configuration (*Figure 6.7*) focuses on synergy in the warehouse activities from receiving to sorting, while differentiation occurs in the packing and shipping area. This approach implies a shared receiving process and common storage provisions across channels. Also during the picking phase, operations proceed without differentiation based on channels. After the picking activity, there is a separation between the flows for the packing and shipping activity.

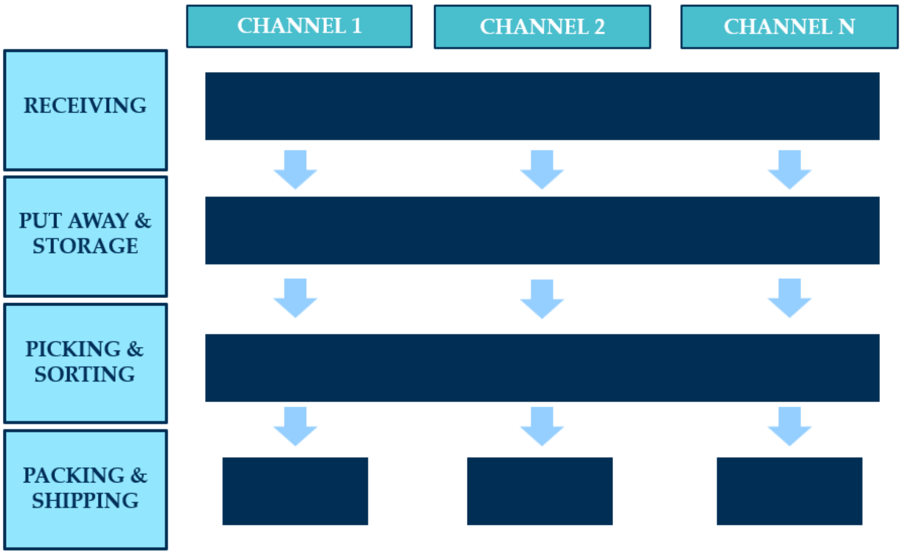

Figure 6.7: Specialization of the packaging and shipping

5. **Integration of the entire process**
   The last configuration (*Figure 6.8*) is characterized by a complete synergy across all the warehouse areas, from the receiving to shipping. In this approach, activities for all channels are homogeneously managed throughout the entire workflow of the warehouse. This solution is adopted when the differences between the channels don't justify the separation of the activity or when there is a prevalent channel and the percentages of the other channels don't justify the creation of dedicated processes.

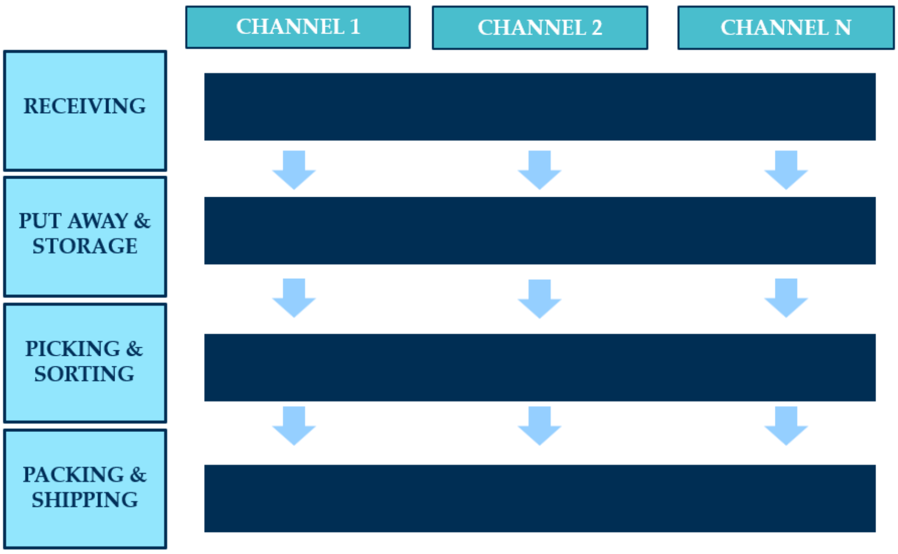

Figure 6.8: Integration of the entire process

6.3.2. Examples of the warehouse configurations

To provide practical examples of warehouse configurations adopted by omnichannel companies, the case studies are used:

1. **Integration of the receiving area**
   Case 13.1 presents a warehouse (*Figure 6.9*), which manages two distinct channels: the traditional channel responsible for store replenishment and the B2C e-commerce channel, which fulfills online orders. This configuration is characterized by synergy only in the receiving activity and the goods are received in a common receiving area and then they are stocked in different ways based on the channel; the products dedicated to the traditional channel are stocked on pallets, while the products dedicated to the online channel are stocked in boxes containing only one typology of article.
   The differentiation in storage methods consequently results in distinct picking strategies for each channel, enabling a tailored approach to address the differing order dimensions of the two channels; in the traditional channel, shops often order in pallet quantities, whereas e-commerce customers typically place orders for individual pieces.
   In the traditional channel, a "man-to-goods" picking system with batch picking is employed, where human operators carry out the picking task by physically locating the required products. Batch picking necessitates a subsequent sorting step, performed during the picking and supported by a tablet and an RFID scanner.
   In the online channel, a "goods-to-person" picking system is implemented, characterized by the utilization of shelf-climbing robots that are responsible for executing the order picking process. They retrieve the required items from designated storage shelves and transport them to a picking station, where the selected items are assembled into boxes.
   The final area is also distinct between the two channels; in the traditional channel, boxes are delivered to the point of sale, while in the online channel, a secondary packaging process is necessary before the delivery.

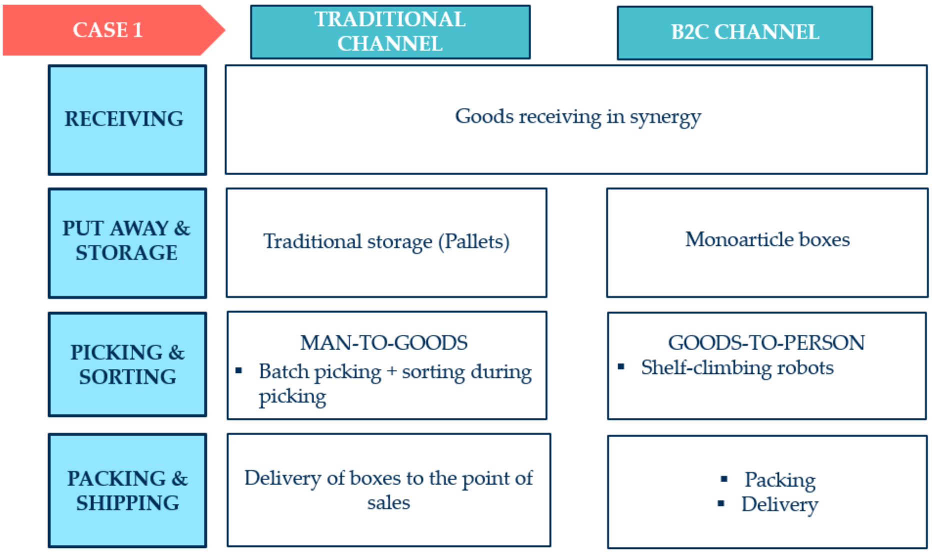

Figure 6.9: Example of integration of the receiving area

2. **Integration of the receiving and storage**

Case 3 proposes a warehouse (*Figure 6.10*) which manages the traditional channel, involving the fulfillment of the stores, and the B2C channel, responsible for the fulfillment of orders delivered to the home of the customers and the orders delivered to the shops and collected by the customers. The configuration has a synergy in the receiving and storage activity, while the channels are differentiated from the picking activity.

The receiving area is shared between the two channels, where all incoming goods are processed without differentiation based on channels.

Also the storage area is unified and the SKUs stored within the warehouse are organized in pallets, independently from the channel they serve.

Then, the differentiation between the two channels is performed from the picking activity; for the traditional channel, a manual picking system is adopted, with the picking performed at the first level of the warehouse, while for the online channel, it's introduced an automation system (RCSRS), able to handle single pieces efficiently.

Regarding the packaging and shipping activities, in the traditional channel, pallets are wrapped in film before being shipped, while the online channel employs an automated packaging line operating with the principle of

packaging on demand that tailors the packaging size to the specific dimensions of each order.
Then, the orders are moved to a shipping bay where they are prepared for delivery.

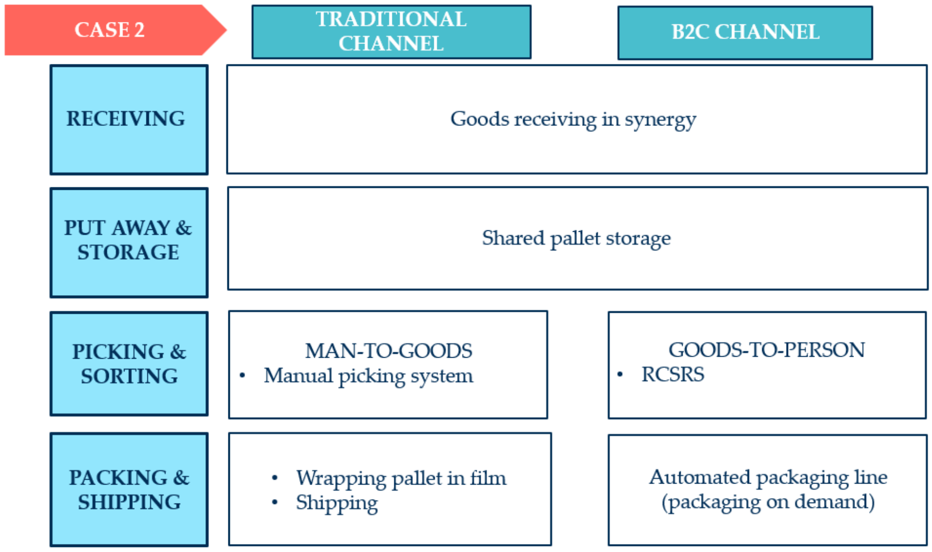

Figure 6.10: Example of integration of the receiving and storage

3. **Specialization of the picking, sorting**

In the warehouse presented in Case study 13.2 (*Figure 6.11*), the channels that are managed are the traditional channel that refills the stores and the e-commerce B2C, which fulfills the online orders. The configuration is characterized by the differentiation in the picking and sorting activities.

As in the previous case, the receiving and storage area are common for the two channels, with the latter managed utilizing selective pallet racks to accommodate pallets for both the traditional and online channels.

The differentiation between the two channels is in the picking activity; in the traditional channel, the picking activity is managed with a logic "man-to-goods", the sorting while picking and the use of RFID technology to ensure the accuracy of the picked items for each order.

In the online channel, a “goods-to-person” picking method is employed, utilizing a Robot Mobile Fulfillment system (RMFS) with the adoption of AGV that moves shelves to the designated picking stations in which the operators perform the picking activity.

Subsequently, the picked orders from both the traditional and online channels converge in the packaging area, in which a dedicated packaging station is set up for the packing process. Following the packaging phase, the orders from both channels proceed to the shipping area, where the cartons are prepared for shipment.

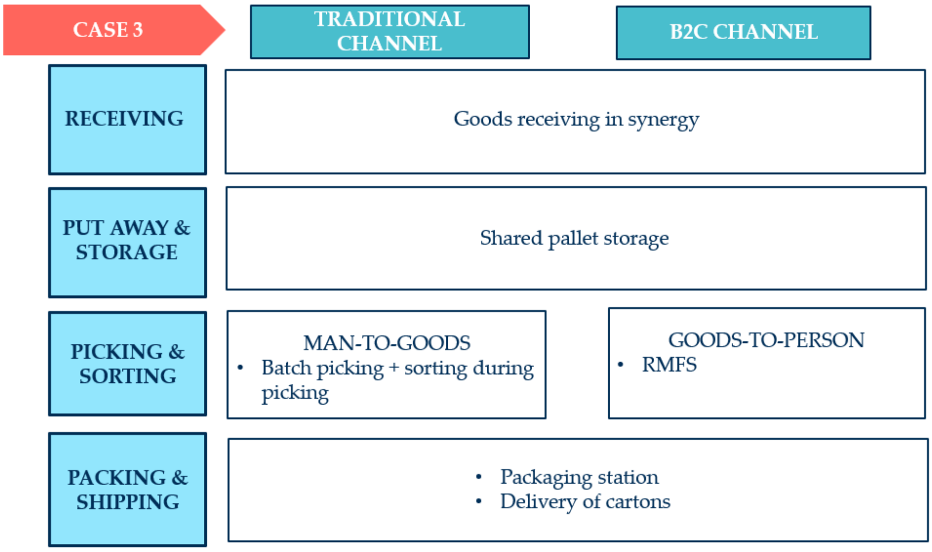

Figure 6.11: Example of specialization of the picking, sorting

4. **Specialization of the packaging and shipping**

Case 16 proposes a warehouse (*Figure 6.12*) that handles both the traditional channel, which restocks the physical stores, and the e-commerce B2C channel, which is responsible for fulfilling online orders. The configuration is characterized by a differentiation only in the packing and shipping area.

The receiving area is common for both the traditional and online channels, as the storage system is organized using selective pallet racks that accommodate pallets from both channels.

The picking activity is managed through the "pick to box" system, where the picking area is divided into distinct picking stations (also called 'picking zones'), each assigned to one or more pickers, which are interconnected by a conveyor system on which bins are placed [1]. Each picker is responsible for gathering the required products for specific orders within their designated area and placing them into bins that move along the conveyor system through different picking zones.

The only distinction in the picking process between the two channels is that in the traditional channel, each order corresponds to one single carton, while in the online channel, multiple orders are grouped in a single carton because store orders are typically larger and can fill an entire carton, while online orders are smaller and may not fully utilize the carton's space. As a result, an additional sorting phase is necessary for online orders and during this manual sorting process, the cartons are separated to ensure that each carton contains the correct individual orders.

The final phase of the process, which is separated into the two channels, involves the packing and shipping activities.

In the traditional channel, this phase includes tasks such as the closing of the cartons, the labeling and the palletization. In contrast, the online channel follows a different approach because the packed orders are then grouped on pallets for transportation optimization, like the traditional channel's practice.

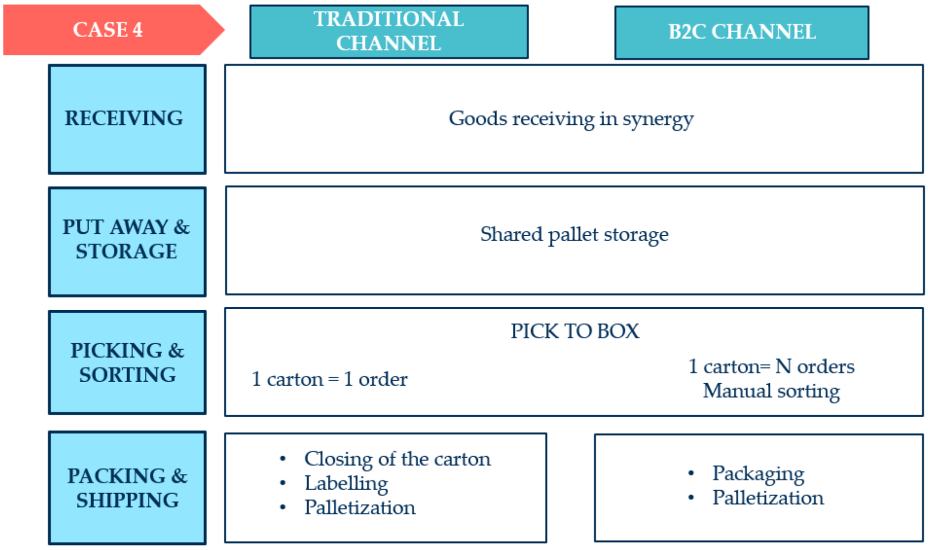

Figure 6.12: Example of specialization of the packaging and shipping

5. **Integration of the entire process**

Case study 2 proposes a warehouse (*Figure 6.13*) in which they provide the hardware and the automation solution, which serves both the traditional channel, which restocks physical stores and the e-commerce B2C channel, which is responsible for fulfilling online orders. The configuration is characterized by an integrated approach across all phases of the operations.
Similarly to the previous cases, the receiving process is shared among all the channels and it is managed without channel differentiation.
Subsequently, the storage operations are effectively coordinated through the implementation of a shuttle system (AVS/RS), which possesses the capability to accommodate double-deep storage for cartons for both channels.
Following that, a conveyor system moves the cartons from the storage area to the picking station, where an operator performs the picking activity, thanks to a monitor positioned in front of the operator that displays crucial information, such as the precise quantity of items to be picked from the box. Based on this information, the operator can pick the correct number of products from the box and place them into another box that arrives through the conveyor system.
The final stage involving packaging is executed in the same way for both channels using a conventional manual packaging assembly line.

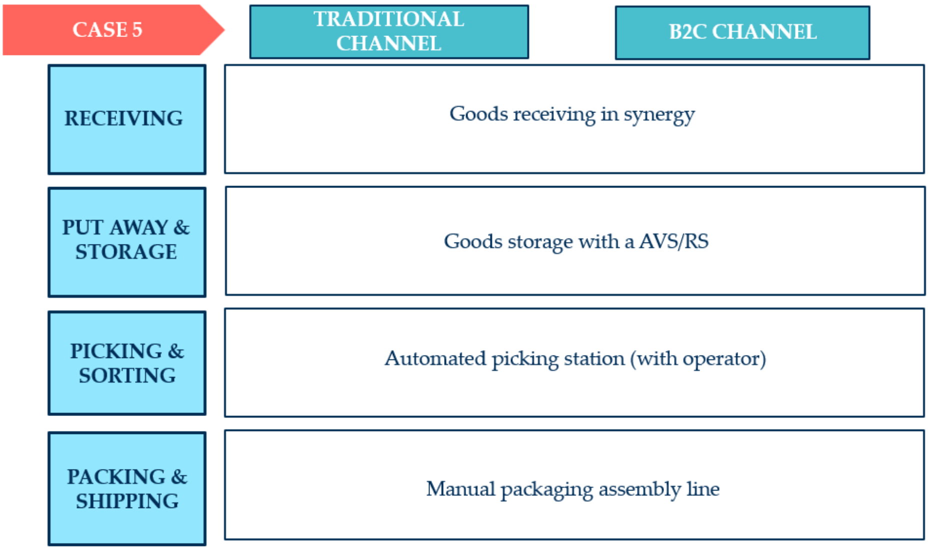

Figure 6.13: Example of integration of the entire process

6.4. Decisional criteria for the integration or specialization of warehouse areas

After defining the different warehouse configurations, the analysis of the case studies has revealed several criteria that guide the decision-making process regarding integration and specialization among various warehouse configurations:

- **Differences in the order profile**
  The difference in the order profile, including variations in order characteristics such as size, weight, and number of order lines, can lead to complexity in managing the different channels together in the warehouse, driving the choice towards a configuration that emphasizes specialization for each channel, as underlined by Case study 13.1.
  In particular, differences in the order size among various channels push toward separation between the different channels [3].
  The larger the difference between store replenishment orders and online orders in characteristics, the more complexity and differentiation the warehouse must handle and the more complex and differentiated the configurations become [8].

- **Percentage incidence of the different channels**
  When a particular channel has a low percentage incidence, specializing that channel may not be economically justified due to the low volume of orders associated with it, as observed in Case study 7.

- **Differences in the packaging requirements**
  Significant differences in packaging requirements make more challenging to integrate areas and leverage synergies due to the diverse needs of each channel.

Heterogeneity in packaging requirements can create complexities in handling and fulfillment processes.
The difference in packaging requirements for store and end customer deliveries is a fundamental factor for integration decisions [51]; in particular, the bigger the difference in the requirements, the more complicated it is to integrate inventories in integrated warehouse solutions.

- **Differences in the unit of shipping**
  Differences in the unit of shipping between channels increase the complexity of handling these units together. This attribute has a particular influence on the shipping activity.
- **Differences in the service level requested**
  Strong differences in customer expectations between channels favor separating the warehouse operations to better prioritize the channels with higher service levels. This criterion is particularly relevant in the picking, sorting area [6].
- **Overlapping of the assortment**
  If there is a high level of overlap between the assortment of the channels, it's more convenient to integrate the activities of the warehouse because this choice allows to obtain space savings [6] and to achieve the possibility of pooling the demand [34]. This important attribute has a particular influence on the put away, storage area.
- **Different responsibilities and ownership of the stock**
  As underlined by Case study 15, if there are different ownership and responsibilities of the stock, is more convenient to separate the different activities in the warehouse because separating the activities ensures clear accountability and facilitates efficient management of stock.

6.4.1. Experts' group

Based on the results of the survey conducted during the experts' group, the perceived importance of the decision criteria for choosing warehouse configuration can be ranked as follows:

- *Differences in the order profile*: 71
- *Percentage incidence of the different channels*: 67
- *Differences in the packaging requirements*: 67
- *Differences in the unit of packaging*: 66
- *Differences in the service level requested*: 62
- *Overlapping of the assortment*: 60
- *Different responsibilities and ownership of the stock*: 56

6.5. Conclusions and analysis of the results

The analysis conducted in this research question underlines that the current academic literature is focused only on the integration and specialization of storage and picking areas across different channels within the warehouse. Moreover, in this current situation, there is the absence of a structured framework that provides a comprehensive visualization and analysis of the various alternatives for storage and activity integration. To bridge this gap, a structured framework is introduced in this study, analyzing the two decisions and the resulting alternatives.

Due to the importance of these areas, the literature has predominantly focused on them, often overlooking other essential warehouse functions. To address this gap, this Thesis extends the analysis, including the configurations related to the integration and separation of the other warehouse areas, providing a more comprehensive understanding of omnichannel warehousing.

The final gap within the literature related to this research question is the absence of a well-defined set of criteria to support the decision-making process of integration and separation of the various warehouse areas. The current literature doesn't provide a structured list of criteria that can serve as guideline and to address this gap, this study leverages insights from the case studies to formulate a cohesive and practical set of criteria that can assist companies in making informed decisions regarding the integration or separation of different warehouse areas.

6.5.1. Analysis of the framework for the integration or specialization of storage and picking

Through an extensive review of the literature concerning the integration or separation of storage and picking operations, four distinct alternatives have emerged. To analyze these different alternatives based on the insights from the literature, a framework is defined, and it has been applied to case studies that explain their decision regarding the choice of integration or specialization of storage and picking activities.

The warehouses examined in the case studies have been grouped and categorized within the established framework (*Table 6.2*) to yield a comprehensive diagram that illustrates the practical implementation of real-world scenarios.

	Integrated picking	**Separated picking**
Integrated storage	3	5
Separated storage	/	4

Table 6.2: Number of case studies on the different configurations

The details related to the specific case studies in the different configurations are represented in *Table B.8*.

From this analysis of the case studies, it becomes evident that there is a substantial degree of consistency among the different integration or separation solutions. However, a notable exception arises concerning the alternative of integrated storage and separated picking, which is supported by 5 case studies in its favor, compared to the lower results of the other alternatives.

This configuration stands out as the most significant within the context of the case studies analysis, and also the literature emphasizes its importance, as it offers the ability to integrate storage while realizing benefits such as space savings, shared inventory, and demand pooling. Furthermore, this alternative facilitates the specialization of the picking activity, ensuring the segregation of channels to provide distinct service levels to various channels and enabling more effective management of differing order profiles among these channels.

As previously underlined, the choice taken in the context of omnichannel warehousing strongly depends on the context and for this reason, this configuration is not always the best solution that the omnichannel can adopt, but it also depends on the decision criteria that define the context in which the warehouse operates.

6.5.2. Analysis of the framework for the integration or specialization of all the warehouse areas

Based on the five configurations elucidated through the analysis of case studies, a comprehensive framework has been developed to encapsulate the various configuration possibilities, illustrated in *Figure 6.14*.

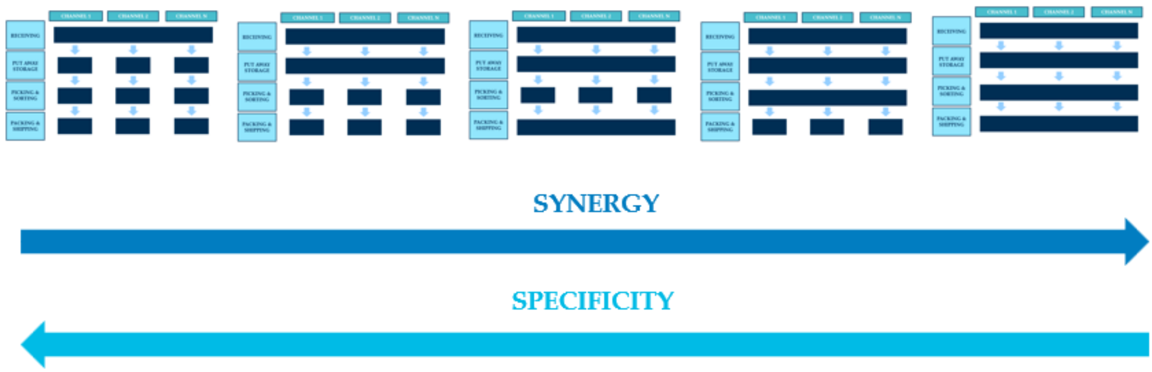

Figure 6.14: Framework of the different configuration alternatives

This framework takes into account all the alternative configurations outlined within the case studies, providing a valuable tool for companies involved in the design of omnichannel warehouses and broadening the spectrum of options compared to the analysis of just the storage and picking activities.

As illustrated in the figure, there is an increasing level of synergy among channels as one progresses from the first configuration to the last, while specificity rises from the last configuration to the first. Based on the level of synergy and specificity that the omnichannel warehouse aims to achieve, this framework can serve as a support for the decision related to configuration.

Also in this case, the case studies don't suggest a best solution that can be universally adopted in the omnichannel warehouse, but the decision can vary based on the unique context of the operation.

6.5.3. Analysis of the decisional criteria

The analysis of the survey results leads to the conclusion that nearly all the decision criteria mentioned are perceived as relevant by the experts' group, with scores ranging from 56 to 71.

According to the survey responses, the "*Differences in the order profile*" received the highest score (71), indicating that it is the most critical factor to consider in the configuration decision-making process.

Following closely behind, the other criteria that needed to be taken into consideration are the "*Percentage incidence of the different channels*" (67), "*Differences in the packaging requirements*" (67) and the "*Differences in the unit of packaging*" (66).

The other criteria are perceived as less relevant, with the "*Different responsibilities and ownership of the stock"* receiving the lower score (56), probably because most of the experts don't separate responsibility and ownership of the stock in their warehouses.

As stated, these decision criteria can guide the choice of configuration for the integration or specialization of warehouse areas, influencing the decision toward a more integrated or specialized solution. *Figure 6.15* can be a support tool in the decision of the configurations, illustrating the impact of the decision criteria, from the least to the most influential.

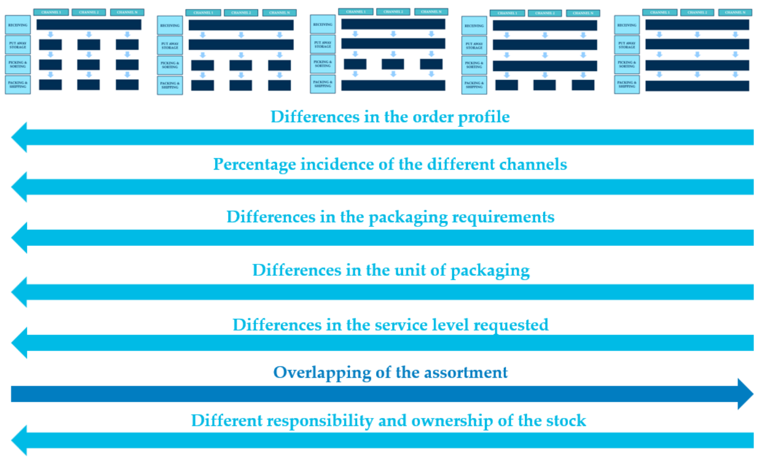

Figure 6.15: Influence of the decisional criteria on the warehouse configuration

7 Flexibility in automation: Main trends

7.1. Introduction

The analysis of the impacts of the omnichannel challenges underscores the need for flexibility to meet the omnichannel challenges. In the context of manual operations, flexibility is easier to obtain compared to an automation context, and for this reason, the focus of this chapter is on the management of flexibility in presence of automation. In particular, the focus is on the picking area, the most time-consuming activity in warehouse operations.

To address this objective, the research question formulated is the following: "*How it is possible to manage flexibility in presence of automation?*" and the primary focus of this research question is to investigate the role of automation in effectively managing the need for flexibility associated with omnichannel operations, specifically in the picking area of the warehouse. The structure of this research question is illustrated in *Figure 7.1*.

Given the unique requirements and challenges in the omnichannel context, automation has emerged as a critical element for optimizing warehouses. In particular, automation is identified as one of the management variables in RQ2, and the analysis of the impacts of omnichannel challenges on this management variable reveals that automation is one of the most affected variables, with a total of 14 citations from papers and case studies.

The decision to focus on the picking activity is due to the importance of this activity in the warehouse, as it is the most time-consuming, labor-intensive activity [39]. Moreover, from the analysis of the results of RQ2, the picking, sorting area stands out as the one most impacted by omnichannel channels, with a total of 27 citations from papers and case studies.

The chapter is structured as follows: first, the definition and analysis of flexibility is provided, highlighting its significance in the omnichannel warehouse and exploring its various dimensions. Moreover, the different ways to reach flexibility are analyzed through a survey conducted in an experts' group.

Subsequently, this chapter analyzes two responses gathered from the survey conducted in the experts' group. The first focuses on the types of automation technologies employed in the picking operation, through a comprehensive examination of the current state of automation solutions with a focus on flexibility and the definition of a set of criteria that can be used to differentiate and select among the array of available automation solutions.
In the final section, another answer to the survey is analyzed, related to an innovative automation paradigm designed to effectively address the inherent requirements of flexibility and scalability typical of the omnichannel context.

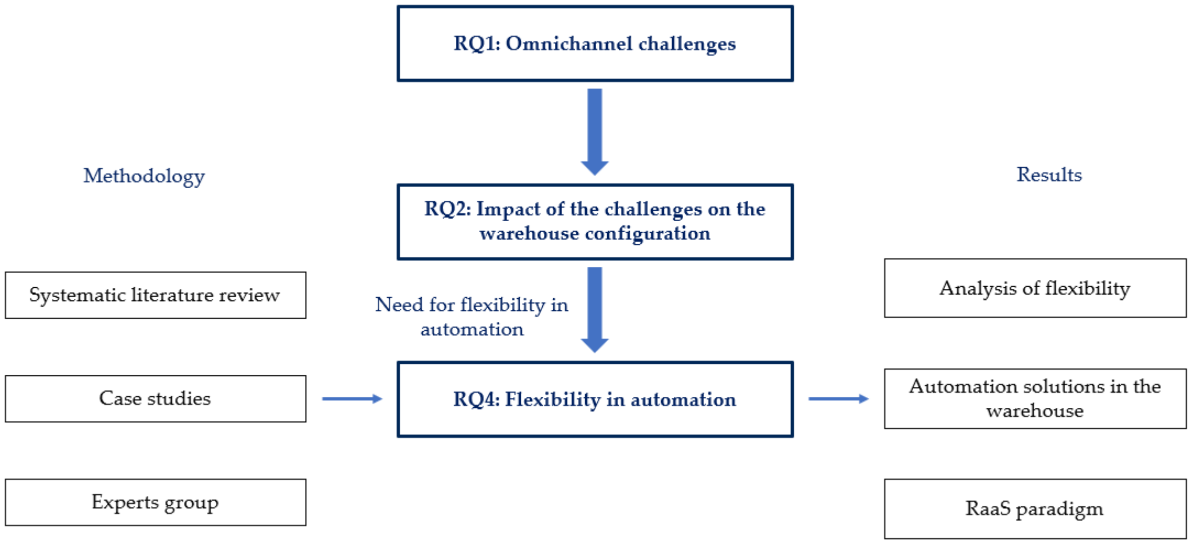

Figure 7.1: Structure of the RQ4

7.2. Flexibility in omnichannel context

The analysis of the impact of the omnichannel challenges on warehouses highlights a fundamental need: flexibility in automation solutions. Specifically, in RQ2, a total of 12 citations from papers and 7 citations from case studies underline the need for flexibility when considering the impact of the omnichannel challenges on warehouse configuration. The details of the citations from the papers and case studies are reported in *Table B.9*.

Flexibility in automation is crucial in the omnichannel landscape because automation cannot be as flexible and scalable as manual work, in which is possible to easily modify the capacity using the countermeasures described in the RQ2, such as hiring additional operators, working on more shifts and utilizing overtime. Moreover, the manual work is also more flexible in terms of handling different order dimensions.

Due to the stringent performance requirements of omnichannel operations, manual work is not suitable for this environment, necessitating an automation solution with flexible characteristics that aim to obtain levels of flexibility like manual operations.

Flexibility in terms of capacity, particularly in the picking activity, plays a vital role in addressing omnichannel challenges outlined in the first research question, such as "*Demand variability (often in a non-repetitive way)*"; "*High peaks in terms of entity, period, duration*"; "*Growth rate difficult to predict (unpredictability of the environment)*" and "*Incidence of the different channels that change in time*".

In such a dynamic landscape, committing to a fixed automation solution becomes inconvenient, as it may not accommodate the inevitable alterations that the company's operational context will undergo. Given the unpredictability of this environment, companies are inclined to invest in automation solutions that can easily evolve, remaining aligned with the evolving needs of the operational landscape.

7.2.1. Flexibility analysis

Flexibility is the capability of managing, resolving and adapting to unexpected, new, or changing requirements and it's vital in omnichannel retailing, due to the greater number of options offered during the order fulfillment process [59]. A flexible automation solution can easily adapt to the changes in the environment and in particular, flexibility in terms of capacity, which is typically difficult to achieve in streamlined warehouse operations, has thus become significantly more important for the success of omnichannel [3].

The importance of flexibility has also increased due to the wider assortment and the more rapid rate of new product launches, creating the need to handle a variety of order sizes catering to both physical retail stores and e-commerce [3].

Omnichannel retailing requires more flexibility, as it implies greater product assortment and product variation, while automation implies more streamlined and less flexible handling of goods and it can be sensitive to changes in product characteristics and size variation, impacting its adoption in this context [6].

7.2.2. Scalability analysis

Another important requirement for automation solutions, closely related to flexibility, is scalability, which is the capability of an automation system to easily increase its capacity over time to meet evolving business demands.
In the omnichannel context, challenges related to forecasting make difficult to plan the capacity of automation solutions and create difficulties for the managers in the dimensioning of the automation system.

To cope with this situation, some case studies, such as Case study 1 and 13.2, have suggested oversizing of the automation system as a strategy to achieve scalability, but this approach involves investing in excess capacity that remains underutilized for a significant portion of the time, resulting in unnecessary costs.

To reach a good level of flexibility and scalability in automation systems, new solutions and paradigms have been studied to address this weakness in automation and meet the evolving requirements of companies.

7.2.3. Dimensions of flexibility

Deeply analyzing the concept of flexibility, it's not possible to give one single definition, but it comprises several dimensions [60]:

- **Changes related to the capability of handling requested**
  This dimension of flexibility revolves around the warehouse's capacity to efficiently manage varying volumes of goods over time without compromising operational efficiency.
  This dimension of flexibility entails the ability to scale operations up or down in response to changes in customer demand, seasonal variations, or unforeseen market developments. For instance, during peak seasons like holidays or promotional events, warehouses may experience an increase in orders across both physical retail and online channels. Conversely, quieter periods might necessitate a downsizing of operations to avoid overcommitting resources.
- **Changes in the mix of the unit of handling**
  Flexibility also extends to handling different types of units loads within the same warehouse. For instance, a warehouse might need to handle diverse items, ranging from traditional boxes to cartons, pallets, or hanging garments, necessitating a flexible approach to material handling.
- **Time to develop and modify the solution**
  Rapid development and implementation of solutions is another dimension of flexibility. The capacity to rapidly conceptualize, design, and deploy new solutions, as well as the ability to promptly modify existing ones, allows the warehouse to effectively adapt to evolving market conditions.
  In the ever-changing landscape of omnichannel, where consumer preferences and market trends can shift rapidly, the agility to respond promptly is crucial.
- **Possibility to move the hardware**
  Another dimension of flexibility is the capability to relocate warehouse hardware, for example, due to changing lease agreements or strategic reconfigurations. By having the capacity to easily relocate key components of the warehouse infrastructure, businesses can respond to evolving market conditions and customer demands with agility and efficiency.

- **Changes in the mix of the order dimension**
  Another dimension of flexibility is the ability to efficiently manage different order dimensions in the same warehouse, ranging from large orders originating from physical retail channels to smaller orders generated by online channels.
  In the context of omnichannel warehousing, where orders can exhibit substantial variability in terms of size and composition based on the channel, the ability to manage this mix of order dimensions is crucial.
- **Changes in the unit load with time**
  The last dimension is related to the ability to handle changing unit loads over time. This aspect highlights the adaptability of a warehouse to shifting demands and changing product characteristics, whether transitioning from handling large pallets to individual boxes or vice versa.
  In the context of omnichannel warehousing, where the assortment of products can be diverse and the order profiles can vary significantly, the capability to adjust unit load handling is of crucial importance.

7.2.4. How to increase flexibility in automation: experts' group

The survey conducted within the experts' group aimed to identify key factors that enhance flexibility in the warehouse. Through the analysis of literature and case studies, three primary alternatives have emerged:

- **Type of storage and movement technology**
  This factor is related to the automation technology employed within the warehouse for the storage and movement of goods. The level of achievable flexibility varies significantly depending on the chosen automation solutions and different types of automation technologies offer distinct degrees of flexibility.
- **Mix between traditional and automated warehouse**
  Another significant factor highlighted is the potential for flexibility through a hybrid approach that combines elements of traditional and automated warehousing. Integrating human operators within the warehouse operations can enhance flexibility compared to a purely automated setup and striking the right balance between these two approaches is a possible approach to achieving flexibility in the warehouse.
- **RaaS paradigm**
  The third factor identified by the case studies introduces a novel paradigm for managing the automation fleet within the warehouse: the Robots-as-a-Service (RaaS) model, which offers an innovative solution for increasing flexibility and scalability in omnichannel warehouses.

Under this paradigm, managers have the option to rent a portion of their automation fleet, allowing them to adapt and expand their automation capabilities as needed to meet evolving demands.

Upon analyzing the results of the survey, the following numerical breakdown of responses was obtained:

- *Type of storage and movement technology*: 71
- *Mix between traditional and automated warehouse*: 67
- *RaaS paradigm*: 50

Based on the survey results, it is evident that the primary factor influencing flexibility in automated warehousing is the type of technology adopted. Consequently, the next section of this chapter conducts an in-depth analysis of various automation technologies and their respective flexibility capabilities, aiming to provide a comprehensive understanding of the role of technology in shaping flexibility.

Furthermore, the experts' group recognized the significance of the hybrid approach involving a mix of traditional and automated warehousing. This acknowledgement aligns with existing literature on the subject, which has thoroughly explored the combination of these two warehouse paradigms, as suggested by [57]. Therefore, this Thesis will not delve further into the analysis of the hybrid approach, as it has already been covered in existing research.

The survey results reflect that the RaaS paradigm received a lower score in comparison to the other two factors, which are more established in both literature and practical applications. However, this lower score should not diminish the importance of the RaaS paradigm, but it underscores its emerging and innovative nature within the realm of warehouse management. Although it may not be as well-developed or widely adopted as other factors, its potential to enhance flexibility in the warehouse is increasingly recognized, as evidenced by the results from the case studies. Therefore, the Thesis will explore the RaaS paradigm in more depth, recognizing its capacity to contribute to the evolution of warehouse flexibility, even if it is not as mature or widely acknowledged as other factors.

7.3. Automation solutions in the warehouse

In recent years, warehouse automation has emerged as a critical success factor for companies because it allows to increase the efficiency in warehouse operations and, at the same time, it guarantees ergonomics and safety [6], reduced operational costs, the ability to store a wide assortment range and it also enables faster throughput [8].

While automation solutions have historically been associated with the handling of standardized products, the landscape has evolved significantly due to recent technological advancements. This transformation has led to a significant expansion in the capabilities of automation, which now also enables flexibility in handling different types of products [8]. This shift has a particular impact in the context of omnichannel operations, where the diversity of products is an important challenge.

On the other hand, automation systems are expensive and require substantial capital investment. As a result, companies with elevated turnover rates and a substantial volume of customer orders are more inclined to allocate resources toward automation implementation [8], while it is more difficult for small and medium enterprises to invest in automation solutions.
It also seems more feasible to automate for smaller goods and standardized packages, while high variation in goods size, with both small, medium-sized and big bulky packages increases the complexity and need for advanced and varied automation solutions [8].

Warehouse automation covers various operations, such as storage, picking, sorting, and packing, while receiving and return handling are more often handled manually [6]. Within this context, picking emerges as a critical area with significant implications for operational efficiency and cost management because it is one of the most time-consuming, laborious activities and a huge cost center. Therefore, to achieve operational excellence in the order fulfillment process, warehouse managers greatly emphasize warehouse automation in the picking process, to minimize unproductive operations [39].
By introducing automation in the order picking process, companies stand to achieve notable benefits such as cost reduction, shorter delivery response times, better picking accuracy, and space utilization [61].
The automation in the picking activity allows to overcome the conventional man-to-goods picking system, characterized by the strong drawback of the unproductive picker walking when moving from shelf to shelf and back to the central depot. This issue is particularly pronounced when dealing with small orders, typical of the online channel, as the fraction of unproductive work while walking to and from the depot and between shelves is proportionally large [45]. The conventional model of picker-to-parts warehousing often proves unsuitable for meeting these specific requirements and as a result, the application of automated warehousing systems has gained prominence as a solution to address these challenges [45].

7.3.1. Literature review

To obtain a comprehensive understanding of automation solutions, a literature review was undertaken to investigate the current state of the academic situation.

The objective of this section is to explore the literature and practical case studies to examine the potential automation solutions proposed in the omnichannel warehouse context that can be adopted to cope with the flexibility needed in the omnichannel context, with a focus on the picking activity. It is important to note that the aim is not to determine a definitive “best" solution, as logistics involves trade-offs and various factors need to be considered. Instead, the aim is to investigate possible automation responses to the challenges identified initially and determine how these solutions can help meet the need of flexibility typical of omnichannel operations.

The results of this literature review revealed a wide range of automation solutions that can be categorized based on the framework proposed by [62]. This framework provides a structured approach for classifying automation solutions specifically within the context of warehousing operations and offers an initial definition of the automation categories.

In *Figure 7.2*, a framework developed modifying the framework proposed by [62] explains the current automation warehouse solutions.

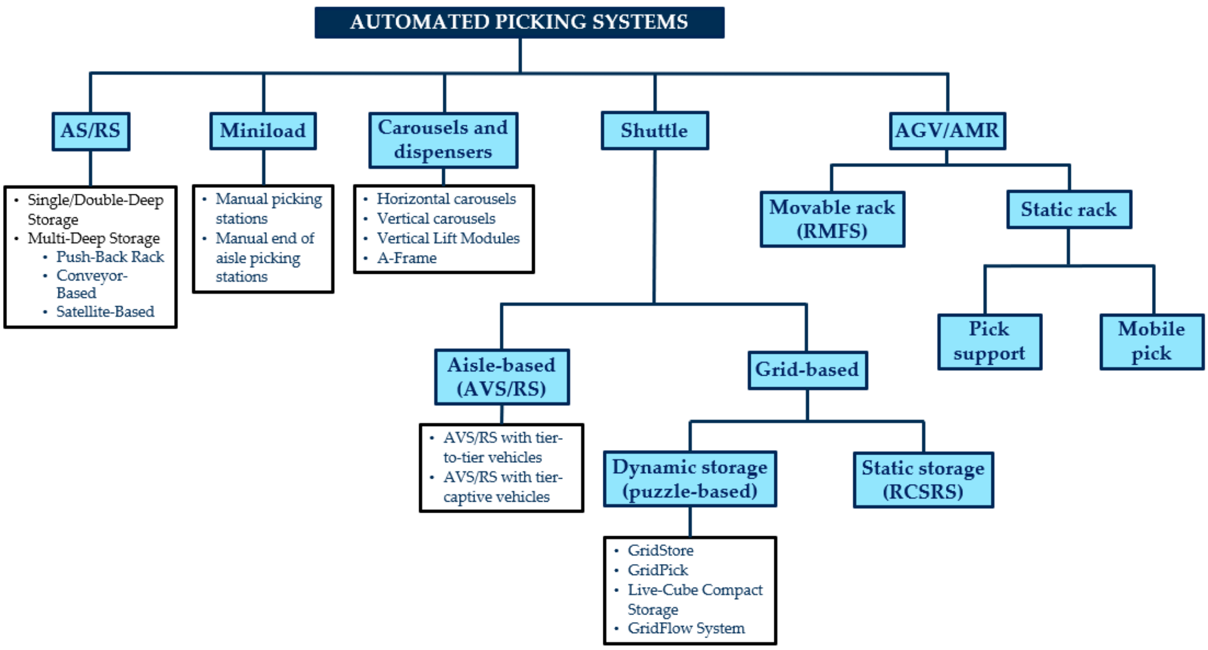

Figure 7.2: Framework of the warehouse automation solutions

From the research conducted, nine categories of automation solutions can be identified and [62] gives a first definition of the solutions:

1. **Automated Storage Retrieval System (AS/RS)**
   The first automation solution consists of racks and automated handling systems, such as cranes or automated forklifts, where driving and lifting in the aisle take place simultaneously [62]. An AS/RS is defined as a combination of equipment and controls that handle, store and retrieve materials as needed with precision, accuracy, and speed under a defined degree of automation [63], based on automated equipment able to reduce labor requirements and avoid capital expansion by exploiting unused vertical space [64].
   In this setup, pickers remain in their picking stations, resulting in reduced unproductive travel time. This is achieved through the retrieval of required products via the AS/RS, which then is delivered to the picking station through AGV, conveyors or forklift trucks [1], where the operators execute the picking task by selecting the necessary quantity of items from the retrieved containers.
   The paper [63] introduces a novel AS/RS approach, distinct from the typical approach that uses stacker cranes, characterized by an increased level of flexibility. The primary advantage of this solution is its ability to handle B2C e-commerce orders with flexibility and efficiency compared to traditional AS/RS. This innovative AS/RS is particularly well-suited to handling valuable, irregular, small, and delicate items in a timely and highly flexible manner.

   This AS/RS solution can be categorized into two categories:

   - *Single/Double-Deep Storage*
     In this first category, the depth of the storage is equal to one or two pallets [62].

   - *Multi-Deep Storage*
     The second category comprises AS/RS, which can also be used to store loads double-deep in the racks. For this purpose, cranes can be equipped with double-deep telescopic forks. In a typical crane-based compact storage system, a storage and retrieval crane takes care of movements in the horizontal and vertical directions of the rack, and an orthogonal conveying mechanism takes care of the depth movement.
     There are three categories of automation solutions based on the mechanism of the depth movement [62]:
     - *Push-Back Rack*, in which the crane (or automated forklift) stores the loads by mechanically pushing them into the storage lanes.
     - *Conveyor-Based*, in which the racks are equipped with conveyors.
     - *Satellite-Based*, in which a satellite or a shuttle is used to perform the depth movement.

2. **Miniload**

The miniload is an automated solution similar to AS/RS, but it's designed to handle smaller units such as totes, boxes, and cartons instead of larger pallets [1].

In the miniload system, the SKUs are placed in boxes stored in racks and they are retrieved by a storage/retrieval machine [65].

This solution exists in two distinct configurations [1]:

- *Manual picking stations*

  This configuration is composed of three different blocks [65]. The first is a miniload aisle, which contains an aisle-captive S/R machine, with each aisle connected to the conveyor system by small input/output conveyors. Then, there's a conveyor system that facilitates the movement of boxes between the miniload aisles and the pick stations. The last component is the picking stations, linked to the loop by I/O conveyors. Each picking station is assigned to a single picker and all the items in a specific order are picked by the same picker. This system eliminates the need for picker travel, as containers are automatically moved one by one towards the picker and then taken away once the picking is complete.

  When an order is released into the system, the S/R machines in the aisle where the products are stored retrieve the corresponding totes, each containing a single SKU, and transfer them to the end of the aisle where they are placed onto the closed-loop conveyor for transport to one of the workstations. At the picking station, the order picker collects the required number of products from the totes and puts them in a so-called order tote. The totes with the remaining products are placed back onto the closed-loop conveyor and are subsequently returned to the storage area [86].

  The configuration described is a relatively expensive solution, but it's able to guarantee a high picking capacity. Given the substantial cost associated with its implementation, this configuration is typically chosen when dealing with high complexity scenarios involving a large number of items and a significant picking activity [1].

- *Manual end of aisle picking stations*

  In this configuration, there are no conveyors in front of the system. Instead, pickers are stationed at the end of each aisle to carry out the picking tasks directly. This arrangement assigns one picker to each aisle, streamlining the picking process [65].

Due to its lower complexity and reduced requirements for conveyors and automation infrastructure, this configuration is considered a cost-effective option for warehouses with low picking activity [1].

3. **Carousels and dispensers**
   Carousels represent another category of automation, which consists of several shelves linked together and rotating in a closed loop [62]. They are operated by a picker (human or robotic) with a fixed position in front of the carousel [66]. The carousels are highly versatile and one of the main advantages is that, rather than having the picker travel to an item (as is the case in a warehouse where items are stored on shelves), the carousel rotates the items to the picker. Moreover, while the carousel is traveling, the picker has the time to perform other tasks, such as packing or labeling the retrieved items, or attending to another carousel [88].

   This category of automation solutions can be further classified into four distinct types [62]:

   - *Horizontal Carousels*
     Horizontal carousels consist of automated storage and retrieval systems in which shelves are linked together and rotated in a closed loop. The rotation takes place around the vertical axis and the picker in front of the system retrieves the goods.

   - *Vertical Carousels*
     Similar to horizontal carousels, vertical carousels are also automated storage and retrieval systems with interconnected shelves that rotate in a closed loop. However, in this case, the rotation of shelves takes place around the horizontal axis.

   - *Vertical Lift Module*
     The Vertical Lift Module is similar to a carousel but operates differently. When an item is required, the inserter/extractor locates the trays in which the item is stored and brings the tray to the picker positioned in front of the system.

   - *A-Frame*
     The A-Frame is an automated dispensing system, where products are automatically dispensed, while replenishment is still carried out manually. A-Frames require a lot of fixed installed machinery, so a flexible adjustment to varying workloads seems problematic. In addition, they have strict requirements on product shape, size, and packaging [45].

4. **Aisle-based shuttle - AVS/RS**

The Autonomous Vehicle-based Storage and Retrieval System (AVS/RS) is an automation solution characterized by a high level of flexibility [67]. It requires an investment similar to the AS/RS, while they offer a much higher retrieval capacity because the throughput capacity of AS/RS is constrained, since only one crane is responsible for handling loads at all vertical levels within a given storage aisle [62].

Moreover, they are notably more flexible in terms of capacity as they allow users to easily adjust the number of vehicles in the system to achieve the required throughput [68].

In typical AVS/RS systems, shuttles are employed, capable of moving in both the x-direction and y-direction on any level within the aisle and lifting devices installed at the end of each aisle enable the transfer of mini-loads between tiers [69]. This system is characterized by flexible travel within the aisle [70].

Autonomous vehicle storage and retrieval systems are widely used in e-commerce warehouses due to their high throughput, flexibility and their ability to increase warehouse speed [71]. The AVS/RS serves as a viable alternative to the miniload system for handling the movement of small units within a warehouse. While both systems share a similar operational logic, the AVS/RS offers a notable advantage in terms of higher throughput capacity. However, it's important to note that the enhanced capabilities of the AVS/RS come with a higher associated cost compared to the miniload system [1].

Another benefit of this solution is the significant increase in storage area utilization due to the large number of tiers selected [90].

A distinction within the AVS/RS system is based on the assignments of the vehicles to the tiers and two types of configurations are used:

- *AVS/RS with tier-to-tier vehicles*

  In a tier-to-tier AVS/RS, the vehicle can change tiers using the lift and access any storage position in the storage racks. This configuration proves particularly advantageous for scenarios involving palletized unit loads [71].

- *AVS/RS with tier-captive vehicles*

  In this setup, the autonomous vehicle is responsible for the movements of the loads in only one tier. These systems with tier-captive configurations are suitable for storing small-sized loads and the cost of the system is low compared to the tier-to-tier system [71]. A typical handicap associated with a tier-captive AVS/RS design is that, since there is a single lifting mechanism installed at each cross-aisle, lifts mostly become bottlenecks in the system.

This dynamic may result in higher utilization rates for lifts compared to shuttles, impacting the overall system efficiency [70].

5. **Grid-based shuttle - Dynamic storage (puzzle-based)**
The grid-based shuttle category is a variant of the shuttle-based AVS/RS, in which shuttles move on a grid [62].
In a puzzle-based storage system, shelves are designed to slide along two orthogonal directions, dynamically uncover the aisles, and they are progressively shifted to load/unload bays that are usually located on the perimeter of the system.
The puzzle-based storage is an innovative storage system in which shelves are moveable and hence allow the flexible arrangement of aisles [72], making it a promising solution, as long as retrieval times are fast enough and the required investment is not too high [72].

Several variants of the puzzle-based storage systems exist:

- *GridStore*
GridStore is a high-density storage system for physical goods, whose features are scalability, modularity of the structure and decentralized control. Modules communicate only with neighbor modules to which they are connected in the grid. They are also capable of communicating with the items they contain, for example, with the use of RFID [73].

- *GridPick*
Based on the GridStore architecture, GridPick is an order picking system that is filled with high-density storage containers without any fixed lanes or aisles [62].

- *Live-Cube Compact Storage*
This system stores unit loads, such as pallets, multi-deep at multiple levels of storage grids, each located on its shuttle. Live-cube compact storage systems realize high storage space utilization and high throughput due to full automation and independent movements of unit loads in three-dimensional space [74].
Each unit load is located on its shuttle and shuttles move unit loads at each level in the x and y directions, with a lift taking care of the movement in the z-direction [74].

- *GridFlow System*
This system aims to offer a cheaper and more flexible system solution in which AGVs are used to move the pallets instead of conveyors.

The use of AGVs instead of conveyors makes the system more flexible concerning design and throughput changes [62].

6. **Grid based shuttle - Static storage (RCSRS)**
Robot Compact Storage and Retrieval System (RCSRS) is an automated unit-load storage and order picking system that uses robotic technology [75]. This system is a grid-based system in which items are stored in a very dense storage stack with a grid on top, where robots with lifting capabilities can extract bins from the storage frames and transport them to the workstations, which are located at the lowest level next to the storage stacks [62].

The popularity of this system is due to several reasons [75]:

- *Flexible, modular structure*. A company can start with a small grid, which can be built within any existing warehouse, and then gradually expand it over time without stopping production [76]. Because the RCSRS is a completely modular system, the number of robots and ports can be easily modified, as the capacity of the system can be flexibly modified [77]. In this particular solution, there are no constraints and the shape of the structure can be modified based on the needs of the company [1]. In particular, the layout is flexible and the grid can be built around pillars and other static obstacles [78].
- *Flexible throughput capacity*. By inserting more robots and workstations, throughput capacity can be expanded, even over a short horizon [75].
- *Relatively low costs*. Compared with some other automated storage systems, the robots are small and relatively inexpensive [79].
- *Compact storage space*. Bins are put on top of each other and robots transport bins on the grid roof, which eliminates travel aisles, while inventory items are stored in vertical stacks and robots only move along the roof of the grid, thereby significantly reducing the required storage space. The RCSRS is known to reduce storage space by 75% compared with conventional storage systems with aisles and shelves [77]. The high storage density is reached thanks to the lack of aisle.
- *Short response times*. Robots can move flexibly, using congestion-free shortest paths between locations. High-speed robots that can work all day in a compact space are employed to significantly reduce processing time [77].

The weakness of this solution is the low selectivity. In particular, to retrieve a target bin, all bins located above must be reshuffled, causing the depth-wise position of bins to change repeatedly. Therefore, the amount of work required for a robot to process bins depends heavily on the sequence in which orders are processed [77], because if a requested bin is not on the top level, the sorting robots must re-sort the bins, lifting all bins that are blocking the requested bin and move them to nearby locations. After sorting, the transport robots can grab the bin and bring it to the workstation, where pickers can take a product out of the bin to satisfy an order [100].

AGV/AMR

An automated guided vehicle system (AGVs) is an advanced material handling system widely used in various automated systems, particularly in e-commerce warehouses. Compared with the traditional automatic systems, the AGV system is becoming a promising alternative, with an obvious advantage in terms of flexible deployment and the convenience of real-time routing and rescheduling [80].

This automation category groups together AGVs (Automated Guided Vehicles) and AMRs (Autonomous Mobile Robots) because of the shared operational principles and management strategies they employ. The only difference between AMR and AGV is that the AGV typically follows fixed paths or tracks for material transportation, requiring infrastructure changes like magnetic tapes or wires, while AMR is a robot that operates autonomously and can navigate in an uncontrolled environment without the need for fixed paths or tracks [81].

In contrast, AGVs can only follow fixed paths and move to predefined points on the guide path, while AMRs can move to any accessible and collision-free point within a given area [82]. For this reason, AMRs offer higher flexibility than AGVs; for example, small changes as a layout change would typically take substantial time for most AGV guidance systems, causing periods of inactivity and risk economic losses and decreases in productivity. AMRs, however, can adapt quickly to changes in the operating environment [82].

Compared to an automated guided vehicle (AGV) system in which a central unit takes control of scheduling, routing, and dispatching decisions for all AGVs, AMRs can communicate and negotiate independently with other resources like machines and systems and thus decentralize the decision-making process [82].

The automation solutions that adopt AGV and AMR systems are:

7. **AGV/AMR - Movable rack (RMFS)**

The Robotic Mobile Fulfillment System (RMFS) is characterized by a high level of flexibility and scalability [83] [84], in which robots capable of lifting and carrying movable shelves retrieve the movable shelf racks and transport them to the pickers. In RMFS, mobile robots carry inventory shelves autonomously from the storage area to picking stations and back [85].
At the picking stations, human pickers complete the order picking and potential packing tasks, eliminating the need for pickers to traverse aisles and even double the warehouse productivity [105].

Due to the elimination of non-value-adding picker walking, MRFS have a high picking performance, making them well suited for the tight deadlines of e-commerce; in fact, this system is widely used in e-commerce distribution centers [86].
In contrast to other parts-to-picker systems, MRFS have a flexible layout and come by without fixedly installed hardware [45].
RMFS has strong expansibility and flexibility because it can rapidly improve the throughput capacity of the system by increasing the number of robots and pickers during peak periods, such as shopping festivals [86], allowing this system to be flexible to varying workloads [45].
An MRFS provides added benefits of flexibility and scalability in addition to the associated advantages of automation [87]. In particular, by adding more robots, pods and/or workstations, the throughput capacity of handling additional orders can be addressed economically and in a relatively short period [87].
Moreover, RMFSs offer enormous storage flexibility because the allocation of a shelf to a storage location can be modified after every picking operation, which allows for the layout to be adapted in real-time, whether in response to changing demand or simply to leverage immediate opportunities [88].

In an RMFS, the warehouse is mainly divided into the storage area and picking area, where items are stored on removable shelves that are distributed in a storage zone consisting of parallel aisles [109]. When customers' orders enter the system and are linked to the robot's task, the robot can transport the movable shelves to the corresponding picking stations through an automatic guided function to help the human worker. It then moves the shelves back to the storage area [109].

8. **AGV/AMR - Static Rack (Pick support)**
   In this system, an AGV/AMR automatically follows the picker closely and transports the roll cages, so that the picker can drop off the retrieved items, allowing to reduce unproductive walking times in a picker-to-parts system.
   These AGV/AMR carry the picked units in bins (or on pallets, containers, or roll cages if large-sized SKUs are processed) and autonomously accompany pickers on their way through the warehouse [45].
   AGV/AMR-assisted order picking is often applied for heavy and bulky items, that cannot be carried by the picker back to the depot, so vehicle support is required anyway. The additional investment for upgrading a traditional forklift to an AGV/AMR is comparatively low [45].
   An AGV/AMR-assisted system is also easily scalable by adding or reducing pickers and AGV/AMR to adapt to varying workloads, for example, due to seasonal changes in customers' orders, such as end-of-season sales [89].

9. **AGV/AMR - Static Rack (Mobile pick)**
   These systems automate the whole picking process, where the AGV/AMR automatically goes to the picking location and picks up the item without any help from the picker. Like the previous variants, once the order is complete, the AGV/AMR transports the picked items to the depot.

7.3.2. Case studies

After the analysis of the literature, through the analysis of the case studies, the different automation solutions adopted in real omnichannel warehouses were identified, allowing researchers to validate or refine the theoretical insights gained from academic studies.

While certain case studies may avoid giving explicit details about their chosen automation solutions due to privacy concerns, this approach sheds light on the practical application of automation solutions by elucidating their real-world implementation within omnichannel companies.

In this paragraph, the most relevant automation solutions proposed by the case studies are clustered according to the defined framework and deeply explained.

Miniload

In Case study 5, the implementation of a miniload system emerges as a solution for effectively managing the requirements of an omnichannel warehouse. In particular, this technology is used for the handling of online orders to ensure high performance to meet the expectations in this channel, while the traditional channel is managed through a man-to-good logic.

Aisle-based shuttle - AVS/RS

In Case study 1, an AVS/RS was strategically implemented for the management of the Micro Fulfillment Center, specifically catering to online order fulfillment, that utilizes shuttle systems designed to handle light loads. This solution employs shuttles for horizontal movement within each level of the storage facility, while the lifts, able to transport four containers per cycle, are used for vertical movement between the different levels.
One of the standout advantages of this AVS/RS solution is its ability to guarantee high performance in terms of operational speed and the utilization of this technology extends beyond the order picking, encompassing the buffering and sequential consolidation of orders as well.

Case study 2 proposes a solution characterized by an AVS/RS to address the complexities of omnichannel order fulfillment.
This solution is characterized by a high level of flexibility and high scalability with no limitations in the dimensions of the systems.
While well-suited for omnichannel contexts, a critical threshold emerges: when online orders exceed 20-25% of total orders, potential bottlenecks arise because when the percentage of e-commerce is high, a lot of cartons exit from the shuttle systems to perform a low number of picking (because e-commerce orders have a low number of order lines) and create a bottleneck in the shuttle.

Also Case study 11 implements the AVS/RS solution in the warehouse.

Grid-based shuttle - Dynamic storage (puzzle)

In Case study 10, an innovative automated compact warehouse that manages boxes is employed, which can guarantee high storage density and high picking performance.
Another advantage of this solution is flexibility, offering the possibility to increase the productivity of the warehouse thanks to the possibility to scale the number of shuttles to face increment of demand or enlargement of the product assortment.
This flexibility extends beyond scalability, encompassing the physical constraints of the warehouse itself: the system exhibits the capacity to integrate seamlessly with varying roof shapes and heights, underlying its adaptability to diverse warehouse infrastructures.

Grid-based shuttle - Static storage (RCSRS)

In case studies 3 and 9, the adoption of the RCSRS emerges as an automation solution with a distinctive emphasis on flexibility, a fundamental characteristic in the omnichannel landscape.
Case study 3 underscores the inherent flexibility of this solution due to its capability to adjust the number of robots based on variations in demand, enabling the company to modify its capacity in alignment with shifting demand volume.

Case study 9 also emphasizes the significance of flexibility in choosing this automation because it guarantees a good level of flexibility thanks to the possibility of modifying the capacity of the automation system.

AGV/AMR - Movable rack (RMFS)

Case study 13.2 adopts an RMFS in which a fleet of AGVs move the shelves and transport them to designated picking stations, where the operators perform the picking activity. The point of strength of this solution is flexibility, with the possibility to change the number of AGVs with time. Additionally, the case study underscores the flexibility associated with the seamless transfer of technology between different warehouse sites. In particular, by utilizing this solution, the company managed to relocate the technology from one site to another, all while preserving fully stocked shelves, with only a brief operational interruption of two weeks.

AGV/AMR - Static Rack (Mobile pick)

The warehouse of Case study 13.1 adopts a solution centered on mobile pick AMR. Within this setup, robots select boxes and transport them to assigned picking stations, where the picking activity is performed by human operators. This configuration, while entailing a high investment, leads to significant benefits in terms of flexibility, thanks to the possibility of adjusting the number of robots based on demand.

Case 14 proposes an innovative automation solution to face the challenges of the omnichannel environment. The proposed solution introduces mobile picking robots that autonomously retrieve boxes and transport them to designated picking stations. The innovativeness of this solution lies in its dynamic adaptability to omnichannel's variable demands because rather than a traditional fixed investment, the system introduces a unique renting model for the robots, called RaaS, which gives the possibility to cope with the variability of flows in the year, managing the peaks typical of omnichannel without the oversizing of the warehouse. The RaaS paradigm will be analyzed in the next chapter.

In Case study 12, the company proposes the implementation of AMRs to companies operating within the omnichannel context. These AMRs are utilized to manage bin movements within the warehouse and when an order is received, an AMR starts collecting the bins containing the requested products and transports them to picking stations, where human operators carry out the picking process.

The primary strength highlighted by this solution lies in its flexibility, allowing to adapt to various warehouse layouts and ensuring scalability by enabling the addition of more machines.

Another consideration is the achievable throughput, which is relatively low compared to other automation solutions, which might not be suitable for companies with high productivity demands.

The automations solutions adopted in the case studies analysis are clustered in the framework represented in *Figure 7.3*.

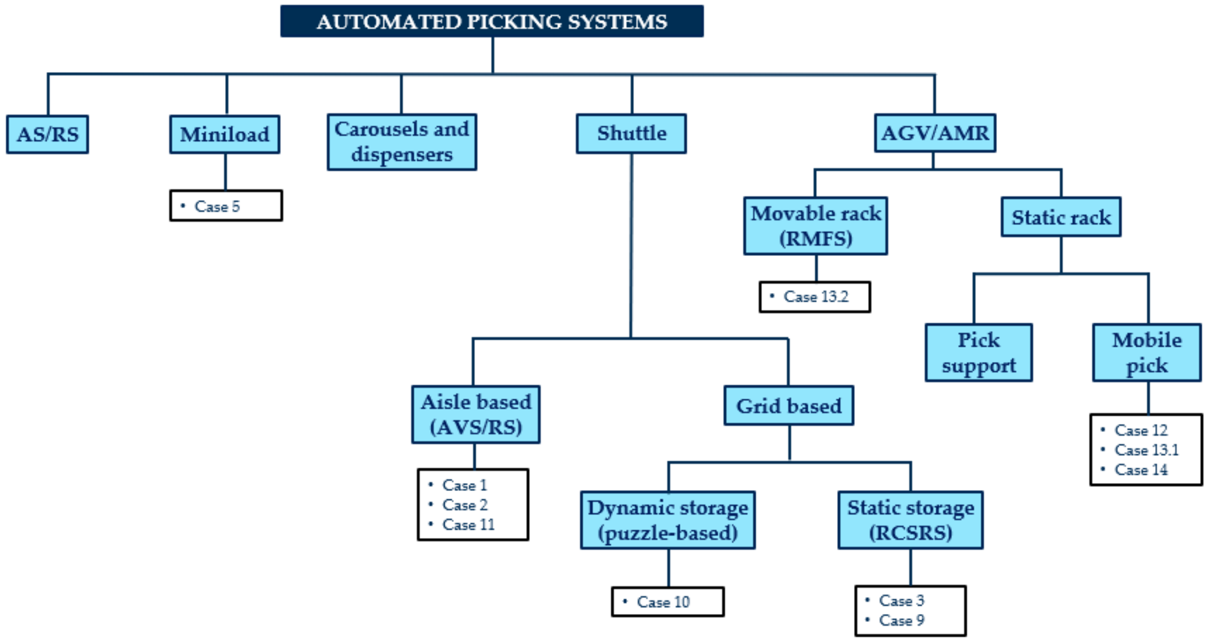

Figure 7.3: Case studies associated to the warehouse automation solutions

7.3.3. Criteria driving the choice of automation

The analysis of various automation solutions in the literature and case studies, along with insights gained from discussions with logistics experts through semi-structured interviews, leads to the conclusion that there is no one-size-fits-all automation solution. Instead, the choice of automation solution should be based on the specific needs of the company and the context in which it operates.

The case study analyses helped to identify valuable decision criteria that help in selecting the most fitting solution:

- **Articles characteristics**
  The first criterion is related to the specific characteristics of the articles which are handled in the warehouse. As suggested by Case 1, the attributes of the articles, such as temperature requirements, dimensions, weight and typology of unit load play a crucial role in determining the suitability of automation solutions.

- **Building characteristics**

  The physical attributes of the warehouse building, such as height, flooring and shape, have a direct impact on the feasibility and efficacy of automation solutions. As underlined by Case 12, the height of the building emerges as a critical factor, especially in the case of systems necessitating vertical space and it becomes a key constraint in the decision-making process for automation solutions.

  Furthermore, the type and condition of the flooring within the warehouse play a role in determining the viability of certain automation technologies. For instance, AGV systems require a specific type of smooth surface to ensure optimal functioning.

  Additionally, Case 10 underlines the importance of the shape of the building, encompassing both its layout and available floor space, contributing to the configuration and design of the chosen automation system.

- **Performance objectives**

  The objectives of the company affect the choice of the automation solution because the different automations are characterized by different performances and based on that, the solution that best fits the company is chosen.

  The performance objectives that can be achieved in the warehouse can be of different typologies like speed, cost, quality or flexibility.

- **Mix capex/opex**

  An important consideration in the decision to automate the warehouse is the financial aspect. Based on the needs of the company, it’s important to balance the capital expenditure and the operating expenditure. Certain automation solutions may demand higher upfront investments for equipment, software, and implementation, while subsequently offering lower ongoing operational costs. On the other hand, some solutions might have lower initial costs but entail higher ongoing expenses due to maintenance, energy consumption, or labor requirements.

  This consideration requires a comprehensive cost analysis that takes into account the total cost of ownership over the system's lifecycle.

- **Integration with existing systems**

  Another pivotal criterion is the integration potential of an automation solution with pre-existing hardware and software systems. This criterion considers the relationship between automation technology and existing systems and it holds particular significance within the context of omnichannel operations, where automation might be initially introduced in one channel and subsequently extended to others or it could be introduced when a new channel is added.

7.4. RaaS

In response to flexibility and scalability needs of the omnichannel warehouse, a possible response identified by the case studies is an emerging paradigm known as Robots-as-a-Service (RaaS), which offers a promising avenue for addressing the dynamic demands of modern warehousing.
The concept of Robots-as-a-Service entails a business model where robotics companies provide the option for clients and customers to rent robots for varying durations, whether short-term or long-term [90].

This concept is part of the broader trend of servitization, where businesses are shifting from traditional product-based models to offering rentable services, and the servitization within the warehouse automation context, which describes the shift from traditional product-based business models towards rentable services, is an opportunity to utilize automation without the typical disadvantages, such as installation and configuration efforts, long setup and ramp-up times [91]. Moreover, servitization allows for utilizing a resource without paying large investments upfront and saving fixed costs when the resource is no longer needed [91]. Since service fees are charged at a predictable rate, uncertainty about costs is eliminated [91].
The basic idea is to rent a resource when it is needed, to integrate it quickly and effortlessly into a process, and to finally return it after use, leading to higher levels of sustainability due to higher degrees of resource utilization, that can be achieved through lower idle times of resources and greater adaptation to demands [91].

From the analysis of the real application of the RaaS paradigm and the study performed on the automated picking system analysis, it's possible to state that the RaaS paradigm is mainly applied to *AGV/AMR* automation solutions.
This paradigm is not yet deeply analyzed in the literature because it is an emerging trend not yet studied in the logistics field.
The academic landscape concerning RaaS in the context of warehouse automation is in its early stages. With the presence of only one article in the literature that acknowledges the broader concept of RaaS and its applications in industrial areas, there is a distinct lack of research that specifically delves into the integration of RaaS within the logistics and warehouse domain. This scarcity underscores the need for a more focused analysis of how RaaS can be effectively incorporated into the complexities of warehouse operations.

In practical applications, there is a growing interest in Robots-as-a-Service, as evidenced by an expanding array of case studies that highlight its potential benefits and successful implementations.
For instance, in the context of Case study 12, while a fully established RaaS business model might not be in place yet, there is a clear recognition of the inherent advantages of this paradigm. The overview of the current RaaS application in the warehouse environment is summarized in *Table A.1*.

7.4.1. Raas advantages

According to Case study 14, the RaaS paradigm allows companies to obtain flexibility in the warehouse, thanks to the possibility of buying an initial fleet of robots at the beginning and then rent other robots for a limited period as needed, especially during peak demand periods or times of operational intensity. Organizations can tailor their approach to suit their specific needs, whether that involves renting robots to increase the capacity during peak seasons, gradually transitioning from renting to ownership, or vice versa [90].

Moreover, the RaaS model presents a valuable opportunity for companies to achieve scalability in their automation, thanks to the possibility of initially purchasing a core fleet of robots and subsequently expanding the fleet through rentals. This involves renting a fleet of robots for extended periods to accommodate the growth in volume across different channels.

The RaaS perfectly suits the need for flexibility and scalability that characterizes the omnichannel landscape. Specifically, RaaS addresses the dimension of flexibility related to changes in the capability of handling requests.

As highlighted in Case study 12, Robots-as-a-Service presents a significant advantage in terms of its potential impact on investment costs, offering the ability to transform the nature of automation costs from capital expenditures (CAPEX) to operational expenditures (OPEX), resulting in a reduction of investment risks.

In fact, by opting to rent automation resources, companies can mitigate the investment cost and simply pay for the use a monthly or yearly fee. This change in the cost component can eliminate a barrier related to the high cost of investment that prevent companies from adopting automation solution [91], particularly smaller organizations [92].

Traditionally, the acquisition of automation solutions for warehouses has posed a substantial financial problem and the RaaS model strategically eliminates or reduces these financial barriers by offering the possibility to lease or rent robots without having to shell out an exorbitant amount of money at the outset [90].

For instance, as highlighted in Case study 6, the adoption of RaaS can be seen as a potentially disruptive solution because the return on investment is immediate.

Furthermore, the RaaS model offers another important advantage: it eliminates the necessity for customers to possess complicated robotics expertise in configuring, operating, modifying, or decommissioning robotic applications [91].

By removing this requirement for specialized knowledge, RaaS effectively eliminates the barrier of 'lack of expertise' that has traditionally impeded companies from embracing robotics on a broader scale.

This characteristic of the RaaS approach ensures that companies can easily engage with and deploy automation solutions without the need for internal robotics knowledge, thus democratizing access to automation [91].

7.4.2. RaaS and omnichannel challenges

The RaaS paradigm effectively addresses the challenges posed by the omnichannel environment, including:

- **Demand variability (often in a non-repetitive way)**
  RaaS mitigates the challenge related to the unpredictable and often non-repetitive fluctuations in demand within the omnichannel by allowing for dynamic adjustments in automation capacity, reducing the impact of errors in the dimensioning of this capacity.
  By adopting RaaS, organizations can reduce uncertainty and technical barriers to automation adoption, allowing them to swiftly deploy robots to manage changing demands without the burden of substantial upfront costs [93].
  Case study 14 underlines the importance of the adoption of a RaaS solution in addressing demand variability throughout the year, with periods characterized by different volumes of demand.
- **High peaks in terms of entity, period, duration**
  The RaaS paradigm can effectively cope with the challenge related to the high peaks that are difficult to predict. With RaaS, the management of such demand peaks becomes significantly more manageable through the ability to rent additional robots during peak periods.
  Case study 5 emphasizes that RaaS can serve as a viable alternative to the approach of oversizing the automation system to accommodate peaks.
  As noted in Case study 14, adopting the RaaS paradigm, a warehouse can be designed for standard capacity throughout the year, while additional robots can be rented to manage peak periods efficiently.
- **Growth rate difficult to predict (unpredictability of the environment)**
  The RaaS paradigm effectively addresses the challenge related to the unpredictable growth rates in the omnichannel environment, leading to fluctuating demand volumes over time.
  Case study 2 highlights the suitability of RaaS for managing unpredictability in the omnichannel context by initially implementing a small system and subsequently expanding it based on actual needs.
  This becomes crucial in mitigating the risk of making incorrect decisions regarding automation investment because the capability of RaaS to modify and adjust solutions post-implementation provides a mechanism to rectify wrong decisions and offers a level of adaptability and flexibility that is not easily achievable through traditional automation approaches.
- **Incidence of the different channels that change in time**
  The RaaS paradigm effectively addresses the dynamic changes in the incidence of different channels over time.

As the volumes of various channels experience shifts, managing these fluctuations separately can result in significant variations in workload, but with the adoption of the RaaS paradigm, the fluctuations in the channels can be managed easily, thanks to the possibility of modifying the size of the fleet.

- **High growth rate of the online channel**
  The RaaS approach also holds significance in managing the high growth rate of the online channel. The online channel's rapid expansion demands scalability in order fulfillment operations and RaaS presents an effective solution to address this requirement by facilitating the expansion of the initial robotic fleet.

7.4.3. RaaS requirements

To be successful, the RaaS needs the following requirements:

- **Standardization of the robots**
  For RaaS to effectively operate, Case study 2 emphasizes that the automation robots need a standardization that allows them to be rented out to various customers, underscoring the necessity for a consistent and uniform robotic fleet that can be easily deployed across different warehouses.
  The important aspect required by the automation associated with this paradigm is the characteristic of standardization, meaning that the automation offered to the customers is always the same, to be universally utilized by different players within the industry.
- **Software requirements**
  Another critical requirement for companies embracing the RaaS paradigm is the readiness of their software infrastructure, as underlined by Case study 14. Specifically, these companies need to possess software systems capable of effectively managing the dynamic nature of RaaS operations, with the software that must be designed to accommodate a fluctuating number of robots within the operational framework.
- **Development of a market**
  One of the pivotal prerequisites for realizing the potential benefits of RaaS is the widespread availability of this solution within the market. The emergence of a thriving RaaS market is crucial for maintaining competitive costs and ensuring the viability of this business model.
  However, as highlighted by Case study 14, the current status of the RaaS market is not yet fully developed. Although there is interest from retailers and automation providers in this innovative approach, the adoption rate remains limited, with high costs in the solution.

This issue can be attributed to a combination of factors: on the supply side, the novelty and innovation of the RaaS concept may pose challenges for implementation, while on the demand side, the concept is relatively new and unfamiliar to the market, which may contribute to limited awareness and understanding.
As a consequence of the nascent stage of the market, which leads to a lower utilization of resources, costs associated with RaaS solutions can be relatively high because retailers have to allocate resources for robot rentals rather than sell them.

- **Mobility**
  Traditionally, warehouse automation is often anchored to a specific warehouse without the possibility of moving it from the warehouse to which it is designed, limiting the mobility and subsequent flexibility of the automation. In a RaaS context, mobility refers to establishing robots that can be easily and effortlessly deployed for a new task in different warehouses and it is expected that these robots will perform tasks in constantly changing locations and environments [91]. To guarantee mobility, rapid setup times and swift reconfiguration of different robotic applications are needed.

7.4.4. RaaS business models

Business models in the context of Robots-as-a-Service (RaaS) encompass a comprehensive framework that outlines the costs and responsibilities attributed to both participating entities: the service provider and the service customer. Ideally, a service customer should be able to quickly identify the break-even of a RaaS application and thus, determine whether the application is economical [91].

Overall, different business models can be distinguished either based on time or service usage [91] (*Figure 7.4*):

- **Time-based**
  This is the most straightforward form of service business, where a company will provide a service and bill the customer for the entire duration. In this model, a company rents a robot for an hourly/daily/monthly/annual fee [91].
- **Usage-based**
  Rather than renting a robot for a fixed time period, there are also business models in which customers pay for the usage of a service.

  For example, companies can rent a “sorting capability”, which consists of a robot to perform sorting of products and the customers pay the intelligent operation, i.e. each performed action [91].

On a slightly higher level, warehouse robots can be rented to perform a full spectrum of tasks. For instance, warehouse capabilities can be rented, in which AGVs locate a good in a shelf, perform a pick operation, and deliver it to an assembly line. In this case, customers pay per completed task (locate, pick, and deliver), as offered by some important players [91].

The highest level of usage-based business models is a full-on robotic outsourcing of an entire job/profession. This application within the industrial domain is still considered at an early stage, but the potential of this solution is high, because the adoption of robotic outsourcing during high seasonal demands could be an appealing concept for companies, which would otherwise hesitate to hire employees temporarily [91].

The companies who own the equipment hold much of the risk when it comes to usage bases leases because if the customer is not using the equipment or it's not being used as much as projected, there's little incentive for a company to offer a usage-based RaaS model. For this reason, robotics companies often set minimums to counteract any underutilization [90].

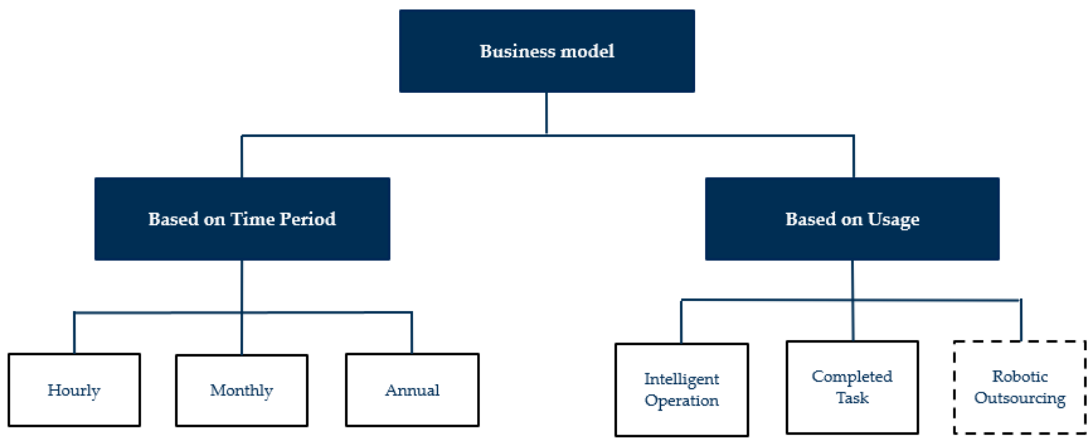

Figure 7.4: RaaS business model (Source: [91]*)*

The factors that need to be considered by RaaS providers to estimate the costs for their services are [91]:

- **Hardware costs**
  This factor is one of the main drivers of the RaaS service fees. In addition, the lifespan of hardware needs to be considered, as in when a robot/ sensor needs to be replaced with a new or later model.

- **Integration and programming costs**
  Skilled technicians and programmers are required to set up a robot or robotic system on a RaaS customer's site. These high personnel costs are also anticipated to substantially contribute to the overall service fee.

- **Maintenance costs**
  A robot, tool or sensor could fail due to malfunction or general wear. In this case, the RaaS provider is expected to quickly replace the faulty part to minimize disruption.

- **Logistic costs**
  Transporting a robot to a customer's site and removing it after the service period has ended is also expected to cause costs. These costs mainly depend on the geographic distance and the size/weight of the equipment.

- **Storage costs**
  Ideally, the robotic hardware would be constantly rented and thus, be in a RaaS customer's warehouse, but this is considered unrealistic and storage costs for the period in which the robot is unrented are necessary. Moreover, RaaS providers are expected to store spare parts in case one of the robots on site fails due to a malfunction. Consequently, the RaaS provider is expected to maintain a storage facility.

- **Software costs**
  As mentioned in previous sections, a robotic system is a combination of hardware and software. Therefore, RaaS providers are also expected to pay software license/support fees, for example, for programming environment and sensor interfaces.

- **Disposal costs**
  After a robot, tool or sensor reaches the end of its lifespan, a RaaS provider is expected to be responsible for disposal.

7.5. Conclusions and analysis of the results

Upon reviewing the existing literature, a notable gap within the current academic literature becomes evident, specifically related to the analysis of flexibility applied to automation in the context of omnichannel warehousing. Previous research primarily examined automation solutions within a broader context and automation solutions have been assessed based on various requirements and criteria, with flexibility being just one among many factors considered. However, this Thesis addresses this gap by placing flexibility as the central and primary objective of the investigation.

This Thesis conducts a thorough examination of flexibility and how it can be reached in automation solutions. To reach this objective, an analysis of the automation solution with a focus on flexibility has been performed through the analysis of the academic literature and case studies.

Moreover, the prevailing trend in the current literature focused on warehouse automation is predominantly centered around the examination of specific automation solutions and their associated quantitative performance evaluations. This emphasis on technical and operational aspects often neglects a more holistic examination of the decision-making process related to automation in warehouse operations.
To bridge this gap, this Thesis analyzes the criteria driving the choice of automation influencing the selection of automation solutions for warehouses.

The comprehensive analysis of the existing literature reveals a noticeable gap in research regarding the lack of specific analysis of automation for the omnichannel warehouse. Despite the increasing prominence of omnichannel operations in the modern business landscape, there appears to be a scarcity of academic attention dedicated to investigating novel paradigms or specific automation solutions that could arise from an examination of the characteristics of omnichannel logistics. To bridge this gap, an analysis of the automation solutions implemented by omnichannel warehouse has been performed.

Moreover, to analyze the automation that suits the omnichannel environment, the RaaS paradigm has been analyzed in this Thesis. This paradigm remains significantly underexplored within the existing literature, with only a paper delving into its application, which primarily addresses RaaS in industrial contexts at large, lacking a specialized focus on warehouse applications. This Thesis aims to analyze this paradigm, specifically examining the application of RaaS within omnichannel warehouses as a proactive approach to enhancing flexibility in the automation applied to the omnichannel warehouse.

7.5.1. Analysis of the automation solutions: literature review

The literature review analysis identified various typologies of warehouse automation solutions. Clustering the papers of the literature in the different automation solutions, without counting [62], *Table 7.1* is defined.

Automated picking system	Number of papers	Number of papers that mention flexibility
Automated Storage Retrieval System (AS/RS)	4	1
Miniload	4	/
Carousels and dispensers	3	/
Aisle-based shuttle - AVS/RS	6	4
Grid-based shuttle - Dynamic storage (puzzle based)	4	1
Grid-based shuttle - Static storage (RCSRS)	6	5
AGV/AMR - Movable rack (RMFS)	23	11
AGV/AMR - Static rack (Pick support)	2	/
AGV/AMR - Static rack (Mobile pick)	/	/

Table 7.1: Number of papers on the automation solutions

The details with the specific papers that cite the different automation solutions are represented in *Table B.10*.

The analysis of the literature review has identified a wide array of automation solutions, effectively addressing the various categories outlined in [62]. This comprehensive evaluation affirms the existence of a vast spectrum of automation options, leading to the conclusion that modern warehouses have a wide range of choices when selecting automation systems.

As companies evaluate their unique needs and characteristics, they can make informed decisions regarding the adoption of the most suitable automation solution.

Table 7.1 sheds light on a notable trend: a significant focus is related to the *AGV/AMR with movable rack (RMFS)*. The adoption of this solution is especially prevalent in the e-commerce sector due to its capacity to guarantee high performance in terms of speed, productivity and flexibility.
An example of an e-commerce company that adopted this solution is Amazon, which acquired Kiva Systems in 2012, subsequently deploying RMFS across ten of its warehouses by November 2014 [51]. This proactive adoption by Amazon serves as a powerful proof of the efficacy and relevance of the RMFS within the dynamic landscape of e-commerce logistics, amplifying the significance of this automation solution. The heightened interest in the practical application of this automation solution pushed the literature to analyze this topic.

Another insight that is possible to gain from the table is a general homogeneity in the distribution among the other automation solutions. The slight outlier is related to *AGV/AMR with static rack (Mobile pick)*, which have received comparatively limited attention within the academic discourse, with no citations from the literature.
Regarding this solution, the relatively low exploration of the *AGV/AMR with a static rack (Mobile pick)* underscores its emerging nature within the existing literature. Despite the potential advantages it offers, particularly within the dynamic realms of e-commerce and omnichannel operations, the research string finds a limited number of papers dealing with this solution, which might be because of the nascent development of the literature in this area.

Looking at flexibility analysis of the different automation solutions, a clear distinction emerges regarding the automation solutions that can enhance flexibility: *Aisle-based shuttle - AVS/RS* (4 citations related to flexibility out of 6 total citations), *Grid-based shuttle - Static storage (RCSRS)* (5 citations related to flexibility out of 6 total citations) and *AGV/AMR - Movable rack (RMFS)* (11 citations related to flexibility out of 23 total citations). This analysis underscores that, according to the literature, the automation solutions that offer the highest level of flexibility are the ones mentioned.

7.5.2. Analysis of the automation solutions: case studies

The case studies analysis further emphasizes the diversity of automation solutions applicable in omnichannel warehouses and the clustering of the automation solutions adopted by the case studies allows to define *Table 7.2*.

Automated picking system	Number of case studies	Number of case studies that mention flexibility
Automated Storage Retrieval System (AS/RS)	/	/
Miniload	1	/
Carousels and dispensers	/	/
Aisle-based shuttle - AVS/RS	3	2
Grid-based shuttle - Dynamic storage (puzzle)	1	1
Grid-based shuttle - Static storage (RCSRS)	2	2
AGV/AMR - Movable rack (RMFS)	1	1
AGV/AMR - Static rack (Pick Support)	/	/
AGV/AMR - Static rack (Mobile pick)	3	3

Table 7.2: Number of case studies applications on the automation solutions

The details related to the list of the specific case studies that apply the automation solutions are represented in *Table B.11*.

The analysis of the case studies underscores the consistency between the insights derived from these practical implementations and the automation trends identified in the literature review. Specifically, consistent with the literature, the case studies reinforce the absence of a one-size-fits-all automation solution.

Instead, the landscape is characterized by a proliferation of diverse solutions, reflecting the multifaceted nature of omnichannel warehousing challenges and requirements, where different companies may find distinct automation strategies to be better suited to their unique operational contexts.

In contrast with the literature review, certain automation solutions, like *Carousels and dispensers* and *AGV/AMR with static rack (Pick support)*, have not received extensive attention within the practical implementations. Remarkably, none of the examined case studies employed these types of automation technology.
A significant observation stemming from the case study analysis is the absence of implementations in the case study warehouses of automated solutions associated with *AS/RS*, due to the mismatch between *AS/RS* capabilities and the requirements of the omnichannel context. Notably, *AS/RS* systems are designed to handle palletized loads, whereas omnichannel operations often involve the movement of smaller units, such as cartons or boxes. This disparity in load characteristics likely contributes to the limited applicability of *AS/RS* solutions in omnichannel operations.

In contrast to its limited coverage in existing literature, the *AGV/AMR with static rack (Mobile pick)* solution emerges as a pivotal element in real-world case applications. Despite not receiving citations in academic papers, this solution finds extensive practical implementation and relevance across the analyzed cases. Among the various automation solutions, the *AGV/AMR with static rack (Mobile pick)* stands out prominently in the case study analysis, with three cases of its adoption, underscoring its potential as a promising solution for effectively managing omnichannel warehouses.

Looking at flexibility analysis of the automation solutions, the case studies analysis allows to confirm the three solutions suggested by the literature analysis: *Aisle-based shuttle - AVS/RS* (2 citations related to flexibility out of 3 total citations), *Grid-based shuttle - Static storage (RCSRS)* (2 citations out of 2 total citations) and *AGV/AMR - Movable rack (RMFS)* (1 citation related to flexibility out of 1 total citation). Moreover, the case studies analysis allows to complete the list of automation solutions that can be adopted to increase flexibility in the picking warehouse, adding to this list the *AGV/AMR – Static rack (Mobile pick)*, with a total of three citations related to flexibility out of three total citations. Also in this case the adoption of a mixed approach allows for a complete analysis, including an automation category that was not included in the analysis of the literature.

Concluding, according to the analysis of the literature and case studies, the automation solutions which can be adopted to increase flexibility of the warehouse are the following: *Aisle-based shuttle - AVS/RS*, *Grid-based shuttle - Static storage (RCSRS)*, *AGV/AMR - Movable rack (RMFS)* and *AGV/AMR – Static rack (Mobile pick)*.
The summary of these findings and the related number of citations are represented in *Table 7.3*.

Automated picking system	Number of papers that mention flexibility	Number of case studies that mention flexibility
Aisle-based shuttle - AVS/RS	4	2
Grid-based shuttle - Static storage (RCSRS)	5	2
AGV/AMR - Movable rack (RMFS)	11	1
AGV/AMR - Static rack (Mobile pick)	/	3

Table 7.3: Automation solutions able to increase flexibility

7.5.3. Analysis of the RaaS paradigm

The emergence of the Robots-as-a-Service (RaaS) paradigm presents a promising and transformative solution to address the crucial requirements for flexibility and scalability in automation, which are typical of omnichannel warehouses.

In particular, this paradigm can be closely linked with AGV/AMR solutions to enhance flexibility in the picking process, thanks to the possibility of renting robots as needed and dynamically adjusting their automation capacity. This level of flexibility is essential for effectively managing the numerous challenges associated with omnichannel operations, but as mentioned in the case studies and from the results of the survey conducted during the experts' group, the current state of the RaaS paradigm presents a critical issue related to its limited market penetration. This challenge is primarily due to the relatively early stage of the market, resulting in comparatively high costs associated with RaaS solutions, with associated difficulties in the development of this solution from the demand side of the market.

8 Conclusions and future developments

8.1. Main findings

The primary focus of this Thesis is to examine the concept of the omnichannel warehouse, focusing on effectively tackling the complex challenges inherent in this dynamic context.

A comprehensive research background has been conducted to establish the contextual framework for this Thesis, encompassing an analysis of the omnichannel strategy from a logistics perspective and an exploration of fundamental warehouse management principles.

The following sections concisely summarize the key findings that address the four research questions.

RQ1. What are the main characteristics and challenges that omnichannel warehouses have to deal with?

To address the first research question concerning the main challenges faced by omnichannel warehouses, a comprehensive analysis has been conducted, combining a literature review and a case studies analysis.

The literature review served as the initial step, leading to the development of a preliminary list of challenges, which has been modified and enriched by the insights obtained from the case studies, resulting in a comprehensive list of omnichannel challenges that significantly impact warehouse operations.

The resulting list encompasses a total of 22 challenges, categorized into four categories:

- **Increase of the expectations regarding the service level**
  - *Lead time reduction*
  - *Different service levels for different channels*
  - *Flexible deliveries*
  - *Postponement of the cut-off/continuous receivement of orders*
  - *Important to guarantee product availability*
- **Changes in the order profile**
  - *Dimensional difference in the order profile*
  - *Different units of picking*
  - *Different packaging and units of delivery*

  - *Different order frequency*
- **Changes in the demand profile**
  - *Demand variability (often in a non-repetitive way)*
  - *High peaks in terms of entity, period, duration*
  - *Growth rate difficult to predict (unpredictability of the environment)*
  - *Incidence of the different channels that change in time*
  - *Relevance of the return flow*
  - *Increase of the phase-in/phase-out frequency*
  - *High growth rate of the online channel*
  - *Fragmented demand base*
  - *Wide product assortment requested*
- **Constraints**
  - *Existing building*
  - *Warehouse already operative*
  - *Software not designed for omnichannel*
  - *Solution development/implementation time*

In addition to compiling a list of omnichannel challenges, this analysis goes a step further by quantifying the importance of each challenge, achieved through the application of three distinct scoring methods:

- *Literature score*: The first score is based on the frequency of citations in academic papers of each challenge. It reflects the prevalence of each challenge within the academic discourse and measures its significance.
- *Case study score*: The second score is derived from the number of times a specific challenge is mentioned in the interviews conducted during the case study analysis. This score offers validation from real-world scenarios and serves as an indicator of the challenges that are encountered and recognized by industry practitioners.
- *Experts' group score*: Another valuable methodology employed is the consultation of experts' group, in which a survey was conducted to assigns scores to each challenge category. The insights gathered from experts provide a quantitative assessment of the challenges, considering their industry expertise and practical experience.

By combining these three distinct scoring methods, this analysis identifies and categorizes omnichannel challenges and provides an understanding of their relative importance.

The analysis of the literature indicates that certain challenges are consistently emphasized. Specifically, the most frequently cited challenges include the "*High growth rate of the online channel*", with a total number of 26 citations, the "*Lead time reduction*" (22 citations) and the "*Relevance of the return flows*" (14 citations).

The case studies analysis allows to improve the list of challenges identified in the literature. This methodology serves to validate the relevance of challenges identified through the literature while also uncovering new challenges that had not been extensively addressed in academic sources, such as the challenge category related to the constraints or the challenge related to the "*Growth rate difficult to predict (unpredictability of the environment)*". Moreover, the case studies emphasize the significance of two challenges with particular emphasis: the "*Dimensional difference in the order profile*" and the "*Lead time reduction*", with 4 citations each.

The analysis of the experts' group results serves as a general confirmation of the list of challenges identified with the other two methods, with similar scores given by the participants to the different categories.
The significance of employing a methodology that combines insights from the literature and case studies is further underscored by the input from the experts' group, in which a key finding emerged: the category related to constraints is deemed the most important. Notably, this category had not been prominently identified in the existing academic literature, but it is identified as a fundamental challenge through the analysis of case studies.

From *Table 8.1*, it's evident that the category related to constraints, mainly related to the building and the information systems, is not identified in the literature, but it emerges as significant in the case studies and in the experts' group.

Category	**Literature score**	**Case study score**	**Experts' group score**
Increase of the expectations regarding the service level	35	12	70
Changes in the order profiles	14	11	71
Changes in the demand profile	66	11	69
Constraints	/	9	75

Table 8.1: Scores of the challenges categories

RQ2. How do the identified characteristics affect the warehouse areas and the management variables of the warehouse?

In the second research question, the literature review and the case studies analysis have been used to define the impacts of the omnichannel challenges on the warehouse configurations.

The result is a comprehensive framework in which the influence of each challenge on the following categories is identified:

- **Warehouse areas**. This category pertains to the various physical areas within a warehouse, encompassing:
  - *Receiving*
  - *Put away, storage*
  - *Picking, sorting*
  - *Packing, shipping*
- **Management variables**. The second category refers to the different variables critical for managing an omnichannel warehouse. These variables include:
  - *IT*
  - *Automation*
  - *Planning*
  - *Human resources*

Two separate tables are generated within these categories for each of the challenges identified in the omnichannel landscape. These tables serve to identify and document the impacts of these challenges on the various components of the warehouse areas and the management variables.

When considering the impact of omnichannel challenges on different warehouse areas (*Table 8.2*), it becomes evident that the most significant influence is observed in the picking and sorting area, with a total of 27 mentions across both the literature and case studies.

Additionally, the packing and shipping area is also considerably affected, receiving a total of 12 mentions. Interestingly, the case studies play a prominent role in highlighting the impact on this area, contributing to half of the mentions, underscoring the case studies' ability to identify emerging trends, such as the practice of “packaging on demand”, which has implications for packing and shipping operations.

Conversely, the impact on the receiving activity is relatively low, with only three citations, suggesting that challenges related to omnichannel operations have a more modest effect on the initial stage of receiving goods in the warehouse.

Warehouse areas	Literature review	Case studies	Total
Receiving	3	/	3
Put away, storage	10	2	12
Picking, sorting	20	7	27
Packing, shipping	6	6	12

Table 8.2: Number of papers and case studies on the warehouse areas

Regarding the impact of challenge categories, the "*Increase of the expectations regarding the service level*" category exerts the most substantial influence on various warehouse areas, accumulating 23 mentions across all areas.
Surprisingly, despite the importance attributed by the experts' group, the category related to constraints has a limited impact on warehouse areas, with only one citation, suggesting that while constraints are recognized as significant, they may not have a direct and immediate impact on specific physical areas within the warehouse.

When analyzing the impact of omnichannel challenges on management variables (*Table 8.3*), there is a relatively homogeneous distribution of mentions, with no specific variable significantly more affected than the others. However, it is worth noting that the human resources management variables receive slightly fewer mentions than the other management variables.
Furthermore, a notable pattern emerges when examining the distribution of mentions between the literature review and the case studies: case studies play a more substantial role in highlighting the impact on management variables than warehouse areas, particularly when considering the automation, planning and human resources variables, underscoring the significance of case studies in providing insights into the nuanced effects on these design aspects.

Management variables	Literature review	Case studies	Total
IT	12	4	16
Automation	6	8	14
Planning	10	6	16
Human Resources	6	5	11

Table 8.3: Number of papers and case studies on the management variables

Heterogeneity becomes apparent in terms of the impact of different challenge categories on the management variables. Notably, the "*Constraints*" category receives relatively few citations, with only 3 mentions, as does the "*Changes in Order Profiles*" category, with 3 mentions. In contrast, the categories related to "*Changes in the Demand Profile*" and "*Increase of the expectations regarding the service level*" garnered a substantial number of citations, totaling 33 and 18, respectively.
In particular, the "*Changes in Demand Profile*" category stands out for its notable impact on planning and the human resource variables, as it is the only category that influences this last variable.

RQ3. What is the level of integration and specialization of functional areas in the omnichannel warehouse?

To address the third research question concerning the level of integration and specialization of functional areas in the omnichannel warehouse, two analyses have been conducted.

Based on the existing literature, the first analysis focuses on the decision to integrate or separate storage and picking, which are two key warehouse activities, formulating the framework proposed in *Table 8.4*.

Specifically, the two decisions to be made are the following:

- *Integration or specialization of storage activity*
- *Integration or specialization of picking activity*

Considering these two fundamental decisions, the framework delineates four alternative configurations for omnichannel companies:

- *Integration of storage and picking*
- *Integration of storage and specialization of picking*
- *Specialization of storage and integration of picking*
- *Specialization of storage and picking*

	Integrated picking	**Separated picking**
Integrated storage	Full integration	▪ Different picking methods ▪ Different staff ▪ Different time windows ▪ Different parts of the warehouse
Separated storage	/	▪ Separate part of the WH ▪ OFC/MFC for online

Table 8.4: Framework for the integration or specialization of storage and picking

The analysis of these decisions involves identifying the advantages and disadvantages of each of these four configurations within omnichannel warehouse management.

Furthermore, the examining case studies provide valuable insights into these choices made by real-world omnichannel applications, underlying a considerable degree of consistency among these applications in terms of their integration or separation solutions. However, a noteworthy exception arises when considering the alternative of integrated storage and separated picking, as it stands out with the support of five case studies. The configuration of integrated storage and separated picking emerged as the most prominent and favored choice, supported by case studies and literature review.

The second analysis expanded the framework beyond storage and picking and enhanced the existing understanding of omnichannel warehousing by introducing a new framework for making decisions regarding the integration and specialization of various warehouse areas. This expanded framework encompasses not only the storage and picking activities but also considers all the warehouse areas:

- *Receiving*
- *Put away, storage*
- *Picking, sorting*
- *Packing, shipping*

Through the analysis of case studies, five distinct warehouse configurations are identified, each representing a different approach to integrating or separating these various warehouse areas:

1. *Integration of the receiving area*
2. *Integration of the receiving and storage*
3. *Specialization of the picking, sorting activities*
4. *Specialization of the packaging and shipping*
5. *Integration of the entire process*

For each of the outlined warehouse configurations, an in-depth analysis is conducted to assess the treatment of different warehouse areas within each configuration. Additionally, a practical, real-case example from the case studies is provided to illustrate the application of each configuration.

It is crucial to highlight that there is a different degree in terms of synergy and specificity across these configurations. Specifically, as we progress from the initial to the final alternative, there is an increasing synergy and a decreasing of specificity.

The analysis of the case studies also allows to identify the following decisional criteria for the decision between the different warehouse configurations:

- *Differences in the order profile*
- *Percentage incidence of the different channels*
- *Differences in the packaging requirements*
- *Differences in the unit of packaging*
- *Differences in the service level requested*
- *Overlapping and specificity of the assortment*
- *Different responsibilities and ownership of the stock*

According to the survey responses, the "*Differences in the order profile*" received the highest score (71). Following closely behind, the other criteria that needed to be taken into consideration are the "*Percentage incidence of the different channels*" (67), "*Differences in the packaging requirements*" (67) and the "*Differences in the unit of packaging*" (66).

The other criteria are perceived of lower relevance, particularly the "*Different responsibilities and ownership of the stock*", which received the lower score (56).

These decision criteria play a crucial role in selecting a configuration, guiding the decision toward a more integrated or specialized solution, as defined in *Figure 8.1*.

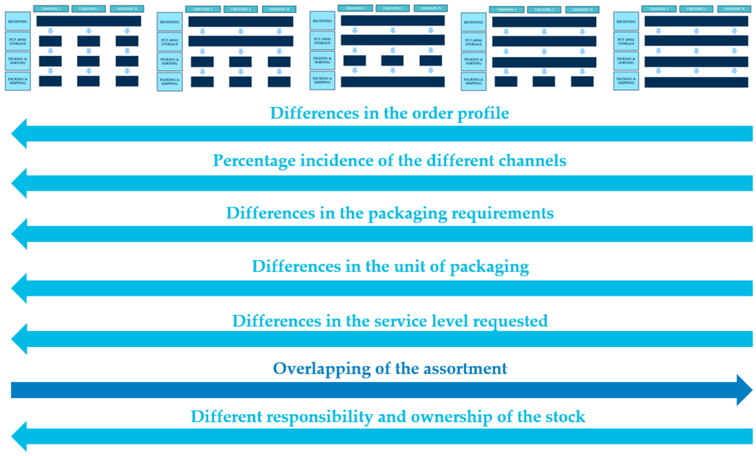

Figure 8.1: Influence of the decisional criteria on the warehouse configuration

RQ4. How it is possible to manage flexibility in presence of automation?

The last research question delves into managing flexibility in the picking activity applied to the automation.

To address this question, an extensive analysis of flexibility and scalability has been conducted based on existing literature, and the various dimensions of flexibility are analyzed.

The insight from the literature and case studies allows to shape a survey conducted among experts to identify key factors contributing to achieving flexibility in automation.
The three elements explored in the survey and the related scores are as follows:

- *Type of storage and movement technology* (71)
- *Mix between traditional and automated warehouse* (67)
- *RaaS paradigm* (50)

Survey results indicate that the type of technology adopted is the primary factor influencing flexibility in automated warehousing and for this reason it has been analyzed.
Furthermore, experts participating in the survey recognize the significance of a hybrid approach, which combines traditional and automated warehousing to achieve flexibility in omnichannel operations. However, it's important to note that this topic is already studied in the literature, and this thesis will not focus on it.
While the survey results suggest that the RaaS paradigm received a lower score compared to the other two factors, it is important to note that this highlights the emerging and innovative nature of RaaS within the field of warehouse management, suggesting that RaaS has potential for future growth and it needs a specific study.

A methodology based on literature review and case studies is employed to analyze the survey's first answer, specifically related to the typology of automation solutions for picking activities in warehouses. This methodology allows to analyze the characteristics of automation solutions with a focus on flexibility and their real-world applications in omnichannel warehouses.

The automation solutions are categorized into the following categories:

- *Automated Storage Retrieval System (AS/RS)*
- *Miniload*
- *Carousels and dispensers*
- *Aisle-based shuttle - AVS/RS*
- *Grid-based shuttle - Dynamic storage (puzzle-based)*
- *Grid-based shuttle - Static storage (RCSRS)*
- *AGV/AMR - Movable rack (RMFS)*

- *AGV/AMR - Static rack (Pick support)*
- *AGV/AMR - Static rack (Mobile pick)*

This literature review analysis confirms the existence of a wide range of automation solutions.
From this analysis, a significant focus is related to the *AGV/AMR with movable rack (RMFS)*.
Another insight that is possible to gain is the general homogeneity in the distribution of the other automation solutions, with the only outlier related to the *AGV/AMR with static rack (Mobile pick)*, which has received comparatively limited attention within the academic discourse.

Regarding flexibility analysis of different automation solutions, the following emerge as potential solutions to enhance flexibility: *Aisle-based shuttle - AVS/RS* (4 citations related to flexibility out of 6 total citations), *Grid-based shuttle - Static storage (RCSRS)* (5 citations out of 6 total citations) and *AGV/AMR - Movable rack (RMFS)* (11 citations related to flexibility out of 23 total citations).

To gain insights into the actual applications of various automation solutions in the context of omnichannel warehouses, a case studies analysis is conducted and the findings from the case studies' analysis align with the conclusions drawn from the literature review, underscoring the absence of a one-size-fits-all automation solution for omnichannel warehouses.

In contrast with the literature review, specific automation solutions, like *AS/RS*, *Carousels and dispensers* and *AGV/AMR with static rack (Pick support)*, have not received extensive attention in the real application of omnichannel warehouses. On the other hand, in contrast to its limited coverage in existing literature, the *AGV/AMR with static rack* solution emerges as a pivotal element in real-world case applications.

Looking at flexibility analysis of the automation solutions, the case studies analysis confirms the three solutions suggested by the literature analysis: *Aisle-based shuttle - AVS/RS* (2 citations related to flexibility out of 3 total citations), *Grid-based shuttle - Static storage (RCSRS)* (2 citations out of 2 total citations) and *AGV/AMR - Movable rack (RMFS)* (1 citation related to flexibility out of 1 total citation). Moreover, the case studies analysis allows to complete the list of automation solutions that can be adopted to increase flexibility in the picking warehouse, adding to this list the *AGV/AMR – Static rack (Mobile pick)*, with a total of three citations related to flexibility out of three total citations.

Concluding, according to the analysis of the literature and case studies, the automation solutions which can be adopted to increase flexibility of the warehouse are the following: *Aisle-based shuttle - AVS/RS*, *Grid-based shuttle - Static storage (RCSRS)*, *AGV/AMR - Movable rack (RMFS)* and *AGV/AMR – Static rack (Mobile pick)*. The summary of these findings and the related number of citations are represented in *Table 8.5*.

Automated picking system	Number of papers that mention flexibility	Number of case studies that mention flexibility
Aisle-based shuttle - AVS/RS	4	2
Grid-based shuttle - Static storage (RCSRS)	5	2
AGV/AMR - Movable rack (RMFS)	11	1
AGV/AMR - Static rack (Mobile pick)	/	3

Table 8.5: Automation solutions able to increase flexibility

Furthermore, the criteria that can support the choice of the automation solution are the following:

- *Articles characteristics*
- *Building characteristics*
- *Performance objectives*
- *Mix capex/opex*
- *Integration with existing systems*

The second aspect related to the survey response involves analyzing the Robots-as-a-Service (RaaS) paradigm, which offers the opportunity to rent a portion of a robotic fleet.
This paradigm allows for crucial advantages in the omnichannel context, such as flexibility, scalability, and impacts on investment costs.

Moreover, the Raas allows to address the following challenges of the omnichannel context: "*Demand variability (often in a non-repetitive way)*", "*High peaks in terms of entity, period, duration*", "*Growth rate difficult to predict (unpredictability of the environment)*", "*Incidence of the different channels that change in time*" and "*High growth rate of the online channel*".

This chapter also analyzed the Raas requirements needed for the correct functioning of this solution:

- *Standardization of the robots*
- *Software requirements*
- *Development of a market*
- *Mobility*

Furthermore, an analysis of the Raas business models is performed, and two possibilities are identified:

- *Time-based*, where a company will provide a service and bill the customer for the entire duration.
- *Usage-based*, in which customers pay a service's usage for each performed action.

From the analysis conducted, the RaaS paradigm emerges as a promising approach for achieving the flexibility and scalability required in omnichannel automation. However, it is worth noting that this solution is still in the nascent stages of market development, with widespread adoption yet to be realized.

8.2. Academic implications

From an academic perspective, this Thesis addresses several critical gaps that have emerged from the current body of scientific research in omnichannel warehousing. Specifically, it offers a comprehensive framework that starts from the challenges related to omnichannel operations and it delves into the impact of these challenges on warehouse, aiming to thoroughly analyze warehouse configuration in the omnichannel context.

Within this Thesis, different academic contributions are provided to the existing literature.

The first contribution of this Thesis is the establishing of a comprehensive list of challenges faced by omnichannel warehouses. Furthermore, by assigning scores to these challenges based on the literature, case studies, and results of the experts' group, the research provides insights into the relative significance of each challenge. This approach highlights differences between the perceived importance of challenges in the existing literature and the practical scenarios revealed in case studies.

The second contribution to the existing literature is a structured analysis of how these challenges influence warehouse configuration and the effective countermeasures to address these challenges. Through this analysis, the research highlights the warehouse areas and management variables most affected by omnichannel challenges, emphasizing the disparity between extensively examined areas and variables and those that remain under-studied.

Additionally, the study analyzes the gap between the findings in the literature and those derived from case studies concerning the impact of omnichannel challenges on warehouse configuration.

Building upon the analysis of the impacts of omnichannel challenges on warehouse configuration, a pivotal theme for omnichannel warehouses has been developed: the strategic decision between the integration and specialization of areas across different channels.

This Thesis introduces a comprehensive framework that systematically examines the alternatives related to this critical decision, particularly in the context of storage and picking areas. Moreover, it extends the scope of analysis beyond these areas, extending the consideration related to the integration and specialization decision to the other warehouse areas, introducing five different configurations that warehouses can adopt, providing a more holistic perspective on the strategic decisions inherent in omnichannel warehousing. To facilitate the decision-making process regarding the integration and specialization of various warehouse areas and the selection among the different configurations, a set of decisional criteria has been formulated.

The last contribution of this Thesis involves the examination of an innovative theme, addressing the critical necessity of flexibility in automation within omnichannel warehousing and the potential solutions to achieve this flexibility.
A study related to the different automation solutions and their ability to enhance flexibility in the warehouse is performed, highlighting the differences between the findings from the literature review and case studies.
This Thesis identifies another possible way for enhancing warehouse flexibility, known as RaaS (Robots-as-a-Service). While this paradigm has been adopted in other contexts, its application in logistics remains relatively unexplored.

8.3. Managerial implications

This section highlights how this Thesis can be a valuable resource for managers tasked with designing warehouses in the context of omnichannel operations.

Specifically, this Thesis provides valuable insights for managers engaged in omnichannel warehouse design by increasing their understanding of the complexities inherent in this environment.

Furthermore, examining omnichannel challenges and their implications for warehouse operations provides valuable assistance to managers regarding the warehouse design process. This assistance encompasses understanding how these challenges can affect different warehouse areas and managerial factors, along with practical recommendations for implementing effective strategies to mitigate these challenges.

This Thesis also extends substantial support to managers who face the pivotal decision in the design of an omnichannel warehouse handling multiple channels within the same facility: the choice between integrating or separating warehouse areas for different channels.

It places specific emphasis on the storage and picking areas, providing a comprehensive exploration of the rationale for either integrating or separating each of these two crucial areas, while delineating their respective advantages and disadvantages and offering insights into when it is preferable to opt for a specific choice.

This comprehensive analysis empowers managers to thoroughly understand the options available to them concerning the integration or separation of these two key areas. The support provided to managers concerning the integration or separation decision extends beyond the storage and picking activities and it encompasses all other areas within the warehouse, providing managers with a comprehensive overview of available alternatives and offering practical examples of warehouses that have made different choices in this regard.
A comprehensive list of influential factors is provided to further aid managers in selecting the configuration that aligns best with their requirements. This list assists them in making the most suitable decision for their unique circumstances.

Another valuable aspect of this Thesis for managers is its contribution to enhancing flexibility of automation solutions, an essential requirement in omnichannel warehouses. To aid managers in selecting the appropriate automation technology for their warehouse, this Thesis presents a comprehensive overview of all available automation solutions, complemented by an in-depth analysis of the respective level of flexibility. Furthermore, the Thesis introduces managers to a new paradigm, the RaaS paradigm, which can be implemented in their automated warehouses to increase flexibility of automation.

8.4. Limitations and further developments

This section presents the critical limitations of this study and proposes avenues for future research.

One of the primary limitations of this study is the relatively small number of companies included in the case studies analysis (16). While these companies provide valuable insights into various industries operating in omnichannel environments, the limited sample size may only partially represent part of the population of omnichannel companies. A significant future development is expanding the scope of companies involved in the study to validate and generalize the findings with a larger and more diverse set of companies.

Additionally, the case studies in this Thesis primarily focused on warehouses located in Italy. To gain a more comprehensive understanding of omnichannel warehousing on a global scale, future research could extend the geographical area of analysis to include warehouses outside of Italy, providing valuable insights into the current state of omnichannel warehousing worldwide.

Another limitation relates to the approach used to derive the main insights from the case studies and literature review analysis. In formulating conclusions for various research questions, the author relied solely on counting the citations for various elements from the papers and case studies. However, this simplistic method of citation counting exhibits certain drawbacks, as it fails to account for the relative importance of each citation.

Instead, it treats all mentions equally and assigns them identical weight in the final results. A potential enhancement to this approach could involve assigning varying weights based on the significance of the papers or case studies, or considering the importance attributed to the paper or case study within the research context.

The five configuration alternatives concerning the choice between integrating and specializing different areas across channels are implicitly examined, with insights derived from the examples provided by the case studies.
Starting from the formalization of the existence of these configurations, it becomes evident the need for future research about a more in-depth study of these configurations.

The last limitation of this work is related to the RaaS paradigm. Given the novelty of this topic in both academic research and real-world case applications, the research conducted in this Thesis is a starting point for potential future developments. One possible direction for future research is introducing a quantitative evaluation of this solution, potentially using simulation approaches. This would allow for a thorough examination and estimation of the RaaS paradigm's benefit within the omnichannel warehouse's context.

Furthermore, the analysis of the RaaS paradigm undertaken in this Thesis could be revisited, especially when this paradigm has matured. This would involve analyzing the market and adoption trends to assess the development status of this paradigm, which is currently in its early stages of evolution.

Bibliography

[1] *Logistics Management course,* 2021 - 2022.

[2] G. Marchet, M. Melacini, S. Perotti, M. Rasini and E. Tappia, "Business logistics models in omni-channel: a classification framework and empirical analysis," *International Journal of Physical Distribution and Logistics Management,* vol. 48, pp. 439-464, 2018.

[3] J. H. Kembro, A. Norrman and E. Eriksson, "Adapting warehouse operations and design to omni-channel logistics: A literature review and research agenda," *International Journal of Physical Distribution and Logistics Management,* vol. 48, pp. 890-912, 2018.

[4] K. Mahadevan and S. Joshi, "Omnichannel retailing: a bibliometric and network visualization analysis," *Benchmarking,* vol. 29, pp. 1113-1136, 2022.

[5] D. R. Bell, S. Gallino and A. Moreno, "How to win in an omni-channel world," *MIT Sloan Management Review,* vol. 55, pp. 45-54, 2014.

[6] J. H. Kembro and A. Norrman, "Warehouse configuration in omni-channel retailing: a multiple case study," *International Journal of Physical Distribution and Logistics Management,* vol. 50, pp. 509-533, 2020.

[7] N. Faber, M. B. M. de Koster and A. Smidts, "Organizing warehouse management," *International Journal of Operations and Production Management,* vol. 33, pp. 1230-1256, 2013.

[8] J. H. Kembro and A. Norrman, "Which future path to pick? A contingency approach to omnichannel warehouse configuration," *International Journal of Physical Distribution and Logistics Management,* vol. 51, pp. 48-75, 2021.

[9] D. A. Gioia, K. G. Corley and A. L. Hamilton, "Seeking qualitative rigor in inductive research," *Organizational Research Methods,* vol. 16, pp. 15-31, 2012.

[10] S. Winkelhaus, E. H. Grosse and C. H. Glock, "Job satisfaction: An explorative study on work characteristics changes of employees in Intralogistics 4.0," *Journal of Business Logistics,* vol. 43, p. 343–367, 2022.

[11] M. Binder and J. S. Edwards, "Using grounded theory method for theory building in operations management research: a study on inter-firm relationship governance," *International Journal of Operations & Production Management,* vol. 30, pp. 232-259, 2010.

[12] M. G. Pratt, "From the editors: For the lack of a boilerplate: Tips on writing up (and reviewing) qualitative research," *Academy of Management Journal,* vol. 52, pp. 856-862, 2009.

[13] S. E. Fawcett, M. A. Waller, J. W. Miller, M. A. Schwieterman, B. T. Hazen and R. E. Overstreet, "A Trail Guide to Publishing Success: Tips on Writing Influential Conceptual, Qualitative, and Survey Research," *Journal of Business Logistics,* vol. 35, pp. 1-16, 2014.

[14] C. F. Durach, J. H. Kembro and A. Wieland, "A New Paradigm for Systematic Literature Reviews in Supply Chain Management," *International Journal of Physical Distribution and Logistics Management,* vol. 51, pp. 1090-1107, 2021.

[15] D. Denyer and D. Tranfield, "Producing a systematic review," *The sage handbook of organizational research methods,* vol. 39, pp. 672-689, 2009.

[16] D. Denyer, D. Tranfield and J. E. Van Aken, "Developing Design Propositions through Research Synthesis," *Organization Studies,* vol. 29, pp. 393-413, 2008.

[17] E. H. Grosse, S. M. Dixon, W. P. Neumann and C. H. Glock, "Using qualitative interviewing to examine human factors in warehouse order picking: technical note," *International Journal of Logistics Systems and Management,* vol. 23, pp. 499-518, 2016.

[18] V. Venkatesh, H. Bala and T. A. Sykes, "Impacts of information and communication technology implementations on employees' jobs in service organizations in India: A multi-method longitudinal field study," *Production and Operations Management,* vol. 19, pp. 591-613, 2010.

[19] K. M. Eisenhardt, "Building Theories from Case Study Research," *The Academy of Management Review ,* vol. 14, pp. 532-550, 1989.

[20] N. Anand, H. K. Gardner and T. Morris, "Knowledge-based innovation: Emergence and embedding of new practice areas in management consulting firms," *Academy of Management Journal,* vol. 50, pp. 406-428, 2007.

[21] J. Zhang, S. Onal, R. Das, A. Helminsky and S. Das, "Fulfilment time performance of online retailers – an empirical analysis," *International Journal of Retail and Distribution Management,* vol. 47, pp. 493-510, 2019.

[22] M. Savelsbergh and T. Van Woensel, "City logistics: Challenges and opportunities," *Transportation Science,* vol. 50, pp. 579-590, 2016.

[23] E. Eriksson, A. Norrman and J. H. Kembro, "Contextual adaptation of omni-channel grocery retailers' online fulfilment centres," *International Journal of Retail and Distribution Management,* vol. 47, pp. 1232-1250, 2019.

[24] P. J. Daugherty, Y. Bolumole and S. J. Grawe, "The new age of customer impatience: An agenda for reawakening logistics customer service research," *International Journal of Physical Distribution and Logistics Management,* vol. 49, pp. 4-32, 2019.

[25] H. Min, "Exploring Omni-Channels for Customer-Centric e-Tailing," *Logistics,* vol. 5, p. 31, 2021.

[26] M. Janjevic, D. Merchán and M. Winkenbach, "Designing multi-tier, multi-service-level, and multi-modal last-mile distribution networks for omni-channel operations," *European Journal of Operational Research,* vol. 294, pp. 1059-1077, 2021.

[27] A. Risberg and H. Jafari, "Last mile practices in e-commerce: framework development and empirical analysis of Swedish firms," *International Journal of Retail and Distribution Management,* vol. 50, pp. 942-961, 2022.

[28] S. Derhami, B. Montreuil and G. Bau, "Assessing product availability in omnichannel retail networks in the presence of on-demand inventory transshipment and product substitution," *Omega (United Kingdom),* vol. 102, p. 102315, 2021.

[29] K. H. Leung, D. Y. Mo, G. T. S. Ho, C. H. Wu and G. Q. Huang, "Modelling near-real-time order arrival demand in e-commerce context: a machine learning predictive methodology," *Industrial Management and Data Systems,* vol. 120, pp. 1149-1174, 2020.

[30] A. Hübner, J. Wollenburg and A. Holzapfel, "Retail logistics in the transition from multi-channel to omni-channel," *International Journal of Physical Distribution and Logistics Management,* vol. 46, pp. 562-583, 2016.

[31] L. Wei, R. Kapuscinski and S. Jasin, "Shipping consolidation across two warehouses with delivery deadline and expedited options for E-commerce and Omni-channel Retailers," *Manufacturing and Service Operations Management,* vol. 23, pp. 1634-1650, 2021.

[32] M. Lafkihi, S. Pan and E. Ballot, "Freight transportation service procurement: A literature review and future research opportunities in omnichannel E-commerce," *Transportation Research Part E,* vol. 125, pp. 348-365, 2019.

[33] A. Hübner, A. Holzapfel and H. Kuhn, "Operations management in multi-channel retailing: an exploratory study," *Operations Management Research,* vol. 8, pp. 84-100, 2015.

[34] S. Saghiri, E. Aktas and M. Mohammadipour, "Grocery omnichannel perishable inventories: performance measures and influencing factors," *International Journal of Operations and Production Management,* vol. ahead of print, p. ahead of print, 2023.

[35] H. Buldeo Rai, S. Verlinde and C. Macharis, "City logistics in an omnichannel environment. The case of Brussels," *Case Studies on Transport Policy,* vol. 7, pp. 310-317, 2019.

[36] R. Larke, M. Kilgour and H. O'Connor, "Build touchpoints and they will come: transitioning to omnichannel retailing," *International Journal of Physical Distribution and Logistics Management,* vol. 48, pp. 465-483, 2018.

[37] J. L. G. de Borba, M. R. Magalhães, R. S. Filgueiras and M. Bouzon, "Barriers in omnichannel retailing returns: a conceptual framework," *International Journal of Retail and Distribution Management,* vol. 49, pp. 121-143, 2021.

[38] A. Risberg, "A systematic literature review on e-commerce logistics: towards an e-commerce and omni-channel decision framework," *International Review of Retail, Distribution and Consumer Research,* vol. 33, pp. 67-91, 2023.

[39] S. Kumar, J.-B. Sheu and T. Kundu, "Planning a parts-to-picker order picking system with consideration of the impact of perceived workload," *Transportation Research Part E: Logistics and Transportation Review,* vol. 173, p. 103088, 2023.

[40] H. M. G. Albán, T. Cornelissens and K. Sörensen, "Scattered storage assignment: Mathematical model and valid inequalities to optimize the intra-order item distances," *Computers and Operations Research,* vol. 149, p. 106022, 2023.

[41] S. Onal, W. Zhu and S. Das, "Order picking heuristics for online order fulfillment warehouses," *International Journal of Production Economics,* vol. 256, p. 108747, 2023.

[42] N. Boysen, S. Schwerdfeger and K. Stephan, "A review of synchronization problems in parts-to-picker warehouses," *European Journal of Operational Research,* vol. 307, pp. 1374-1390, 2023.

[43] S. Wagner and L. Mönch, "A variable neighborhood search approach to solve the order batching problem with heterogeneous pick devices," *European Journal of Operational Research,* vol. 304, p. 461–475, 2023.

[44] J. H. Kembro, E. Eriksson and A. Norrman, "Sorting out the sorting in omnichannel retailing," *Journal of Business Logistics,* vol. 43, pp. 593-622, 2022.

[45] N. Boysen, R. de Koster and F. Weidinger, "Warehousing in the e-commerce era: A survey," *European Journal of Operational Research,* vol. 277, pp. 396-411, 2019.

[46] M. Heininger, "Predicting Packaging Sizes Using Machine Learning," *Operations Research Forum,* vol. 3, p. 43, 2022.

[47] P. Berling, L. Johansson and J. Marklund, "Controlling inventories in omni/multi-channel distribution systems with variable customer order-sizes," *Omega (United Kingdom),* vol. 114, p. 102745, 2023.

[48] J. Wollenburg, A. Holzapfel, A. Hübner and H. Kuhn, "Configuring retail fulfillment processes for omni-channel customer steering," *International Journal of Electronic Commerce,* vol. 22, pp. 540-575, 2018.

[49] D. Zhang, L. G. Pee and L. Cui, "Artificial intelligence in E-commerce fulfillment: A case study of resource orchestration at Alibaba's Smart Warehouse," *International Journal of Information Management,* vol. 57, p. 102304, 2021.

[50] J. Wollenburg, A. Hübner, H. Kuhn and A. Trautrims, "From bricks-and-mortar to bricks-and-clicks: Logistics networks in omni-channel grocery retailing," *International Journal of Physical Distribution and Logistics Management,* vol. 48, pp. 415-438, 2018.

[51] S. L. K. Freichel, J. Wollenburg and J. K. Wörtge, "The role of packaging in omni-channel fashion retail supply chains – How can packaging contribute to logistics efficiency?," *Logistics Research,* vol. 13, pp. 1-20, 2019.

[52] N. Boysen, R. de Koster and D. Füßler, "The forgotten sons: Warehousing systems for brick and mortar retail chains," *European Journal of Operational Research,* vol. 288, pp. 361-381, 2021.

[53] M. Bernon, J. Cullen and J. Gorst, "Online retail returns management: Integration within an omni-channel distribution context," *International Journal of Physical Distribution and Logistics Management,* vol. 46, pp. 584-605, 2016.

[54] J. H. Kembro and A. Norrman, "Exploring trends, implications and challenges for logistics information systems in omni-channels: Swedish retailers' perception," *International Journal of Retail and Distribution Management,* vol. 47, pp. 384-411, 2019.

[55] S. Wruck, I. F. A. Vis and J. Boter, "Risk control for staff planning in e-commerce warehouses," *International Journal of Production Research,* vol. 55, pp. 6453-6469, 2017.

[56] G. T. S. Ho, S. K. Choy, P. H. Tong and V. Tang, "A forecasting analytics model for assessing forecast error in e-fulfilment performance," *Industrial Management and Data Systems,* vol. 122, p. 2583–2608, 2022.

[57] M. Schiffer, N. Boysen, P. S. Klein, G. Laporte and M. Pavone, "Optimal Picking Policies in E-Commerce Warehouses," *Management Science,* vol. 68, pp. 7497-7517, 2022.

[58] J. S. Lamb, S. C. Wirasinghe and N. M. Waters, "Planning delivery-by-drone micro-fulfilment centres," *Transportmetrica A: Transport Science,* 2022.

[59] M. F. Sorkun, I. Ö. Yumurtacı Hüseyinoğlu and G. Börühan, "Omni-channel capability and customer satisfaction: mediating roles of flexibility and operational logistics service quality," *International Journal of Retail and Distribution Management,* vol. 48, pp. 629-648, 2020.

[60] *Research Observatory "Gino Marchet"*, 2021.

[61] Y. Jaghbeer, R. Hanson and M. Johansson, "Automated order picking systems and the links between design and performance: a systematic literature review," *International Journal of Production Research,* vol. 58, pp. 4489-4505, 2020.

[62] K. Azadeh, R. De Koster and D. Roy, "Robotized and automated warehouse systems: Review and recent developments," *Transportation Science,* vol. 53, pp. 917-945, 2019.

[63] K.-Y. Hu and T.-S. Chang, "An innovative automated storage and retrieval system for B2C e-commerce logistics," *International Journal of Advanced Manufacturing Technology,* vol. 48, pp. 297-305, 2010.

[64] L. Custodio and R. Machado, "Flexible automated warehouse: a literature review and an innovative framework," *International Journal of Advanced Manufacturing Technology,* vol. 106, pp. 533-558, 2020.

[65] Y. A. Bozer and F. J. Aldarondo, "A simulation-based comparison of two goods-to-person order picking systems in an online retail setting," *International Journal of Production Research,* vol. 56, pp. 3838-3858, 2018.

[66] N. Litvak and M. Vlasiou, "A survey on performance analysis of warehouse carousel systems," *Statistica Neerlandica,* vol. 64, pp. 401-447, 2010.

[67] H. Li, J. Lyu, L. Zhen and D. Zhuge, "A joint optimisation of multi-item order batching and retrieving problem for low-carbon shuttle-based storage and retrieval system," *Cleaner Logistics and Supply Chain,* vol. 4, p. 100042, 2022.

[68] Y. Li and Z. Li, "Shuttle-Based Storage and Retrieval System: A Literature Review," *Sustainability (Switzerland),* vol. 14, p. 14347, 2022.

[69] B. Y. Ekren, "A simulation-based experimental design for SBS/RS warehouse design by considering energy related performance metrics," *Simulation Modelling Practice and Theory,* vol. 98, p. 101991, 2020.

[70] B. Y. Ekren and B. Arslan, "A reinforcement learning approach for transaction scheduling in a shuttle-based storage and retrieval system," *International Transactions in Operational Research,* vol. 0, pp. 1-22, 2022.

[71] Y. Yu, J. Yang and X. Guo, "Retrieval sequencing in autonomous vehicle storage and retrieval systems," *International Journal of Production Research,* 2023.

[72] A. Alfieri, M. Cantamessa, A. Monchiero and F. Montagna, "Heuristics for puzzle-based storage systems driven by a limited set of automated guided vehicles," *Journal of Intelligent Manufacturing,* vol. 23, no. 65, pp. 1695-1705, 2012.

[73] K. R. Gue, K. Furmans, Z. Seibold and O. Uludag, "GridStore: A puzzle-based storage system with decentralized control," *IEEE Transactions on Automation Science and Engineering,* vol. 11, pp. 429-438, 2014.

[74] N. Zaerpour, Y. Yu and R. B. M. de Koster, "Optimal two-class-based storage in a live-cube compact storage system," *IISE Transactions,* vol. 49, pp. 653-668, 2017.

[75] B. Zou, R. de Koster and X. Xu, "Evaluating dedicated and shared storage policies in robot-based compact storage and retrieval systems," *ERIM Report Series Reference,* vol. 52, pp. 788-811, 2016.

[76] X. Chen, P. Yang and Z. Shao, "Simulation-based time-efficient and energy-efficient performance analysis of an overhead robotic compact storage and retrieval system," *Simulation Modelling Practice and Theory,* vol. 119, p. 102560, 2022.

[77] D. Ko and J. Han, "A rollout heuristic algorithm for order sequencing in robotic compact storage and retrieval systems," *Expert Systems with Applications,* vol. 203, p. 117396, 2022.

[78] M. Beckschäfer, S. Malberg, K. Tierney and C. Weskamp, "Simulating storage policies for an automated grid-based warehouse system," *Lecture Notes in Computer Science,* vol. 10572, pp. 468-482, 2017.

[79] B. Zou, R. de Koster and X. Xu, "Operating policies in robotic compact storage and retrieval systems," *Transportation Science,* vol. 52, pp. 788-811, 2018.

[80] M. Qi, X. Li, X. Yan and C. Zhang, "On the evaluation of AGVS-based warehouse operation performance," *Simulation Modelling Practice and Theory,* vol. 87, pp. 379-394, 2018.

[81] "Mobile Industrial Robots," [Online]. Available: https://www.mobile-industrial-robots.com/it/approfondimenti/inizia-con-gli-amr/agv-vs-amr-whats-the-difference/. [Accessed 2023].

[82] G. Fragapane, R. de Koster, F. Sgarbossa and J. O. Strandhagen, "Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda," *European Journal of Operational Research,* vol. 294, pp. 405-426, 2021.

[83] Y. Zhuang, Y. Zhou, E. Hassini, Y. Yuan and X. Hu, "Rack retrieval and repositioning optimization problem in robotic mobile fulfillment systems,"

Transportation Research Part E: Logistics and Transportation, vol. 167, p. 102920, 2022.

[84] X. Li, X. Yang, C. Zhang and M. Qi, "A simulation study on the robotic mobile fulfillment system in high-density storage warehouses," *Simulation Modelling Practice and Theory,* vol. 112, p. 102366, 2021.

[85] S. Teck and R. Dewil, "Optimization models for scheduling operations in robotic mobile fulfillment systems," *Applied Mathematical Modelling,* vol. 111, pp. 270-287, 2022.

[86] C. Chi, S. Wu, D. Xia and Y. Wu, "Dynamic Picking and Storage Optimization of Robotic Picking Systems," *Wireless Personal Communications,* vol. 128, pp. 1-23, 2023.

[87] D. Roy, S. Nigam, R. de Koster, I. Adan and J. Resing, "Robot-storage zone assignment strategies in mobile fulfillment systems," *Transportation Research Part E: Logistics and Transportation Review,* vol. 112, pp. 119-142, 2019.

[88] A. Rimélé, M. Gamache, M. Gendreau, P. Grangier and L.-M. Rousseau, "Robotic mobile fulfillment systems: a mathematical modelling framework for e-commerce applications," *International Journal of Production Research,* vol. 60, pp. 3589-3605, 2022.

[89] L. Xie, H. Li and L. Luttmann, "Formulating and solving integrated order batching and routing in multi-depot AGV-assisted mixed-shelves warehouses," *European Journal of Operational Research,* vol. 307, pp. 713-730, 2023.

[90] "Built In," [Online]. Available: https://builtin.com/robotics/robotics-as-a-service-raas. [Accessed 2023].

[91] A. Buerkle, W. Eaton, A. Al-Yacoub, M. Zimmer, P. Kinnel, M. Henshaw and Ma, "Towards industrial robots as a service (IRaaS): Flexibility, usability, safety and business models," *Robotics and Computer-Integrated Manufacturing,* vol. 81, p. 102484, 2023.

[92] "Geekplus," [Online]. Available: https://blog.geekplus.com/en/robotics-blog/everything-you-need-to-know-about-robots-as-a-service-0 . [Accessed 2023].

[93] "Supply Chain Dive," [Online]. Available: https://www.supplychaindive.com/news/robots-as-a-service-a-low-risk-path-to-warehouse-automation/562136/. [Accessed 2023].

[94] "Insights," [Online]. Available: https://insights.rlist.io/p/report-page-3-raas-monetization.html. [Accessed 2023].

[95] "Control," [Online]. Available: https://control.com/news/what-does-the-robot-as-a-service-model-look-like-for-warehouse-automation/ . [Accessed 2023].

[96] "Locus Robotics," [Online]. Available: https://locusrobotics.com/why-locus/raas/ . [Accessed 2023].

[97] "InVia Robotics," [Online]. Available: https://inviarobotics.com/robotics-as-a-service/ . [Accessed 2023].

[98] "HaiRobotics," [Online]. Available: https://www.hairobotics.com/hai-raas. [Accessed 2023].

[99] C. Guo, R. G. Thompson, G. Foliente and X. T. R. Kong, "An auction-enabled collaborative routing mechanism for omnichannel on-demand logistics through transshipment," *Transportation Research Part E: Logistics and Transportation Review,* vol. 146, p. 102206, 2021.

[100] S. Ma, "Fast or free shipping options in online and Omni-channel retail? The mediating role of uncertainty on satisfaction and purchase intentions," *International Journal of Logistics Management,* vol. 28, pp. 1099-1122, 2017.

[101] N. Kim, B. Montreuil, W. Klibi and M. Z. Babai, "Network inventory deployment for responsive fulfillment," *International Journal of Production Economics,* vol. 255, p. 108664, 2023.

[102] C. Dethlefs, M. Ostermeier and A. Hübner, "Rapid fulfillment of online orders in omnichannel grocery retailing," *EURO Journal on Transportation and Logistics,* vol. 11, p. 100082, 2022.

[103] R. M. Difrancesco, I. M. van Schilt and M. Winkenbach, "Optimal in-store fulfillment policies for online orders in an omni-channel retail environment," *European Journal of Operational Research,* vol. 293, pp. 1058-1076, 2021.

[104] S. Mou, "Integrated Order Picking and Multi-Skilled Picker Scheduling in Omni-Channel Retail Stores," *Mathematics,* vol. 10, p. 1484, 2022.

[105] M. Melacini, S. Perotti, M. Rasini and E. Tappia, "E-fulfilment and distribution in omni-channel retailing: a systematic literature review," *International Journal of Physical Distribution and Logistics Management,* vol. 48, pp. 391-414, 2018.

[106] S. K. Jena, "Impact of bundling on the omnichannel supply chain under price competition," *Journal of Business and Industrial Marketing,* vol. 37, pp. 2468-2487, 2022.

[107] A. Hübner, A. Holzapfel and H. Kuhn, "Distribution systems in omni-channel retailing," *Business Research,* vol. 9, pp. 255-296, 2016.

[108] Q. H. Duong, L. Zhou, M. Meng, P. Ieromonachou and D. T. Nguyen, "Understanding product returns: A systematic literature review using machine learning and bibliometric analysis," *International Journal of Production Economics,* vol. 243, p. 108340, 2022.

[109] A. Hübner, H. Kuhn and J. Wollenburg, "Last mile fulfilment and distribution in omni-channel grocery retailing: A strategic planning framework," *International Journal of Retail and Distribution Management,* vol. 44, pp. 228-247, 2016.

[110] P. Sawicki and H. Sawicka, "Optimisation of the two-tier distribution system in omni-channel environment," *Energies,* vol. 14, p. 7700, 2021.

[111] B. Davis-Sramek, R. Ishfaq, B. J. Gibson and C. Defee, "Examining retail business model transformation: a longitudinal study of the transition to omnichannel order fulfillment," *International Journal of Physical Distribution and Logistics Management,* vol. 50, pp. 557-576, 2020.

[112] V. E. Castillo, J. E. Bell, W. J. Rose and A. M. Rodrigues, "Crowdsourcing Last Mile Delivery: Strategic Implications and Future Research Directions," *Journal of Business Logistics,* vol. 39, pp. 7-25, 2018.

[113] M. Vazquez-Noguerol, J. Comesaña-Benavides, R. Poler and J. C. Prado-Prado, "An optimisation approach for the e-grocery order picking and delivery problem," *Central European Journal of Operations Research,* vol. 30, pp. 961-990, 2022.

[114] E. Simangunsong and I. E. Subagyo, "Investigation and analysis of omnichannel logistics models: A study in the electronic retail industry in Indonesia," *Operations and Supply Chain Management,* vol. 14, pp. 221-231, 2021.

[115] M. M. Zarei, J. Chaparro-Pelaez and Á. F. Agudo-Peregrina, "Identifying consumer’s last-mile logistics beliefs in omni-channel environment," *Economic Research-Ekonomska Istrazivanja,* vol. 33, pp. 1796-1812, 2020.

[116] A. Hübner, J. Hense and C. Dethlefs, "The revival of retail stores via omnichannel operations: A literature review and research framework," *European Journal of Operational Research,* vol. 302, pp. 799-818, 2022.

[117] D. Taylor, S. Brockhaus, A. M. Knemeyer and P. Murphy, "Omnichannel fulfillment strategies: defining the concept and building an agenda for future inquiry," *International Journal of Logistics Management,* vol. 30, pp. 863-891, 2019.

[118] B. Mrutzek-Hartmann, H. Kotzab, I. Ö. Yumurtacı Hüseyinoğlu and S. Kühling, "Omni-channel retailing resources and capabilities of SME specialty retailers – insights from Germany and Turkey," *International Journal of Retail and Distribution Management,* vol. 50, pp. 1129-115, 2022.

[119] S. A. B. Rasmi, Y. Wang and H. Charkhgard, "Wave order picking under the mixed-shelves storage strategy: A solution method and advantages," *Computers and Operations Research,* vol. 137, p. 105556, 2022.

[120] J. Liu, S.-Y. Liew, B. Y. Ooi and D. Qin, "Dynamic Order-Based Scheduling Algorithms for Automated Retrieval System in Smart Warehouses," *IEEE Access,* vol. 9, pp. 158340-158352, 2021.

[121] D. Claeys, I. Adan and O. Boxma, "Stochastic bounds for order flow times in parts-to-picker warehouses with remotely located order-picking workstations," *European Journal of Operational Research,* vol. 254, pp. 895-906, 2016.

[122] R. Andriansyah, L. F. P. Etman, I. J. B. F. Adan and J. E. Rooda, "Design and analysis of an automated order-picking workstation," *Journal of Simulation,* vol. 8, pp. 151-163, 2014.

[123] B. C. Park, E. H. Frazelle and J. A. White, "Buffer sizing models for end-of-aisle order picking systems ," *IIE Transactions (Institute of Industrial Engineers),* vol. 31, pp. 31-38, 1999.

[124] R. Manzini, R. Accorsi, G. Baruffaldi, T. Cennerazzo and M. Gamberi, "Travel time models for deep-lane unit-load autonomous vehicle storage and retrieval system (AVS/RS)," *International Journal of Production Research,* vol. 54, pp. 4286-4304, 2016.

[125] N. Zaerpour, Y. Yu and R. de Koster, "Small is beautiful: A framework for evaluating and optimizing live-cube compact storage systems," *Transportation Science,* vol. 51, pp. 34-51, 2017.

[126] J. Hao, J. Yu, Y. Yu and L. L. Zhang, "Optimal design of a 3D compact storage system with the I/O port at the lower mid-point of the storage rack," *International Journal of Production Research,* vol. 53, pp. 5153-5173, 2015.

[127] B. Wang, X. Yang and M. Qi, "Order and rack sequencing in a robotic mobile fulfillment system with multiple picking stations," *Flexible Services and Manufacturing Journal,* vol. 35, pp. 509-547, 2023.

[128] A. Bolu and O. Korcak, "Adaptive Task Planning for Multi-Robot Smart Warehouse," *IEEE Access,* vol. 9, pp. 2746-27358, 2021.

[129] P. Yang, G. Jin and G. Duan, "Modelling and analysis for multi-deep compact robotic mobile fulfilment system," *International Journal of Production Research,* vol. 60, pp. 4727-4742, 2022.

[130] M. Merschformann, T. Lamballais, M. B. M. de Koster and L. Suhla, "Decision rules for robotic mobile fulfillment systems," *Operations Research Perspectives,* vol. 127, p. 102789, 2019.

[131] T. Lamballais, D. Roy and M. B. M. de Koster, "Estimating performance in a Robotic Mobile Fulfillment System," *European Journal of Operational Research,* vol. 256, pp. 976-990, 2017.

[132] Y. Zhuang, Y. Zhou, Y. Yuan, X. Hu and E. Hassini, "Order picking optimization with rack-moving mobile robots and multiple workstations," *European Journal of Operational Research,* vol. 300, pp. 527-544, 2022.

[133] H. Qin, J. Xiao, D. Ge, L. Xin, J. Gao, S. He, H. Hu and J. G. Carlssond, "JD.com: Operations Research Algorithms Drive Intelligent Warehouse Robots to Work," *Interfaces,* vol. 52, pp. 42-55, 2022.

[134] R. Yuan, J. Li, W. Wang, J. Dou and L. Pan, "Storage Assignment Optimization in Robotic Mobile Fulfillment Systems," *Complexity,* vol. 2021, p. 4679739, 2021.

[135] R. Yuan, J. Li, X. Wang and L. He, "Multirobot Task Allocation in e-Commerce Robotic Mobile Fulfillment Systems," *Mathematical Problems in Engineering,* vol. 2021, p. 6308950, 2021.

[136] J. Zhang, F. Yang and X. Weng, "A building-block-based genetic algorithm for solving the robots allocation problem in a robotic mobile fulfilment system," *Mathematical Problems in Engineering,* vol. 2019, p. 6153848, 2019.

[137] R. S. Teck and R. Dewil, "A bi-level memetic algorithm for the integrated order and vehicle scheduling in a RMFS," *Applied Soft Computing,* vol. 121, p. 108770, 2022.

[138] N. Yang, "Evaluation of the Joint Impact of the Storage Assignment and Order Batching in Mobile-Pod Warehouse Systems," *Mathematical Problems in Engineering,* vol. 2022, p. 9148001, 2022.

[139] L. Zhu and H. Li, "Workstation layout strategies in Robotic Mobile Fulfillment Systems considering carbon emissions," *Cleaner Logistics and Supply Chain,* vol. 4, p. 100050, 2022.

A Appendix A: RaaS application

The list of the existing RaaS applications are mentioned in *Table A.1*.

Name	Function	Typology	Company	Country	Pricing
AMR	Pick	AMRaaS	Ronavi Robotics	Russia	/
Chuck	Pick	AMRaaS	6 River	USA	US$250K for 8 robots (1st yr) + $50K/annual after
FetchCore	Pick	AMRaaS	Fetch Robotics	USA	annual or monthly license/robot
LocusBots	Pick	AMRaaS	Locus Robotics	USA	/
Flex Series	Pick	AMRaaS	ForwardX Robotics	China	/
Geek+ Robots	Pick	Picker-as-a-Service	Geek+ Robotics	China	Per transaction/per pick
InVia Robot Pickers	Pick	Picker-as-a-Service	InVia Robotics	USA	10 cents per pick
TORU	Pick	Picker-as-a-Service	Magazino	Germany	6 cents per pick
Haipick	Pick	Picker-as-a-Service	Hai Robotics	China	/

Table A.1: RaaS applications (Source [94] *and* [95]*)*

The description of the companies and solutions mentioned in the *Table A.1* is the following [94]:

- Ronavi Robotics is a Russia-based robotics firm that provides autonomous mobile Robots-as-a-Service (AMRaaS). Its primary offering is the H1500 AMR, which can handle payloads of up to 1500 kg.
- 6 River Systems is a US-based company that provides collaborative mobile robots for warehouses. Its flagship product is the autonomous warehouse robot, Chuck, which collaborates with warehouse workers on task guidance, picking and load carrying. 6 River's offering runs at about $250,000 for 8 robots in the first year, with annual maintenance costs of around $50,000 after that.
- Fetch Robotics is a robotics company based in California, USA. The company is developing the VirtualConveyor line of autonomous mobile robots (AMR) that help transport items within warehouses, deliver items to conveyor lines, pick up and drop off carts and carry pallets to their target locations. These AMRs are available based on an annual or monthly licensing model.
- Locus Robotics is a US-based robotics company that provides autonomous mobile robot-as-a-service solutions to warehouses. The shoulder-height Locus Robots autonomously move to picking locations where workers can load items onto the configured bins. Once the robots have fulfilled their picking mission, they automatically head toward the packing/shipping stations.
  Locus Robots-as-a-Service (RaaS) is a smart, innovative, subscription-based program that makes it easy to add powerful autonomous mobile robotics to warehouse operations [96].
- ForwardX Robotics is a Beijing-based robotics company. The company builds computer vision-powered autonomous mobile robots (AMRs) for warehouse automation and attempts to balance technological outreach with the changing business model. The company provides RaaS-based solutions for their mobile robots for logistics and material handling applications [95].
- Geek+ Robotics is a China-based firm that develops Goods-to-Person (GTP) robotic picking systems. Geek+ picker-AMRs can identify and pick an entire shelf or a single pallet, moving at 1.5m/s to their target locations.
  Geek+ has developed a game-changing RaaS system, integrated with operationally ready robots and AI algorithms. This includes robot leasing services, which can be tailored to customer demand, and supplementary on-site operational and management support [92].
- InVia Robotics is a US-based firm that develops mobile order-picking robots available on a pay-as-you-use model of about 10 cents per pick. InVia picker robots can pick items at different vertical locations using scissor lifts and suction cups.

Through this solution, there is no need to buy robots or be a robotics expert to reap the benefits of warehouse automation because it’s all managed by InVia. Through the Robots-as-a-Service (RaaS) model, it is possible to avoid large infrastructure investments and pay just for the productivity the automation delivers. The payment is done through a monthly subscription fee, so the customer only pays for what he needs based on your throughput requirements. Included in the price there is also the maintenance services of the equipment over the lifetime of the service contract [97].

- Magazino is a robotics company based in Germany that offers mobile picking Robots-as-a-Service (about 6 cents per pick). Its flagship picking robot, TORU, is a taller-than-human robot that can extend itself via its telescoping tower to retrieve small boxes from shelf racks, using a vacuum gripper that can pick up, lift and deposit boxes weighing up to 5.8 kg. It features a backpack compartment that can store and carry up to 16 boxes to its target location.
- HaiRobotics offers a subscription-based model for the entire robotics system solution, including operation, maintenance, and management services. HAI RaaS is flexible and easy to scale thanks to the ability to subscribe more robots to the operation when throughput demand increases [98].

B Appendix B: Additional tables

In this second appendix, additional tables are presented.

Challenge	Papers
Lead time reduction	[6] [3] [54] [23] [8] [27] [26] [31] [44] [29] [32] [35] [21] [2] [99] [100] [22] [101] [102] [103] [104] [24]
Different service levels for different channels	[23] [47]
Flexible deliveries	[26] [24] [23] [25] [6] [44]
Postponement of the cut-off/continuous receivement of orders	[6] [8]

Important to guarantee product availability	[23] [28] [27]
Dimensional difference in the order profile	[3] [30] [8] [29] [51] [31] [33] [23]
Different units of picking	[6] [50]
Different packaging and units of delivery	[6] [51]
Different order frequency	[31] [32]
Demand variability (often in a non-repetitive way)	[3] [33] [29] [34] [23] [8] [34]
High peaks in terms of entity, period, duration	[2] [35] [6] [29]
Growth rate difficult to predict (unpredictability of the environment)	/
Incidence of the different channels that change in time	[36]
Relevance of the return flow	[6] [2] [54] [27] [30] [51] [53] [37] [105] [25]

	[106] [107] [108] [24]
Increase of the phase-in/phase-out frequency	[6] [3]
High growth rate of the online channel	[54] [23] [26] [30] [51] [33] [21] [2] [105] [25] [106] [99] [100] [107] [22] [109] [110] [111] [112] [38] [113] [114] [115] [116] [39] [117]
Fragmented demand base	[26] [32] [8]
Wide product assortment requested	[8] [3] [6] [54] [27] [30] [44]

	[105] [118]
Existing building	/
Warehouse already operative	/
Software not designed for omnichannel	/
Solution development/implementation time	/

Table B.1: Papers that mentioned the different challenges

Challenge	Case studies
Lead time reduction	Case 1 Case 2 Case 3 Case 10
Different service levels for different channels	Case 10 Case 11
Flexible deliveries	Case 1 Case 3 Case 7
Postponement of the cut-off/continuous receivement of orders	Case 2
Important to guarantee product availability	Case 4 Case 5
Dimensional difference in the order profile	Case 2 Case 5 Case 9 Case 3
Different units of picking	Case 9 Case 11
Different packaging and units of delivery	Case 1 Case 3 Case 11
Different order frequency	Case 2 Case 13
Demand variability (often in a non repetitve way)	Case 2 Case 5
High peaks in terms of entity, period, duration	Case 2 Case 10
Growth rate difficult to predict (unpredictability of the environment)	Case 2

Incidence of the different channels that change in time	/
Relevance of the return flow	Case 4
Increase of the phase-in/phase-out frequency	/
High growth rate of the online channel	Case 8
Fragmented demand base	Case 3
Wide product assortment requested	Case 1 Case 11 Case 13.1
Existing building	Case 1 Case 12
Warehouse already operative	Case 13.2 Case 15 Case 1
Software not designed for omnichannel	Case 4 Case 5 Case 12
Solution development/implementation time	Case 3

Table B.2: Case studies that mentioned the different challenges

		Warehouse areas			
Challenges	**Methodology**	**Receiving**	**Put away, storage**	**Picking, sorting**	**Packing, shipping**
Lead time reduction	slr	1	3	5	1
	case study				3
Different service levels for different channels	slr		1	3	
	case study		1		
Flexible deliveries	slr			1	
	case study			1	1
	slr				

Postponement of the cut-off/continuous receivement of orders	case study				
Important to guarantee product availability	slr		2		
	case study				
Dimensional difference in the order profile	slr			4	1
	case study			1	2
Different units of picking	slr				
	case study			2	
Different packaging and units of delivery	slr	1	1		1
	case study				
Different order frequency	slr				
	case study			1	
Demand variability (often in a non repetitve way)	slr		1	1	
	case study				
High peaks in terms of entity, period, duration	slr			1	
	case study			1	
Growth rate difficult to predict (unpredictability of the environment)	slr				
	case study				
Incidence of the different channels that change in time	slr				
	case study				
Relevance of the return flow	slr	1	1	1	1
	case study			1	
	slr				

Increase of the phase-in/phase-out frequency	case study				
High growth rate of the online channel	slr			1	1
	case study				
Fragmented demand base	slr			1	1
	case study				
Wide product assortment requested	slr		1	2	
	case study				
Existing building	slr				
	case study		1		
Warehouse already operative	slr				
	case study				
Software not designed for omnichannel	slr				
	case study				
Solution development/implementation time	slr				
	case study				
Total		3	12	27	12

Table B.3: Number of papers and case studies on the different challenges in the warehouse areas

		Warehouse areas			
Challenges	**Methodology**	**Receiving**	**Put away, storage**	**Picking, sorting**	**Packing, shipping**
Lead time reduction	slr	[6]	[40] [41] [119]	[44] [45] [39] [42] [43]	[71]
	case study				Case 2 Case 3 Case 5
Different service levels for different channels	slr		[47]	[72] [45] [44]	
	case study		Case 13.2		
Flexible deliveries	slr			[44]	
	case study			Case 1	Case 7
Postponement of the cut-off/continuous receivement of orders	slr				
	case study				
Important to guarantee product availability	slr		[6] [73]		
	case study				
Dimensional difference in the order profile	slr			[44] [8] [50] [3]	[32]

	case study			Case 3	Case 3 Case 8
Different units of picking	slr				
	case study			Case 9 Case 12	
Different packaging and units of delivery	slr	[50]	[51]		[51]
	case study				
Different order frequency	slr				
	case study			Case 13	
Demand variability (often in a non repetitve way)	slr		[36]	[44]	
	case study				
High peaks in terms of entity, period, duration	slr			[74]	
	case study			Case 11	
Growth rate difficult to predict (unpredictability of the environment)	slr				
	case study				
Incidence of the different channels that change in time	slr				
	case study				
Relevance of the return flow	slr	[37]	[53]	[54]	[51]
	case study			Case 12	
Increase of the phase-in/phase-out frequency	slr				
	case study				

High growth rate of the online channel	slr			[23]	[23]
	case study				
Fragmented demand base	slr			[3]	[8]
	case study				
Wide product assortment requested	slr		[30]	[3] [8]	
	case study				
Existing building	slr				
	case study		Case 1		
Warehouse already operative	slr				
	case study				
Software not designed for omnichannel	slr				
	case study				
Solution development/implementation time	slr				

Table B.4: Papers and case studies for the different warehouse areas

		Management variables			
Challenges	**Methodology**	**IT**	**Automation**	**Planning**	**Human resources**
Lead time reduction	slr	1	1	2	
	case study		2	1	
Different service levels for different channels	slr	3			
	case study		1		
Flexible deliveries	slr				
	case study				
Postponement of the cut-off/continuous receivement of orders	slr			1	
	case study				
Important to guarantee product availability	slr	3			
	case study	3			
Dimensional difference in the order profile	slr		2		
	case study				
Different units of picking	slr				
	case study				
Different packaging and units of delivery	slr		1		
	case study				
Different order frequency	slr				
	case study				
Demand variability (often in a non repetitve way)	slr	2		2	2
	case study				3
	slr		1		2

High peaks in terms of entity, period, duration	case study		1		
Growth rate difficult to predict (unpredictability of the environment)	slr	1			1
	case study		1	1	1
Incidence of the different channels that change in time	slr				
	case study				1
Relevance of the return flow	slr	2		1	1
	case study				
Increase of the phase-in/phase-out frequency	slr		1		
	case study				
High growth rate of the online channel	slr			1	
	case study		1	1	
Fragmented demand base	slr			1	
	case study			1	
Wide product assortment requested	slr			2	
	case study			2	
Existing building	slr				
	case study		1		
Warehouse already operative	slr				
	case study				
Software not designed for omnichannel	slr				
	case study	1			
Solution development/implementation time	slr				
	case study		1		

Total		16	14	16	11

Table B.5: Number of papers and case studies on the different challenges in the management variables

		Management variables			
Challenges	**Methodology**	**IT**	**Automation**	**Planning**	**Human resources**
Lead time reduction	slr	[54]	[3]	[55] [3]	
	case study		Case 1 Case 2	Case 3	
Different service levels for different channels	slr	[54] [48] [6]			
	case study		Case 10		
Flexible deliveries	slr				
	case study				
Postponement of the cut-off/continuous receivement of orders	slr			[6]	
	case study				
Important to guarantee product availability	slr	[6] [54] [48]			
	case study	Case 1 Case 4 Case 5			
Dimensional difference in the order profile	slr		[6] [8]		

	case study				
Different units of picking	slr				
	case study				
Different packaging and units of delivery	slr		[6]		
	case study				
Different order frequency	slr				
	case study				
Demand variability (often in a non repetitve way)	slr	[54] [73]		[2] [76]	[3] [8]
	case study				Case 5 Case 11 Case 15
High peaks in terms of entity, period, duration	slr		[6]		[23] [57]
	case study		Case 13.2		
Growth rate difficult to predict (unpredictability of the environment)	slr	[54]			[55]
	case study		Case 2	Case 5	Case 5
Incidence of the different channels that change in time	slr				
	case study				Case 1
Relevance of the return flow	slr	[37] [53]		[37]	[55]
	case study				
Increase of the phase-in/phase-out frequency	slr		[6]		
	case study				

High growth rate of the online channel	slr			[39]	
	case study		Case 1	Case 8	
Fragmented demand base	slr			[32]	
	case study			Case 3	
Wide product assortment requested	slr			[6] [8]	
	case study			Case 4 Case 11	
Existing building	slr				
	case study		Case 12		
Warehouse already operative	slr				
	case study				
Software not designed for omnichannel	slr				
	case study	Case 5			
Solution development/implementation time	slr				
	case study		Case 13.2		

Table B.6: Papers and case studies for the different management variables

Papers	Case studies
[47] [3] [51] [34] [30]	Case study 9 Case study 12

Table B.7: Citations related to the integration/specialization decision in RQ2

	Integrated picking	Separated picking
Integrated storage	Case study 2 Case study 7 Case study 16	Case study 8 Case study 5 Case study 13.2 Case study 3 Case study 12
Separated storage	/	Case study 1 Case study 4 Case study 11 Case study 13.1

Table B.8: Case studies that adopted the different configurations

Papers	Case studies
[44] [51] [52] [8] (1) [6] (1) [3] [8] (2) [6] (2) [23] [57] [54] [6] (3)	Case 11 (1) Case 15 Case 5 Case 11 (2) Case 2 Case 1 Case 8

Table B.9: Citations related to the need of flexibility in RQ2

Automated picking system	Papers	Papers that mention flexibility
Automated Storage Retrieval System (AS/RS)	[63] [61] [64] [120]	[63]
Miniload	[65] [121] [122] [123]	/
Carousels and dispensers	[61] [66] [45]	/
Aisle-based shuttle - AVS/RS	[124] [71] [70] [67] [69] [68]	[71] [70] [67] [68]
Grid-based shuttle - Dynamic storage (puzzle)	[72] [73] [125] [74]	[72]
Grid-based shuttle - Static storage (RCSRS)	[75] [79] [77] [78] [76]	[75] [79] [77] [76] [78]

	[126]	
AGV/AMR - Movable rack (RMFS)	[85] [127] [83] [128] [86] [129] [45] [87] [130] [88] [131] [132] [133] [84] [134] [135] [136] [137] [65] [138] [61] [82] [139]	[83] [86] [45] [87] [88] [84] [135] [136] [138] [61] [139]
AGV/AMR - Static rack (Pick support)	[45] [89]	/
AGV/AMR - Static rack (Mobile pick)	/	/

Table B.10: Papers that mentioned the automation solutions

Automated picking system	Case studies	Case studies which mention flexibility
Automated Storage Retrieval System (AS/RS)	/	/
Miniload	Case study 5	/
Carousels and dispensers	/	/
Aisle-based shuttle - AVS/RS	Case study 1 Case study 2 Case study 11	Case study 2 Case study 11
Grid-based shuttle - Dynamic storage (puzzle)	Case study 10	Case study 10
Grid-based shuttle - Static storage (RCSRS)	Case study 3 Case study 9	Case study 3 Case study 9
AGV/AMR - Movable rack (RMFS)	Case study 13.2	Case study 13.2
AGV/AMR - Static rack (Pick support)	/	/
AGV/AMR - Static rack (Mobile pick)	Case study 13.1 Case study 14 Case study 12	Case study 13.1 Case study 14 Case study 12

Table B.11: Case studies that adopt the automation solutions

List of Figures

List of Tables